TOWARDS CLEAN AIR IN NEPAL

Benefits, Pollution Sources, and Solutions

WHERE’S MY BLUE SKY?: LIVE ART CHALLENGE IN NEPAL

Creativity and advocacy for clean air came to life at the ‘Where’s My Blue Sky?’ Live Art Challenge. Twenty-six young local artists turned their canvases into compelling statements against air pollution, raising awareness and urgency in the fight for cleaner air in Nepal. The Challenge was implemented by Sattya Media Collective, with support from the World Bank.

Artworks from the Challenge is featured throughout the report and is credited to the individual artists.

Cover Art: Creationa Waiba, Finalist, Where’s My Blue Sky?’ Live Art Challenge.

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KOREA GREEN GROWTH TRUST FUND

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Acknowledgement

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Strategic guidance was received from Dina Umali-Deininger (Regional Director, Planet Vertical, South Asia), David Sislen (World Bank Division Country Director for Maldives, Nepal, and Sri Lanka), Ann Jeannette Glauber and Christophe Crepin (both Managers of the Environment Department in the South Asia Region), Preeti Arora (Operations Manager of the Maldives, Nepal, and Sri Lanka), Steve Danyo and Maha Ahmed (both Program Leaders, Planet Vertical, South Asia).

The report carried out original pollution-policy analysis, and created a unique model for Nepal, called the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model for Nepal, or "GAINS-Nepal." The model was developed by Markus Amann (Senior Emissions Modeling Expert) and Wolfgang Schoepp (Senior Environmental Scientist) jointly with experts from the International Institute for Applied Systems Analysis (IIASA) in close partnership with local experts, namely Dr. Kundan Lal Shrestha (Kathmandu University), Professor Rejina Maskey (Tribhuvan University), and Professor Shree Raj Shakya (Tribhuvan University). The report drew on detailed air quality monitoring data provided by a team from the World Bank's Department of Environment. All potential errors in this report are the fault of the main authors, not the experts they partnered with. Experts from IIASA supporting the development of GAINS-Nepal include Pallav Purohit, Adriana Gomez-Sanabria, Gregor Kiesewetter, Zbigniew Klimont, and Fabian Wagner.

The team deeply appreciates the contribution of the World Bank staff who peer reviewed the report: Arturo Ardila Gomez (Lead Transport Economist), Daniel Mira-Salama (Lead Environmental Specialist), Craig Meisner (Senior Environmental Specialist), and Ivan Jaques (Senior Energy Specialist).

The team would like to thank Charles Warwick for editorial support. The team is grateful to Sarah Jene Hollis for the excellent graphic design of this report, including figures, maps, schematics, photos, and overall report layout. The support from Akash Shrestha (External Affairs Officer) and Avinashi Paudel (External Affairs Associate), in providing communications support including managing media relations and dissemination was greatly appreciated.

We acknowledge financial support from the World Bank's Resilient Asia Program, funded by the UK government's Foreign Commonwealth Development Office and the Swiss Agency for Development and Cooperation. The UK funding is delivered through Climate Action for a Resilient Asia (CARA), the UK's flagship regional programme to build climate resilience in South Asia, Southeast Asia and the Pacific islands. We also acknowledge valuable funding from the Korean Green Growth Trust Fund (KGGTF).

The team is grateful for the comments received during the stakeholder consultations held on March 26, 2025, where preliminary findings were presented and feedback was collected. The participants included stakeholders from the Department of Environment (DoE), Ministry of Industry, Commerce and Supplies (MoICS), the Alternative Energy Promotion Center (AEPC), among several other government agencies, private sector, development partners, academia, and local governments. While developing this report, the team held several consultations with the Ministry of Forests and Environment, DoE, MoICS, Department of Transport Management, AEPC, Nepal Electricity Authority, National Disaster Risk Reduction and Management Authority, Lalitpur Metropolitan City, Kathmandu Metropolitan City, Chandragiri Municipality, Changunarayan Municipality, FHI 360, the International Center for Integrated Mountain Development (ICIMOD), and several development partners, and private sector stakeholders.

List of Acronyms

AEPC	Alternative Energy Promotion Center
ALRI	Acute Lower Respiratory Infections
AOD	Aerosol Optical Depth
AQI	Air Quality Index
AQM	Air Quality Management
As	Arsenic
BC	Black Carbon
CCMD	Climate Change Management Division (of MOFE)
Cd	Cadmium
CO	Carbon Monoxide
COPD	Chronic Obstructive Pulmonary Disease
DALY	Disability Adjusted Life Years
DoE	Department of Environment (of MOFE)
DoI	Department of Industries (of MOICS)
DoLI	Department of Local Infrastructure (of MoUD)
DOLOS	Department of Labor and Occupational Safety (of MoLESS)
DoS	Department of State, USA
DoTM	Department of Transport Management (of MoPIT)
DPC	Development Policy Credit
EIA	Environmental Impact Assessment
EPA	Environment Protection Act
EPI	Environmental Performance Index
EPR	Environment Protection Rules
ESMAP	Energy Sector Management Assistance Program
EV	Electric Vehicles
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
GIZ	Gesellschaft für Internationale Zusammenarbeit
GoN	Government of Nepal

GRID	Green Resilient and Inclusive Development
GW	Gigawatt
HC	Hydrocarbon
HEI	Health Effects Institute
HKH	Hindu-Kush Himalayas
ICE	Internal Combustion Engine
ICIMOD	International Centre for Integrated Mountain Development
IEA	Industrial Enterprises Act
IEE	Initial Environmental Examination
IER	Industrial Enterprises Regulations
IGP-HF	Indo-Gangetic Plain and Himalayan Foothills
IHD	Ischemic Heart Disease
IIASA	International Institute for Applied Systems Analysis
INGOs	International Non-Governmental Organizations
KfW	Kreditanstalt für Wiederaufbau
KVAQMP	Kathmandu Valley Air Quality Management Action Plan
LDV EV	Light-Duty Vehicles Electric Vehicle
LDV ICE	Light-Duty Vehicles Internal Combustion Engine
LPG	Liquified Petroleum Gas
MERRA2	Modern-Era Retrospective analysis for Research and Applications, Version 2
MoALD	Ministry of Agriculture and Livestock Development
MoLESS	Ministry of Labor, Employment and Social Security
MoEST	Ministry of Environment, Science and Technology
MoEWRI	Ministry of Energy, Water Resources, and Irrigation
MoF	Ministry of Finance
MoFAGA	Ministry of Federal Affairs and General Administration
MOFE	Ministry of Forest and Environment
MoHA	Ministry of Home Affairs
MoICS	Ministry of Industry, Commerce, and Supplies
MOPE	Ministry of Population and Environment
MoPIT	Ministry of Physical Infrastructure and Transportation
MoUD	Ministry of Urban Development
MoWS	Ministry of Water Supply
MW	Megawatt
NAAQs	National Ambient Air Quality Standards
NCR	National Capital Region

NEEP	Nepal Energy Efficiency Programme
NGOs	Non-Governmental Organizations
NH_3	Ammonia
Ni	Nickel
NOC	Nepal Oil Corporation
NPR	Nepali Rupee
NVMES	Nepal Vehicular Mass Emission Standard
PM	Particulate Matter
Pb	Lead
RE	Renewable Energy
RETS	Renewable Energy Test Station
REEP-GREEN	Renewable Energy and Energy Efficiency Programme - Green Recovery and Empowerment with Energy in Nepal
SEA	Strategic Environmental Assessment
SOPs	Standard Operating Procedures
US EPA	United States Environment Protection Agency
VAT	Value Added Tax
VSBK	Vertical Shaft Brick Kilns
WHO	World Health Organization
WRF-Chem	Weather Research and Forecasting model coupled with Chemistry

Executive Summary

The main objectives of this report are to identify the levels, patterns, and sources of air pollution in Nepal, assess its health and economic impacts, and propose solutions to improve air quality. The recommendations are based on a foundational diagnostic review of Nepal's existing air quality management actions. The report aims to provide comprehensive insights and actionable policy options for the government, stakeholders, and the public to support urgent and effective interventions.

A. The state and trends of air pollution in Nepal

The Kathmandu Valley and the Terai are Nepal's air pollution hotspots, with no significant improvement over the last decade. The key pollutant of concern for human health is Particulate Matter (PM) smaller than 2.5 microns (i.e. $PM_{2.5}$), due to its ability to penetrate deeply into the lungs and other vital organs. Figure 0.1 shows that air pollution concentrations are highest in the country's capital, Kathmandu, and the southern plains of the Terai, near India. Trends analysis carried out by this report shows that the air pollution level has remained largely unchanged over the last decade. The World Health Organization (WHO) has set targets to guide countries in mitigating air pollution and safeguarding public health. The WHO's ultimate target for annual mean $PM_{2.5}$ concentration is 5 $\mu g/m^3$, with an initial interim goal of 35 $\mu g/m^3$ to encourage incremental progress.[1] These benchmarks emphasize the urgency and scale of effort required to address air pollution in regions like the Kathmandu Valley and the Terai, where current levels significantly exceed these safety limits.

B. The human and economic cost of air pollution

Air pollution is the number one risk factor for death and disability in Nepal, surpassing malnutrition (second) and tobacco (third). It reduces life expectancy by 3.4 years for the average Nepali and causes approximately 26,000 premature deaths annually. Air pollution heavily contributes to various diseases: 75 percent of chronic obstructive pulmonary disease cases, 46 percent of strokes, 44 percent of ischemic heart disease, 41 percent of lower respiratory infections, 38 percent of lung cancer, 30 percent of neonatal issues like low birth weight and preterm birth, and 20 percent of diabetes.

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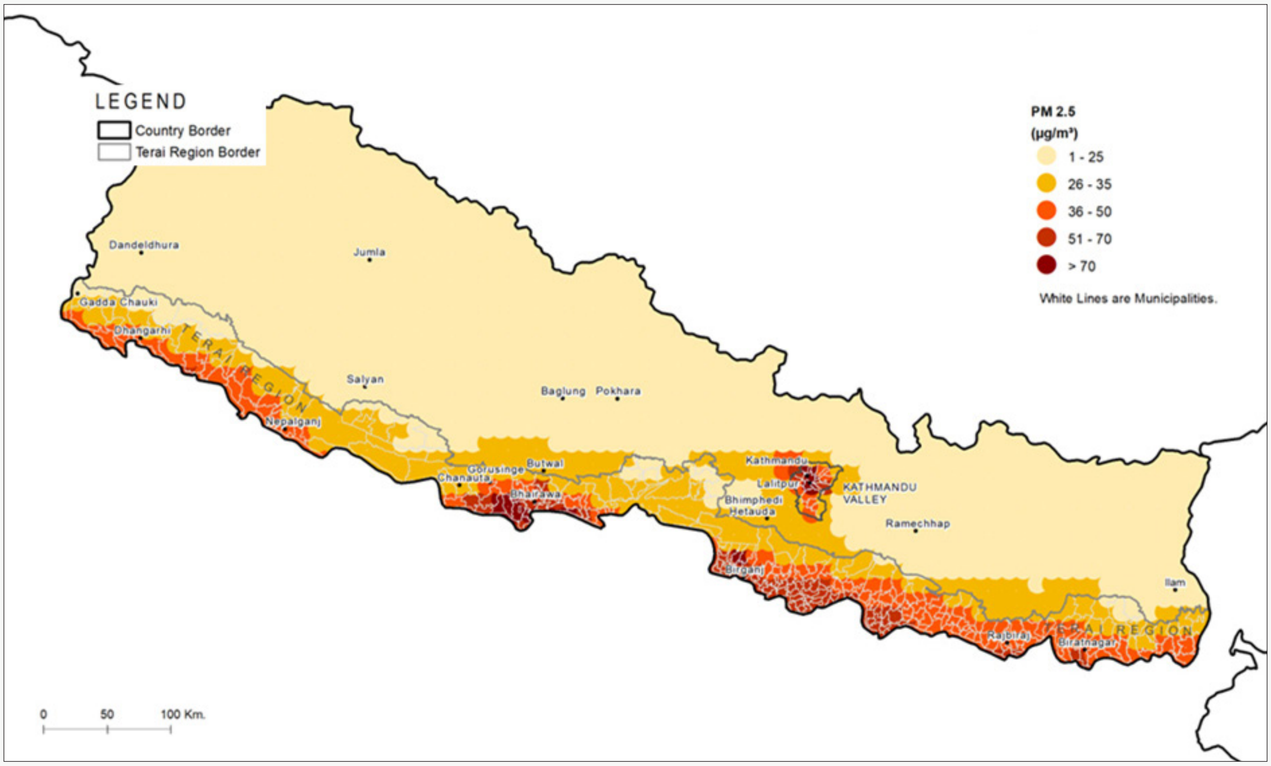
1 The unit $\mu g/m^3$ stands for micrograms per cubic meter i.e., one millionth of a gram of pollutant in one cubic meter of air.

Figure 0.1: Average annual air pollution concentrations in Nepal, 2021



Source: GAINS-Nepal estimates produced for this report.

The economic impacts of air pollution are substantial. It affects labor productivity due to increased health-related absences and impaired cognition. The negative impact on the tourism industry and the aviation sector is also significant. The economic cost of poor air quality is estimated to exceed six percent of Nepal's Gross Domestic Product (GDP) each year.

If no additional measures are taken, the impact of air pollution is projected to intensify significantly by 2035. Under the baseline scenario, average $PM_{2.5}$ concentrations will reach 52 µg/m^3 in the Kathmandu Valley and 42 µg/m^3 in the Terai, far above the WHO interim target of 35 µg/m^3. These levels would result in tens of thousands of additional premature deaths, particularly impacting children and the elderly, a further strain on healthcare system, and a growing drag on productivity and competitiveness. Without intervention, the economic burden is also expected to grow proportionally. This underscores the cost of inaction that results in irreversible damage to health and the economy.

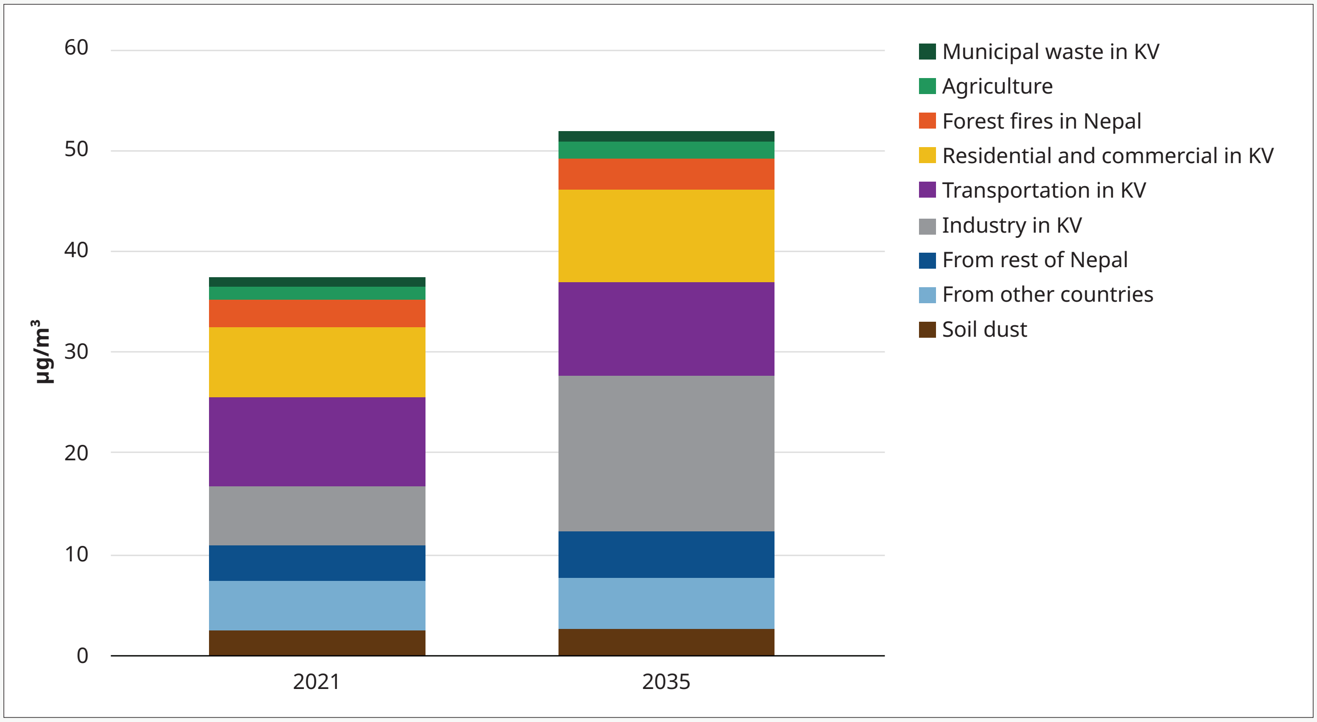
> **The economic impacts of air pollution are substantial. ...If no additional measures are taken, the impact of air pollution is projected to intensify significantly by 2035.**

C. The main sources of air pollution in the Kathmandu Valley and the Terai

In the Kathmandu Valley, the main sectoral sources of air pollution are currently (i) industrial production, (ii) cooking, and (iii) mobility, and these will remain dominant over the next decade unless further action is taken (see Figure 0.2).[2] Industrial fuel combustion – led by boiler usage – is expected to increase significantly. Forest fires dominate during the dry months (February to May) and constitute the fourth largest local source of annual average air pollution exposure, the most relevant metric for adverse impacts on public health.

Transboundary air pollution significantly impacts air quality in both the Kathmandu Valley and (especially) the Terai region. Figure 0.2 indicates that about a quarter of the pollution in the Kathmandu Valley comes from outside the Valley (more than half of that from outside of the country). Despite being surrounded by hills, the Kathmandu Valley experiences pollution transport from regional sources, as wind patterns and atmospheric conditions carry pollutants into the area. In the Terai, transboundary pollution is even more dominant, largely driven by its geographic proximity to other countries in the Indo-Gangetic Plain Himalayan Foothills (IGP-HF) area (Figure 0.3). Two thirds of $PM_{2.5}$ exposure in the Terai comes across the international borders, a region with high agriculture and industrial emissions (Figure 4.4).

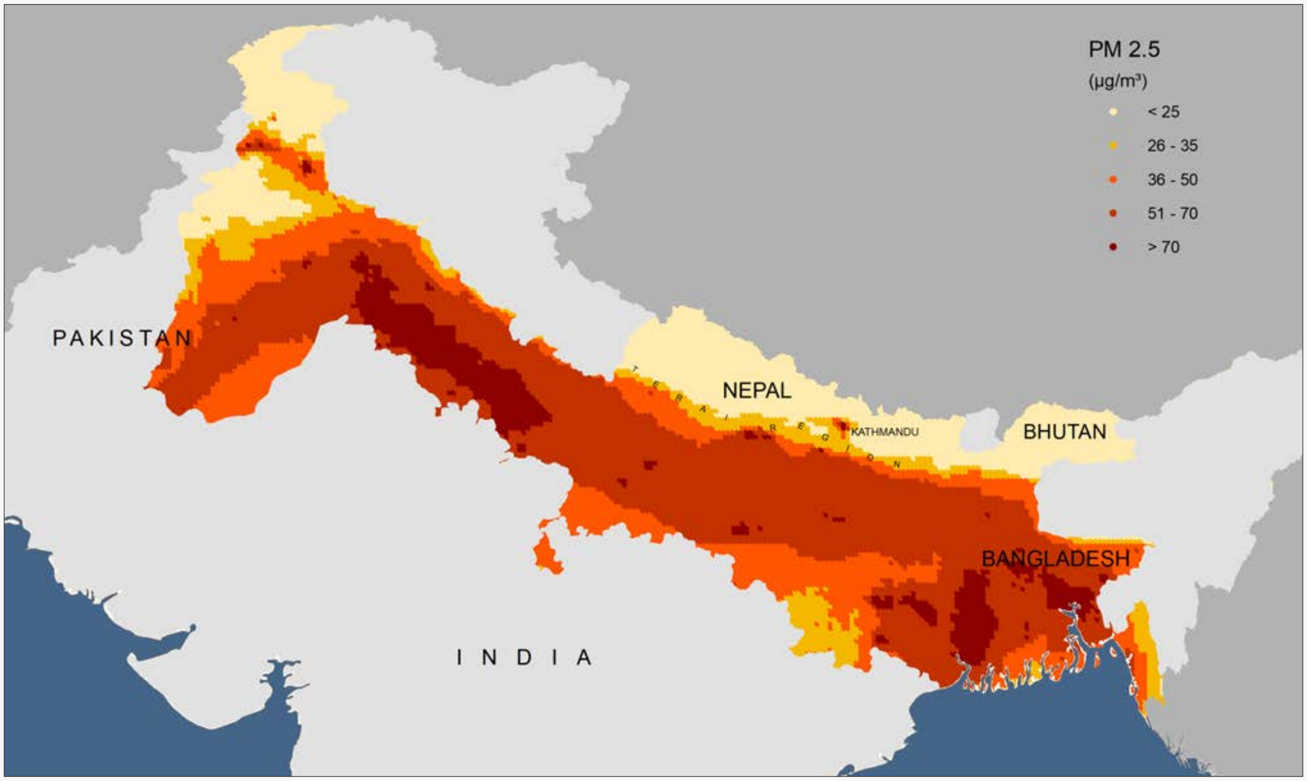
Figure 0.2: Population-weighted $PM_{2.5}$ annal average exposure in Kathmandu Valley, 2021-2035, by sector



Source: GAINS-Nepal estimates developed for this report.

2 Figure 0.2 is an aggregation of data contained within Figure 4.7 of the main report to highlight the contributions of sectors overall rather than specific sub-sectoral contributions detailed in Chapter 4.

Figure 0.3: Air pollution concentrations in Nepal and the other four countries sharing the Indo-Gangetic Plain and Himalayan Foothills (IGP-HF) airshed, 2021



Source: GAINS estimates produced for this report.

D. Identifying priority measures to address air pollution and meet the "35 by 35" target

In the Kathmandu Valley, the 35 µg/m³ target can be reached with just three measures: cleaner production technology, cleaner cooking, and cleaner Heavy-Duty Vehicles (HDVs).

1. Cleaner boilers (running on cleaner fuels such as electricity or pellets/briquettes with adequate filters) are the most critical technology to adopt by industries (predominantly small and medium enterprises).
2. Cleaner cookstoves, i.e., electric induction stoves or fan-assisted biomass stoves. Their adoption is greatly facilitated through almost universal electricity access in the Kathmandu Valley.
3. Inspection & Maintenance (I&M) of Heavy-Duty Vehicles (HDV), with enforced repair and/or scrapping programs for vehicles that do not comply and upgrading the Light-Duty Vehicles (LDVs) to a stricter vehicle emissions standard (Euro IV).

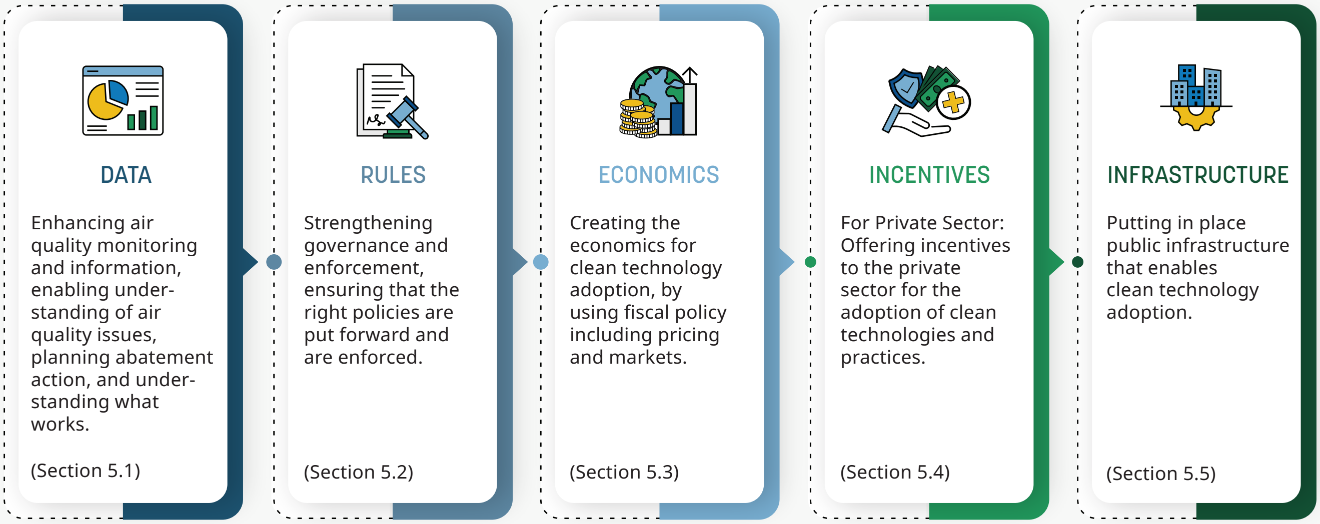
These three priority measures are listed in rank-order of ***pollution abatement potential*** (by how many $\mu g/m^3$ the air quality can be improved), assuming perfect efficiency and complete adoption of these technologies and practices. They are also among the most ***cost-effective*** measures to take. The cost per 1 $\mu g/m^3$ of improvement ranges from USD 1 million to USD 5 million.

For the Terai, the same three measures are crucial but insufficient to meet the 35 $\mu g/m^3$ target; to achieve this target it is critical that neighbors also act. The report shows that the Terai can theoretically meet the target independently, but only at great expense. Even with perfect implementation of the three priority cost-effective measures, more expensive actions (costing USD hundreds of millions for a 1 $\mu g/m^3$ improvement) would be necessary. Since most pollution comes from neighboring countries, it is advised that the Terai focus on local priority actions and collaborate with nearby regions on pollution control. It is therefore a priority for Nepal to engage in regional coordination efforts to strengthen the collaboration and implementation of common priority measures across the countries of the IGP-HF region. Participation in the annual Science Policy Finance Dialogue that the World Bank has been organizing since 2022, together with the International Centre for Integrated Mountain Development (ICIMOD), is critical.

E. Policy recommendations and solutions

For the Government of Nepal to support the three priority pollution abatement measures identified, requires promoting policies that build the five foundations of Air Quality Management (AQM). Figure 0.4. indicates these five enabling foundations. Moving the country to cleaner production, cooking, and vehicles, which are the priority sectors in terms of abatement potential, and reducing forest and agricultural fires, which are seasonal priorities, requires several levers to be pushed, including (1) enhancing air quality data, (2) strengthening rules (such as emissions or technology standards) and their enforcement, (3) aligning the economics for facilitating a clean transition (by taxing pollution, or exempting cleaner alternatives), (4) offering incentives to the private sector (nudging cleaner technology and practice adoption), and (5) establishing infrastructure that enables clean technology adoption (ensuring the supply of clean electricity or modern biomass).

Figure 0.4: The five enabling foundations for clean air in Nepal



Data

It is necessary to improve the operations of the existing 30 monitoring stations in Nepal to ensure that all stations report data continuously throughout the year. Enhancing the current monitoring stations to track additional air pollutants and expanding the network are important steps for the medium-term. Improving communication with the public about air pollution levels through user-friendly websites, smartphone applications, and health-related advisories is also essential. This report has provided a first-order air pollution source profile, but it is important for Nepal to continue refining and updating this source data through ongoing source apportionment campaigns and strengthening emissions inventories.

Rules

Nepal is enhancing its institutional framework for air quality management by defining the roles and responsibilities of federal, provincial, and local governments. The country is also adopting stricter standards for industrial and vehicular emissions. Completing this regulatory reform process is necessary. Additionally, stricter enforcement of the regulations, such as improved inspection programs for vehicles and industries, is essential.

Economics

Establishing a supportive economic framework to accelerate the adoption of cleaner technologies and practices is essential. Nepal has implemented several price-based policy measures, including a pollution tax introduced in 2008 and a green tax in 2024. To enhance the impact and credibility, the revenue from these environmental taxes should be redirected toward incentivizing clean sectoral transitions. This includes supporting priority actions such as cleaner industrial production technologies, subsidized electric cooking solutions, and investments in electric vehicle (EV) infrastructure. A tax recycling model would enable Nepal to align fiscal and environmental objectives more clearly. Similarly, overlapping environmental levies should be consolidated where possible, reinforcing transparency and building sustained public support for air quality action.

Incentives

Providing incentives for the adoption of cleaner technology is important, especially for small and medium enterprises in major industries contributing to air pollution. The use of boilers, furnaces, and kilns (listed in order of importance) for heat generation is significant for cleaner air. Similarly, implementing end-of-pipe technologies, such as filters (scrubbers, electrostatic precipitators, baghouse, cyclones, etc.), is necessary. Offering technical and financial support to firms can encourage the adoption of cleaner technologies.

Infrastructure

Establishing adequate infrastructure is crucial for adopting cleaner technologies like electric cookstoves, EVs, or industrial production technology powered by electricity or modern biomass. In Nepal, important aspects include electricity provision (generation and distribution of hydroelectricity), the availability of electric charging stations, and the planning and construction of roads to reduce air pollution.

Using this framework, the Government of Nepal is well-poised to take immediate action in some sectors, while near-term preparatory studies may be needed to enable effective implementation in others. Table 0.1 illustrates the multi-sectoral foundation to advance AQM over the next few years and suggests a suite of key measures to take.

Table 0.1: Multi-sector foundations for AQM planning for Nepal

AQM Foundation	Industry	Transportation	Residential Energy	Agriculture	Forests
Data 	Establish pilot stack emissions testing protocols for priority industries. Collect industrial emissions data for a representative sample of key industrial sectors. Use remote sensing for stack emissions detection. *(DoE, MoICS)*	Develop a national digital vehicle database integrating registration, inspection, and emissions test results. Use remote sensing for emissions (activity) monitoring on key corridors. Establish data integration between inspection centers and enforcement agencies. *(DoTM, DoE)*	Expand national household energy use surveys focused on cooking energy patterns and pollution exposure. Track adoption and usage rates of electric and improved biomass stoves. Use geospatial mapping to identify high-pollution-risk residential clusters. *(AEPC)*	• Conduct satellite-based monitoring of agricultural burning across the Terai. • Map spatial patterns of agricultural residue availability for cleaner fuel production. • Track seasonal variations in residue burning practices. *(MoALD, and MoFE/DoE)*	Develop early warning systems using forest dryness and fire risk indices. Deploy remote sensing for real-time forest fire detection. Map high-risk zones for preventive fire management interventions. Map spatial patterns of biomass residue availability for cleaner fuel production. *(MOFE, NDRRMA).*
Rules 	Introduce stricter industrial emissions standards. Introduce biomass co-firing mandates for industries using coal (e.g. brick kilns). Enhance the enforcement of industrial emission standards, including strengthening stack testing and inspection. Delegate regulatory enforcement authority to provincial governments with clear accountability frameworks. *(DoE, and Provinces)*	Enforce Euro VI equivalent standards for all combustion vehicle categories. Mandate dust control and road cleaning as part of all public works contracts. Strengthen vehicle inspection centers and certify private inspection stations under strict federal standards. *(DoTM/MoPIT)*	Support RETS to become a national testing and certification hub and formalize national performance standards for clean cookstoves. Strengthen local governments' role in monitoring and promoting household energy programs. *(MoICS, NBSM, AEPC, MoEWRI)*	Assign local government roles in enforcing seasonal burning bans and strengthen enforcement. Institutionalize a crop residue management system through public-private partnerships. *(MoALD, MoFE/DoE, and Municipalities)*	Strengthen coordination between forestry departments, fire services, and disaster management agencies. Formalize rapid response protocols for peri-urban forest fire management. *(MoFE, NDRRMA, Municipalities)*

AQM Foundation	Industry	Transportation	Residential Energy	Agriculture	Forests
Economics 	Scale up the Green Tax (on fossil fuels) and use revenues for clean technology transitions, and environmental protection. Offer tax benefits for early adopters of verified cleaner production technologies (including cleaner boilers and furnaces). Reduce import duties for clean fuel and technology. Offer accelerated terminal depreciation of existing old polluting technology. *(MoF)*	Scale up the Green Tax (on fossil fuels) Continue to offer substantial import duty reductions for EVs and electric two-wheelers. Establish scrappage incentives for outdated, high-emissions vehicles. *(MoF, MoPIT, DoTM)*	Scale up the Green Tax (on fossil fuels) Offer tax exemptions for electric and efficient biomass cookstoves. Introduce electricity tariff structures that incentivize off-peak cooking with induction stoves. Provide rural energy subsidies tied to cleaner household energy adoption. *(MoF, NEA, AEPC)*	Offer tax benefits for mechanized agricultural solutions to agricultural waste burning, such as "happy/super seeders" and alternative residue management equipment. Support market creation for agricultural residues. Realign fertilizer subsidies toward optimized, low-emission fertilizer application. *(MoALD, MoF)*	Offer tax benefits for forest-derived biomass pellet and briquette production. Provide incentives for sustainable harvesting of forest residue for energy production. *(MoFE, MoF)*
Incentives 	Provide financial incentives (such as grants and concessional lending) for industries shifting to electric or modern biomass boilers. Provide technical assistance for energy audits and cleaner production roadmaps. Establish awards for clean technology pioneers. *(MoICS, MoF)*	Implement a scrappage program for heavy-duty diesel vehicles. Penalize fraudulent emissions certifications and impose penalties. Offer tax credits for companies investing in EV fleets. *(MoPIT, DoTM, MoLJPA, MoF)*	Introduce cash rebates for households purchasing certified clean cookstoves. Offer microfi-nance-backed loan programs for household clean energy technologies. Support domestic manufacture of certified clean stoves. *(AEPC, MoICS)*	Subsidize purchase of happy/super seeders and rice straw balers. Support farmer cooperatives in offering residue collection services. Provide incentives for low-emissions fertilizer technologies. *(MoALD)*	Provide grants for communi-ty-based forest fire management initiatives. Incentivize private sector investment in fire management technologies. Offer incentives for early detection and reporting of wildfires. *(MoFE)*

AQM Foundation	Industry	Transportation	Residential Energy	Agriculture	Forests
Infrastructure	Ensure dedicated, reliable electric feeder lines to major industrial parks. Modernize stack designs to facilitate routine inspection and data collection. Create centralized clean industrial zones with shared clean energy access. *(MoICS, NEA, IDM)*	Install fast-charging EV stations along highways and urban centers. Upgrade residential electrical capacity for overnight charging. Pilot urban low-emission zones with supporting EV infrastructure. *(NEA, Municipalities)*	Expand distribution grid improvements in peri-urban and rural areas for cooking electrification. Upgrade residential electrical capacity for cooking electrification Conduct a stocktaking of households without clean electricity access. Deploy mini-grids where main grid extension is not feasible. *(NEA, CBS, AEPC)*	Establish regional crop residue collection and processing centers in the Terai. Build decentralized composting hubs linked to agricultural cooperatives. Pilot mobile biomass pelletizers in high-yield areas. *(MoALD, Municipalities, AEPC)*	Establish community fire watch towers with radio communication. Set up decentralized water storage for forest firefighting purposes. Procure and operate helicopters equipped for early fire spotting and suppression. *(MoFE, MoHA, NDRRMA)*

Note: This table summarizes the key measures, discussed in the main text of the report and lists the key institutions for implementation (institutions are listed in brackets and in italics).

On a day with high air pollution levels, a pedestrian crosses the street. *Source: Anuj Adhikary/World Bank.*

By implementing the recommendations outlined in this report, Nepal can achieve significant improvements in air quality, leading to better health outcomes, economic benefits, and a more sustainable environment.

F. The Government of Nepal is committed to improving air quality and has set ambitious targets, which the World Bank aims to support

The goal: achieving 35 μg/m³ of annual average pollution concentrations by the year 2035. The Government of Nepal has recognized the urgency of addressing air pollution and has incorporated air quality improvement measures into its Sixteenth Five-Year Plan. In alignment with regional efforts to combat air pollution, Nepal has endorsed the "35 by 35" aspirational goal as part of the Indo-Gangetic Plain and Himalayan Foothills (IGP-HF) Science Policy Finance Dialogue process, as have all the other countries—Bangladesh, Bhutan, India, and Pakistan. This goal aims to achieve annual average $PM_{2.5}$ concentration of 35 μg/m³ by the year 2035, which also coincides with the WHO interim target 1 for $PM_{2.5}$. In parallel, Nepal is actively working on integrating this target into its new and updated ambient air pollution standards, demonstrating a strong commitment to improving air quality and protecting public health.

The World Bank's strategic engagement with Nepal, prioritizes the reduction of air pollution, among other important goals, such as job creation and economic growth. The 2025 Country Partnership Framework (CPF) for Nepal prioritizes air pollution reduction and supports the government's interim goal to reduce air pollution in line with the 35 μg/m³ goal, in line with Nepal, IGP-HF countries, WHO, and the World Bank's own global Corporate Scorecard Indicators. The World Bank plans to support these targets through a series of projects, which aim to improve air quality, by focusing in phases on the three priority measures identified: adoption of cleaner boilers, cookstoves, and vehicle technology.

Meeting 35 μg/m³ is only a first step in the movement towards clean air. For instance, after China began to successfully combat air pollution about a decade ago, Beijing's annual average concentrations of $PM_{2.5}$ have declined from more than 80 μg/m³ to around 31 μg/m³ in 2024. Similarly, Mexico City achieved a steady decline from about 60 μg/m³ to below 40 μg/m³ over a ten-year period (1993-2003), and Ulaanbaatar reduced $PM_{2.5}$ levels from over 130 μg/m³ to approximately 60 μg/m³ between 2011 and 2019. While these cities have made significant progress, they continue working to promote cleaner energy and transportation and to tighten industrial regulations, to move closer to the World Health Organization guideline value for $PM_{2.5}$ set at 5 μg/m³.

Addressing air pollution will have significant co-benefits for Nepal. Measures that improve air quality can yield development synergies in other sectors, such as energy security through reduced reliance on imported fossil fuels, and industrial cost savings through improved energy efficiency. Cleaner transport systems can reduce congestion and fuel costs while improving urban livability. These benefits strongly align with Nepal's Sustainable Development Goals (SDGs) commitments and Nationally Determined Contribution (NDC) targets[3]. However, maximizing these co-benefits also requires anticipating potential tradeoffs. For instance, transitions in polluting industries may result in localized job losses unless complemented by green job creation. Understanding and managing these tradeoffs will be critical to ensuring a just and sustainable clean air transition.

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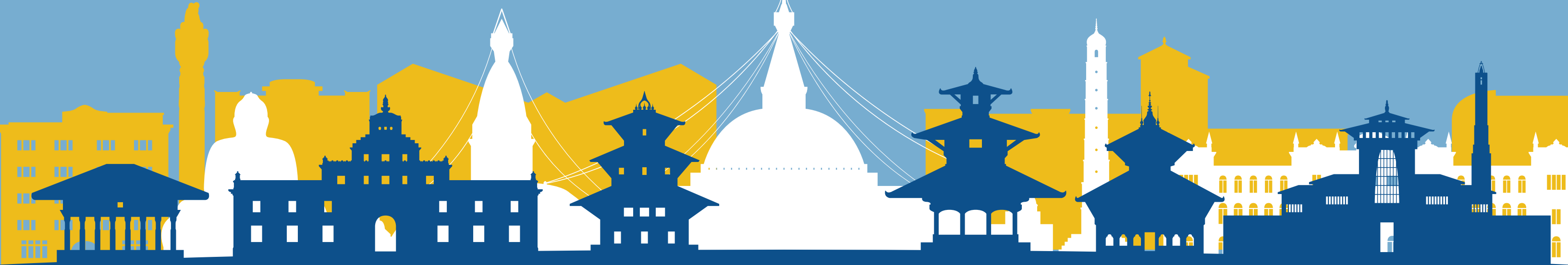
3 The SDGs are a global agenda of 17 goals set by the United Nations (UN) to achieve social, economic, and environmental sustainability by 2030. The NDCs are country-specific climate action plans under the Paris Agreement that outline targets to reduce emissions and adapt to the impacts of climate change.

This is a personification of air, which is under severe distress. The air is being engulfed by emissions and is struggling to breathe.
Source: Unique Maharjan, 16, 1st Runner-up, 'Where's My Blue Sky?' Live Art Challenge.

Addressing air pollution is core to the recent World Bank CPF, for the period FY2025 – FY2031, for Nepal. The CPF for Nepal (World Bank, 2025) identifies two central challenges to Nepal's development pathway: (a) lack of sustainable, inclusive, and job-creating growth; and (b) Nepal's extreme exposure to natural disasters, including those caused by and exacerbated by climate change, and includes reducing the number of people exposed to hazardous air pollution.

Addressing air pollution in Nepal requires both multi-sectoral actions and multi-jurisdictional (including by other countries) action. By implementing the recommendations outlined in this report, Nepal can achieve significant improvements in air quality, leading to better health outcomes, economic benefits, and a more sustainable environment.



Introduction

Background and context

Hazardous air pollution poses significant health and economic challenges for Nepal. Air pollution raises public health concerns in Nepal, particularly in the country's two geographic hotspots: the Kathmandu Valley and the Terai (southern plain areas bordering India). In these two areas, the annual average $PM_{2.5}$ (i.e. particulate matter of less than 2.5 micrometers in diameter, which is the most critical air pollutant) concentrations reach 37 and 39 μg/m^3, respectively. This exposure is between seven to eight times higher than the World Health Organization (WHO) guideline value of 5 μg/m^3. These levels of air pollution shorten the average life expectancy of Nepal's residents by more than three years, and lead to almost 26,000 premature deaths each year (World Bank, 2019). Beyond health impacts, poor air quality leads to reduced labor productivity and negatively impacts tourism (lower visibility of the Himalayas and cancelled flights) (Kathayat et al. 2023). Overall, poor air quality is estimated to cost the equivalent of more than six percent of Nepal's Gross Domestic Product (GDP) each year (World Bank, 2019).

Cleaning Nepal's skies is a government priority. Nepal's Sixteenth Five-Year Plan, adopted in 2024, acknowledges the health and environmental impact of air pollution and emphasizes the need for adopting stricter standards and implementing air pollution control measures. Recognizing the consequences of poor air quality, Nepal is currently strengthening its air quality targets and associated policy and regulatory framework, including updating its National Ambient Air Quality Standards (NAAQS) to a level consistent with WHO guidance.

Black carbon (BC), which is a sub-set of $PM_{2.5}$, is a significant Short-Lived Climate Pollutant (SLCP) and is leading to accelerated glacial melting. SLCPs such as BC have a significant impact on climate change because their effects are more immediate and pronounced over shorter timescales than long-lived greenhouse gases such as carbon dioxide. BC accelerates glacial melting considerably causing rates about twice as fast owing to BC deposition on white snowy surfaces (World Bank, 2021). According to the Global Climate Risk Index, Nepal was already the 12th most affected country particularly due to its steep terrain and heavy monsoons, putting the country at risk of floods including Glacial Lake Outburst Floods (GLOFs), landslides, and droughts. BC significantly increases the risks of these hazards.

In this painting, a hurt bird asks, *"Where's my blue sky?"* The red color represents the suffering of all living beings amidst the pervasive dust and grime. To bring this vision to life, the artist used an impasto technique, incorporating materials like tissue paper, rags, and grass from the ground. This approach not only adds depth and dimension to the piece, but also underscores the importance of reuse.
Source: Ranjit Kunwar, 21, Winner, 'Where's My Blue Sky?' Live Art Challenge.

Air pollution is a transboundary problem, creating a regional emergency. The Indo-Gangetic Plain and Himalayan Foothills (IGP-HF) airshed[4] in South Asia includes parts of Bangladesh, Bhutan, India, Nepal, and Pakistan. It is the global air pollution hotspot with almost one billion people exposed to the highest worldwide annual average concentrations of $PM_{2.5}$. Multiple jurisdictions across the five countries contribute and are exposed to emissions that circulate within the larger IGP-HF airshed jurisdiction. For this reason, it is critical that these countries across this region take action to address air pollution.

Air pollution is a multisectoral issue in Nepal. The primary sources of air pollution emerging from Nepal include industrial emissions, vehicular emissions, and household air pollution (from cooking and heating with solid fuels). In addition to these three main sources, forest fires are a seasonal issue in Nepal, particularly in the dry months from February to May. Addressing these sources requires coordinated policy actions and regional collaboration.

4 An airshed is a geographic area where air pollutants are confined and circulate due to topography and weather conditions, impacting air quality within its boundaries.

Report methodology

The report utilizes a comprehensive set of data, including air quality data from the national air quality monitoring network, emission inventory, administrative energy statistics, technology effectiveness and costing inventory, and employs advanced atmospheric, economic, and effectiveness modeling. It also includes an in-depth review of air quality institutions and policies, along with gap analysis. The modeling framework used to analyze the movement of pollution, its sources, and the impact of pollution abatement measures is the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) integrated assessment model. This model incorporates new emissions inventory information collected for the report and uses a chemical transportation model to provide insights on spatial dispersion. Local air quality experts from Tribhuvan University, Kathmandu University, and the International Centre for Integrated Mountain Research (ICIMOD) quality controlled the model findings presented. Stakeholder consultations are scheduled for February, April, and May 2025 with key government stakeholders from various Ministries, including environment, transport, energy, health, and education.

Structure of the Report

The report is organized into five chapters, each addressing distinct aspects of air quality management in Nepal. The chapters encompass an overview of air quality issues, a comprehensive analysis of pollution sources, an assessment of health and environmental impacts, and proposed solutions. Specifically:

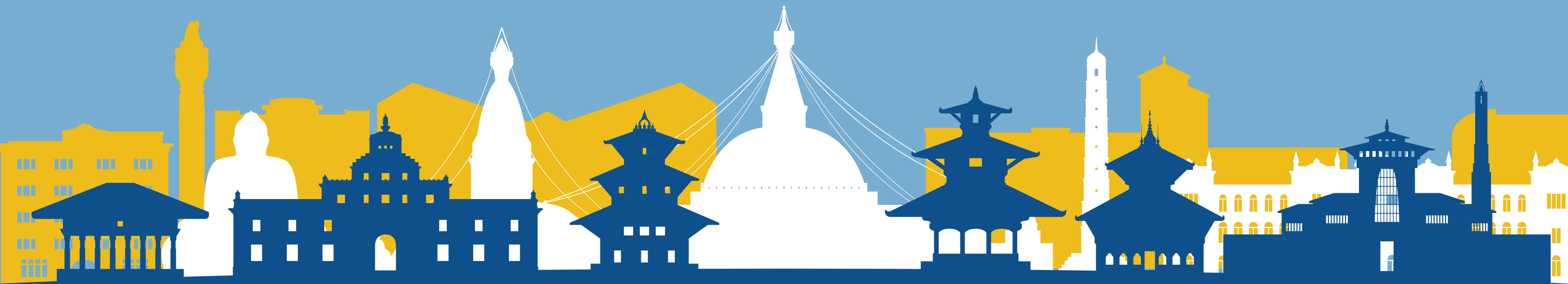
Chapter 1
Reviews the patterns and trends of air pollution.

Chapter 2
Reviews Nepal's air quality management governance structure and institutions.

Chapter 3
Examines the health, economic, and human development benefits of reducing air pollution.

Chapter 4
Examines the key sources of air pollution, current and future, identifies abatement measures, and evaluates their effectiveness and efficiency.

Chapter 5
Identifies the enabling foundations to help address air pollution in Nepal, including for adopting the priority measures identified in chapter 4. The chapter discusses opportunities for strengthening air quality information systems, awareness raising, governance and enforcement, pricing and market policies, incentives to engage the private sector, and infrastructure development.



CHAPTER 1:

Nepal's Air Quality

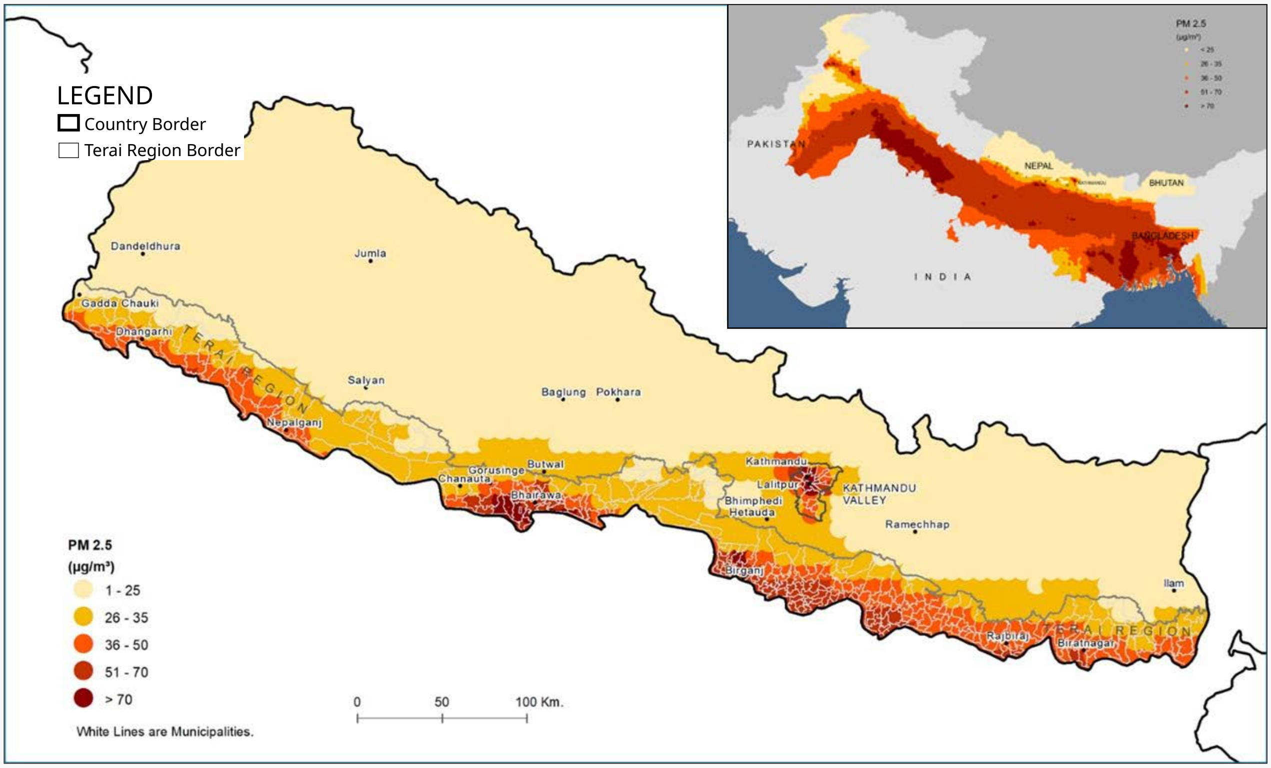
Chapter 1 reviews the patterns and trends of air pollution in Nepal. Section 1.1 synthesizes the existing knowledge on the spatial and temporal variation of air quality in Nepal (a more detailed discussion is presented in Annex A), with focus on the most polluted regions, namely the Kathmandu Valley and the Terai. Section 1.2 describes the current state and recent developments of Nepal's Air Quality Monitoring network.

1.1 Patterns of air quality

Nepal's two hotspots for air pollution are the Kathmandu Valley and the Terai. Nepal's capital city is located in the Kathmandu Valley and the Terai (or more precisely the Terai plains), stretch along the northern edge of the IGP-HF airshed (Figure 1.1). Kathmandu, with its unique topography surrounded by mountain ridges, restricts the movement of air. Many mountain valleys and the Terai experience temperature inversions that trap air pollutants near the ground. Nepal, and particularly the Terai, is highly affected by other countries in the IGP-HF region when pollutants are transported within the same airshed that is shared by parts of Bangladesh, Bhutan, India, Nepal, and Pakistan (Lüthi et al., 2015). Kathmandu is also affected by other countries, but to a lesser degree. See chapter 4 for a detailed discussion of air pollution sources (both geographic and sectoral).

Kathmandu's air pollution often reaches 'unhealthy' or 'very unhealthy' levels. *Source: Sabrina Dangol/World Bank.*

Figure 1.1: $PM_{2.5}$ concentrations (µg/m³) in Nepal and other four countries sharing the Indo-Gangetic Plain and Himalayan Foothills (IGP-HF) region, 2021



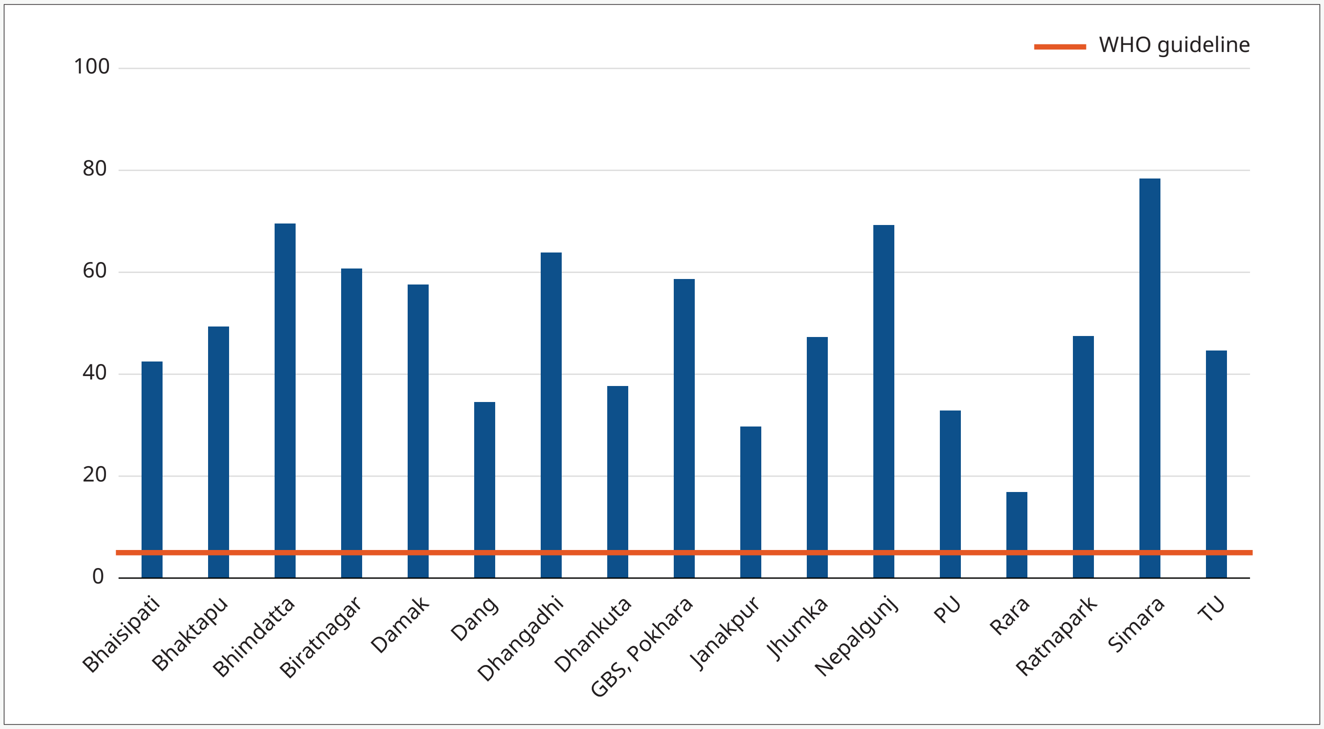
Source: GAINS-Nepal estimates produced for this report.

This report focuses on the pollutant responsible for the greatest burden of disease, namely particulate matter of 2.5 micrometers in diameter or less, known as $PM_{2.5}$, is the most critical air pollutant due to its severe health impacts. These minute particles, about 30 times smaller than the thickness of a human hair, penetrate deeply the respiratory system reaching the lung alveoli and the bloodstream.[5] While larger particles are normally filtered out in the nose and throat, $PM_{2.5}$ can bypass these filters and cause inflammation, oxidative stress, and systemic damage (Krittanawong et al., 2023). This can result in a host of severe health problems, including cardiovascular diseases, stroke, and respiratory disorders. Additionally, $PM_{2.5}$ is highly correlated with other priority pollutants like Nitrous Oxide (NO_x) and Sulphur Dioxide (SO_2), owing to their common origin from vehicle exhaust, industrial processes, and the combustion of fossil fuels in general. These pollutants coexist in emissions and moreover, interact with one another chemically in the atmosphere: NO_x and SO_2 can undergo chemical transformation into secondary $PM_{2.5}$ particles, further worsening air pollution levels.

None of the monitoring stations across the Kathmandu Valley and the Terai report $PM_{2.5}$ concentrations that are within the World Health

5 Bumrungrad International Hospital. 2024. *The Health Risks of $PM_{2.5}$*. Accessed through https://www.bumrungrad.com/en/health-blog/january-2024/the-health-risks-of-pm-2-5.

Figure 1.2: Annual average $PM_{2.5}$ concentrations in the Kathmandu Valley and the Terai region, by monitored locations



Source: World Bank based on DoE's annual reports on Status of Air Quality in Nepal, 2021 and 2023.

Note: For stations where the latest $PM_{2.5}$ data was not reported, 2021 data is included to ensure broader representation. By 2023, DoE has reported data from a total of sixteen stations within the Kathmandu Valley and the Terai, stations which had minimal gaps. It is important to note that the annual averages across these monitoring stations shown in this graph have been calculated based on partial data coverage, as shown in Figure 1.7, which could affect reliability of the reported values.

Organization (WHO) guidance level, which is 5 μg/m³.[6] Figure 1.2, which draws on the government's air quality monitoring network, shows that in the Kathmandu Valley readings exceed 40 μg/m³ and most stations in the Terai are even higher. Not only are the current pollution concentrations higher than the WHO guideline value, but they are also higher than WHO interim target values 1 (15 μg/m³), 2 (25 μg/m³), and 3 (35 μg/m³). All sixteen stations, which were reported by the Department of Environment (DoE) in its annual publications on Status of Air Quality in Nepal 2021 and 2023, exceeded WHO's standard for $PM_{2.5}$ of 5 μg/m³ for annual average concentrations. Stations in the Kathmandu Valley recorded high concentrations due to elevated levels of urban emissions from vehicles, construction activities, and the valley's bowl-shaped topography that traps pollutants. More information on the location of these stations and a comparison of their PM_{10} levels is provided in Section A.5.

Air pollution in the Kathmandu Valley is concentrated in the city center and the eastern part. The ventilation in Kathmandu is constrained by the surrounding mountain ridges, which trap localized air pollution, restrict airflow and allow pollution to accumulate within the valley. The city

6 This guidance level is a quantitative target to help governments minimize health risk through exposure to air pollution. The WHO global air quality guidelines state that this long-term target is "defined as the lowest exposure level of an air pollutant above which the GDG is confident that there is an increase in adverse health effects." It is important to note that this does not mean that below 5μg/m³ is "safe." What exact level of exposure is risk free is not determined. The WHO guidelines document writes: "This approach avoids consideration about what level of exposure should be considered safe, given that the available evidence cannot currently identify levels of exposure that are risk free for any of the pollutant–outcome pairs considered in this document."

center and the eastern parts of the valley report the highest level of pollution due to dense urban activities and proximity to industrial areas and being a pathway for air pollutants to enter or leave the valley. Annual $PM_{2.5}$ in central Kathmandu and in Bhaktapur city is found to be somewhat higher than other suburban areas such as *Bhaisepati* and *Kirtipur*.[7] Among Kathmandu Valley stations, the lowest $PM_{2.5}$ levels were recorded at *Pulchowk* which can be attributed to its location on the rooftop of a campus building that reduces direct exposure to ground-level pollution sources and allows for better dispersion of pollutants. In contrast, *Khumaltar* and *Shankhapark* recorded the highest levels at 46 μg/m^3 and 50 μg/m^3, respectively. Both stations reflect urban emissions, with *Shankhapark* experiencing particularly high pollution due to its proximity to the ring road. Corroborating evidence shows that the concentration of other air pollutants (such as nitrogen dioxide) is higher near roads, industrial, and built-up areas in central Kathmandu compared to rural and suburban areas (Gurung et al. 2017b).

In the Terai, air pollution levels were slightly higher than the Kathmandu Valley. In many Terai stations, the $PM_{2.5}$ levels reached levels 12-15 times higher than the WHO guideline value, likely driven by industrial activities, agricultural residue burning, and cross-border pollution. Biratnagar, the largest city in the eastern Terai, had an annual mean $PM_{2.5}$ concentration of 61 μg/m^3 in 2021. More information on the sources of this pollution is provided in Chapter 4.

In the Kathmandu Valley, the air quality over the last seven years, for which there was data, has remained stable. The trend analysis of $PM_{2.5}$ concentrations across three monitoring stations *Bhaisipati*, *Pulchowk*, and *Ratnapark* suggests that air pollution levels in the Kathmandu Valley have remained relatively stable over the past decade, with no significant improvements or deterioration (Figure 1.3). While minor fluctuations were observed, the annual averages have consistently exceeded the WHO's air quality guideline of 5 μg/m^3. In most cases, the pollution levels have remained well above the WHO Interim Target 3 (15 μg/m^3) and even surpassed a more lenient Interim Target 1 (35 μg/m^3) at some stations in certain years. For the Terai, the same annual trends analysis was not possible, given patchy data. For the Kathmandu Valley, statistical interpolation was needed to arrive at the trends analysis displayed in Figure 1.3.[8] To establish accurate long-term air quality trends that enable evidence-based policymaking, it is crucial to improve data monitoring across all 30 stations in Nepal. Details on how this can be achieved is further discussed in Section 5.1.

Air pollution in the Kathmandu Valley exhibits a seasonal pattern, with higher levels in winter and lower levels in summer. Figure 1.4 shows that in the winter and spring months (dry season) Kathmandu experiences the worst air quality while summer monsoons[9] are associated with cleaner air. During the winter months, cooler temperatures and the valley's bowl-shape traps the pollutants close to the ground, deteriorating the air quality. The summer monsoon season is conversely marked by a very noticeable improvement in air quality as rain washes the pollutants out of the atmosphere.[10] Heavy rainfall can temporarily improve air quality, reducing atmospheric lifetime of $PM_{2.5}$. During the dry season, Kathmandu's air quality is worsened by emissions from brick kilns across the IGP-HF and forest fires (Kuikel et al., 2024). Heavy rainfalls are continuously concentrated over three summer months, followed by dry and dusty conditions with low air quality for the remainder of the year (Hamal et al., 2021).

Air pollution peaks in the morning and evening because of human activities and natural processes. Air pollution levels generally follow a diurnal cycle, meaning they peak during the morning and evening

7 The annual mean $PM_{2.5}$ concentration at *Ratnapark* in central Kathmandu was 39.2 μg/m^3 and at *Bhaktapur*, on the east side of the valley, was 49 μg/m^3. Both stations recorded higher $PM_{2.5}$ levels than at other suburban sites in the southern and southwestern parts of the valley (*Bhaisepati* 38.9 μg/m^3 and *Kirtipur* 37 μg/m^3 (DoE, 2024).

8 The annual averages were calculated for stations with at least 70 percent data coverage across all seasons, but many did not meet this threshold. For those with limited data, interpolation was applied to estimate missing values and improve trend analysis. The process involved calculating daily average $PM_{2.5}$ concentrations, deriving station-specific ratios from overlapping data, and using these ratios to estimate missing values.

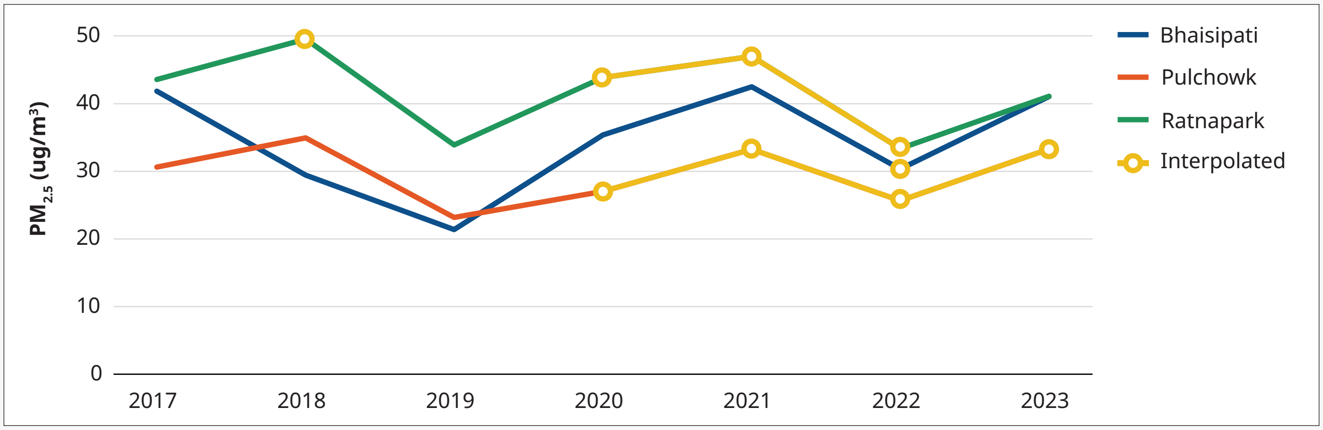
9 Mid-June to late-September; all stations had unhealthy air throughout January.

10 PM_{10} measurements around the Kathmandu Valley from 2002 to 2007 showed levels dropping by two-thirds to three-quarters on the day after a heavy rainfall (Aryal et al., 2008).

because of high emission rates. Pollution drops in the middle of the day as winds ventilate the valley but then increases at night when the cool air traps the pollutants near the surface. These effects are further magnified by topographical factors such as the enclosed geography of the valley. More detailed information on the dynamics of air pollution in the Kathmandu Valley is presented in Annex A.

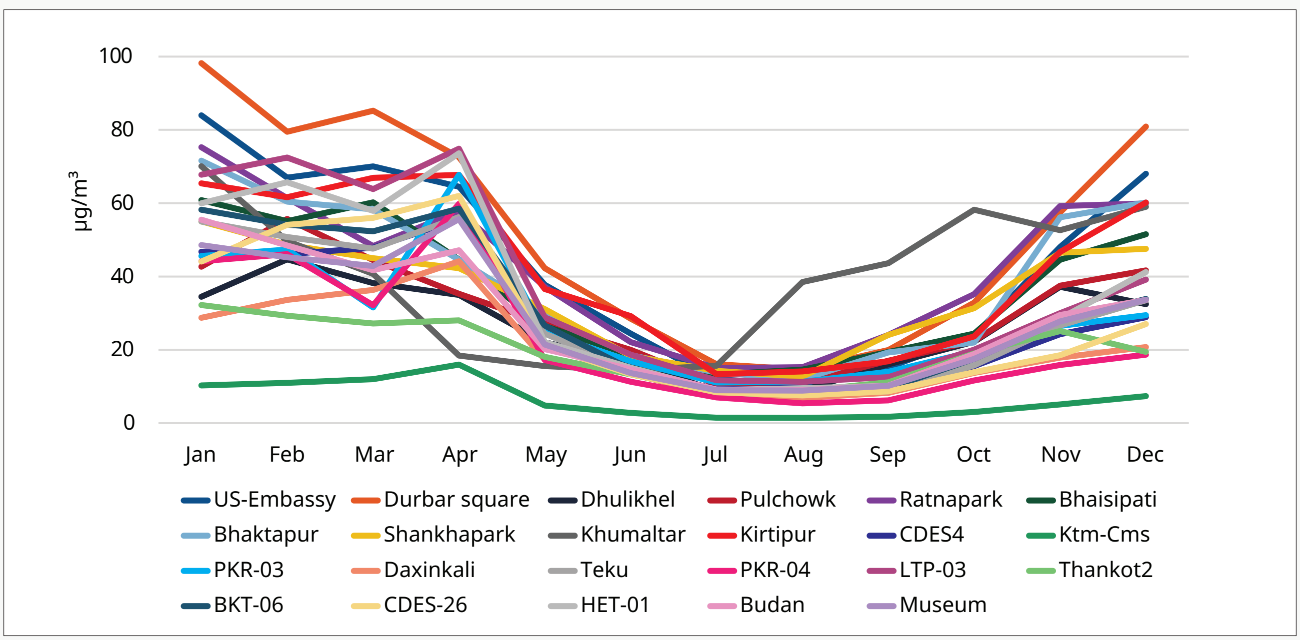
While air pollution is a problem throughout Nepal, it is by far the highest in the Terai during the dry season. Like the pattern in Figure 1.4, the Terai has the most polluted individual days in winter

Figure 1.3: Annual average $PM_{2.5}$ ($\mu g/m^3$) concentration trends in the Kathmandu Valley (2017-2023)



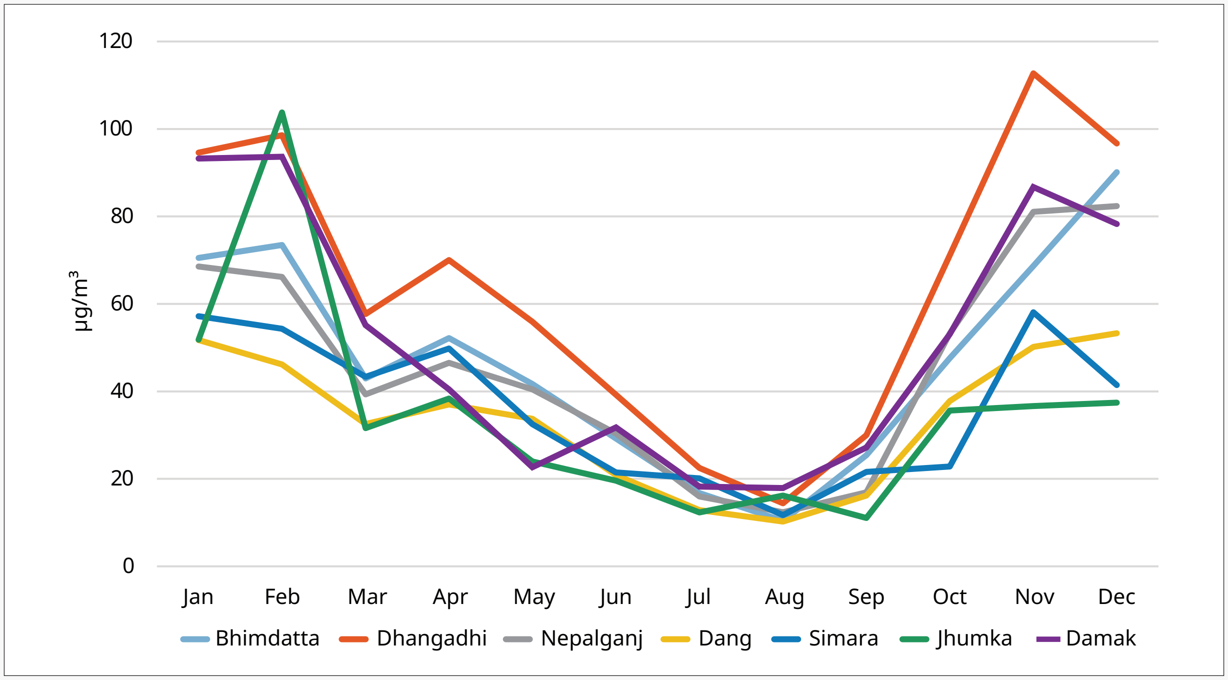
Source: World Bank analysis based on data from the Nepal national monitoring network.

Figure 1.4: Monthly trends of $PM_{2.5}$ in the Kathmandu Valley (monthly average concentrations of the years with available data)



Source: World Bank analysis based on the data from DoE's national air quality monitoring stations and a network of low-cost sensors installed by the Central Department of Environmental Science at Tribhuvan University (TU-CDES) in collaboration with Duke University.

Figure 1.5: Monthly trends of $PM_{2.5}$ in the Terai (monthly average concentrations of the years with available data)



Source: World Bank analysis based on data from the Nepal national monitoring network.

and spring months (with monthly averages near 100 µg/m^3), coinciding with the timing of forest fires and/or crop residue burning (Figure 1.5). The flat and low-lying plains of the Terai house more than half of Nepal's population (CBS, 2023) and are consistently polluted throughout the dry season. The high concentration of industrial zones and the high population density contribute to air pollution in the Terai (see chapter 4 for a detailed pollution source analysis). High pollution levels in the Terai, compared to the Kathmandu Valley, are associated with specific meteorological conditions and local sources.

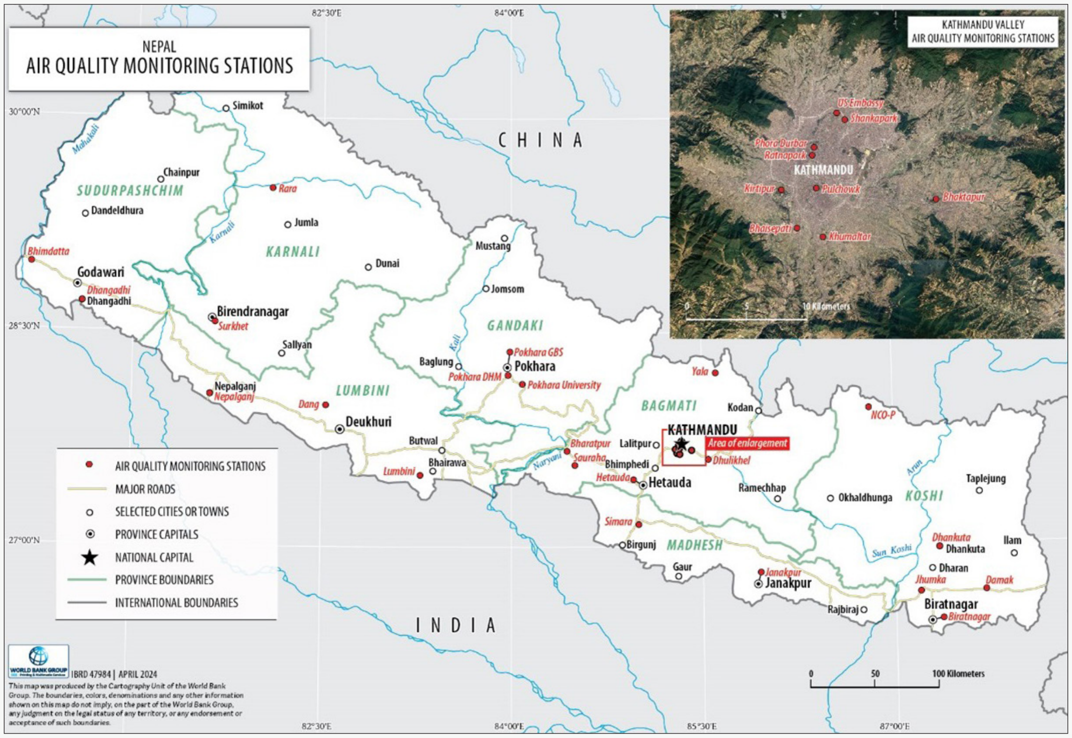
The Terai air pollution follows a specific diurnal pattern with high pollution levels in the morning and evening. All monitoring stations indicate having the cleanest air of the day in the early afternoon, followed by a rapid increase in $PM_{2.5}$ levels in the evening (DoE, 2024). Many stations demonstrated winter and spring morning and evening $PM_{2.5}$ maxima of 200-300 µg/m^3. Unlike the Kathmandu Valley, the Terai does not have clean air sweeping in at night due to pollutants from neighboring IGP-HF states.

1.2 Air quality monitoring

Nepal's Air Quality Monitoring network has expanded in recent years. In 2002, six stations were established to collect daily PM_{10} samples at urban, suburban, and roadside locations. Since 2016, the DoE has gradually expanded the network to a total of 30 monitoring stations across Nepal, including seven in the Kathmandu Valley. Each of the DoE's 30 air quality monitoring stations is equipped with a GRIMM[11] Electronic Dust Monitor (EDM) 180 that measures PM1, $PM_{2.5}$, PM_{10}, Total Suspended Particles (TSP), and a Lufft Smart Weather Sensor that measures several meteorological parameters. Four stations (*Ratnapark, Dhulikhel, Chitwan*, and *Lumbini*)

11 GRIMM refers to GRIMM Aerosol Technik GmbH, a German manufacturer of air quality and aerosol monitoring equipment.

Figure 1.6: Map of reference-grade air quality monitoring stations in Nepal



also measure CO, NO_x, SO_2, ozone, as well as black carbon, which is also measured at Chitwan. One ozone analyzer is also installed at *Pulchowk* station. The data are collected every minute, via the stations' data loggers, and transmitted to a central server at the National Information Technology Centre (NITC). The dataset is made available for download in Comma-Separated Values (CSV) format through the official pollution monitoring website.[12] Two additional stations are managed by the US Department of State (DoS) at *Phora Durbar* and U.S. Embassy in *Chakrapath* that measure hourly $PM_{2.5}$ with a MetOne E-BAM and ozone with an instrument from Teledyne API. These data are made publicly accessible through the US Environment Protection Authority (EPA) AirNow website.[13] Similarly, a high-altitude black carbon station on Yala Glacier set up by ICIMOD forms the 30th element of the nationwide network. This network is shown in Figure 1.6. Alongside the federal nationwide network, a short-lived citizen-driven initiative named "Drishti" added another layer to AQ monitoring in 2016; the group established a network of 18 low-cost air quality sensors around the Kathmandu Valley. Through active social media engagement, Drishti was effective in raising public awareness about air quality until 2019.

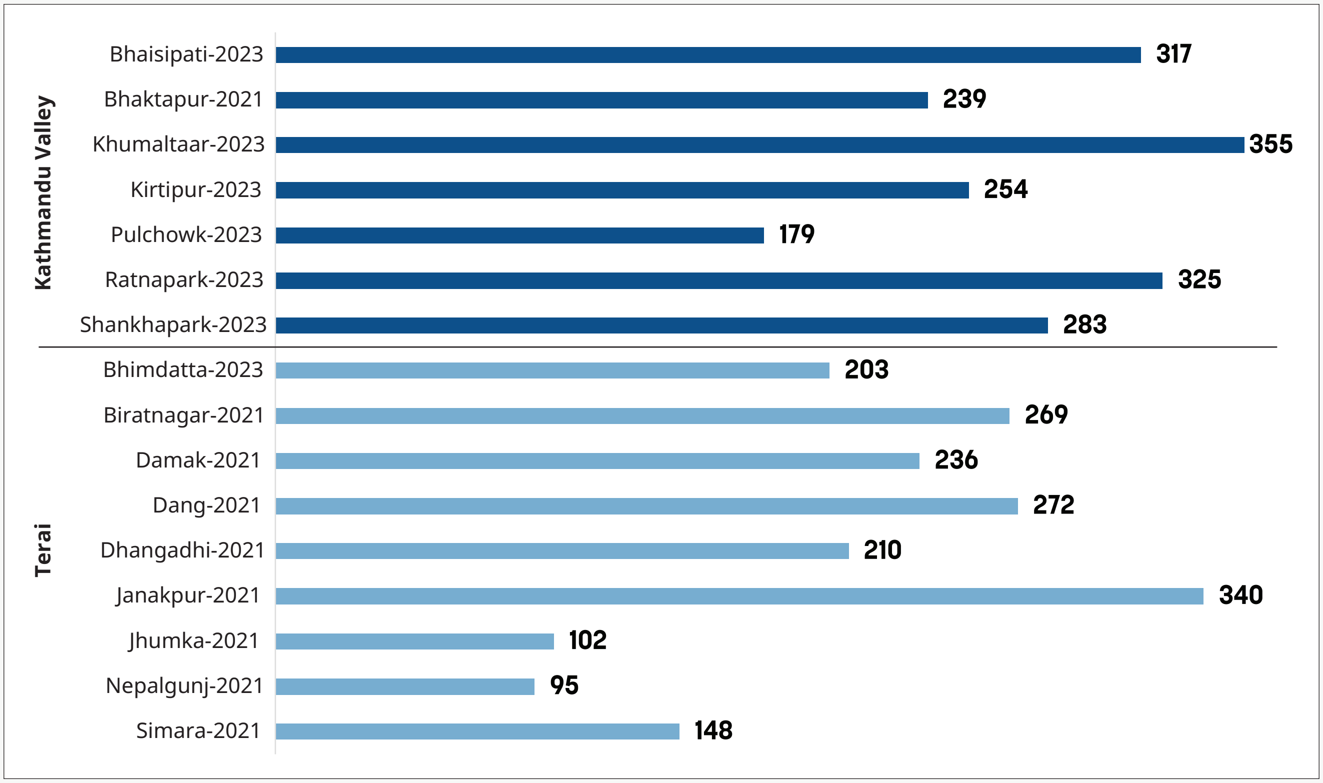
The current air quality (AQ) monitoring network requires further strengthening to ensure data quality. The DoE network lacks official documentation on data cleaning techniques and detailed record-keeping (Kim Oanh et al., 2024). While the DoE's annual report outlines some quality control rules, such as filtering out outliers,[14] there is room for improvement, particularly in presenting

12 MOFE. *Air Quality Monitoring.* Accessed through: http://www.pollution.gov.np/.

13 EPA. *AirNow.* Accessed through: https://www.airnow.gov/?city=Kathmandu&country=NPL.

14 DoE's annual report on Status of Air Quality in Nepal-2021 outlines quality control rules for filtering out outliers ($PM_{2.5} \geq 1500$ μg/m³; $PM_{10} \geq 3000$ μg/m³; TSP≥ 5000 μg/m³) before data display.

Figure 1.7: Total days of $PM_{2.5}$ data availability in 2021 and 2023



Source: DoE's annual report on Status of Air Quality in Nepal, 2021 and 2023.

complete seasonal coverage and analyzing the causes of pollution events. The network faces significant data gaps, with partial data coverage at most stations (see Figure 1.7). By 2021, 28 monitoring stations had been established, but data was reported for only 17. By 2024, 30 stations existed, but data was reported for only 10 (DoE, 2024). Persistent gaps in data coverage[15] highlight the need for detailed reporting on data interruptions, learning from past challenges, proactive equipment maintenance, and better management practices to improve data reliability.

The lack of reliable and accessible AQ monitoring data limits the DoE's ability to manage air quality in the country. The DoE has long-term plans to expand their monitoring network to a total of 56 stations that would provide reliable and continuous air quality information across the country (ICIMOD, 2016). With more than half of their eventual target number of stations in place, the data gaps and poor performance of the existing network severely limit the Department's ability to assess baseline concentrations across the country for all seasons.

The lack of stack emissions monitoring limits the DoE's ability to enforce compliance with industrial standards. Currently, DoE does not have the capacity to carry out stack monitoring. Monitoring systems that track emissions from industrial units provide a basis for enforcing robust industrial emissions regulations. A pilot running stack emissions monitoring would be a useful first start. As a next step, a Continuous Emissions Monitoring System (CEMS) can be considered. See box 5.1 describing the CEMS experience in China. However, adopting such capacity requires significant finance as well as human resource capacity for the operation and

15 Figure 1.7 shows that four stations recorded $PM_{2.5}$ data for fewer than 183 days, indicating these stations have data availability for less than half a year. Nepalgunj (95 days) has the lowest number of days with available $PM_{2.5}$, followed by *Jhumka* (102 days), Simara (148 days) in the Terai region, and *Pulchowk* (179 days) in the Kathmandu Valley.

maintenance of sophisticated systems that may require significant training and skills development.

Advancements in AI-powered satellite monitoring are increasingly capable of detecting and quantifying industrial emissions. AI-driven analysis of high-resolution satellite data can identify emission plumes, detect large-scale events like fires and flaring, and improve transparency by providing independent, large-scale monitoring. However, limitations such as lower spatial resolution, atmospheric interference, and the need for regulatory-grade precision prevent satellite-based methods from fully replacing CEMS.

It is important for Nepal to set an annual average $PM_{2.5}$ ambient air quality standard. The WHO's Air Quality Guideline (AQG) has established a global benchmark that provides a basis for countries to assess the baseline level of ambient air pollution. The key air pollutants for which threshold limits are developed under AQG are $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3 along with heavy metals such as lead, arsenic, and cadmium (WHO AQG, 2021). AQG also recommends interim targets for pollutants to help encourage a shift from higher to lower pollutant concentrations.[16] In Nepal, the air quality levels are assessed based on the nationally set limits as outlined by NAAQS.

Table 1.1 compares the WHO's target for pollutants with Nepal's nationally set standards.

Table 1.1 reveals that the NAAQs only specifies 24-hour averages and lacks annual average limits for both $PM_{2.5}$ and PM_{10}. This omission underscores a critical gap in Nepal's air quality standards, specifically for regulating activities that lead to exceedances, and for evaluating long-term exposure to particulate matter, which have adverse consequences for human health.

Clean air is achievable if we embrace renewable energy; otherwise, our blue sky may vanish forever. *Source: Mukti Chalise, 20, Finalist, Where's My Blue Sky?' Live Art Challenge.*

Table 1.1: Comparison of the WHO recommended AQG levels and NAAQS for various pollutants.

Parameters	WHO (µg/m³)		NAAQS (µg/m³)	
	24-hour average	Annual average	24-hour average	Annual average
TSP	-	-	230	-
PM_{10}	45	15	120	-
$PM_{2.5}$	15	5	40	-
SO_2	40	-	70	50
NO_2	25	10	80	40
Lead	-	-	-	0.5
Benzene	-	-	-	5

Note: CO and O_3 have not been included in the table as their standards have been provided for a different averaging period.

16 Interim targets set annual average thresholds at 5 µg/m³ for $PM_{2.5}$ and 15 µg/m³ for PM_{10}, and 24-hour averages at 15 µg/m³ for $PM_{2.5}$ and 45 µg/m³ for PM_{10}.

CHAPTER 2:

Air Quality Governance in Nepal

This chapter provides a review of Nepal's air quality management governance structure. Section 2.1 gives an overview of the institutional framework and governance structure. Section 2.2 describes the current legal framework, standards related to air quality management, and environmental fiscal policies targeted at improving air quality. Section 2.3 describes past policies and initiatives aimed at specific sectors that affect air quality, while section 2.4 describes the results of some of these regulatory initiatives.

2.1 Institutional framework and governance structure related to air quality

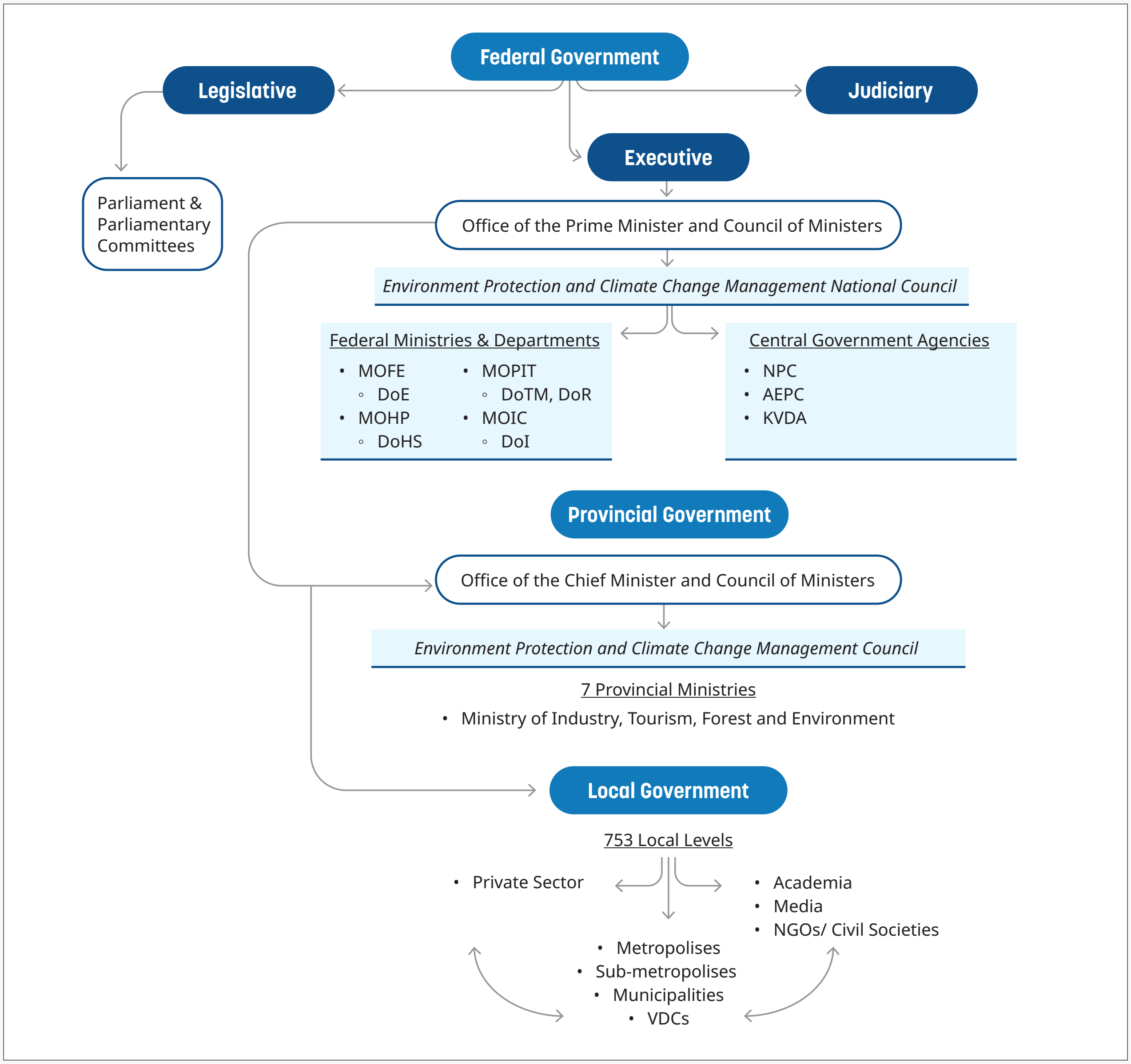
Figure 2.1 shows Nepal's governance structure that involves legislative, executive, and judicial branches, along with various ministries, departments, and local bodies, working together to control air pollution through policies and regulations. The Federal Parliament is responsible for law-making related to pollution control, with several committees addressing this multi-sectoral issue. The judiciary helps to ensure adherence to air quality standards and pollution control measures, while the executive implements budgets, enforces policies, and coordinates the ministries and departments involved.

The existing governance mechanism for managing air quality is characterized by ambiguity due to several factors: lack of clear roles and responsibilities, multi-sectoral involvement, absence of a dedicated parliamentary committee, insufficient legal and regulatory frameworks, judicial and executive challenges for compliance, and gaps in monitoring and enforcement. Therefore, the current governance mechanism for AQM in Nepal needs to be strengthened by establishing a clear institutional structure with well-defined roles and responsibilities, enhancing capacity, ensuring robust coordination among key stakeholder agencies and levels of government, and developing systems for regular monitoring and enforcement.

At the federal level, nine ministries, directly or indirectly, contribute to air pollution management in the country. Among them, the Ministry of Forest and Environment (MoFE) and its Environment and Biodiversity division is responsible for formulating policies and strategies related to pollution control, environmental standards, and biodiversity conservation. Under MoFE, the Department of Environment (DoE)[17] plays a crucial role in air quality

17 The Environmental Monitoring and Assessment Unit oversees the air quality monitoring network and conducts environmental impact assessments; the Pollution Control and Regulatory Unit enforces pollution standards, conducts environmental inspections, and issues pollution control certificates to industries that comply with emission standards; the Environmental Study and Statistics Unit collects environmental data and prepares annual reports on environmental trends and monitoring results to support evidence-based policy-making.

Figure 2.1: Governance structure for air quality management in Nepal



management by drafting and enforcing air quality standards, managing air quality monitoring stations, sharing air pollution data from various platform, and preparing periodic reports on air pollution for decision making. The MoFE issues pollution control certificates to industries complying with emission standards. Apart from MOFE, other line ministries have their own specific roles within the management of different sources of air pollution: the Ministry of Industry, Commerce, and Supplies (MoICS) oversees the control of industrial pollution; the Department of Labor and Occupational Safety (DOLOS) oversees the inspection of equipment for worker safety; the Ministry of Health and Population (MoHP) oversees different health issues caused by deteriorated air; and finally, the Ministry of Physical Infrastructure and Transportation (MoPIT) manages vehicular air pollution. Additionally, other ministries directly or indirectly contribute to the air pollution management in Nepal, such as the Ministry of Energy, Water Resources, and Irrigation (MoEWRI), the Ministry of Urban Development (MoUD), the Ministry of Agriculture and Livestock Development (MoALD), the Ministry of Federal Affairs and General Administration (MoFAGA), and the Ministry of Finance (MoF).[18] The Nepal Planning Commission (NPC) is the central advisory body that formulates national visions, periodic plans, policies, budgeting, annual government programs and monitoring and evaluation systems. The NPC also provides recommendations, insights, and guidance to the sectoral ministries, departments, and local bodies, supports the plan and program development, and monitors the implementation of programs. A National Council on Environment Protection and Climate Change Management, chaired by Prime Minister, has also been established to provide high level guidance on the subject. This council, however, hasn't been very active, despite being required to meet once a year.

At the provincial level, the Chief Minister (CM) is the head of the government and chairs the Environment Protection and Climate Change Management Council that operates within the policy framework of the federal government. Each of the seven provinces of Nepal has established ministries that address environmental management, with portfolios including forests, tourism, or industry[19]. These ministries are responsible for policy implementation and sustainable management of resources at the provincial level, in alignment with federal environmental strategies. The provincial Environment Ministries are charged with overall responsibility of planning, enacting, and reviewing air pollution standards and policies under their jurisdiction; however, provinces lack the capacity to effectively carry out these mandates.

At the local level, municipalities along with their respective wards, are accountable for air pollution control by engaging communities in efforts to achieve and maintain clean air standards. The Local Governance Operation Act, 2017 delineates the rights, duties, and responsibilities of urban and rural municipalities, empowering them to enact local laws and regulations for the conservation of environmental protected areas, environmental pollution and hazard control, and solid waste management. A few municipalities have attempted to reduce solid waste. With a total of 753 local governments across the seven provinces, these entities handle service delivery and execute development activities. Local stakeholders, including private sectors, communities, NGOs, International Non-Governmental Organizations (INGOs), civil societies, academia, and media, also actively contribute to air quality management in Nepal.

However, gaps and challenges remain in the institutional arrangement and regulatory reforms are needed to clarify mandates and advance Nepali federalism for Air Quality Management (AQM). This involves identifying mandates for policy formulation, monitoring, and enforcement across federal, provincial, and municipal levels, and among various ministries and agencies. Strengthening the Department of Environment (DOE), Department of Industry (DOI), Department of Local Infrastructure (DOLI) and Department of Transport Management (DOTM) is crucial, including financing, training programs for enforcement officers, and the procurement of testing and inspection equipment. These efforts should be integrated into a program of regulatory reform with a clear implementation strategy, defined institutional responsibilities, and time-bound targets. The program should be developed collaboratively with relevant ministries and agencies, identifying necessary policy, institutional, and regulatory interventions, including guidelines, standards, and licensing protocols.

18 The Ministry of Energy, Water Resources, and Irrigation (MoEWRI) promotes clean energy alternatives such as hydropower to reduce reliance on fossil fuel and thereby reducing emission of air pollutants. The Ministry of Urban Development (MoUD) oversees urban planning, waste management, and construction practices to reduce dust and emissions. The Ministry of Agriculture and Livestock Development (MoALD) addresses agricultural emissions from the burning of crop residue and methane produced by livestock. The Ministry of Federal Affairs and General Administration (MoFAGA) facilitates liaison and coordination among federal, provincial and local levels. The Ministry of Finance (MoF) provides fiscal incentives and budgetary allocations to support clean energy technologies and air quality initiatives.

19 In Koshi province, the Ministry of Tourism, Forests, and Environment oversees environmental management; in Madhesh, Karnali, and Sudurpashchim provinces, it is managed by the Ministry of Industry, Tourism, and Forest; in Bagmati and Lumbini provinces, the Ministry of Forest and Environment is responsible; and in Gandaki province, it falls under the Ministry of Tourism, Industry, Commerce, and Supplies.

2.2 Existing air quality policies

Article 30 (1) of the Nepali Constitution provides to every individual the fundamental right to a clean and healthy environment.

2.2.1 Environmental law and regulation

Figure 2.2 shows the timeline of key developments in environmental regulations of Nepal. The Government of Nepal (GoN) enforces the Environment Protection Act, 2019 (EPA) and Environment Protection Rules, 2020 (EPR) to control and minimize environmental pollution, thereby protecting public health. While the first EPA was enacted in 1996, its enforcement began a year later in 1997, followed by the promulgation of EPR. With these rules, Nepal made Environmental Impact Assessment (EIA) mandatory. In 2019, the EPA was amended and introduced two additional categories: Baseline or Brief Environmental Study (BES) and Strategic Environmental Assessment (SEA), alongside EIA and Initial Environmental Examination (IEE). The amended EPA has several provisions relevant to air quality, including the issuance of pollution control certificates to industries reducing emissions, the establishment of laboratories, and the establishment of an environmental protection fund.

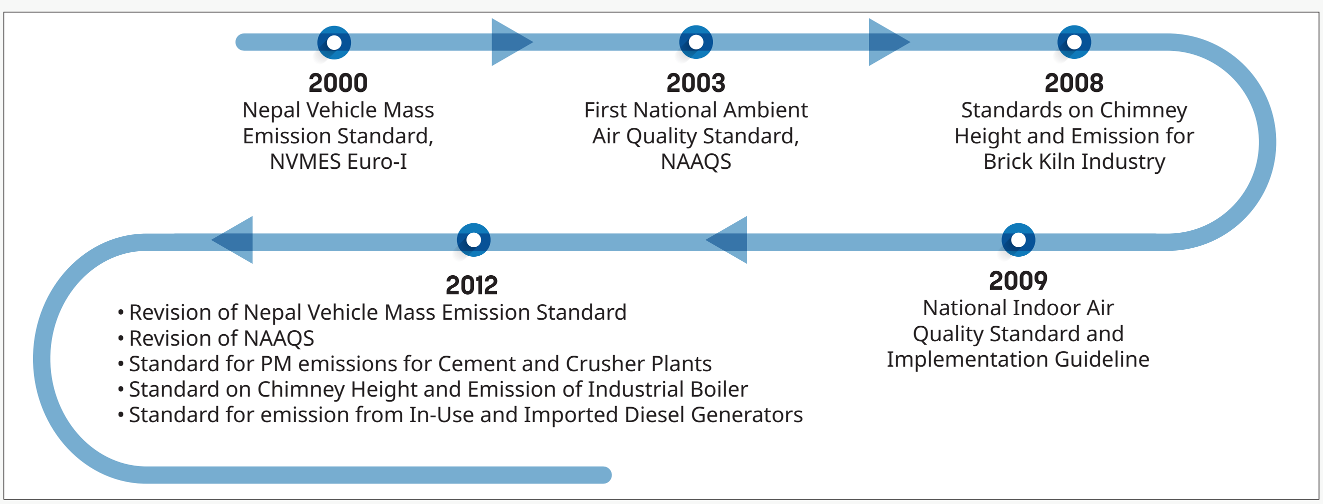
In addition to the EPA and EPR, numerous policies from various sectors address air quality and clean air management in Nepal. This is further discussed in section 2.3.

2.2.2 Air quality standards

Figure 2.3 illustrates a timeline of standards related to air quality management, as introduced by the GoN. It shows how standards have been gradually introduced and revised to address emissions from sources, including vehicles and industries. The timeline represents the country's attempts to tackle air pollution through various standards.

Figure 2.2: Timelines of EPA and EPR

Figure 2.3: Standards related to air quality management



Standards for ambient air quality

The National Ambient Air Quality Standard (NAAQS) was first established in 2003 by the Ministry of Population and Environment (MOPE) and later revised in 2012. A comparison of the former and revised versions of NAAQS is given in Table 2.1. The revised NAAQS in 2012 introduced a standard for $PM_{2.5}$ and implemented stricter standards for benzene, which were absent in the NAAQS-2003.

Standards for the industry sector

To control industrial air pollution, Nepal has introduced several standards in key sectors for key technologies such as brick kilns, cement and crusher plants, industrial boilers, and diesel generators. In 2008, chimney height and emission standards were introduced for brick industries, one of the highest emitting sectors for air pollution. These standards regulate chimney heights to improve the dispersion of pollutants and reduce concentration at the ground level. In 2012, emission standards were introduced for cement and crusher plants, considered to be a major source of dust and fine particulate matter. In the same year, standards were introduced to limit emissions from industrial boilers prevalent across manufacturing sectors for generating steam to produce energy. Coal, diesel, or other fossil fuel-fired boilers emit enormous amounts of pollutants (Khan et al., 2022). The emission standards of 2012 mandated the use of specific chimney heights and emission control devices to restrict emission from boilers, thereby keeping air quality in check. Additionally, emission limits were also introduced for in-use and imported diesel generators, used most frequently in industries as an alternate power source due to the unstable supply of electricity in the country. Detailed information on emission limits is provided in Annex B.

Standards for the mobility sector

In 2000, the Nepal Vehicular Mass Emission Standards (NVMES) were introduced, aligning with the European Emission Standard I (Euro-I)[20]. These standards aimed to control harmful pollutants like carbon monoxide and hydrocarbons emitted from vehicles. By 2012, the NVMES was revised to adopt stricter Euro-III standards, reflecting advancements in vehicle emission control. This revision also prohibited the import of vehicles that did not meet the Euro-III criteria, with an exception for heavy equipment vehicles. These updates were significant in ensuring cleaner vehicle technology and reducing emissions, as many registered vehicles in Nepal were still operating under older emission standards. In 2020, the Nepal Oil Corporation (NOC), a sole importer and distributor of petroleum fuels, started importing Euro-4 standard petrol and diesel, which when complemented with Euro-VI standard vehicles can significantly reduce SOX and NO_x emissions. Detailed information on the guidelines of emission limits for vehicles is provided in Annex B.

Table 2.1: Comparison of NAAQS for various pollutants

Parameters	NAAQS 2003 (µg/m³)		NAAQS 2012 (µg/m³)	
	24-hour average	Annual average	24-hour average	Annual average
TSP	230	-	230	-
PM_{10}	120	-	120	-
$PM_{2.5}$	-	-	40	-
SO_2	70	50	70	50
NO_2	80	40	80	40
Lead	-	0.5	-	0.5
Benzene	-	20	-	5

Note: CO and O_3 have not been included in the table as their standards have been provided for a different averaging period

20 Roman numerals (Euro I, II, etc.) are used for vehicle emission standards, while Arabic numerals (Euro 1, 2, etc.) are used for fuel quality standards,

2.2.3 Environmental fiscal policies

Nepal has experience with introducing environmental fiscal policies, especially targeted at reducing emissions. These policies include additional or incremental taxation on polluting fuels and technologies, and subsidies to cleaner fuels and technologies. Most of the environmental fiscal policies have been introduced upstream, or at the border (through custom centers) for multiple reasons. First, almost all fossil fuels (except a small portion of coal) are imported in Nepal. Since fossil fuels are the main sources of local air pollution and CO_2 emissions, taxing them at the border has a lower administrative cost. Second, upstream taxing covers all consumers (final and intermediate) and helps reduce emissions throughout the economy through pricing as well as substitution effects.[21] Increased fuel prices due to taxation also incentivize consumers to improve their energy efficiency. Examples of environmental fiscal policies recently introduced in Nepal include the pollution tax (an environmental tax on petrol), which was introduced on July 1, 2017, the Green Tax (a tax on fossil fuels more broadly), which was introduced on July 1, 2024, and reduction of import duties of electric vehicles (EVs), which was introduced on July 1, 2022.

A pollution tax, imposed on petroleum products (gasoline and diesel), was the first environmental fiscal policy introduced in Nepal aiming to reduce emissions. As per the Finance Act 2064 BS (2008 AD), the GoN introduced an additional tax at the border point (i.e., customs) on the import of petrol (i.e., gasoline) and diesel. Initially, this pollution tax rate was NPR 0.5 per liter of petrol and diesel. This has since increased threefold and is now NPR 1.5 per liter. Although the government has been collecting this tax for more than 15 years and collected billions of rupees, it has not been utilized for environmental purposes. For example, the government collected NPR 3.08 billion as pollution tax in the fiscal year 2022/23 alone (Nepal Oil Corporation, 2023). In addition to the pollution tax, the government also imposed an infrastructure tax on petrol since 2015. The current rate of infrastructure tax is NPR 10/liter. From July 2015 to March 2023, the government collected NPR 194.5 billion from the infrastructure tax on petroleum products (Republica, 2024).

The GoN has introduced a Green Tax to incentivize emissions reductions and generate public revenue. The Green Tax, introduced through the Finance Act 2024, is imposed on all imported petroleum and coal products. The Green Tax rates are, however, small—NPR 0.5 per kg on coal and coal products and NPR 1 per liter on petroleum products (in addition to the pollution tax discussed above). The government has already started collecting the Green Tax starting July 15, 2024. The funds are flowing into the consolidated budget of the country and have not been earmarked for environmental use.

The government also imposes conventional taxes (e.g., import duty, excise tax, VAT) besides the specific taxes discussed above. While petroleum products receive subsidies in many countries, Nepal does not have subsidies on fossil fuels except a cross-subsidy (not a budget transfer from the government) on Liquified Petroleum Gas (LPG). According to the Department of Customs, the total tax on gasoline was 58 percent of its border price in 2022/23 fiscal year. Similarly, diesel is also taxed at 40 percent of its border price. Nepal's higher petroleum taxes act as a deterrent, keeping fuel use in check and in turn, reducing emissions. If these taxes are reduced, fuel consumption will increase, adding to pollution and environmental degradation. For instance, subsidies and low taxes have underpriced fossil fuels in China[22], making these fuels affordable for industries and therefore leading to increased emissions. This has imposed a significant health burden, with China experiencing some of the highest mortality per ton of SO_2 emission (IMF, 2023). Removing subsidies and adding corrective taxes to fossil fuel prices could achieve a 43 percent reduction in CO_2 emissions globally, preventing 1.6 million premature deaths due to air pollution by 2030 (IMG Blog, 2023).

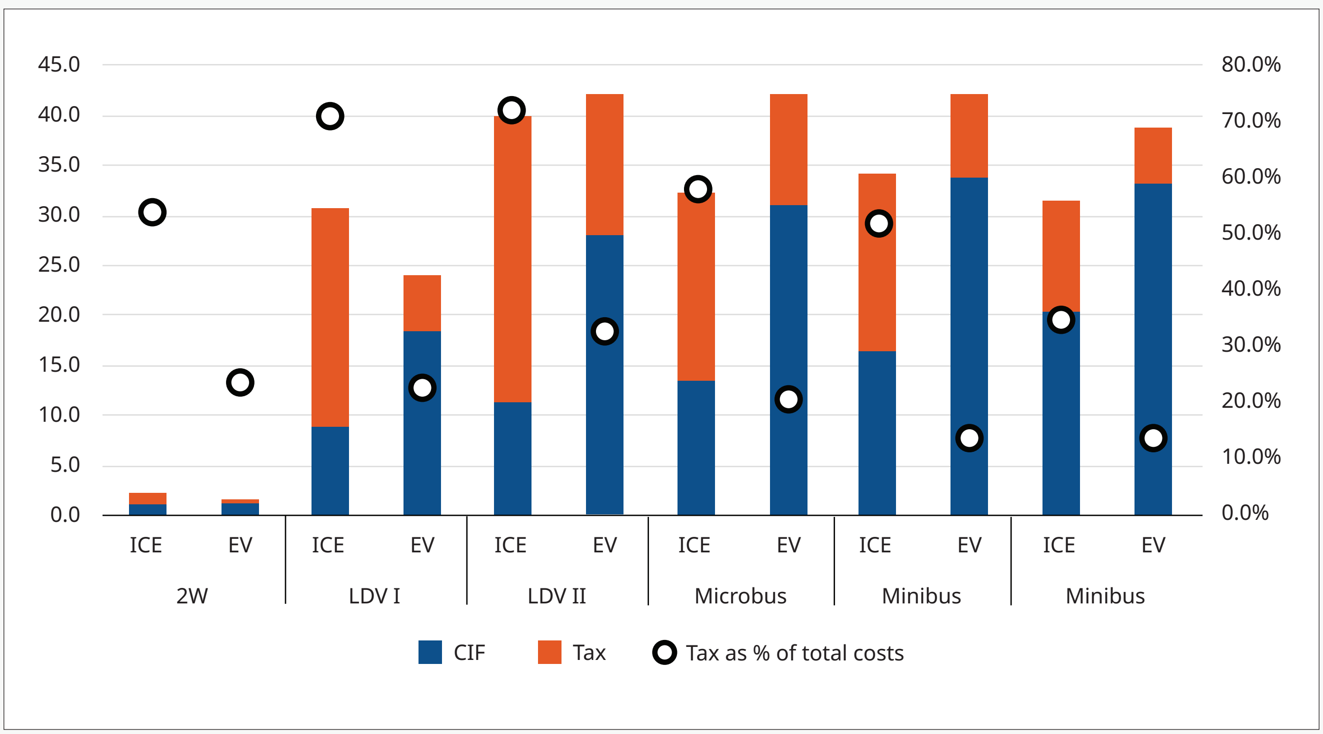
21 Pricing effect refers to reduction of emissions through demand response of increased price, and substitution effect refers to substitution of taxed fossil fuels with cleaner fuels in response to the increased prices due to the environmental taxation.

22 China is the largest subsidizer of fossil fuels globally, with a contribution of 2.2 trillion to global fossil fuel subsidies in 2022.

Reduced duty on EVs is the main subsidy policy for cleaner transportation in Nepal. The GoN has cut duties and excise tax on EVs to promote the substitution of fossil fuels with hydroelectricity and reduce local air pollutants as well as CO_2 emissions from the transport sector. Figure 2.4 presents average prices of various vehicles in Nepal with a breakdown of border prices and taxes. Currently, EVs receive cuts on their import duties and excise tax compared to their Internal Combustion Engine (ICE) counterparts. For example, 1000 CC ICE light-duty vehicles costs, on average, NPR 30.6 Lakh. Of this total, costs, import duties and taxes (including 13 percent VAT) account for NPR 21.8 Lakh (or 71.2 percent). On the other hand, equivalent size EVs (≤ 50 kW) cost NPR 24.1 Lakh, of which duties and taxes account for only 23 percent. The EV of this category is 21 percent cheaper compared to the equivalent ICE vehicles due to much smaller taxes and duties or due to cuts in taxes and duties as compared to ICE vehicles.

The taxation policies in Nepal provide a price advantage to EVs over Internal Combustion Engine (ICE) vehicles, promoting their affordability and adoption. The duties and taxes (including 13 percent VAT) on ICE vehicles as the percentage of border (CIF – Cost, Insurance, Freight) price, are much higher compared to EVs (see Figure 2.4). For example, the taxes on Light-Duty Vehicles (LDV) ICE, on average, is 247 percent of its CIF price, whereas the corresponding value for an equivalent EV is only 30 percent. If the same rates of duties and taxes of LDV ICE vehicles are applied to LDV EVs, the latter would cost NPR 64.3 Lakh, or almost three times as expensive as it is presently. The LDV EV thus receives, on average, NPR 40 Lakh implicit subsidies on its duty and taxes.

Figure 2.4: Border (CIF) prices and taxes of vehicles (Lakh, NPR)



Source: Unpublished report prepared by the World Bank for the High-Level Tax System Reform Advisory Committee (May 2024).

Notes: Taxes include duties, excise and VAT. EV and ICE refer to electric vehicles and internal combustion vehicles, respectively. 2W refers to two-wheeler vehicle and LDV refers to light-duty vehicles. 2W ICE and LDV I (ICE) have an engine capacity less than or equal to 1000 cc; LDV II (ICE) has an engine capacity between 1000 and 1500cc. LDV I (EV) has an engine capacity less than or equal to 50kW, whereas LDV II (EV) has an engine capacity between 50 and 100 kW. Microbus has 11 to 14 seats; minibus has 15 to 25 seats and bus has more than 25 seats. On purchasing price basis, a taxi falls under LDV I.

2.3 Existing sector-specific policies and initiatives related to air quality management

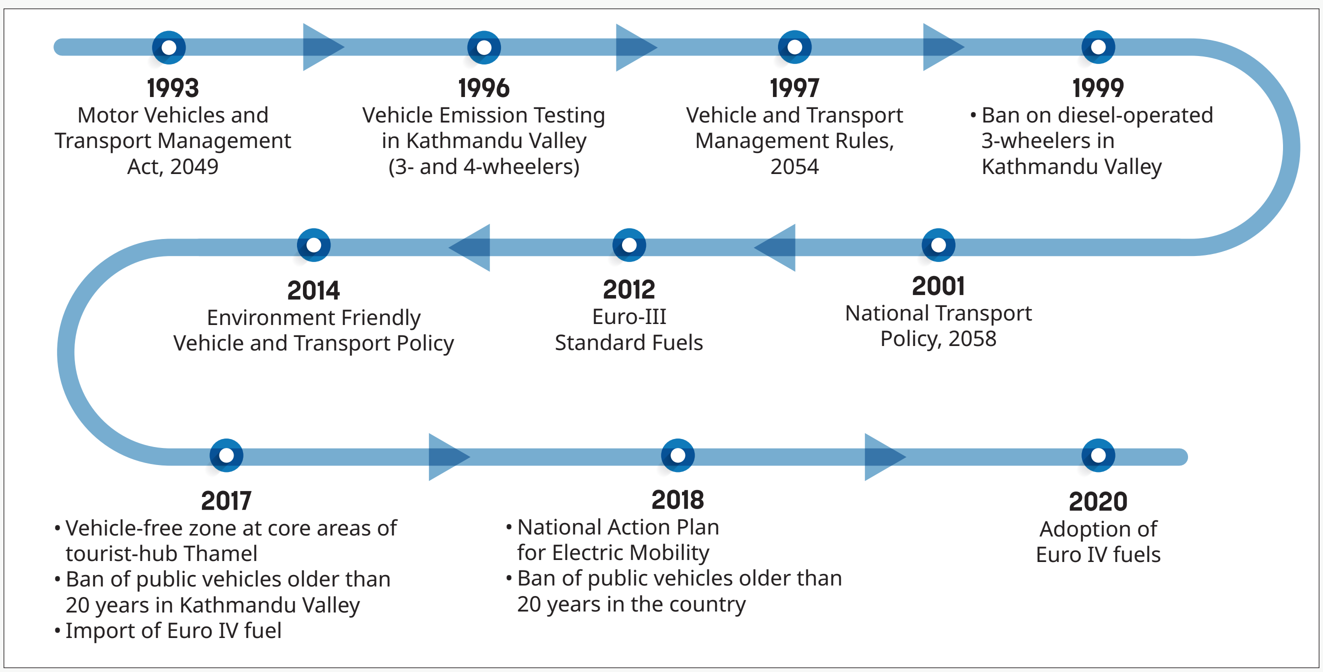
This section outlines several policies and initiatives relating to sectors that significantly contribute to air pollution.

2.3.1 Transport sector policies related to cleaner air

Figure 2.5 provides a chronological overview of policies and initiatives taken by the GoN related to the transport sector, representing efforts toward regulating air pollution through technological upgrades and policy measures. The foundation of transport-based pollution control in the country was established by the Motor Vehicles and Transport Management Act, 1993, which provided legal backing for the emission testing of vehicles. This was expanded further in 1996 to include testing vehicle emissions in 3- and 4-wheelers in the Kathmandu Valley to ascertain that the levels of emission were within permissible limits. Similarly, the Vehicles and Transport Management Rules of 1997 required that the vehicle should always meet the prescribed emission standards. These were the initial steps taken by the government for controlling vehicular emissions and were under the purview of the Pollution Control Division of the Department of Transport Management.

In 1999, the GoN introduced a ban of diesel-fueled three-wheelers, called Vikram tempos, within the Kathmandu Valley (BBC, 1999). This decision marked a significant step towards reducing visible vehicular emissions as it targeted one of the most polluting

Figure 2.5: Policies and initiatives related to transport sector



forms of public transport.[23] The focus on cleaner vehicles continued with the National Transport Policy of 2001, which promoted pollution-free vehicles and mandated regular emission testing. Similarly, the Environment-Friendly Vehicle and Transport Policy, introduced in 2014, targeted a 20 percent share of EVs in Nepal's transport by the year 2020, providing subsidies on EVs and non-motorized transportation.

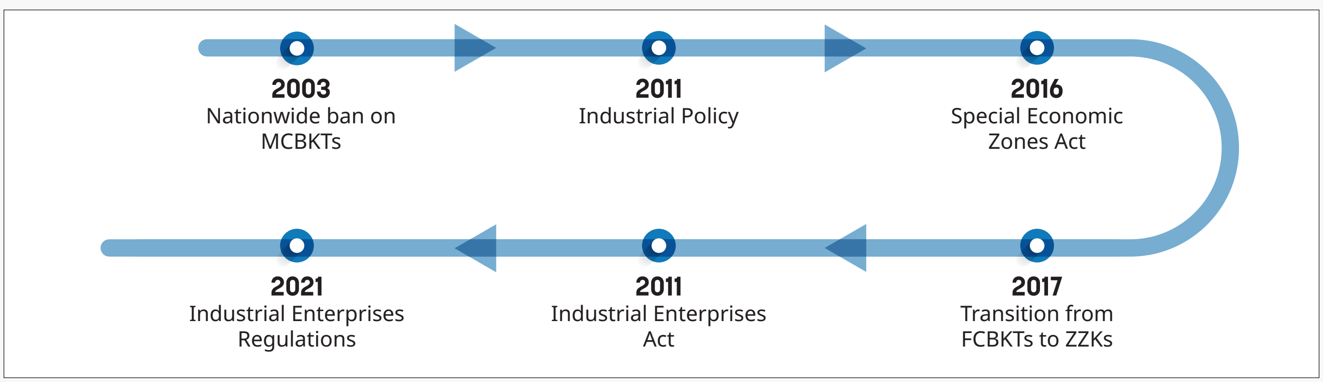
Other localized initiatives have been taken to combat urban congestion and pollution; some have proved successful. For example, the 2017 implementation of vehicle-free zones in Thamel, a significant tourist destination in Nepal, significantly reduced particulate matter in that area. This initiative was undertaken by the joint effort of local level authorities such as the Kathmandu Municipality, Metropolitan Police Division, and Thamel Development Council. Even though the vehicle-free zone rule could not be sustained after the pandemic, this initiative highlights the significance of scaling up local-level interventions to achieve long-term success. In the same year 2017, a ban of vehicles older than 20 years within the Kathmandu Valley was implemented by the DoTM in coordination with traffic police. This decision was extended to a nationwide ban in 2018, with a vision to phase out older polluting vehicles from the road.

To accelerate the implementation of Nepal's Nationally Determined Contributions (NDC), the National Action Plan for Electric Mobility was introduced in 2018. The action plan outlines strategic steps to be taken for increasing the adoption of EVs, with an emphasis on infrastructural development, such as charging stations, policy development, and financial support. Some of the key goals include reducing air pollution and reliance on fossil fuels by strengthening the adoption of electric mobility.

2.3.2 Industrial sector policies related to cleaner air

Figure 2.6 provides a chronological overview of the policies and initiatives related to the industry sector in Nepal, emphasizing their role in managing industrial air emissions. In 2003, the brick sector saw the banning of the extremely polluting moving chimney bull's trench kilns (MCBTKs). While most of

Figure 2.6: Policies and initiatives related to industry sector



23 The ten-seater Vikram tempos were one of the most used and affordable public transports, although each vehicle was accompanied by a very visible plume of black smoke.

the kilns in the Kathmandu Valley were replaced by fixed chimney bull's trench kilns within the year[24], and by zig-zag kilns after 2015, dozens of MCBKTs remained in hidden rural locations even a decade after their ban, and even in 2024 a handful of them can still be spotted in Google Earth imagery. Meanwhile the spread of zig-zag kilns in areas outside of Kathmandu is happening in clusters, with some Terai districts such as Sunsari, converting almost entirely, while other districts are still largely dominated by fixed chimney bull's trench kilns.

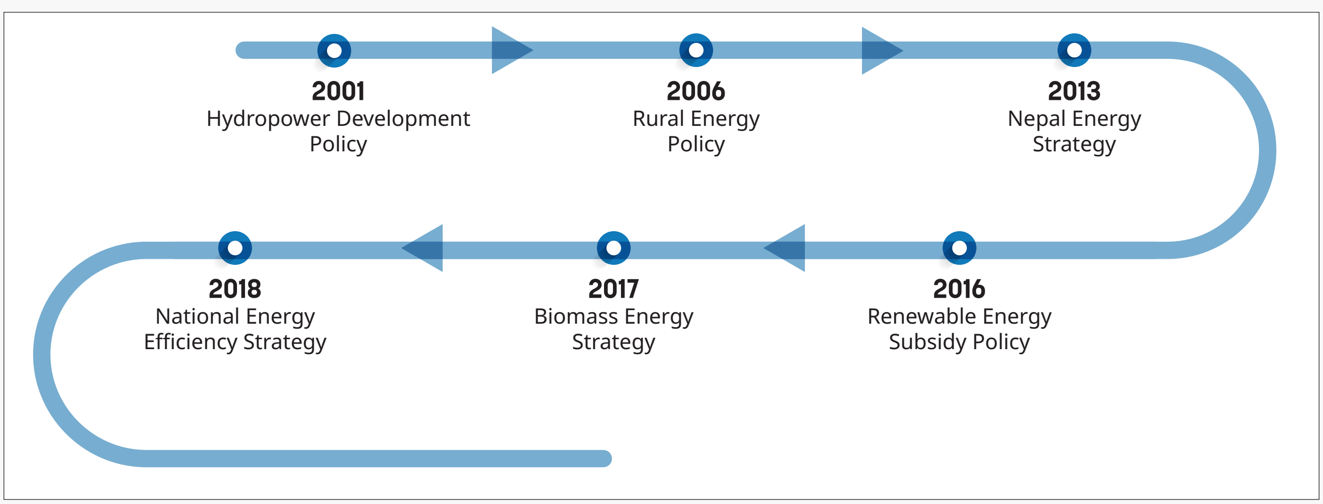
The enactment of the Special Economic zone (SEZs) Act in 2016 has been a significant policy toward pursuing more balanced industrial growth with minimal environmental degradation. The SEZs were established to promote manufacturing and export-oriented industries, through fiscal incentives such as tax exemptions, reduced customs duty, and concession of land. More importantly, the Act requires that industries in the SEZs adhere to national-level emission standards and implement suitable eco-friendly technologies to control emissions.

To further address industrial pollution, the Industrial Enterprise Act (IEA) of 2020 enacted stricter compliance requirements for industries to adopt pollution control measures. Firstly, the Act allows industries investing in pollution control measures to claim expense deductions up to 50 percent of their adjusted taxable income. The Act also reduces customs duty on pollution prevention equipment imports. The Industrial Policy 2011 also supports these tax deductions for investments in pollution control systems. The Industrial Enterprises Regulations (IER) of 2021 further clarify how industries should manage environmental protection and pollution prevention. Secondly, the Act allows issuing penalties in the form of fines and suspension of operating license, for non-compliance with environmental standards.

2.3.3 Energy sector policies related to cleaner air

Figure 2.7 provides a timeline of policies and initiatives related to Nepal's energy sector with implications for air pollution reduction. The Hydropower Development Policy 2001 aims to generate low-cost and clean hydroelectricity, focusing on rural electrification through the development of small and micro-hydropower projects. The policy

Figure 2.7: Policies and initiatives related to energy sector



24 There were also some failed donor-driven pilots to introduce vertical shaft brick kilns.

mandates environmental impact assessments to ensure that the hydropower projects comply with environmental protection standards.

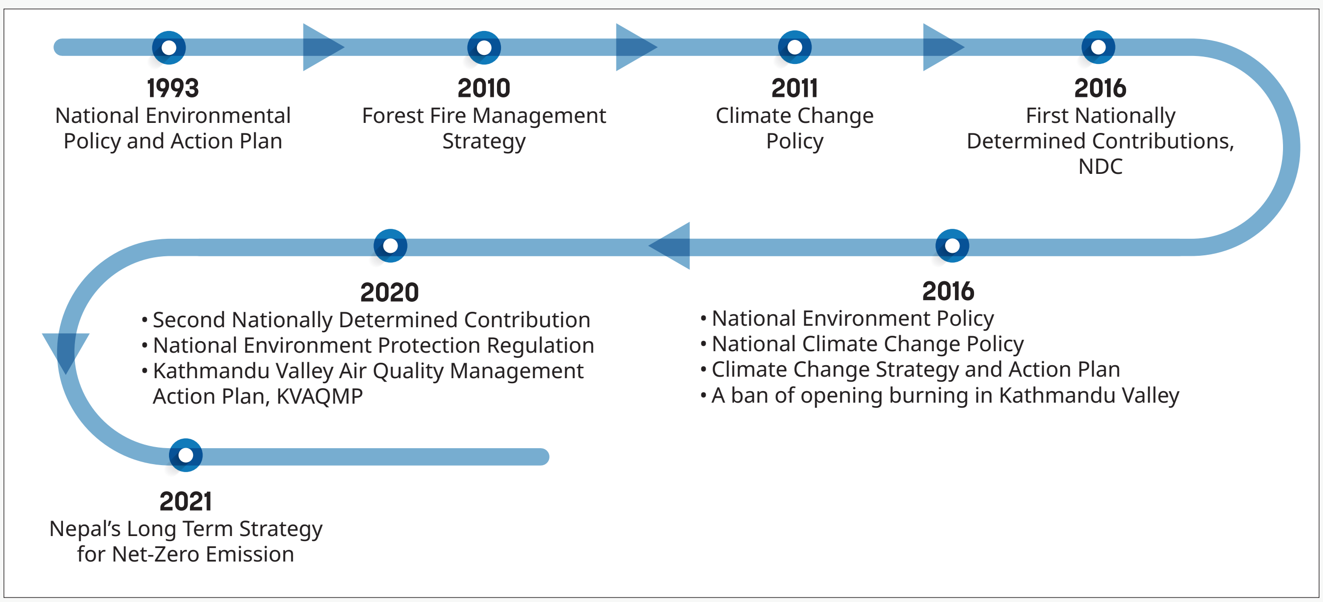
The GoN aims to increase access to clean sources of energy in rural areas. The Rural Energy Policy of 2006, followed by initiatives such as the Renewable Energy Subsidy Policy in 2016 and Biomass Energy Strategy in 2017, have encouraged the adoption of clean and sustainable energy technologies in rural areas. The efforts included subsidizing biogas technologies, improved cookstoves, biofuels, and biomass gasification—all indicative of reduced dependence on traditional biomass and fossil fuel. Likewise, the Nepal Energy Strategy 2013 has highlighted the need to transition toward modern fuels, including hydropower and to reduce indoor air pollution by using improved cookstoves. These policies summarize Nepal's strategic leap toward renewable and clean energy solutions for better air quality.

2.3.4 Other policies and initiatives related to cleaner air

Figure 2.8 provides a timeline of policies and initiatives related to the climate and environment sector, as introduced by the government. The National Environmental Policy and Action Plan (NEPAP), introduced in 1993, implemented some fundamental steps against air pollution: the enforcement of vehicle emission standards, integrating environmental impact assessments, and involving local bodies in urban and industrial planning. These early steps laid the basis for addressing air quality issues.

In 2010, the Forest Fire Management Strategy was implemented in Nepal, which aimed at reducing air pollution resulting from wildfires. The strategy aims at conserving biodiversity and reducing carbon emission from forest fire through policy and institutional strengthening, community mobilization, relevant stakeholder engagement, development of early warning systems, and transboundary collaboration.

Figure 2.8: Policies and initiatives related to climate and environment



In 2011, Nepal introduced the Climate Change Policy, aiming to tackle climate change and its implications through environmental conservation and sustainable development. With the transition to a federal system, the need for a new policy had emerged. Accordingly, in 2019, the National Climate Change Policy was formulated, envisioning the integration of climate change issues into government plans and policies at all levels. This policy extends to sectors such as agriculture, forestry, tourism, transport, disaster, and water resources, each outlined with specific plans and programs. However, air pollution received limited attention in this policy document, aside from section 8.11 which highlighted the development of technologies aimed at reducing black carbon and greenhouse gas emissions.

The first Nationally Determined Contributions (NDC) of 2016 and the Second NDC of 2020 set ambitious goals for transition towards clean energy and reducing dependence on fossil fuel. The First NDC presented targets for renewable energy expansion: achieving 80 percent electrification from renewable sources by 2050, reducing dependence on fossil fuel by 50 percent, and increasing EVs by at least 20 percent no later than the year 2020. The Second NDC expanded these targets to 15,000 MW clean energy generation capacity and 90 percent EV sales by 2030.

The Kathmandu Valley Air Quality Management Action Plan (KVAQMP) was first developed in 2017 and approved by the council of ministers in 2020. The plan identified vehicular emissions, industrial activities, and construction dust as major sources of air pollution in the valley where levels of PM frequently exceeded national and WHO standards The KVAQMP delineates roles and responsibilities to several ministries, departments, and local levels for the implementation of activities to manage air pollution in the valley.[25] As the activities are time-bound, with clear deadlines, measurable indicators, and responsible agencies, the Action Plan is seemingly a powerful policy tool to ensure the cross-sectoral coordination required to achieve clean and healthy air in the Kathmandu Valley; however, the lack of accountability for failure to achieve the specified targets has left the plan falling short of its desired outcome. Additionally, the plan lacks a clearly defined coordination mechanism among stakeholders, leading to challenges in effective implementation.

The National Environment Policy of 2019 aims for the protection of the environment through pollution control, solid waste management, and the enhancement of green spaces. While there isn't a distinct section solely focused on air quality management, Section 8.1 broadly outlines actions related to air, water, and noise pollution control. Some of the measures include establishment of concentration-based and load-based standards to regulate air pollution, issuance of certificates to industries utilizing clean technologies, promotion of eco-friendly cooking stoves, and promotion of clean energy vehicles.

25 The KVAQMP delineates the roles to 10 ministries including the Ministry of Forests and Environment (MoFE), Ministry of Physical Infrastructure and Transport (MoPIT), Ministry of Finance (MoF), Ministry of Industry, Commerce and Supplies (MoICS), Ministry of Energy, Water Resources and Irrigation (MoEWRI), Ministry of Health and Population (MoHP), Ministry of Water Supply (MoWS), Ministry of Education, Science and Technology (MoEST), Ministry of Federal Affairs and General Administration (MoFAGA), and Ministry of Home Affairs (MoHA). The departments include the Department of Environment, Department of Transport Management, Department of Roads, Department of Industry, Department of Water Supply and Sewerage Management, Metropolitan Traffic Police Division, Nepal Electricity Authority, and Nepal Bureau of Standards and Metrology. Local levels include Kathmandu Metropolitan City (KMC), Lalitpur Metropolitan City (LMC), and other municipalities within the valley. Supporting agencies comprise the National Planning Commission (NPC), Office of the Prime Minister and Council of Ministers, Kathmandu Valley Development Authority, High Powered Committee for Integrated Development of the Bagmati Civilization, and Alternative Energy Promotion Center (AEPC). Additionally, other stakeholders include NGOs, private sector entities, community-based organizations (e.g., Tole Development Committees), universities, and research institutions.

The Supreme Court of Nepal prohibited open burning in 2019, followed by a notice from the Kathmandu Metropolitan City (KMC) in 2022 to stop burning solid waste (The Himalayan Times, 2022). Open burning significantly contributes to poor air quality in the Kathmandu Valley, particularly during the winter season. Approximately three percent of the daily generated solid waste in the valley, equivalent to 20 tons per day, is reportedly burnt in open spaces[26]. It is estimated that open burning of solid waste in Nepal leads to a 30 percent increase in $PM_{2.5}$, causing around 300,000 premature deaths from chronic obstructive pulmonary diseases (Saikawa et al., 2020).

2.4 Gaps in plans and policies related to cleaner air

In this section, gaps in the existing policy framework are diagnosed; however, recommendations on filling the policy gaps with respect to Nepal's AQM framework are presented in chapter 5.

NAAQS

The revised NAAQS mandates 24-hour average threshold levels for pollutants including $PM_{2.5}$, PM_{10}, and TSP, but lacks annual average thresholds for these pollutants. Both annual and 24-hour standards are crucial for assessing air quality. For instance, the WHO recommends annual average $PM_{2.5}$ concentration below 5 µg/m³ and 24-hour average below 15 µg/m³. While the 24-hour standards help to understand short-term pollution peaks, annual standards are essential in addressing long-term exposure to

A woman and child, both wearing masks, navigate a dusty road in Nepal, a common sight highlighting the daily challenges posed by the air quality in many parts of the country. *Source: Sabrina Dangol/World Bank.*

26 CEN. *Policy Brief on Air Pollution & Health in Kathmandu Valley- Solid Waste.* Accessed through: https://www.cen.org.np/uploads/doc/uhi-policy-brief-swm-final-62b145f1ce03f.pdf.

The inclusion of annual standards for $PM_{2.5}$ and PM_{10} in NAAQs is crucial as it provides a benchmark to assess impacts related to prolonged exposure to these pollutants, facilitating effective air quality management strategies and regulations.

pollutants and tracking progress in air quality over time. Therefore, the inclusion of annual standards for $PM_{2.5}$ and PM_{10} in NAAQs is crucial as it provides a benchmark to assess impacts related to prolonged exposure to these pollutants, facilitating effective air quality management strategies and regulations.

Nepal Vehicular Mass Emission Standards (NVMES)

While this standard exists to date, vehicle inspections have major gaps. First, they are not mandatory for motorcycles (which are the most common vehicle type) or for heavy-duty diesel vehicles (which are the biggest emitters). The standards apply only to three- and four-wheel passenger and light-duty vehicles. Second, the inspections/measurements are still based on Euro-II standards, while Euro-III and higher standard vehicles are being imported. Third, as identified in the earlier sections, the instruments used to measure emissions are often wrongly calibrated. Fourth, the system is allegedly fraught with corruption, with an open black-market for “green” stickers (Nepali Times, 2019).

National Environment Policy

Despite covering various sources of air pollution, from household fuel use to transportation, the policy lacks clear implementation strategies. The provisions appear as individual statements rather than comprehensive strategies ready for execution. The absence of specified timelines for achieving these goals contributes to the ambiguity of these policies. Moreover, the policy does not establish a clear coordination mechanism among the three tiers of the government, potentially hampering effective policy implementation.

Vehicle emission testing

Since the introduction of the system, there have been growing concerns about policy enforcement effectiveness. If a vehicle fails the emission test, owners often rely on local repair shops to make essential adjustments for proper functionality of the vehicle’s emission control device. However, these repair shops frequently lack the technical expertise and resources required for such changes and resort to providing minimal alterations solely to facilitate test clearance. The availability of authorized repair centers would have simplified the process of making accurate adjustments to minimize vehicle emission, ensuring compliance and facilitating more effective monitoring.

In 2022, the DoE issued a notice to fine vehicles failing pollution tests, leading to random checks in the valley where a significant number of vehicles failed emissions tests. However, these initiatives have been irregular and inconsistent, making them an inefficient approach to monitor and ensure compliance. Additionally, a comprehensive guiding document is lacking that provides details on emission testing instruments, their maintenance, testing methods, and emission standards thereby raising concerns about the accuracy and reliability of the entire process. In addition, the manual record-keeping of issued green stickers in yearly logbooks, without a mandated digital recording procedure, poses challenges in assessing program effectiveness and opens avenues for fraud and corruption (Faiz et al., 2006; Shrestha, 2013).

Ban on diesel-fueled three wheelers

Alongside the ban on “Vikram tempos” (diesel-fueled, three-wheeled public transport vehicles) in 1999, the government introduced incentives that seemingly contradicted this environmental initiative. This included a 99 percent subsidy on customs taxes and an exemption from the Value Added Tax (VAT) for imported 15-seater diesel-powered microbuses (Sushila Maharjan, 2002). The implementation of these mixed measures overlooked the opportunity to fully support the adoption of cleaner alternatives, such as "Safa tempos" (three-wheeled, battery-powered EVs that are used for public transportation). This ultimately limited the growth of the EV market in Nepal in the early 2000s. The electric trolleybus system connecting Kathmandu and Bhaktapur, launched in 1975 as a cleaner public transport alternative, also met with the same fate and was officially shut down in 2009 due to persistent maintenance issues, financial constraints, and operational inefficiencies, among other reasons.

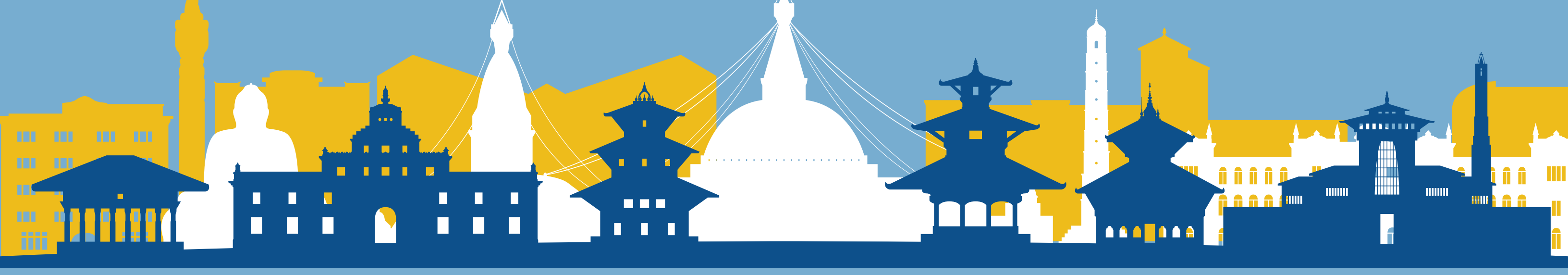
Ban on public vehicles older than 20 years

The GoN initiated phasing out of aging vehicles by introducing a ban on public vehicles over 20 years old, starting enforcement in the Kathmandu Valley on March 1, 2017 (Nepal Gazette, 2017), and then nationwide on March 15, 2018 (Das et al., 2024). The nationwide ban was reinforced by the Supreme Court in 2024 to scrap all leased (public and commercial) diesel and petrol vehicles older than 20 years and EVs older than 30 years. Despite these efforts, the enforcement has been inconsistent as many of the old models remained on the roads, especially in rural areas with limited monitoring. A key issue is the absence of an effective strategy as the government's approach relies on dismantling older vehicles only if they are caught on the roads, but this is inadequate in regions with sparse inspections. A more effective strategy could involve leveraging the DoTM's registration data to compile a list of old vehicles and facilitating their removal by the Traffic Police Division during routine monitoring.

In February 2024, the Gandaki Province introduced the Provincial Vehicle and Transport Regulations 2080, extending the policy to include the scrapping of private vehicles over 25 years old (Provincial Gazette, 2024). However, at the national level, this ban remains limited to leased transport vehicles.

Other implementation challenges include a lack of dedicated scrapping or dismantling facilities. The Nepal Road Safety Action Plan (NRSAP) 2021–2030 highlights the absence of a structured vehicle scrapping mechanism and inadequate Vehicle Fitness Testing Centers (VFTCs) as significant gaps to achieving the intended outcomes of such policies (MoPIT, 2021). The NRSAP emphasizes the urgent need for comprehensive infrastructure to support vehicle scrapping. It calls for establishing Vehicle Fitness Testing Centers in all provinces to ensure regular inspections and proper decommissioning processes.

A painter imagines a future with cleaner air. *Source: Jenish Maharjan, Finalist, Where's My Blue Sky?' Live Art Challenge*



CHAPTER 3:
Benefits of Clean Air in Nepal

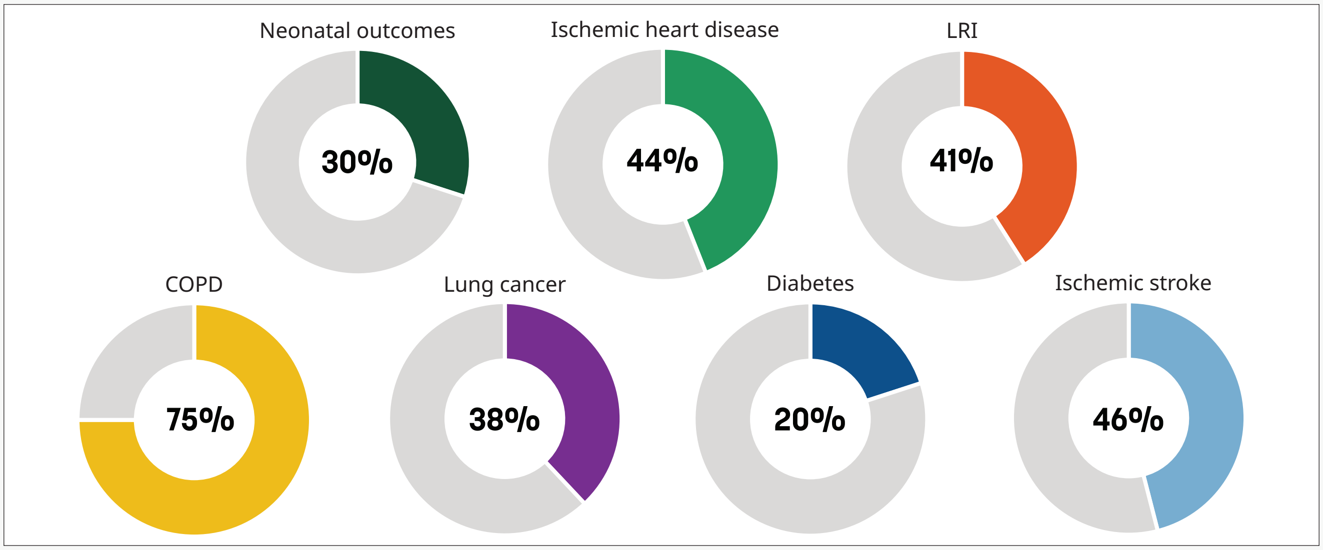
This chapter examines the health, economic, and human development benefits of reducing air pollution in Nepal. Section 3.1 describes the overall health burden of air pollution. Section 3.2 reviews Nepal-specific health studies, focusing on local evidence with respect to the effects of air pollution. Section 3.3 discusses newly emerging evidence on other health impacts, such as childhood stunted growth, preterm birth, and neurological effects. Section 3.4 covers the economic costs associated with air pollution. Section 3.5 outlines numerous development benefits of clean air action, such as improved energy and water security, tourism, aviation safety, and creation of jobs in green energy sectors.

3.1 Health impacts of air pollution and the burden of disease

Air pollution is the number 1 risk factor for death and disability in Nepal, ahead of malnutrition (number 2) and tobacco (number 3).[27] Air pollution is a persistent environmental challenge in Nepal, with significant implications for public health and development. Elevated levels of particulate matter and other pollutants in the air have been associated with a range of health issues and diseases that contribute to the global burden of disease. Key diseases and health conditions associated with air pollution include respiratory diseases (chronic obstructive pulmonary disease (COPD)—asthma, bronchitis, etc.), and cardiovascular diseases (increased risk of heart attacks, stroke, hypertension, lung cancer, acute lower respiratory infections (ALRI), etc.). Air pollution can also weaken the immune system, making individuals more susceptible to respiratory infections like pneumonia, particularly in children and the elderly. Exposure to particulate matter and other pollutants contributes to inflammation and blood clotting, and diabetes. Studies have suggested increased risk of developing diabetes and exacerbating existing diabetes-related complications, low birth weight and preterm birth or babies with low birth weight. The seven disease categories with well-established relationships are routinely included in Global Burden of Disease calculations. Figure 3.1 shows the percentage of deaths in Nepal attributable to air

27 https://www.healthdata.org/research-analysis/health-by-location/profiles/nepal

Figure 3.1: Percentage of deaths from specific causes attributable to total air pollution in Nepal



Data Source: Global Burden of Disease Study 2021 (HEI, 2024).

pollution, for various health conditions[28]. Air pollution's health impact is more severe in Nepal due to higher exposure to pollutants. Compared to global averages, a significantly higher percentage of cases for conditions like COPD (75 percent vs. 40 percent) are linked to air pollution.[29]

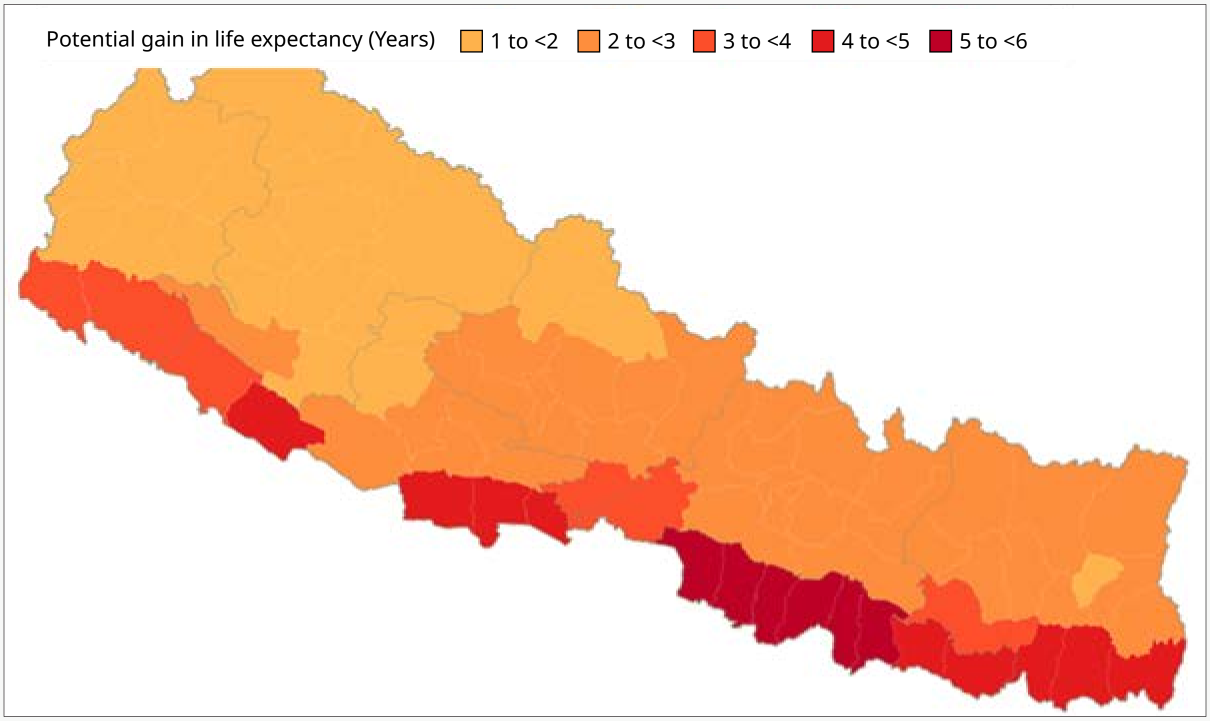
The overall burden due to air pollution on Nepal's public health is large. Figure 3.1 shows seven diseases associated with air pollution in the Global Burden of Disease study for 2021. Air pollution in Nepal was estimated to have led to over 48,500 premature deaths and the loss of more than 1.4 million disability adjusted life years (DALY).[30] These estimates are somewhat larger, but in line with earlier World Bank estimates from 2015, which found 26,000 premature deaths from $PM_{2.5}$ alone (nearly 12,000 from ambient exposure and more than 14,000 from household exposure) (World Bank, 2019). Reducing air pollution levels is crucial for addressing these health impacts and improving public health outcomes worldwide. The Energy Policy Institute (EPIC) of the University of Chicago Air Quality Life Index (AQLI) estimates that exposure to particulate pollution takes 3.4 years off the life of the average Nepalese resident. If Nepal were to reduce particulate pollution to meet the WHO guideline, residents in the mid and eastern Terai region—where nearly 40 percent of Nepal's population resides—would gain 4.8 years of life expectancy. In the capital city of Kathmandu, residents would gain 2.6 years of life expectancy (EPIC, 2024, Figure 3.2).

28 These estimates reflect Total Air Pollution, which includes $PM_{2.5}$ from both ambient and household sources. Other pollutants like NO_2, SO_2, and O_3 are excluded, except for COPD, where ozone exposure is considered. Neonatal deaths are attributed only to $PM_{2.5}$, household air pollution, or both combined. Neonatal outcomes include complications from low birth weight, preterm birth, and lower respiratory infections.

29 Globally, 40 percent of COPD, 30 percent of lower respiratory infections (LRI), 26 percent of strokes, and 20 percent of diabetes, ischemic heart disease, neonatal deaths and lung cancer are associated with air pollution. In Nepal, air pollution related death is much higher, attributable to conditions like COPD (75 percent), stroke (46 percent), and ischemic heart disease (44 percent), LRI (41 percent), lung cancer (38 percent), neonatal outcomes (30 percent), and diabetes (20 percent).

30 Health Effects Institute. 2020. *State of Global Air 2020.* Data source: Global Burden of Disease Study 2019. Institute for Health Metrics and Evaluation (IHME), 2020. These estimates are based on the Global Burden of Diseases estimates which associate air pollution with 7 key risk factors including: ischemic heart disease, lung cancer, chronic obstructive pulmonary disease (COPD), lower-respiratory infections (e.g., pneumonia), stroke, type 2 diabetes, and, more recently, adverse birth outcomes.

Figure 3.2: Potential gain in life expectancy in Nepal from permanently reducing $PM_{2.5}$ from 2022 concentration to the WHO guideline (5 μg/m³)



Data Source: EPIC Air Quality Life Index, 2022.

Both indoor and outdoor sources of air pollution have a significant burden on public health. While outdoor air pollution is dominated by emissions from vehicles, industries, waste burning, and dust resuspension, household air pollution (HAP) is attributed to using traditional fuels of biomass. By 2021, 54 percent of population of Nepal relied on solid fuels such as fuelwood and animal dung for domestic heating and cooking (Census, 2021). The incomplete combustion of fuels on inefficient stoves within poorly ventilated houses of rural areas produces extremely hazardous levels of indoor air pollution, risking women and children developing a wide array of health ailments like allergies of skin and eyes, asthma, cough, respiratory, cardiovascular diseases[31] and leading to around 8,700 deaths every year.[32] The impact of HAP is far-reaching outside homes, as nearly 66 percent of $PM_{2.5}$ emissions from cookstoves directly passes to the outside environment, contributing to ambient air pollution (Adhikari et al., 2020)exact quantification of the contribution of biomass cookstove emissions to outdoor air is still lacking. In order to address this gap, we designed a field study to estimate the emission factors of $PM_{2.5}$ (particulate matter of less than 2.5 μ diameter. While preventive actions like switching to LPG, electric cooking, and biogas contribute to eliminating causes, protection measures like purifiers, better ventilation, and masks can provide immediate relief from exposure to indoor pollution (Refer to Box 5.3). Detailed evidence of the negative health impacts of air pollution on health in Nepal are included in Annex C.

31 A study estimated that 34.6 percent of childhood pneumonia cases, 42.5 percent of acute respiratory infections/pneumonia, and 54.8 percent of chronic obstructive pulmonary disease/asthma cases in Nepal could be attributed to HAP (Shrestha, 2022).

32 Energy Sector Management Assistance Program (ESMAP). 2017. *Nepal: Fostering Healthy Households through Improved Stoves*. Accessed through: https://www.esmap.org/node/57862.

This painting highlights the fragility of our environment, symbolized by a shattering blue sky. It portrays the confluence of current environmental challenges – how smog, dust, and air pollution have become pervasive in our daily lives. *Source: Richene Singh, Finalist, 'Where's My Blue Sky?' Live Art Challenge.*

Additional research on impacts of air pollution on public health in Nepal is needed. The national statistics cited above generally rely on global databases and research conducted outside of Nepal. Extrapolation of health impacts from studies performed in other regions provides useful information but has limitations (Gurung et al., 2013). For example, while the Kathmandu Valley has substantially higher pollution levels, the pollution mix may differ and there may be variations in the physical and chemical characteristics of fuels and in the abatement technologies and practices. Driving habits and congestion patterns and other elements of lifestyle and culture may vary, and health responses may differ due to baseline health, nutrition, health care systems. More local research is needed to overcome the gaps in lack of exposure data, and the absence or poor quality of health records (e.g. absence of International Classification of Disease (ICD) codes in hospital records).

The health and economic impact statistics discussed above underestimate the true burden of disease associated with air pollution since they leave out important disease categories for which the epidemiological evidence is still being established by the global public health community. Other impacts include preterm births and low birth weight, childhood stunting and potential neurological effects, including Parkinson's, Alzheimer's, and cognitive impairment with learning outcomes. These studies are included in Annex C.

3.2 The cost of air pollution

Pollution constrains Nepal's development through its human and economic costs. Mortality, morbidity, and reduced cognition have financial costs on households along with wider economic costs, including

Pollution constrains Nepal's development through its human and economic costs… Reducing the burden of environmental degradation further improves conditions for growth by encouraging foreign investment, tourist inflows, recreation opportunities, and quality of life.

loss of income and time, expenditure on medical services, costs of suffering, and reduced intellectual capacity and productivity. Pollution degrades human capital—the sum of people's productive capacity—an important economic concern given that human capital is fundamental for accelerating economic growth and lifting productivity (World Bank 2019). Reducing the burden of environmental degradation further improves conditions for growth by encouraging foreign investment, tourist inflows, recreation opportunities, and quality of life (World Bank, 2019).

$PM_{2.5}$ is the greatest contributor to Nepal's economic burden due to pollution, with a total forgone output cost in 2015 of USD 130 million per year, and a total welfare loss of USD 1.36 billion in 2015. These costs—as estimated by the World Bank for Nepal's most recent Country Environmental Assessment—represent around 0.6 and 6.4 percent of annual economic activity (GDP equivalent), respectively.[33] More recent estimates, following similar methodologies, but utilizing updated values and methods, find a welfare loss for Nepal of USD 1.4 billion in 2019 due to ambient air pollution alone. When ambient and household air pollution are combined, a cost of more than USD 3.1 billion is estimated, equivalent to more than 10 percent of Nepal's GDP (World Bank, 2021).

Clean air improves productivity and city competitiveness by attracting labor, boosting tourism, and fostering economic innovation. Cities with better air quality are more appealing to skilled workers and businesses, leading to greater investment and job creation. Areas with lower pollution and more natural beauty attract people and economic activities (Kahn et al., 2019). High-quality living conditions also boost access to enterprise finance and venture capital tends to concentrate in healthier, more attractive cities. In contrast, poor air quality undermines long-term economic potential by impairing early childhood development. For example, a 1 $\mu g/m^3$ increase in $PM_{2.5}$ exposure raises stunting by 0.5 percent in children under five, which in turn reduces future productivity and national GDP (Heft-Neal et al. 2022; Galasso and Wagstaff 2019). Cleaner air therefore not only promotes public health but also lays the foundation for sustained economic growth.

3.3 Multiple development benefits of clean air action

The adverse economic effects of air pollution extend beyond the productivity losses and welfare costs associated with public health. In addition, on a seasonal basis, air pollution also reduces the quality of life for millions of people. Air pollution affects many aspects of the country's economy, from agriculture (Nakarmi et al., 2020), to visibility, aviation, and tourism (Kathayat et al., 2023). Air pollution in Nepal is also tied closely to climate change—not just through the co-emission of greenhouse gases by many of the same sources, but also more directly through the contribution of black carbon to the melting of the Himalayan Cryosphere, and through the impact of airborne particles on the microphysics of cloud and fog droplets, thereby altering the spatial and temporal patterns of precipitation and fog (Mani, 2022; Panday, 2022; Saikawa et al., 2019; Yasunari et al., 2010).

33 The economic (monetary) value of the total attributable burden is estimated in terms of (1) forgone labor output, and (2) lost welfare. The forgone labor output value is an estimate of the cost of premature mortality, calculated as the present value of forgone lifetime earnings, and welfare is calculated by multiplying the estimated number of premature deaths with the value of statistical life, a measure of "an aggregate of individuals' willingness to pay (WTP) for marginal reductions in their mortality risks. (Narain and Sall 2016).

Improving air quality in Nepal offers a multitude of co-benefits that extend beyond health improvements. For example, cleaner air significantly reduces aviation risks, enhances the attractiveness of the country for tourists, and reduces glacial melting (which, if unchecked, may lead to flooding, among other water insecurity issues). Measures that promote cleaner technologies and fuels, which lead to cleaner air, also have development co-benefits such as stimulating domestic demand for electricity and creating job opportunities.

One of the key benefits of improving air quality is the reduction of aviation risks. Poor visibility caused by haze and fog, often exacerbated by high levels of $PM_{2.5}$, leads to flight delays and cancellations, impacting both safety and timeliness. For instance, studies at Bhairahawa airport (BWA) have shown a strong correlation between $PM_{2.5}$ concentration and poor visibility. Haze accounts for the highest percentage of delays and its annual occurrence is increasing (Kathayat et al., 2023). By implementing measures to reduce air pollution, Nepal can ensure safer and more reliable air travel, which is crucial for both domestic and international flights.

Enhancing air quality also makes Nepal more attractive to tourists. The country's tourism industry heavily relies on clear views of its natural beauty, including the Himalayas. Poor air quality obscures these views, leading to disappointment among visitors and negatively impacting tourism revenue. For example, air pollution in the Kathmandu Valley has been estimated to lead to annual tourism revenue losses of approximately USD 10 million (Shah & Nagpal, 1997). By improving air quality, Nepal can offer better visibility and a more pleasant experience for tourists, thereby boosting the tourism sector and its contribution to the economy.

Reducing air pollution mitigates the accelerated melting of glaciers caused by anthropogenic black carbon (BC), thereby contributing to water and energy security. Recent evidence suggests that deposits of anthropogenic BC are responsible for more than 50 percent of the accelerating glacier and snow melt (World Bank, 2022). A reduction in glacial melt improves water and energy security by preserving the freshwater stored in glaciers, especially in the Hindu Kush Himalaya (HKH) mountains, which boast nearly 55,000 glaciers. These glaciers,

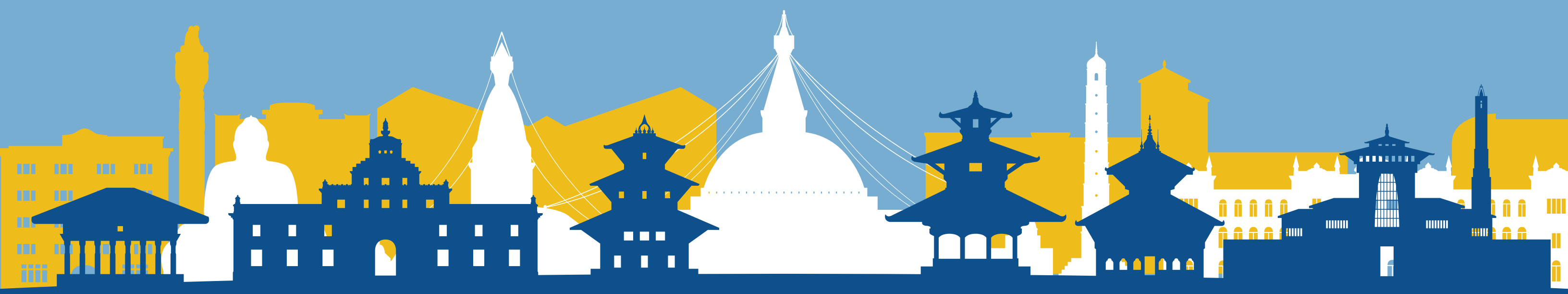
A man connects a charging cable to an electric bus in Nepal, highlighting the country's move towards greener transportation.
Source: Narendra Shrestha/World Bank.

Improving air quality in Nepal offers a multitude of co-benefits that extend beyond health improvements...reduced aviation risks, enhanced tourism, stimulated domestic demand for electricity, and new job opportunities to name a few.

holding an estimated 163 cubic kilometers of ice, supply critical water resources to three major South Asian rivers: the Indus, Ganges, and Brahmaputra, supporting 750 million people. By slowing glacier melt, immediate disaster risks like flash floods and landslides are mitigated and a stable water flow is ensured for agriculture, human consumption, and hydropower generation. Cleaner air plays a pivotal role in maintaining water reserves in dams, bolstering both water and energy security for the region.

Another significant benefit of improving air quality is the stimulation of domestic demand for electricity. Nepal generates surplus hydroelectric power during the rainy season, leading to periods when electricity supply exceeds domestic demand. Expanding electricity use in manufacturing, transport, and cooking would absorb this surplus, boosting economic productivity, and reducing import dependence on fossil fuels, in addition to lowering emissions. For instance, by 2030, electricity demand for EVs could rise significantly under sustainable development scenarios (Karn et al., 2025). This shift towards cleaner energy sources can enhance energy security and reduce the environmental impact of traditional fuel use.

Creating job opportunities is another important co-benefit of improving air quality. The transition to clean energy and technologies requires new skills and creates employment in various sectors. Globally, the renewable energy sector has employed millions of workers, and similar trends can be expected in Nepal (ILO, 2023). As the country adopts cleaner technologies, it can generate numerous green jobs, contributing to sustainable and inclusive economic growth. For example, projects that utilize decentralized renewable energy sources like rooftop solar involve localized installations, creating more jobs in local communities (World Bank & ESMAP, 2023).



Chapter 4:

Key Sources of Air Pollution and Technological Solutions

This chapter examines the key sources of air pollution in Nepal, current and future, and evaluates abatement measures. Section 4.1 identifies the sector/source contributions to $PM_{2.5}$ in the Kathmandu Valley and the Terai. Section 4.2 projects air quality trends to 2035 under a baseline scenario, showing significant increases in $PM_{2.5}$ exposure without further interventions. Section 4.3 identifies cost-effective measures to reduce $PM_{2.5}$ exposure. Section 4.4 discusses the potential to achieve the WHO interim air quality targets (35 μg/m^3) by 2035 through coordinated local and regional actions.

4.1 Key sources – sectoral and geographic – of air pollution for the Kathmandu Valley and the Terai

The existing knowledge on sources of air pollution in Nepal is incomplete and in need of supplementation. Source apportionment studies are crucial for identifying different sources and their relative contributions to air pollution. Such studies enable policymakers to develop targeted emission reduction strategies based on localized and scientifically robust data. In Nepal, the studies conducted so far have largely been short-term, site-specific, and limited to the Kathmandu Valley[34], making it difficult to extrapolate the findings to rest of the country which vary significantly in geography and socio-economic conditions. Additionally, these studies have been conducted at different times using varying methodologies, leading to inconsistencies in reported pollution sources and their relative contributions. The lack of a comprehensive, credible and ongoing nationwide source apportionment network limits our ability to fully understand the sources of air pollution in Nepal and their impacts. A detailed analysis of what has been missing in terms of knowledge of sources is presented in Annex A.

This report developed a Nepal-specific model and data infrastructure to understand the current trends in air quality and to assess the impacts of various abatement measures in the country. This report improves existing knowledge through (a) consideration of a complete set of source categories, (b) coverage

34 A study by Islam et al. (2019) found that anthropogenic combustion sources, including garbage burning, biomass burning, and fossil fuel combustion, were the largest contributors to $PM_{2.5}$ in the Kathmandu Valley. Another study revealed that resuspended dust plays a significant role in elevating $PM_{2.5}$ and PM_{10} levels, particularly during the dry winter months (Islam et al., 2021). These findings highlight multiple sources of $PM_{2.5}$ pollution but remain limited in scope and geographic coverage.

Artwork: Buddha Bahadur Gautam, 'Where's My Blue Sky?' Live Art Challenge.

The GAINS-Nepal model distinguishes about 400 emission source categories.

of an entire year (as opposed to selected months), (c) considerations of secondary particles (formed through chemical reactions), and (d) geographical dispersion of particles.

The new analysis carried out for this purpose employs a world-wide applied and extensively validated scientific methodology—the GAINS (Greenhouse Gas-Air Pollution Interactions and Synergies) model, adapted to the Nepal context (the "GAINS-Nepal model"). It combines an internationally recognized and widely applied scientific tool for air quality management planning with recent governmental energy and industrial statistics, household surveys and road traffic data for Nepal with emission characteristics that have emerged from analyses for comparable conditions in other regions of the Indo-Gangetic Plain and Himalayan Foothills region and other parts of South Asia. The resulting emission estimates were fed into an atmospheric dispersion model (chemical transport model) and the computed $PM_{2.5}$ concentrations are validated with observed $PM_{2.5}$ concentrations in ambient air from monitors.

GAINS-Nepal was developed by a strong partnership between global and local experts. International experts from the International Institute for Applied Systems Analysis (IIASA) and the Iowa State University, who originally developed and continue to refine the GAINS model, collaborated with local experts in emission inventories, energy modeling and air quality monitoring/atmospheric chemistry to develop the GAINS-Nepal model. This partnership included researchers from the Centre for Energy Studies (CES) at the Institute of Engineering (IoE), the Central Department of Environmental Science of Tribhuvan University, and the Department of Chemical Science and Engineering of Kathmandu University.[35] The GAINS methodology, detailed results and comparisons with observations are presented in Annex D.

The GAINS-Nepal model distinguishes about 400 emission source categories, for which it estimates the annual quantities, locations and timing of precursor emissions that generate secondary $PM_{2.5}$ in ambient air. Local activity rates (i.e., the quantities of emission-generating activities) are compiled from relevant local statistics (see Table 4.1) or, if unavailable, estimated based on experience from other countries/states with comparable conditions. Emission factors are primarily derived from local measurements that are deemed representative of the specific sources in the region, and local emission inventories to the extent they are available. The plausibility and robustness of local data is validated with international literature. In total, the analysis considers about 1,100 proven emission control options for which the emission removal efficiencies are derived from world-wide literature considering the local conditions in Nepal and other regions in South Asia with similar characteristics.

Annual mean concentrations of $PM_{2.5}$ in ambient air are computed at a 1 km x 1 km spatial resolution for the Kathmandu Valley and 10 km x 10 km for the Terai. This calculation combines results from three atmospheric chemistry and transport models for (i) local primary $PM_{2.5}$ emissions, (ii) the long-range transport characteristics of primary $PM_{2.5}$ emissions from all South Asia into the Kathmandu Valley, and (iii) the formation and transport of secondary $PM_{2.5}$ emitted throughout South Asia. These models are operated with hourly time steps[36] for the full year, employing the meteorological conditions of 2018, considering for all emission sources the characteristic seasonal and diurnal time patterns, and distinguishing three emission heights.

35 The GAINS-Nepal model was developed in collaboration with local experts, including *Dr. Kundan Lal Shrestha* (Department of Chemical Science and Engineering, Kathmandu University), *Dr. Rejina Maskey Byanju* (Central Department of Environmental Science, Tribhuvan University), and *Dr. Shree Raj Shakya* (Institute of Engineering, Tribhuvan University).

36 Meaning that the models run with one-hour temporal resolutions, so that each hour has a unique estimate of the concentration of air pollution at each grid cell.

Newly imported electric vehicles signify a transition towards cleaner modes of transport. *Source: Narendra Shrestha/World Bank.*

Table 4.1: Main data sources employed for emission estimates for 2021[37]

Types of data employed in the emission estimates
• Nepal sectoral energy balances, by province • Household energy use surveys, by district • Municipal waste statistics • Population data, 1 km x 1 km • Locations and production volumes of brick kilns, cement plants • Road network maps, traffic density data, fleet registration statistics • Land use data for crop land • GAINS-South Asia emission factors, adjusted to Nepal conditions
Specific data sources
• Energy Consumption and Supply Situation in Federal System of Nepal (Bagmati Province)[38] • Energy Consumption and Supply Situation in Federal System of Nepal (reports for Province 1 (Koshi), Province 2 (Koshi) & Bagmati, incl. Annex)[39] • Census data[40] • Energy by province[41] • Land use data for crop land[42]

37 Data for the 2020 baseline year have been corrected to represent actual emission levels and fuel consumption from 2021, which was not impacted as significantly by COVID lockdowns.

38 Water and Energy Commission Secretariat (WECS), Government of Nepal. 2022. Energy Consumption and Supply Situation in Federal System of Nepal (Bagmati Province). Accessed through https://wecs.gov.np/source/Bagmati%20Province.pdf. Accessed in November 2024.

39 Water and Energy Commission Secretariat (WECS), Government of Nepal. 2022. Energy Consumption and Supply Situation in Federal System of Nepal (Province 1 and 2). Accessed through https://wecs.gov.np/source/Final%20Report_%20Province%202.pdf. Accessed in November 2024.

40 National Statistics Office. National Population and Housing Census 2021. Accessed through https://censusnepal.cbs.gov.np/results/downloads/provincial/3?. Accessed in November 2024.

41 National Energy Information System. Bagmati Pradesh Energy Consumption By Fuel Types (2019). Accessed through https://neis.gov.np/report/province/province-3?. Accessed in November 2024.

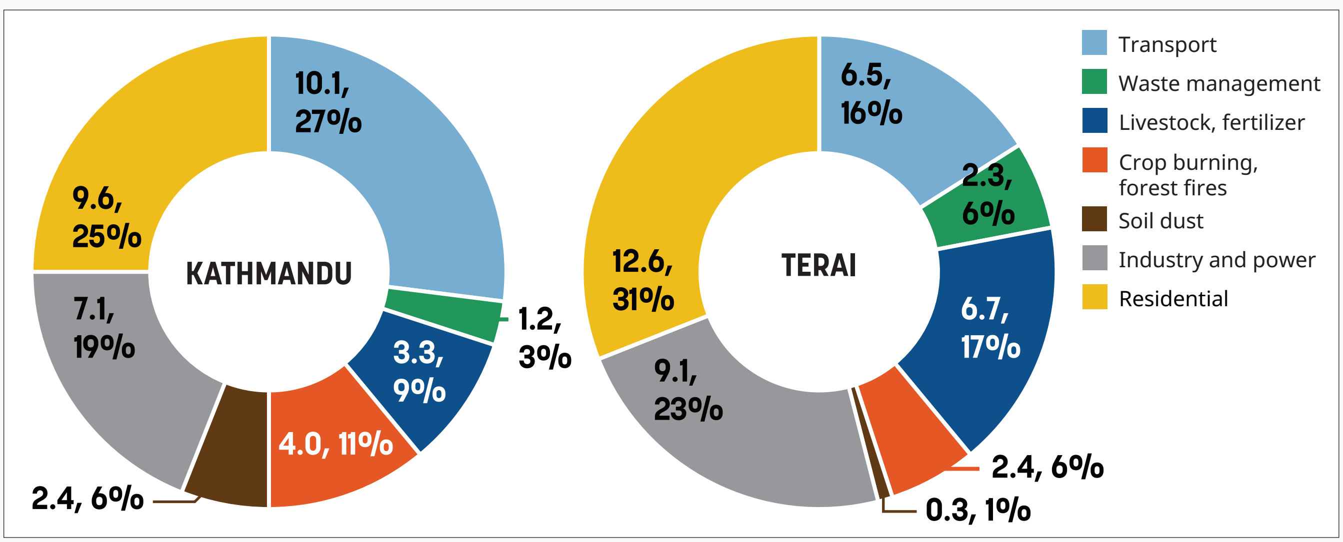
42 Regional Database System. ICIMOD. Accessed through https://rds.icimod.org/Home/Data?any=land+cover+of+koshi+basin&Category=datasets. Accessed in November 2024.

Although public attention and legislative air quality action often focus on episodic concentration peaks at pollution hot spots (such as around the crop burning season around November), worldwide epidemiological evidence indicates long-term exposure to $PM_{2.5}$ as the most powerful predictor for adverse health impacts (WHO, 2021)[43]. With a focus on public health, hourly results are aggregated to annual mean concentrations as the most relevant metric associated with public health impacts. Also, to facilitate air quality management at the airshed level, ambient concentrations occurring in the target regions (i.e., the Kathmandu Valley and the Terai) are aggregated to a population exposure metric, computed as a sum of the products of grid average $PM_{2.5}$ concentrations and population in the grid cell.

In both the Kathmandu Valley and the Terai $PM_{2.5}$ concentrations originate from a multitude of emission sources spanning a wide range of economic sectors (*inter alia*, road transport, solid fuel combustion in households, municipal waste management, industrial activities, and agriculture). Despite pertinent differences in geographic locations, topographic conditions and the types and densities of economic activities between the Kathmandu Valley and the Terai, critical commonalities characterize the nature of the pollution problem in these two regions of Nepal (Figure 4.1). Residential energy use and road transport are major contributors in both urban (Kathmandu Valley) and rural (Terai) environments. Industrial sources, especially process heat boilers with fuel wood, can make substantial contributions in areas where they exist. In rural areas, agricultural activities such as crop burning, and livestock farming are also relevant.

Significant share of $PM_{2.5}$ in ambient air originate from sources outside the local jurisdictions, often in other countries. This is a direct consequence of the long residence time of small particles in the atmosphere and the resulting long-range transport of pollution. At any given site, the exact quantity depends on the geographic location, topographic

Figure 4.1: Contributions of different source sectors to population-weighted annual-average $PM_{2.5}$ concentrations in the Kathmandu and the Terai in 2021 (in μg/m³ and %)



Source: GAINS-Nepal, developed for this report.

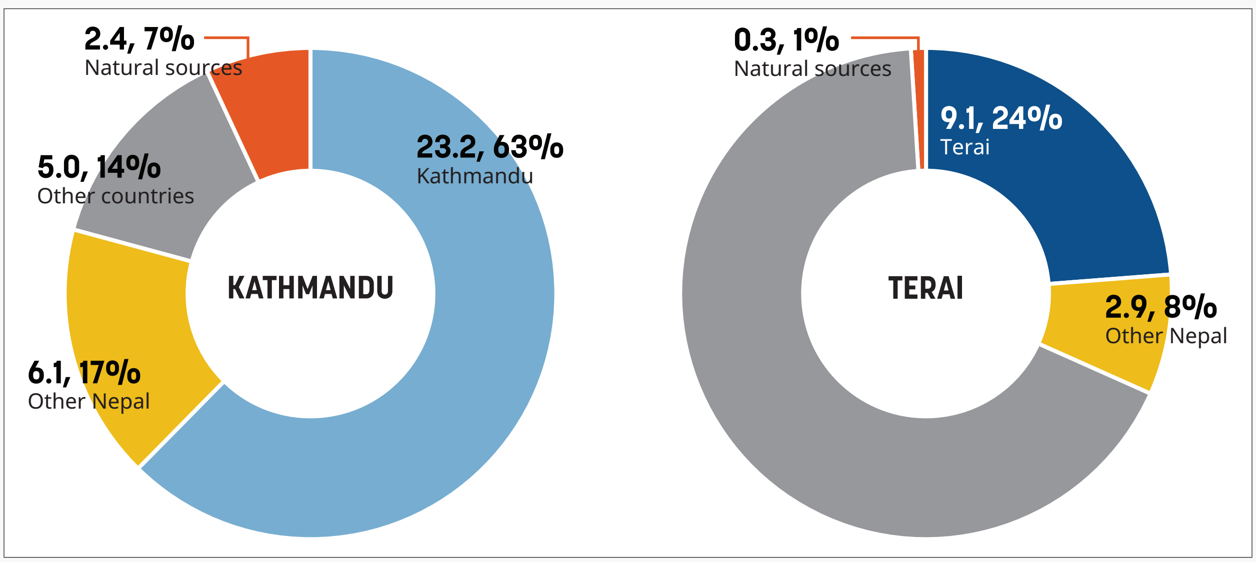
43 As per the WHO's Global Air Quality Guidelines, long-term exposure to $PM_{2.5}$ is associated with increased mortality due to cardiovascular diseases, respiratory diseases, and lung cancer. This report emphasizes that even low levels of long-term exposure can result in adverse health impacts, indicating that risk increases progressively with exposure. Health burden related to short-term exposure to higher concentrations corresponds to a very small fraction of the total air pollution-related burden.

and meteorological conditions and the types and densities of economic activities within the region and in the surrounding airshed.

The sources of $PM_{2.5}$ pollution in Nepal vary significantly by geography. Figure 4.2 shows that even in the Kathmandu Valley, a region with high economic activity that is distant from the plains areas of the IGP-HF region,[44] only 63 percent of $PM_{2.5}$ in ambient air emerges from emissions within the valley, 17 percent are caused by emissions in other parts of Nepal, and 14 percent imported from other countries (the remainder consists of soil dust from natural sources). In the Terai, a region with relatively low population density located in the plains area, close to the Indian border, the inflow of $PM_{2.5}$ pollution from other IGP-HF countries with high emissions accounts for about 68 percent of total $PM_{2.5}$ in ambient air. Only 24 percent is caused by emissions from the Terai itself, and eight percent can be traced to other sources in Nepal.

$PM_{2.5}$ in ambient air comprises many different chemical substances, with different physical and chemical properties. Some are directly emitted, and others are formed chemically from several gases into "secondary" particles downwind of their emission location. Directly emitted 'primary $PM_{2.5}$' includes, inter alia, black carbon, organic carbon and crustal material. All these emissions are diluted in the atmosphere over several hundreds of kilometers, with concentrations declining over distance. Secondary $PM_{2.5}$ is formed from nitrogen oxides (NO_x), sulfur dioxide (SO_2) and volatile organic compounds (VOCs) emitted from a range of fuel combustion sources. In particular, ammonia (NH_3), emitted by agricultural sources such as fertilizer and livestock manure, combines with NO_x (nitric oxide and nitric dioxide) and SO_2 to form ammonium nitrate and ammonium sulfate $PM_{2.5}$ particles. As the formation of secondary particles takes some time, their impact increases with distance from the location where emissions take place, before declining over larger distances.

Figure 4.2: Spatial origin of $PM_{2.5}$ in ambient air in the Kathmandu and the Terai in 2021 (in $\mu g/m^3$ and %)



Source: GAINS-Nepal, developed for this report.

44 Kathmandu is about 90-100km away (by measure of a straight line) from the closest border point Raxaul-Birgunj.

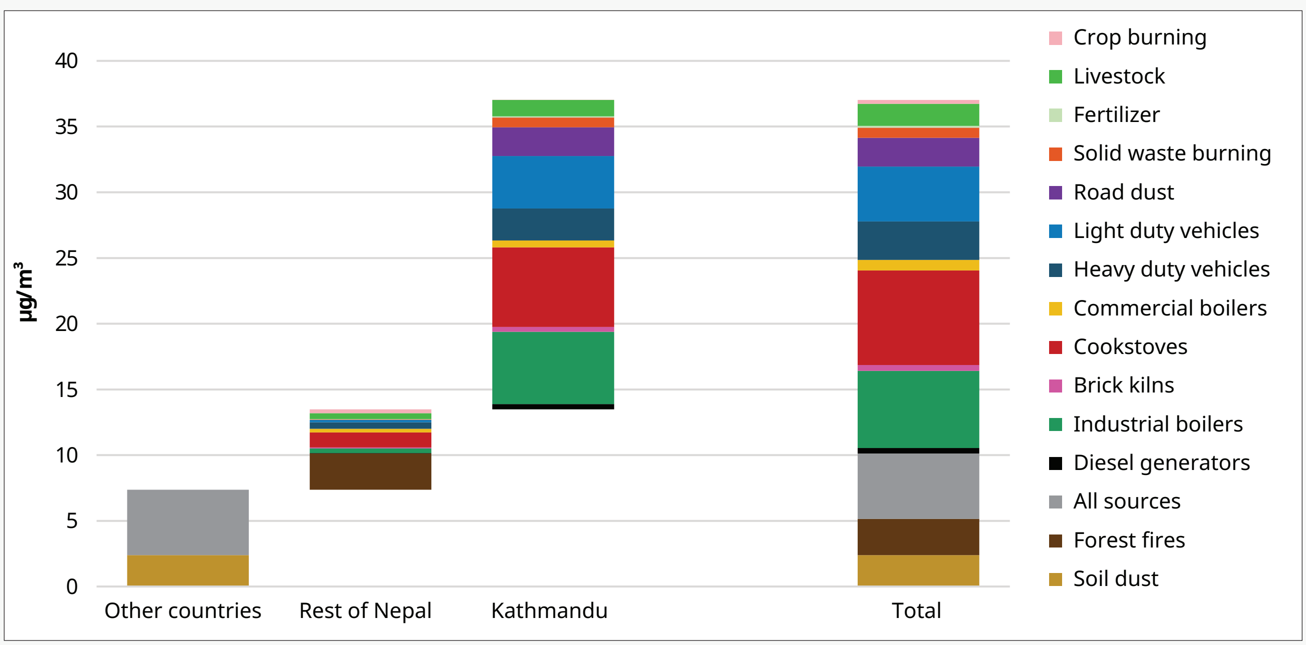
The different transport characteristics of the various $PM_{2.5}$ components emitted at different places have an important impact on the relative contributions of the various emission sources to $PM_{2.5}$ in ambient air at any given location. The geo-physical approach of the GAINS-Nepal model enables the apportionment of $PM_{2.5}$ in ambient air to the various sources of precursor emissions (i) in the target regions of the Kathmandu and the Terai, (ii) in other regions in Nepal, and (iii) in the other countries in the Indo-Gangetic Plain and Himalayan Foothills region.

In the Kathmandu Valley more than three quarters of the local contribution to $PM_{2.5}$ in ambient air (bar labeled "Kathmandu" in Figure 4.3) consists of primary $PM_{2.5}$. 40 percent of this primary $PM_{2.5}$ is related to emissions from road transport, one third to solid fuel combustion in the residential sector, and about 20 percent to industrial boilers. The main local sources of secondary $PM_{2.5}$ (25 percent of the total local contribution) are SO_2 emissions in industrial boilers (36 percent), NO_x emissions from road transport (25 percent), which react in the atmosphere with ammonia from livestock farming.

In contrast, $PM_{2.5}$ from other IGP-HF countries that reaches Kathmandu (left most bar in Figure 4.3 or 14 percent of total $PM_{2.5}$ in Kathmandu) consists of up to three quarters of secondary $PM_{2.5}$. 30 percent of these emerge from NH_3 emissions of livestock farming and fertilizer use, 27 percent from SO_2 and NO_x emissions of power plants and industry, and 20 percent from NO_x emissions of road transport. Note that these sources are very different from those of primary $PM_{2.5}$ (e.g., solid fuel use in the residential sector and industrial boilers, diesel vehicles, industrial processes), and will not be affected by policies that are only focused on direct emissions of $PM_{2.5}$.

In the Terai, higher agricultural emissions lead to a larger share of secondary $PM_{2.5}$ (45 percent of the total local contribution) than in Kathmandu (Figure 4.4). About 45 percent of locally generated secondary $PM_{2.5}$ are linked to agricultural activities, 24 percent to road transport, and about 20 percent to industrial activities (one quarter to brick kilns). In contrast, about two thirds of the local primary $PM_{2.5}$ is caused by the residential sector. However, local sources account for only 24 percent of total

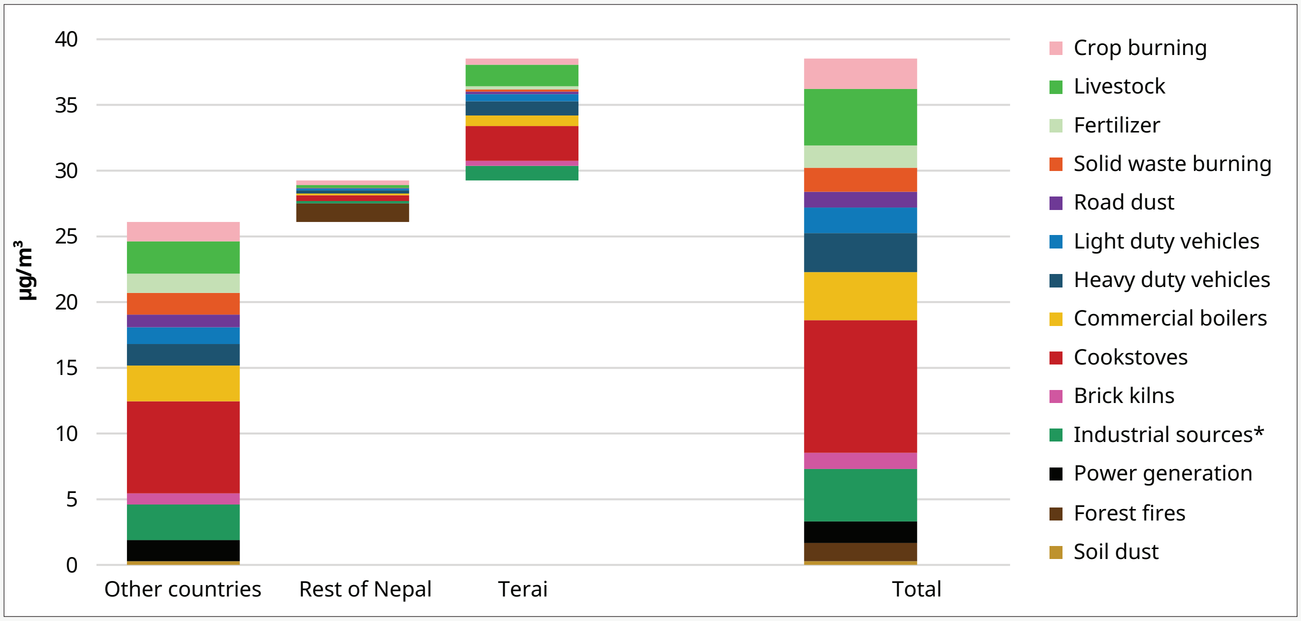
Figure 4.3: Spatial and sectoral origin of $PM_{2.5}$ in ambient air in the Kathmandu Valley, 2021



Source: GAINS-Nepal estimates developed for this report.

Note: Commercial boilers include emissions from space heating and hot water usage by commercial establishments.

Figure 4.4: Spatial and sectoral origin of $PM_{2.5}$ in ambient air in the Terai region, 2021



Source: GAINS-Nepal estimate developed for this report.

** Industrial sources other than brick kilns*

$PM_{2.5}$ in the Terai, while 68 percent is imported from other countries. Due to its location directly adjacent to areas with high emission densities in India, about half of the $PM_{2.5}$ from transboundary sources consists of primary $PM_{2.5}$ (60 percent from the residential sector), while power plants and industry, agriculture, and road transport all contribute to secondary $PM_{2.5}$ in almost equal shares.

Both in the Terai and Kathmandu, the combustion of wood, charcoal, and dung in households to satisfy energy demands such as cooking, heating, and lighting constitutes a significant source of population-weighted $PM_{2.5}$. This source of air pollution is especially important because it contributes both household air pollution—exposure in and around the home, mostly affecting women and children involved with cooking and domestic chores—as well as ambient air pollution after it disperses into the air of the neighborhood and combines with emissions from other sources. The Global Burden of Disease Report estimated that about 33,000 cases of premature deaths occur annually from indoor exposure and 12,700 cases per year in ambient air exposure from this source in Nepal.[45]

While solid fuel consumption has only been partially addressed in some of the earlier Nepalese emission inventories, the recent energy statistics and household surveys together with robust evidence about typical emission characteristics of traditional cookstoves indicate contributions of 25 - 40 percent to total $PM_{2.5}$ exposure in the Kathmandu Valley and the Terai, respectively. Such a range is in line with recent global research. For instance, the Global Burden of Disease Report estimates that the combustion of solid biofuels in households contributes more than one-third to population-weighted annual average $PM_{2.5}$ exposure in Nepal. The recent World Bank report *Striving for Clean*

45 State of Global Air. Health Impact- Burden on Your Health.

Air[46] shows similar results for cities across South Asia, with residential biomass combustion contributing a significant fraction of overall pollution in all cities. Residential air pollution contributes to a range of diseases, with more than three-quarters of premature deaths associated with $PM_{2.5}$ related to heart attack, stroke or respiratory infections (pneumonia).

In addition, small- and medium-sized industrial boilers are found to be another important source of $PM_{2.5}$ concentrations and exposure in the Kathmandu Valley. While this source was not addressed in earlier emission inventories, the recent provincial and district energy statistics[47] report substantial quantities of fuel wood and other biomass for heat generation in the "food and tobacco" industrial sector (e.g., bakeries, breweries, rice parboiling). Combining these statistics with the typical emission characteristics of such biomass boilers and their low stack heights, the calculation results in a population-weighted annual mean $PM_{2.5}$ exposure in the Kathmandu Valley of about five µg/m^3, accounting for about 15 percent of total $PM_{2.5}$.

Although brick kilns have been identified in earlier studies as key contributors to air pollution in Nepal, this report estimates their relative contributions to population-weighted annual mean concentrations of $PM_{2.5}$ at less than three percent in both regions. This estimate emerges from a comprehensive emission inventory specifically compiled for this study, employing the latest available statistics on the locations, production volumes, time patterns, fuel consumption and technological features of the individual brick kilns in the Kathmandu Valley and the Terai. Focusing on 2020/2021, this inventory captures changes in technologies, locations and brick production volumes that have occurred since the earlier studies. Notably, relying on the latest governmental statistics, the emission inventory also covers all other known emission sources in the region, including sources that have often been omitted in earlier studies (e.g., solid fuel consumption in households, industrial boilers, waste management, agricultural activities). This has been combined with advanced fine-scale atmospheric dispersion modeling of primary and secondary $PM_{2.5}$ that extends over the full year.

Forest fires have also caught public attention as a key source causing spring episodes of extremely high $PM_{2.5}$ pollution in the Kathmandu Valley. Based on satellite imagery, this report confirms the dominance of forest fires for $PM_{2.5}$ concentrations in March/April. While these pollution peaks are accurately picked up by the model (see Annex D), when considered over the full year, their contribution to annual mean concentrations in the Kathmandu Valley is estimated at about seven percent. In the Terai, the open burning of agriculture residue—within and outside the country—leads to high pollution events in the fall, which, however, accounts for only six percent of annual exposure.

4.2 Air pollution trends by 2035

The envisaged tripling of GDP in Nepal in 2035 relative to 2020 will have substantial impacts on future air quality. A baseline scenario explores how the anticipated socio-economic growth and progressing implementation of the current pollution control legislation is likely to affect future air quality. The analysis adopts the socio-economic projections outlined in the reports on the 'Energy Consumption and Supply Situation' of the Government's Water and Energy Commission Secretariat for Provinces 1 (Koshi), Province 2 (Madhesh), and Bagmati.[48] Economic output is forecast to increase by seven percent per year in the Kathmandu Valley, meaning that GDP will almost triple in 2035 relative to 2020. This implies a near doubling of fuel use in industrial boilers and furnaces. For the Terai, slightly lower economic growth is envisaged (6.3 percent per year), leading to a 2.5-fold higher GDP in 2035. The population is assumed to grow by about 15 percent.

46 World Bank. 2022. "Striving for Clean Air: Air Pollution and Public Health in South Asia", World Bank, Washington, DC. License: Creative Commons Attribution CC BY 3.0 IGO.

47 Water and Energy Commission Secretariat of the Government of Nepal, Kathmandu. Annex 1 to Energy Consumption and Supply Situation in Federal System of Nepal, Provinces 1 and 2 (2021), Bagmati Province (2022)

48 Energy Consumption and Supply Situation in Federal System of Nepal, Water and Energy Commission Secretariat of the Government of Nepal, Kathmandu. Provinces 1 and 2 (2021), Bagmati Province (2022).

Without further policies, emissions—and consequently air pollution—are projected to increase by 2035, but more slowly than recent trends.

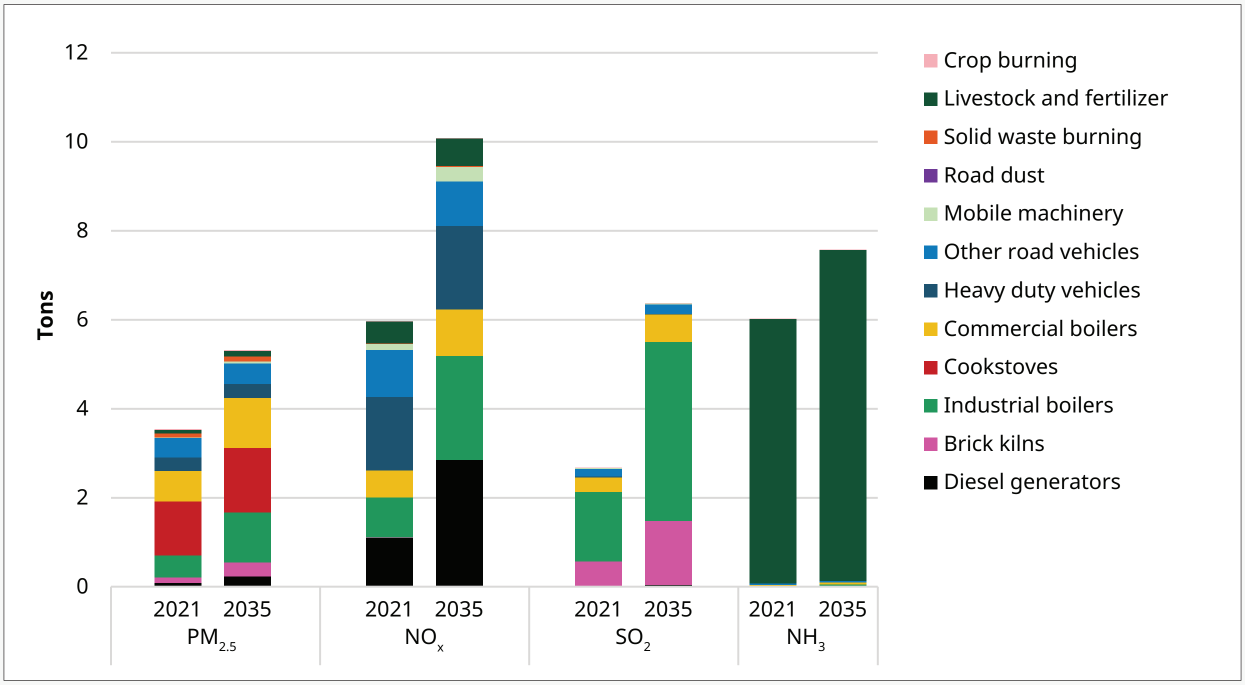
In the modeling, this baseline includes only emission controls that were already under implementation in 2023, and few additional measures programmed for implementation by 2035 (Table 4.2), based on information provided by the local expert team (see Section 2.3). Measures that may have been intended but have not, as yet, been implemented remain as available "options" for the GAINS model to select as "further implementable actions", whereas the measures listed in Table 4.2 are already in place or will come into place by 2035 and are not to be considered as a "future" option.

Without further policies, emissions—and consequently air pollution—are projected to increase by 2035, but more slowly than recent trends. With the above assumptions, the baseline indicates that Kathmandu emission increases for most $PM_{2.5}$ precursors of 30 to 70 percent in the urbanizing Kathmandu Valley, and somewhat lower growth rates in the more rural Terai region (Figure 4.5, Figure 4.6). Steeper increases are expected for SO_2 due to the expanded coal use in the energy baseline. Importantly, the assumed energy policies combined with implementation of current emission control regulations will clearly decouple emission growth from the expected 2.5 to a 3-fold increase in GDP.

Table 4.2: Measures assumed as "already implemented" within the baseline scenario through 2035 and therefore not included as additional options for the cost-effectiveness analysis (policy scenario)

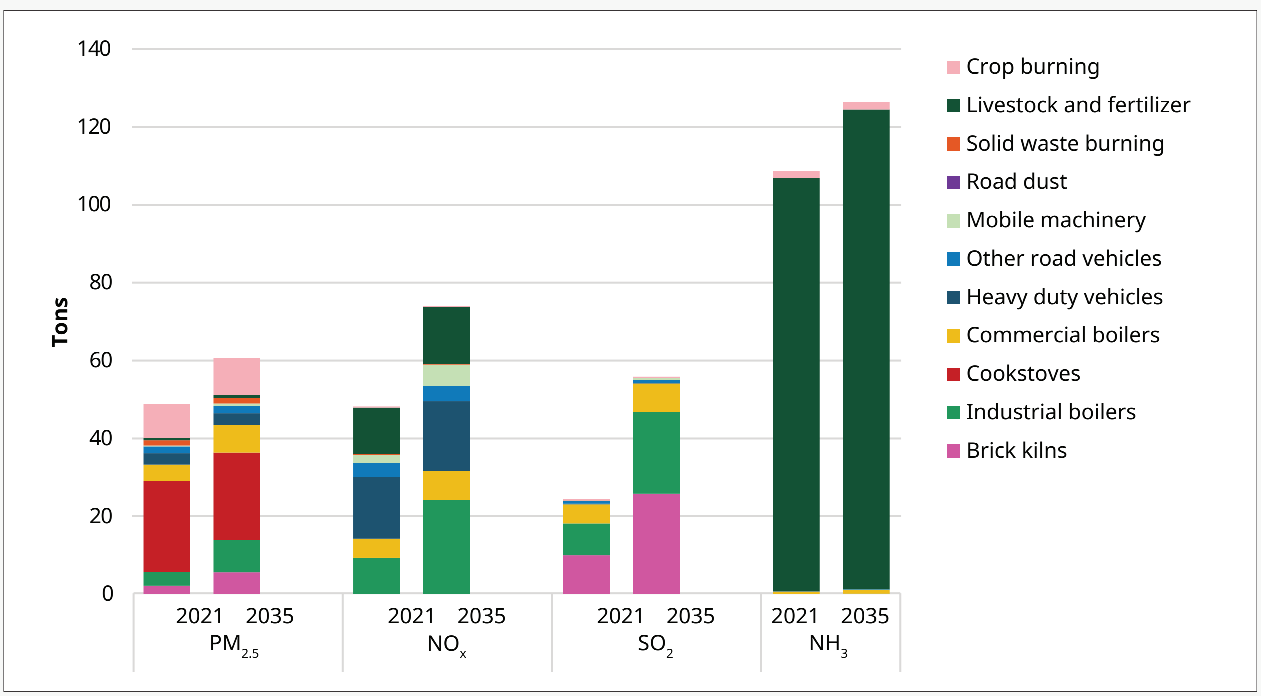
Mobile sources
Heavy-duty trucks and buses, diesel: • All heavy-duty vehicles complying with Euro-I controls in 2035
Light-duty vehicles (cars and vans): • All vehicles complying with Euro-2 controls in 2035 • Continued slow phase-in of electric vehicles
Two- and three-wheelers: • 57 percent of vehicles with four-stroke engines and 13 percent of two-stroke vehicles complying with Euro-1 emission standards
Agricultural machinery: No controls
Construction machinery: No controls
Stationary sources
Diesel generators: • 100 percent low sulfur diesel oil with 0.045 percent S content
Households: • Switch to improved biomass cookstoves (2 percent by 2030) • No major interventions to reduce solid fuel combustion in households (in 2020, 4 percent of households in Kathmandu and 54 percent of households in the Terai used solid biomass for cooking)
Industry: • Particulate matter controls (cyclones) for industrial processes • 95 percent of kilns in the Kathmandu Valley and 30 percent in the Terai operated as zig-zag kilns, the other kilns as fixed chimney bull-trench kilns (FCBTK) and movable chimney bull-trench kilns (MCBTK)

Figure 4.5: Baseline emissions in the Kathmandu Valley, 2021-2035, by sector



Source: GAINS-Nepal estimates developed for this report.

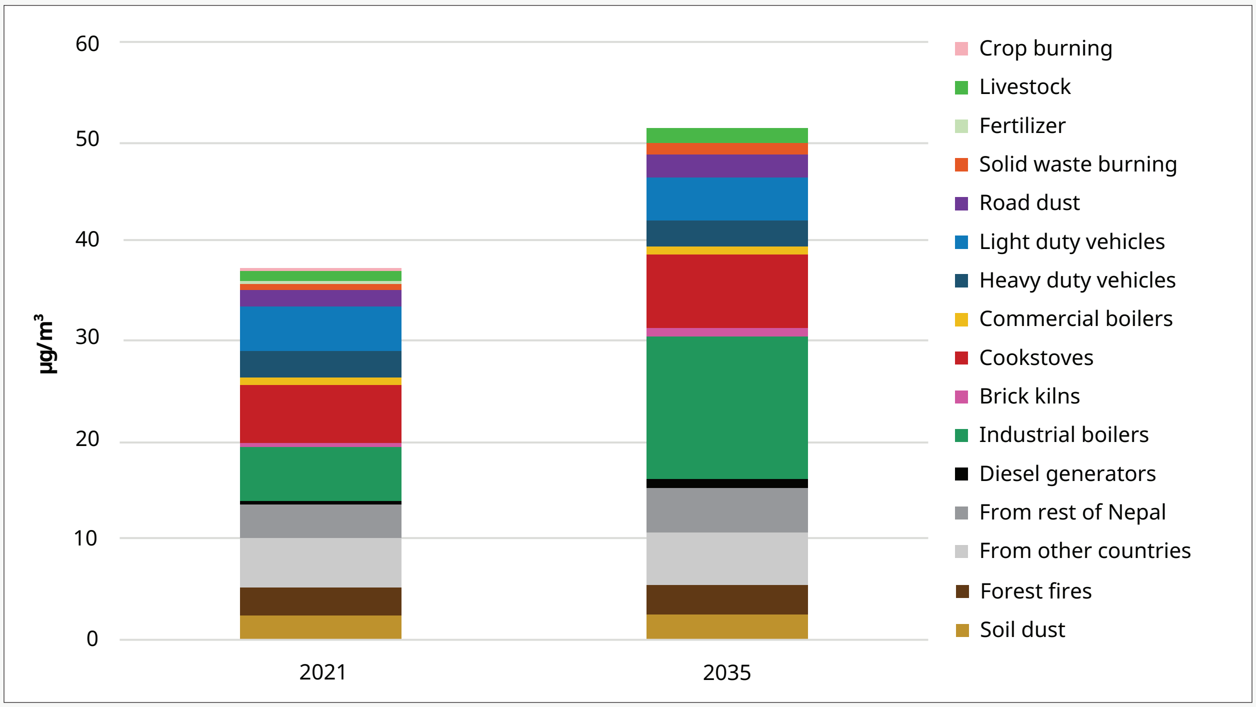
Figure 4.6: Baseline emissions in the Terai, 2021-2035, by sector



Source: GAINS-Nepal estimates developed for this report.

Based on present trends and even with the application of current emission control measures, exposure to $PM_{2.5}$ will continue to increase through 2035. Population-weighted $PM_{2.5}$ exposure in Kathmandu increases in the baseline from 37 μg/m³ in 2021 to 51 μg/m³ in 2035 (Figure 4.7). In terms of geographic origin, most of the pollution will come from Kathmandu, but significant amounts of pollution come from elsewhere in the country and other countries (Figure 4.8). In the Terai, pollution exposure is expected to increase from 39 μg/m³ to 42 μg/m³ in 2035. These calculations assume for India the baseline emission projections for 2030 that were developed by the recent World Bank studies for the Clean Air Plans for Uttar Pradesh and Bihar. Considering the policies that are already in place in these Indian States, these projections anticipate a stabilization of emissions after 2030.

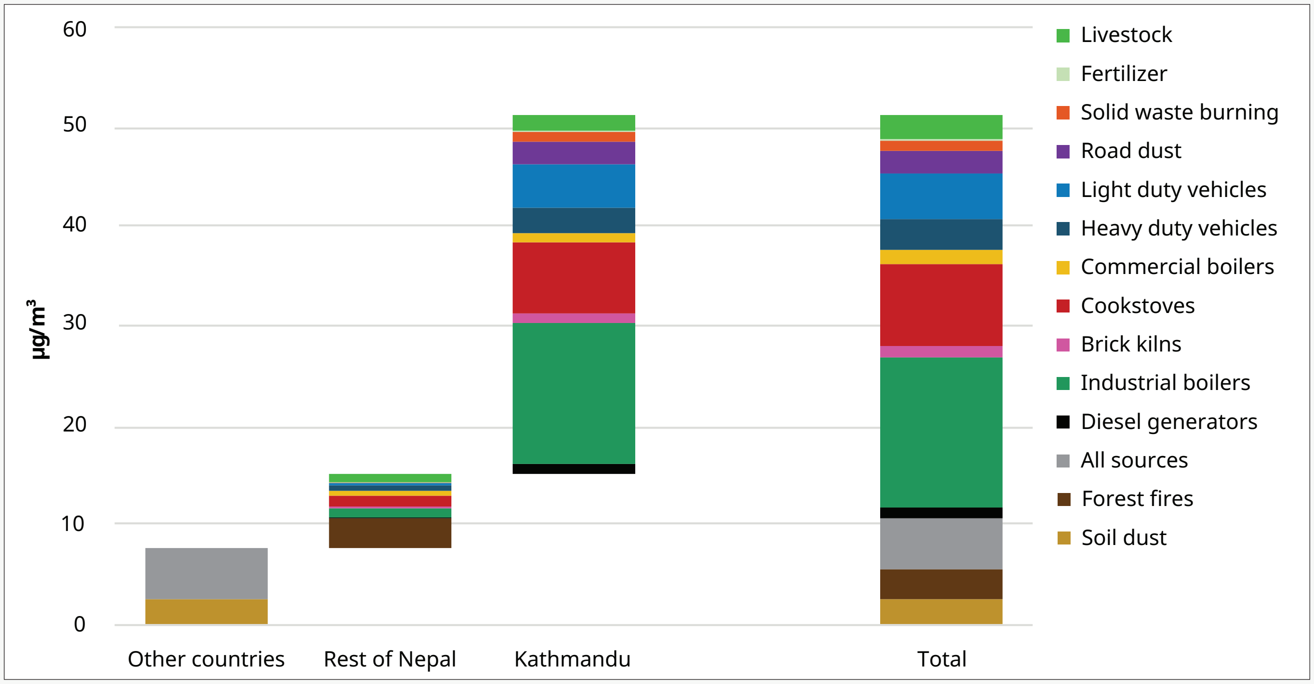
Figure 4.7: Population weighted $PM_{2.5}$ exposure in the Kathmandu Valley, 2021-2035, by sector



Source: GAINS-Nepal estimates developed for this report.

Based on present trends and even with the application of current emission control measures, exposure to $PM_{2.5}$ will continue to increase through 2035.

Figure 4.8: Origin of $PM_{2.5}$ exposure in the Kathmandu Valley for the baseline projection in 2035



Source: GAINS-Nepal estimates developed for this report.

4.3 Priority measures to reduce $PM_{2.5}$ exposure by 2035

This section identifies the priority measures by assessing the pollution abatement potential and the cost-effectiveness of nearly 1,100 measures (primarily technologies). As discussed, between 2021 and 2035, annual average population-weighted exposure to $PM_{2.5}$ concentrations in Nepal is projected to grow by up to one third in 2035, far exceeding the WHO interim target 1 of 35 µg/m³. This projection assumes that certain measures have already been implemented (as of 2023) as discussed in Table 4.2, but that the further implementation of measures is not likely without additional investment. For the analysis, about 1,100 measures for reducing emissions in the Kathmandu Valley and the Terai from each polluting sector were drawn from the comprehensive GAINS database of nearly 2,000 technologies and interventions that have been shown to reduce emissions both of $PM_{2.5}$ and of the precursors that form secondary particulates chemically in the atmosphere (e.g., SO_2, NO_x and ammonia – see Chapter 1).

In total, local measures have been identified that could reduce in 2035 $PM_{2.5}$ population exposure in the Kathmandu Valley and the Terai by about 27 µg/m³ and seven µg/m³, respectively. The exposure reduction potentials in the various source sectors and specific examples of possible emission reduction interventions are presented in Table 4.3 (the contributions from these sources in the 2035 baseline case are shown in the red boxes in Figure 4.8). If combined with commensurate measures in other IGP regions that reduce the pollution inflow into Nepal, such measures would enable achieving the 35 µg/m³ target in the Kathmandu Valley and the Terai (see Section 4.5).

Three measures are the most impactful (in terms of reducing population exposure): cleaner boilers, cleaner cooking, and cleaner transportation. In the Kathmandu Valley, these measures combined would reduce air pollution exposure by 81 percent, and in the Terai by 53 percent, assuming that the measures were implemented fully and effectively (without leakage). In the Kathmandu Valley the following are the top four measures: (1) fully switching to either electric or pellet boilers with filters would

Three measures are the most impactful (in terms of reducing population exposure): cleaner boilers, cleaner cooking, and cleaner transportation.

bring a reduction of more than 30 percent; (2) Cleaner cooking, especially with electric/induction cooking, would yield 20 percent; (3) switching to cleaner vehicles, would bring another 18 percent; and (4) introducing bag filters or similar air pollution control measures in industries would yield another 12 percent. The remaining measures, if implemented perfectly, have impacts in the single digits. Notably, other source sectors contribute a significant share to exposure in Kathmandu and/or Terai on a seasonal or episodic basis (e.g. forest fires and open burning of agriculture residue) and measures where further assessment is required (e.g. road and construction dust). Potential near-term action for these sectors is described in the next section.

The measures were ranked to identify how to reduce $PM_{2.5}$ levels in the Kathmandu Valley and the Terai at least cost. The GAINS-Nepal model was run in an "optimization mode" to identify the cost-effective sequence of measures that can be taken in the Kathmandu/Terai to achieve increasingly stringent targets on $PM_{2.5}$ exposure. The results are presented in the form of a 'marginal cost curve' in Figure 4.9 and Figure 4.10. With resulting $PM_{2.5}$ exposure (including contributions from all sources including the inflow from other areas in Nepal and from other countries in the IGP) shown on the x-axis, the curve starts with baseline exposure at the lower right corner. For each category of measures, the $PM_{2.5}$ exposure reduction potentials are indicated by the horizontal segments (to the left) and their marginal costs by their position on the vertical axis.

For Kathmandu, the most cost-effective measures (shown at the lower right of the chart) include pollution controls for industrial biomass boilers, enforced inspection and maintenance regimes for vehicles, Euro-4 emission standards for light-duty vehicles, improved urban waste management, the replacement of traditional biomass cookstoves by fan-assisted stoves, and particle filters for diesel heavy duty vehicles. Full implementation of these measures could reduce $PM_{2.5}$ exposure in Kathmandu by almost 20 μg/m^3, to about 32 μg/m^3. Other measures could deliver further improvements, although at higher costs. In total, measures in the Kathmandu Valley could reduce $PM_{2.5}$ concentrations to about 25 μg/m^3 in 2035, while the remainder will be caused by the inflow of pollution from outside Kathmandu (Figure 4.9).

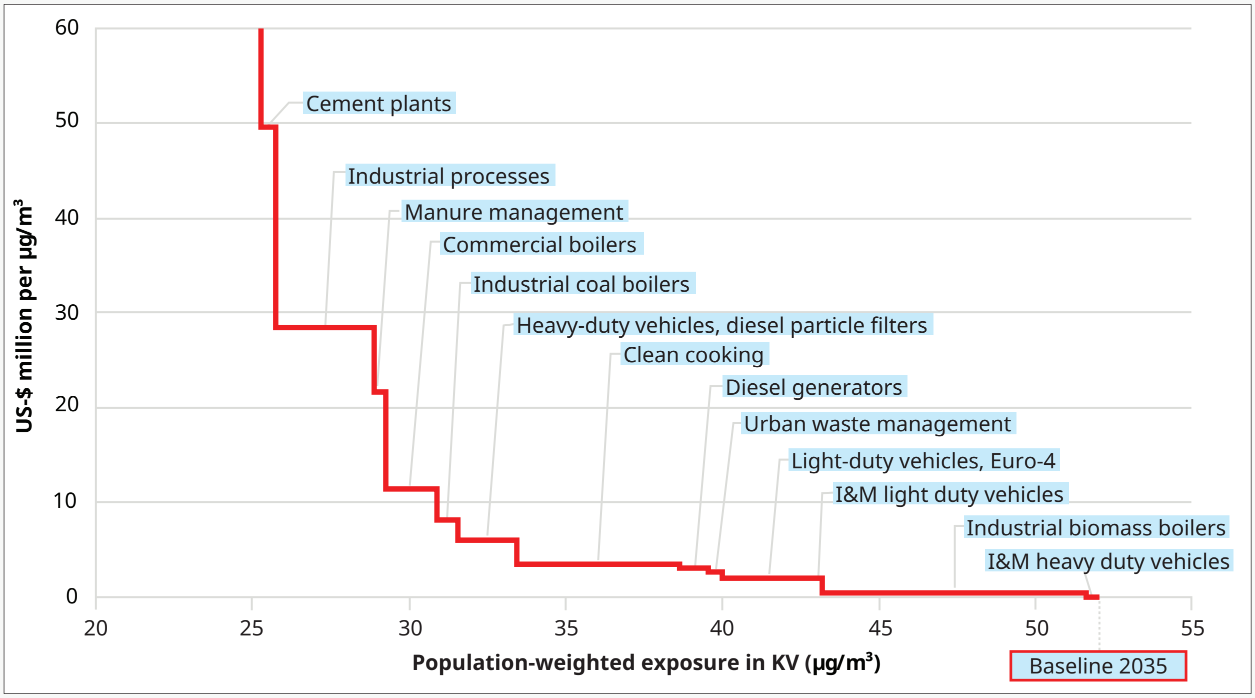
In the Terai, the available local measures will deliver much smaller reductions in $PM_{2.5}$ exposure, due to the lower emission density and the overwhelming influence of pollution inflow from outside, especially from other regions in the IGP-HF. Most of the measures that emerge as most cost-effective in the Kathmandu Valley (e.g., enforced vehicle inspection programs[49], low-emissions industrial biomass boilers, fan-assisted cookstoves) apply in the Terai as well, although some have significantly smaller reduction potential. In addition, banning the open burning of agriculture residue as well as emission controls at cement plants are important in the Terai (Figure 4.10). In total, measures within Terai have the potential to reduce exposure in 2035 by about five μg/m^3, while emissions in outside areas will account for about 29 μg/m^3 out of the total baseline exposure of about 42 μg/m^3.

49 The GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model, which has been used in air quality assessments for Nepal, primarily focuses on the "Improve" dimension of the ASI framework. Rather than emphasizing "Avoid" (reducing travel demand) or "Shift" (moving to public or non-motorized transport), GAINS prioritizes technological improvements—such as cleaner vehicle fuels, emissions control technologies, and electrification—as the key measures for reducing air pollution. This focus is pragmatic because in Nepal and similar countries, economic growth, urbanization, and infrastructure limitations make large-scale shifts in travel behavior unlikely in the short term. In contrast, "Improve" offers the most immediate and scalable benefits, leveraging existing policy momentum around electric mobility and cleaner energy sources. By targeting vehicle and fuel improvements, emissions reductions can be achieved without fundamentally altering mobility patterns, making the approach both politically and logistically feasible.

Table 4.3: The shares of the various sectors in the total potential $PM_{2.5}$ exposure reductions from local measures in the Kathmandu and the Terai in 2035.

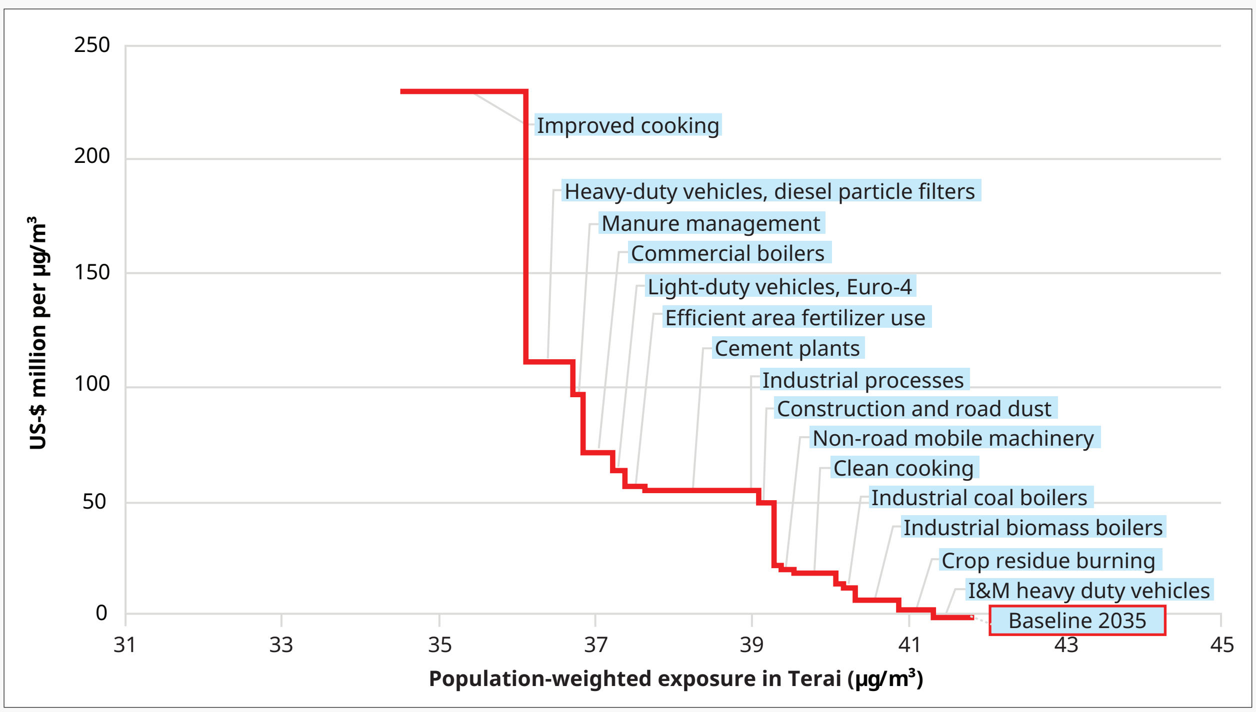
Sector	Key measures	Share of total reduction potential	
		Kathmandu	Terai
Biomass for process heat (industrial applications)	Switch to electric boilers or pellets boilers (with particle filters)	31%	8%
Clean cooking	Elimination of traditional biomass cookstoves through access to clean cooking fuels (electric induction stoves, LPG), replacement of remaining cookstoves by fan-assisted cookstoves.	20%	29%
Enhanced emission standards for vehicles	Euro-IV standards for light-duty vehicles, Euro-VI with diesel particle filters for heavy-duty vehicles, electric two-wheelers	18%	13%
Industrial processes	Emission controls for SO_2 No_x and $PM_{2.5}$. Technologies include Flue Gas Desulfurization (FGD) for SO_2, Selective Catalytic Reduction (SCR) or NO_x, and Electrostatic Precipitations (ESP), Baghouse filters, or cyclone separators or PM.	12%	3%
Boilers in the commercial sector	Replacement programs for traditional biomass-fired boilers, switch to pellets	6%	5%
Diesel generators	Enhanced reliability of grid electricity supply, Euro-VI emission standards and low-sulfur fuel (0.015 percent S content) for remaining generators.	4%	0%
Enforced inspection and maintenance of road vehicles	Mandatory regular inspection and maintenance, enforced repair of broken vehicles, retirement of most polluting vehicles	2%	7%
Industrial coal boilers	End-of-pipe controls for SO_2 NO_x and $PM_{2.5}$ emissions	2%	2%
Urban waste management	Collection and separation of paper, plastic, textile and wood waste, recycling of paper, plastic, textile and wood waste, ban of decentralized open burning of municipal waste, managed (compacted and covered) landfills, collection and reuse of methane	2%	0%
Cement plants	Filters for SO_2 NO_x and $PM_{2.5}$ emissions	0%	17%
Manure management	For industrial farms low-emissions manure storage and manure application	1%	2%
Efficient fertilizer use	Avoiding overfertilization, efficient use of urea fertilizer	0%	4%
Crop residue burning	Ban on open burning of agriculture residue, energetic re-use of crop residue	0%	6%
Brick kilns	Replacement of traditional brick with zig-zag or VSBK kilns, enforced operation	0%	1%
Road dust	Regular road cleaning	0%	2%
Total potential (absolute)		**27 μg/m³**	**7 μg/m³**

Figure 4.9: Cost-effectiveness of additional measures to reduce ambient air pollution in the Kathmandu Valley in 2035



Source: GAINS-Nepal, developed for this report (See Technical Annex D.7 for further details).

Figure 4.10: Cost-optimized policy scenario measures to reduce ambient air pollution in the Terai in 2035



Source: GAINS-Nepal, developed for this report (See Technical Annex D.7 for further details).

Adopting the priority measures identified in this section requires a suite of policy measures, in the five areas of data, rules, economics, incentives, and information, as elaborated in chapter 5. For enterprises to adopt cleaner production technologies at scale, and for households to embrace cleaner cooking technologies, or for any of the other priority interventions, coordinated action is needed across all five dimensions:

1. Data on the impacts of these sectors and technologies on emissions and exposure is needed for planning and enforcement purposes.
2. Rules are needed, especially in the form of emissions performance standards, which mandate certain maximum levels of emissions. Functioning enforcement mechanisms that ensure compliance with the rules are critical.
3. Economic policies are needed as the relative price difference between a fossil-fuel based or a cleaner energy-based technology is determined by the prices of the different sources of fuel/energy, which in turn are affected by taxes, tax exemptions, and other fiscal policies.
4. Incentives are important for nudging enterprises to adopt cleaner production technologies, and households to adopt cleaner cooking technologies.
5. Infrastructure is critical for facilitating the adoption of cleaner technologies, especially for electricity generation and distribution.

4.4 Other priority measures

Forest Fires

Kathmandu had the dubious distinction of being the world's most polluted city on several days each spring, largely due to seasonal rural forest fires causing widespread smoke and haze. To address the growing number and increasing size of forest fires devastating Nepal's community and government managed forests, it is critical in the near-term that NDRRMA establish advanced fire detection and early-warning systems in collaboration with MOFE. Enhanced coordination and training with local governments and communities will also be important to build on enhanced surveillance to quickly identify and then extinguish forest fires before they spread. Additional fire-fighting equipment at the federal level (e.g., helicopters) is also imperative for those fires that spread beyond local capacity.

Over the medium-term, turning forest residue from Tarai forests into pellets to burn in brick kilns not only reduces the intensity of forest fires but also displaces coal imports for use in brick kilns. Preventing and extinguishing forest fires not only reduces some of the worst air pollution episodes in Nepal but also protects the country's biodiversity and carbon stock. Here it will be important to further clarify how to engage Community Forest Users Group (CFUGs) and small medium enterprises (SMEs) in the pelletization industry. Training rural fire fighting teams and manufacturing trainees would create jobs and enable production of cleaner fuels like pellets by supporting forest-based SMEs. Aligning and harmonizing forest and agriculture policies to reduce burning and provide financial incentives for productive uses of biomass wastes is aligned with the existing World Bank Forests for Prosperity Project.

Crop residue burning in the Terai

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 the Terai in the rice-wheat crop cycle, where large quantities of residues need to be cleared quickly. 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 crop residue burning will require scale up of sustainable residue management practices by: (i) implementing policies and regulations aimed at banning the practice, (ii) rewarding sustainable practices through payment for ecosystem services (for e.g. conservation agriculture practices), (iii) promoting markets for, and alternative uses of residues (such as mulching, incorporating them into soil, or using them for feed), (iv) changing the rice-wheat crop cycle, and (v) supporting farmers with adequate technologies and public awareness campaigns. It is essential that options identified are political feasible and the challenges of reforming policies (especially price support and input subsidies) are understood so that proposed technical solutions

Road dust is a major contributor to air pollution in Kathmandu, accounting for 8-12 percent of total $PM_{2.5}$ pollution.

are implementable; thus, it is crucial that farmers be involved in the design and implementation of these solutions.

Reducing road and construction dust

Road dust, composed of resuspended particulate matter (PM), tire and brake wear particles, soil, and debris, is a major contributor to air pollution in Kathmandu, accounting for 8-12 percent of total $PM_{2.5}$ pollution and up to 25 percent of PM_{10}, especially in the dry season pre-monsoon. Construction & Demolition (C&D) waste is a critical source of pollution at construction sites or where it is improperly disposed of, releasing particulate matter through dust and debris. The transportation of such waste further aggravates air pollution by increasing road dust stirred up by vehicles and urban activity. Current regulations on waste management exist but suffer from weak enforcement, particularly in peri-urban and informal settlements. A lack of regulation on road construction leads to lengthy periods of construction where dusty conditions persist. Scaling up investments in mechanized street sweeping, landfill modernization, and alternative waste treatment solutions like composting and waste-to-energy (WTE) is crucial. Effective coordination between municipal governments, private waste companies, and informal waste collectors is needed to ensure compliance and sustainability.

To combat road dust pollution, it is essential to expand mechanical and wet sweeping programs in high-pollution cities, enforce strict penalties for road dust suppression violations at construction sites, and pilot "low-dust zones" in major urban areas. Additional efforts should focus on upgrading road infrastructure by paving high-dust areas and maintaining road quality. Developing an air quality monitoring network for real-time road dust tracking and improving traffic flow to reduce road wear and tear are also crucial. Additionally, introducing a targeted financing mechanism to support municipalities in road paving projects, prioritizing high-dust corridors, and expanding mechanized sweeping schedules in smaller cities (e.g., the Terai). Eventually, adopting sustainable urban planning to reduce dust-prone road networks, encouraging electric vehicle (EV) adoption to lower tire and brake wear emissions, and investing in advanced dust suppression technologies, such as smart dust barriers can be considered. With targeted policies, a 50-60 percent reduction in road dust PM_{10} and up to 40 percent reduction in $PM_{2.5}$ emissions is achievable. Table 4.4 summarizes these key interventions.

Table 4.4: Effectiveness and challenges of dust control strategies

Mitigation Strategy	Effectiveness	Challenges
Street Cleaning (mechanical sweeping, wet sweeping)	Reduces PM_{10} by ~90% on paved roads	Not done regularly in smaller cities.
Water Spraying on Roads	7-10% PM_{10} reduction	Short-lived effect, high water usage.
Paving Roads (including permeable pavers)	Long-term PM reduction	High costs, limited funding for full implementation.
Construction Dust Control (barriers, covers, wet suppression)	Can cut $PM_{2.5}$ by up to 50% at active sites	Weak enforcement on private construction sites.

Note: This information is based on the forthcoming Solutions Note on Waste prepared by the World Bank team.

Achieving clean air progress requires careful preparation and sequencing. In the near term, the industrial sector in Nepal is ripe for the adoption of clean technology because the data is clear, industrial standards are being reformed, policy incentives have been identified that can provide the right signal for nudging enterprises, and infrastructure solutions are available. Other sectors require more preparation with respect to the development of a roadmap to achieve progress across each of these dimensions before finance at scale is recommended. Chapter 5 provides an assessment of these elements across additional sectors; however, more planning and stakeholder engagement is needed before other sectors are ready for implementation of the recommended solutions. Such important planning, evidence-gathering, and stakeholder engagement work could be carried out as next steps toward strengthening Nepal's AQM institutional and governance framework for each relevant sector.

4.5 Reaching 35 μg/m^3 by 2035

Nepal has recognized the paramount importance of working together with the 12 jurisdictions across the five countries of the Indo-Gangetic Plain and Himalayan Foothills (IGP-HF) region on air pollution challenges. The International Centre for Integrated Mountain Development (ICIMOD) and the World Bank have jointly hosted government representatives, finance institutions and other development partners at two Science Policy Dialogues and are actively planning a third Science Policy Finance Dialogue in 2025. These convenings emphasize the crucial role of multi-country collaboration on common methodologies for monitoring, air quality and policy assessment and potentially harmonized air quality targets. The Thimphu Outcome of June 2024 charts the way for development of a regional cooperation mechanism for AQM planning and arrived at a common understanding that parties will consider an aspirational goal of < 35 μg/m^3 for annual average $PM_{2.5}$ concentrations by 2035 ("35 by 35") for long-term Air Quality planning. The 35 μg/m^3 target for annual average concentrations is significant. First, because an aspirational target of this magnitude reflects the seriousness of ambition among the IGP-HF governments as achieving this target would require tremendous effort by all jurisdictions in the region. Second, 35 μg/m^3 refers to international air quality standards for $PM_{2.5}$ such as the Interim Target 1 of the World Health Organization (WHO, 2021), outlining a gradual path towards reaping the substantial benefits of clean air to public health, wellbeing, and development.

Achieving "35 by 35" will require regional collaboration. Focusing on population-weighted exposure, with 37 and 39 μg/m^3 this target was slightly exceeded in the Kathmandu Valley and the Terai in 2021. However, following the envisaged economic development and with the current pollution control regulations, the baseline suggests for 2035 significant higher exposure in the Kathmandu Valley (52 μg/m^3) and in the Terai (42 μg/m^3). At the same time, the above analyses reveal considerable opportunities for air quality improvements through locally applied emission controls. Full implementation of the identified measures in Kathmandu could reduce $PM_{2.5}$ exposure to about 25μg/m^3. In the Terai, local action could counterbalance the envisaged growth but would not be sufficient to reduce exposure to 35 μg/m^3 without significant collaboration through the IGP-HF regional program.

However, full implementation of all locally available emission controls involves significant costs for the economy. For instance, achieving the 35 μg/m^3 target through local measures unilaterally implies annual costs of about USD 6 million in the Kathmandu Valley and USD 500 million in the Terai (the red lines in Figure 4.11 and Figure 4.12). These estimates refer to additional resource costs for emission controls that occur to Nepal's economy, incremental to the baseline costs of current (brown) technology. Costs include additional annualized investments, capital charges and operating costs, and additional costs—or savings—of fuel costs. However, they do not include transfer payments such as taxes and subsidies.

Coordination on control measures across the IGP-HF, and especially with the neighboring Indian States of Uttar Pradesh and Bihar, could help Nepal achieve the 35 μg/m^3 target in its most polluted regions at drastically lower costs. In the

Kathmandu Valley in 2035, coordinated approaches in which a common set of basic measures (Table 4.5) would be implemented across the entire IGP-HF region would reduce the inflow of pollution into the valley by about 2.8 μg/m^3. This will avoid the necessity to take the most expensive measures locally and thereby reduce annual costs for local measures in Kathmandu to less than USD 4 million, i.e., by about one third (Figure 4.11). In the Terai, cooperation on implementing a common set of basic measures across the entire IGP will reduce the inflow by about 5.3 μg/m^3, i.e., from 41.6 μg/m^3 to 36.3 μg/m^3. The remaining gap to the 35 μg/m^3 target can then be achieved through local measures at annual costs of about USD 5 million, only a small fraction of the USD 500 million of the unilateral strategy.

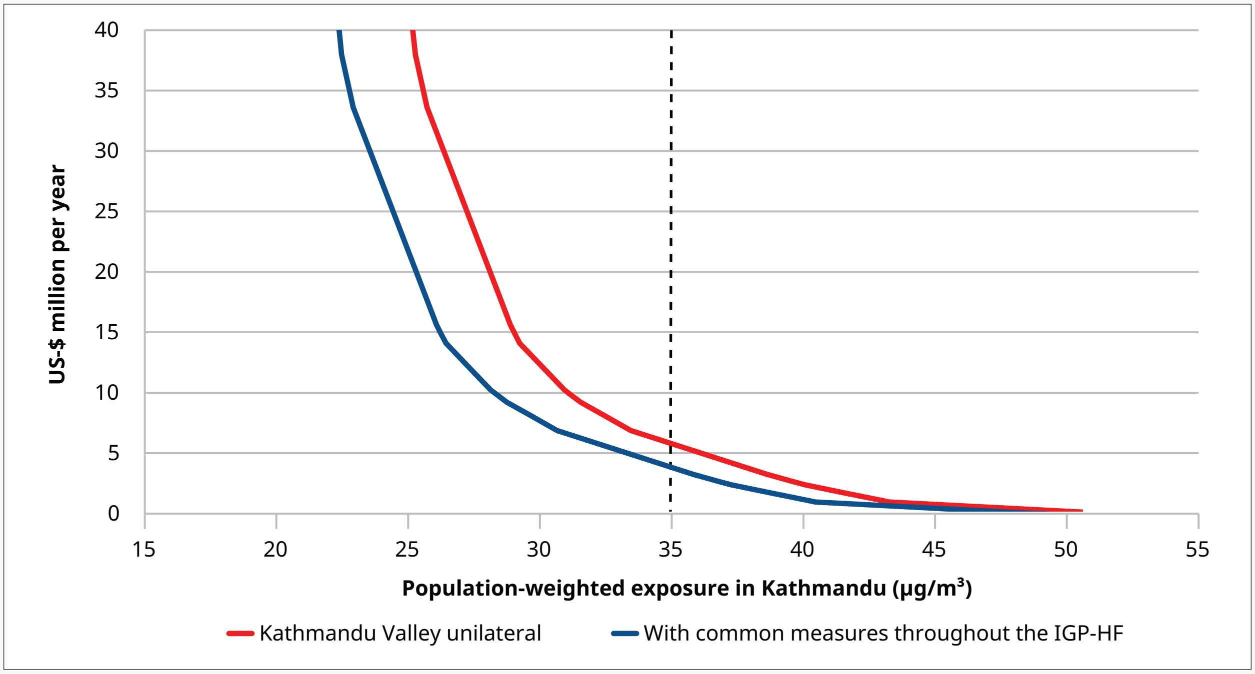
For the Kathmandu Valley, reaching the 35 μg/m^3 interim target is much cheaper than for the Terai. The report estimates that it would cost about USD 6 million per year for the Kathmandu Valley to arrive at the 35 by 35 target through local action. For the Terai, annual costs amount to about USD 500 million if the target was to be met by unilateral local action only. There are differences in costs because the Kathmandu Valley has 4-5 times fewer residents, but also because the Terai would need to support heavy duty vehicle replacement and cleaning cement production, which are much more expensive interventions. It is also important to note that these costs are best case scenarios, assuming perfect efficiency and complete adoption success, and should therefore be seen as the lower case estimates.

For the Terai especially, it is critical that other jurisdictions in the airshed act. For example, if similar pollution controls are taken in other parts of the IGP-HF (mainly India), abatement costs for the Terai drop precipitously to USD 5 million per year (from USD 500 million). However, the envisaged air quality improvements will then only be achieved if commensurate action is indeed taken in the neighboring areas. Thus, it will be critical for Nepal to promote and actively participate in cooperative air quality management with other regions in the IGP-HF, as a minimum through implementation of the measures that occur as most cost-effective in the Terai. In the Kathmandu Valley, where pollution sources in other parts of the IGP-HF have less impact due to the topographic and meteorological conditions, annual pollution abatement costs shrink from USD 6 million to USD 4 million.

Different agents could pay for these additional costs of cleaner air: households, motorists, private sector in industries, or the state. The three priority measures identified, in terms of cleaner cooking, manufacturing, and mobility, can be taken and financed by different agents. For instance, cleaner cookstoves could be financed by the households using them, or by the state who could provide them, or a mixture thereof (the various cleaner cookstoves projects in Nepal had different ways of distributing these costs). For cleaner industries, the private sector could be mandated to adopt, for example, cleaner boilers, furnaces, or kilns, and/or enterprises could receive financial incentives that make these additional investments profitable for them. Finally, motorists, whether private or commercial, could receive incentives to switch to cleaner vehicles (such as with the reduction of import duties on EVs) or be mandated (e.g. through vehicle emission standards or fuel standards) or nudged (e.g. through higher fossil fuel taxes).

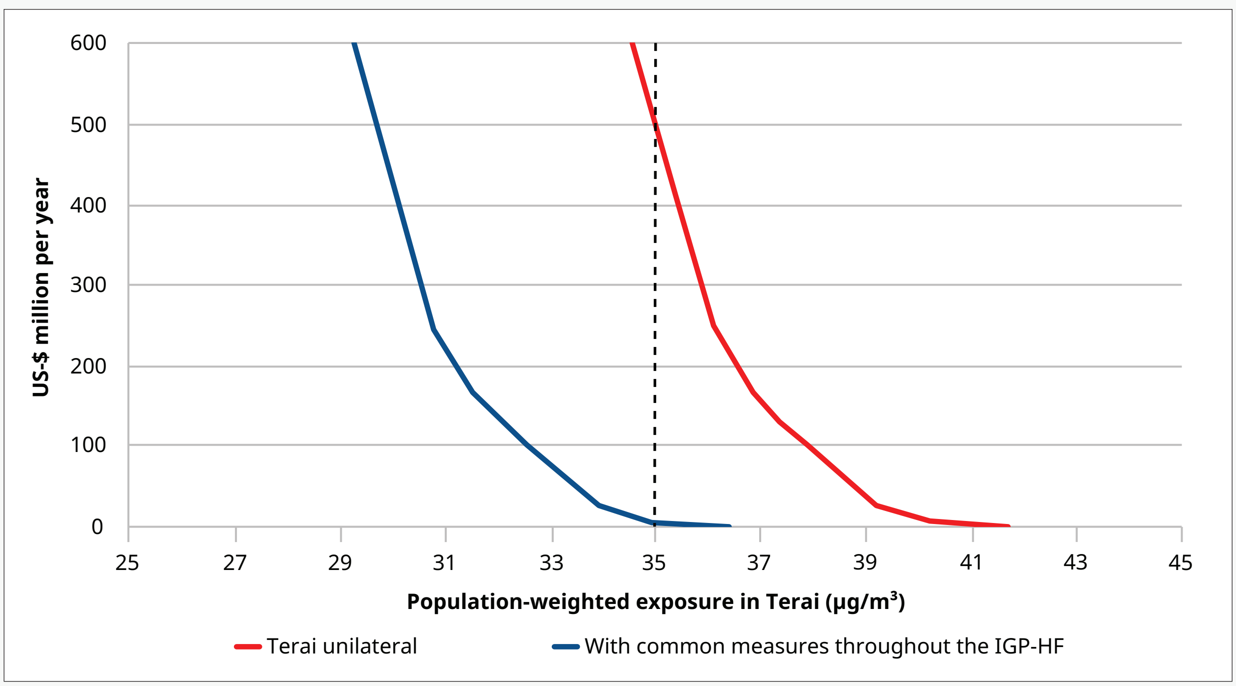
The common set of basic measures that has been proposed for cooperative airshed management in the IGP-HF comprises most of the measures that emerge as cost-effective for the Kathmandu Valley and the Terai. It also contains additional measures that are relevant in other IGP regions, but not in Nepal (e.g., electric cremation, fireworks). Conversely, due to the large fuel wood consumption in process heat boilers in the Kathmandu Valley compared to other IGP regions, emission controls for this source category emerge as an essential element of a cost-effective air quality management strategy in Nepal.

Figure 4.11: Total emission control costs in the Kathmandu Valley for (a) unilateral action in the Kathmandu Valley, and (b) cooperation across the Indo-Gangetic Plain and Himalayan Foothills



Source: GAINS-Nepal, developed for this report.

Figure 4.12: Total emission control costs in the Terai for (a) unilateral action in the Terai, and (b) cooperation across the Indo-Gangetic Plain and Himalayan Foothills



Source: GAINS-Nepal, developed for this report.

Table 4.5: The common set of measures assumed in the cooperative scenario for the other IGP-HF jurisdictions

Mobile sources
• Effective inspection and maintenance for heavy-duty and light-duty road vehicles • Street paving and washing
Power generation
• Large stationary generators: Diesel particle filters according to EU Stage 3B controls for non-road diesel engines50
Households
• Universal access to clean household fuels for cooking (LPG/electricity) to replace biomass fuels (fuelwood, dung) • Residential kerosene lamps: Switch to LPG or LEDs • Filters for restaurant kitchens • Electric cremation • Ban of fireworks • PM controls at heating boilers • New/improved heating stoves burning solid fuels in households
Industry
• Brick production: Zig-zag kilns (55 percent of production capacity) and vertical shaft brick kilns (VBSK) with basic dust control (40 percent of production capacity) • Electrostatic precipitators (2 or 3 fields) at large industrial sources • Basic NO_x controls for industrial boilers • Electrostatic precipitators (1 field) at industrial furnaces • High-efficiency de-dusters (3-fields) in aluminum production • Flue gas desulfurization of large industrial boilers and furnaces • Basic SO_2 controls (-50 percent) at cement, aluminum, steel plants and refineries
Agriculture
• Efficient urea fertilizer use • Stop open burning of agricultural residue

50 European Union. *Emission Standards for Nonroad Engines.* Accessed through: https://dieselnet.com/standards/eu/nonroad.php#s3

Black smoke emerging from a firewood boiler used by a food and beverage enterprise in Tokha Municipality, Kathmandu Valley.
Source: Sulochana Nepali/World Bank.

The cost-effective measures outlined in the report align closely with the priorities in the Air Quality Management Action Plan for the Kathmandu Valley of 2020, introduced by the Ministry of Forests and Environment (MOFE). The Action Plan was built upon the already framed Air Quality Management Action Plan for the Kathmandu Valley of 2017. The revised plan identifies various strategic areas of transport, industries, waste management, indoor air pollution, and proposes sector-wise interventions to reduce air pollution in the valley. To reduce emissions from the transport sector, the Action Plan prioritizes upgrading vehicle and engine technologies and phasing out old high-emitting vehicles from roads. These approaches are in line with this report's recommendations to implement cost-effective measures such as application of Euro-IV standards to light-duty vehicles and particle filters for diesel heavy-duty vehicles to cut vehicular emissions and implement enforced inspection and maintenance regimes to phase out old polluting vehicles. To curb industrial emissions, the Action Plan highlights the importance of compliance with emission standards, the promotion of clean technologies in industrial facilities, and relocation of brick kilns. These activities agree with the emphasis of this report where end-of-pipe controls for industrial boilers and shifting to electric or pellet-based systems are identified as the most cost-effective measures to minimize pollution from industries. To reduce household emissions, the Action Plan emphasizes the promotion of improved cookstoves, complementing this report's recommendation to replace traditional biomass cookstoves with fan-assisted stoves or electric induction stoves.

Achieving the WHO target for $PM_{2.5}$ (5 μg/m³) and interim targets 1 and 2 (35 μg/m³ and 25 μg/m³), would result in substantial health benefits, reducing the burden of disease across all categories for both Kathmandu and Terai.

There are co-benefits where these measures also contribute to other policy priorities—but these benefits are not included in this analysis. The GAINS analysis considers measures that could deliver other air quality improvements than simply reducing exposure to $PM_{2.5}$ in ambient air. However, the analysis does not take these co-benefits into account, nor does it consider simultaneous co-benefits on other policy priorities, for example on greenhouse gas emissions, improvements in soil fertility, etc. However, cost savings that emerge from $PM_{2.5}$ control measures are fully considered; for example, biogas energy from improved solid waste management, reduced fertilizer consumption, sale of recycled materials etc.

A detailed analysis of the burden of disease attributable to ambient $PM_{2.5}$ exposure was conducted for both Kathmandu and Terai in 2021 and 2035. Using the World Health Organization's AirQ+ tool, an assessment of the benefits of achieving the WHO interim targets 1 and 2 has been performed relative to the projected 2035 concentrations of 51 and 42 μg/m³ in the Kathmandu Valley and the Terai, respectively (see details in Annex C).

Achieving the WHO target for $PM_{2.5}$ (5 μg/m³) and interim targets 1 and 2 (35 μg/m³ and 25 μg/m³), would result in substantial health benefits, reducing the burden of disease across all categories for both Kathmandu and Terai. For both locations, achieving WHO Target 1 (35 μg/m³) would reduce the burden by about 15-20 percent across diseases like COPD, ischemic heart disease (IHD), ALRI, and lung cancer. Reaching WHO Target 2 (25 μg/m³) would further decrease the burden by 30-40 percent, while achieving the optimum level (5 μg/m³) could result in a nearly 90 percent reduction in burden for most diseases.

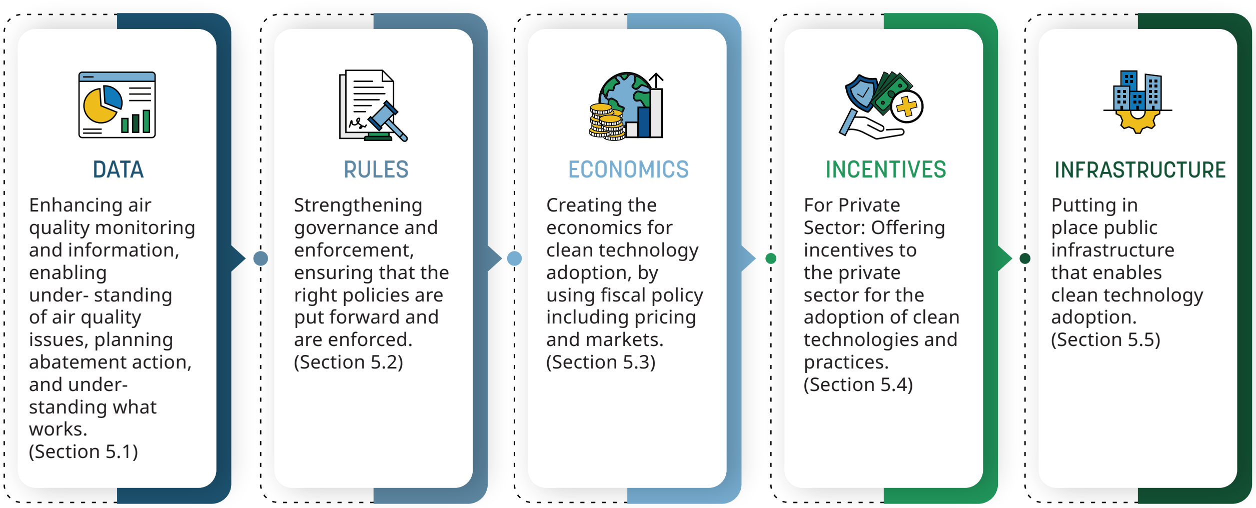
CHAPTER 5:

Creating the Enabling Foundations for Clean Air in Nepal

This chapter identifies a broad set of recommendations for putting in place the enabling foundations to help address air pollution in Nepal, including for adopting the priority measures identified in chapter 4. Chapter 5 has carefully assessed the effectiveness of pollution abatement measures (technologies and practices) and identified the priority measures to take. The adoption of the identified priority (cleaner) technologies across the sectors—whether those are cleaner boilers, cookstoves, vehicles, or any other technology—is a function of a strong enabling foundation being in place. The core elements of a clean air enabling foundation are data, rules, economics, incentives, and infrastructure (Figure 5.1).

Data collection and monitoring enhance understanding and planning; rules enforce robust policies; economics shape fiscal strategies for clean technology; incentives encourage private sector adoption; and infrastructure supports the practical deployment of solutions.

Figure 0.4: The five enabling foundations for clean air in Nepal



Artwork: Anjali Neupane, 'Where's My Blue Sky?' Live Art Challenge.

This chapter can build the foundations of a Nepal Air Quality Management Plan (NAQMP). The furnishing of an NAQMP is crucial, as it would provide the guidance needed for how to work on the five key dimensions of data, rules, economics, incentives, and infrastructure in the multiple sectors required to bring about air quality improvements. The leadership of MOFE and its DoE in this process is critical, and so is the engagement of line Ministries, which cover the many sectors from which air pollution emerges. High-level executive commitment is essential, given the multisectoral nature of air quality challenges.

This national plan must extend beyond the existing Kathmandu Valley Air Quality Management Action Plan (2022), addressing other pollution hotspots such as the Terai. Unlike the Kathmandu Action Plan, which lacks detailed implementation strategies, a NAQMP should offer specific, actionable steps to turn aspirations into reality, ensuring effective and sustained pollution abatement across Nepal. As part of the NAQMP, sectoral road maps would provide guidance for how to reduce emissions in key sectors such as industry, cleaner cooking and transport.

5.1 Data: Strengthen air quality monitoring and information

Enhancements to the air quality monitoring network are required to provide reliable data from many locations around the country. As described in chapter 1, the current monitoring network is hampered by patchy data due to the age and condition of monitoring equipment and human resource constraints—especially far from the capital—lack of consistent protocols for data collection and perennial challenges providing ongoing consulting support for network operations and maintenance. Identifying solutions here—as with other sectors (illustrated in Section 5.2)—should follow a similar formula to establish:

- **Mandates** – It is important to clarify the air quality monitoring roles and responsibilities among federal, provincial and local level. While all three have the mandate to regulate and enforce AQ NAAQS, questions remain such as what is the proper role for each with respect to baseline compliance monitoring? In many countries the federal government issues regulatory minimum requirements for AQ monitoring (e.g., procedures, QA requirements and number of sites and frequency of monitoring) but it is incumbent on provinces to carry out monitoring subject to the federal regulations. Hard questions need to be explored in terms of the appropriate level of government, institutional arrangements and resource allocation for compliance monitoring, especially far from the capital, where it may make sense to either establish federal DoE offices in distant provinces or to capacitate provincial authorities.

- **Mechanisms** – This includes consideration of tradeoffs between the hiring and training of permanent AQ monitoring staff versus the use of consulting support as is current practice. If a consulting model is pursued, the Government of Nepal (GoN) may need to identify and support the appropriate level of government to modify existing procurement mechanisms for hiring firms to provide continuous operation, maintenance and management (supply of spare parts and attending to repairs) for monitoring stations, even across fiscal years, which currently results in annual data gaps when past year contracts lapse. Standard Operating Procedures (SOPs) with rigorous quality assurance and data validation protocols are essential elements of any AQ monitoring program. The government should be supported in analyzing and reporting the data routinely not only through publicly accessible formats such as smartphone apps, but also through annual government reports.

- **Means** – A funding mechanism for implementation options will require aligning allocation of resources with monitoring responsibility (i.e., ensuring that the right agency (with the mandate) has resources, staffing, equipment and capacity to carry out the job). Training programs can be established in collaboration with local research institutions and other IGP-HF partners to ensure that consistent protocols are being used for quality assurance and data validation across the region. Pending adequate staff availability to fully utilize existing equipment, there is further need for additional measurement parameters at existing stations, such as black carbon (BC), Sulfur Dioxide (SO_2), Nitrogen Oxide (NO) and Ozone (O_3) as well as deployment and operation of manual samplers for source apportionment analysis.

- **Accountability** – Establishing clear data quality objectives (DQOs) for AQ monitoring data that include accuracy and completeness requirements, will ensure that only appropriate data are published on a regular schedule and relied on for government decision making. However, establishing DQOs is necessary, but not sufficient. DQO regulations should include both incentives to achieve these requirements and consequences (i.e., mandatory corrective actions) for agencies that fail to meet DQOs.

Data collection solutions are needed across the sectors that impact air pollution to enable ongoing policy assessment. While available information and data has been collected and used for the preliminary assessments presented in chapter 4 of this report, ongoing inventory and modeling is a core responsibility of the federal DoE to maintain the technical foundation for policy assessment. Contributing sources to air pollution evolve and change, and thus the DoE needs the capacity to maintain an updated understanding of source structure as a basis for continually refining policy approaches to regulate those sources. For example, routine collection of emission inventory data requires vehicle data through a digital vehicle registration portal and the industrial facility permitting database are discussed in Section 5.2. However, similar approaches will also be needed from power plants, commercial entities, and other sources that should be routinely reported to MOFE so that the DoE and the Climate Change Management Division (CCMD) have the data to establish and track relevant emissions in a comprehensive emission inventory.

Detailed source apportionment studies are needed to provide quantitative details about the source sectors and the regions responsible for the air pollution in Nepal. Source apportionment is a technique to mathematically work backward from fine particle chemical observations to deduce the main sources giving rise to pollution. It requires, however, detailed analysis of the composition of $PM_{2.5}$ over many samples. Given that this capacity takes many years to establish, initial steps toward routine source apportionment can begin with the deployment of several pairs of manual samplers to prepare, collect, weigh, and archive filter samples for future source apportionment analysis. The DoE could work with provincial officials to establish a source apportionment network (5 pairs of new manual samplers co-located at existing sites; potentially 2-3 within the Kathmandu Valley, and 2-3 in nearby provinces (i.e., within driving range), while ensuring adequate site security and staffing/resources for sample collection. Meanwhile, federal-level filter preparation, weighing and storage facility can be established at a DoE laboratory facility, allowing for the creation of an archive of samples for subsequent analysis. A plan then needs to be prepared for analyzing these stored filter papers at an appropriate frequency.

Support is needed for enhanced planning capacity for policy assessment and scenario planning. A proper role for federal DoE officials—in partnership with local academic institutions familiar with AQM assessment methods—is to develop action plans and determine the appropriate stringency for sector-specific emissions standards, including for industries (such as bricks, metal, etc.), transportation emissions, residential energy use and identify regulatory options for control of forest fires. Importantly, this planning capacity will be most effective if mainstreamed across ministries so that the relevant emitting sectors (e.g., energy, transportation, agriculture, urban development) are also able to assess the air quality implications of their medium- and long-term plans in collaboration with the DoE/MOFE. However, this capacity must be based on solid analytics requiring the emission inventories and source apportionment studies described above. A periodic update of such inventories is required to inform policy formulation.

Localized epidemiological studies are essential to understand and effectively address the health impacts of air pollution in Nepal. The focus should be on establishing localized exposure-response relationship i.e., determining how exposure to pollution results in certain health impacts, specific to the country's unique pollution mix and socio-economic conditions. Similarly, improving health data collection at hospitals and establishing centralized national health database are crucial steps to ensure reliable information is available for advancing health studies on air pollution in Nepal. By integrating air quality data with reliable hospital data, researchers can gain valuable insight into how prolonged exposure to pollution causes chronic health impacts such as respiratory and pulmonary diseases. A critical step to achieve this goal is stronger collaboration between the Ministry of Forest and Environment (MOFE) and the Ministry of Health and Population (MoHP) to establish a structured program that can directly examine the linkages between air pollution and public health outcomes. Nepal's Health Information Management System (HIMS), which currently collects health data from hospitals is focused on communicable diseases, child and maternal health, and general healthcare services. The national HIMS could be expanded to include environmental health indicators and air pollution related morbidity, enabling policymakers to quantify the true health burden of pollution and advocate for stronger evidence-based air quality regulations. Additionally, strengthening the partnership of health research institutions such as the Nepal Health Research Council (NHRC) with the MoHP could further drive evidence-based interventions to mitigate the rising health burden of air pollution in Nepal.

Nepal's scope for AQM planning is appropriately shifting from the municipal scale to airshed scale, which requires national/regional cooperation on data and information sharing. Given that more than one-third of Kathmandu's and more than three-quarters of the Terai's air pollution comes from outside the immediate vicinity, AQM planning must be conducted at the airshed level. The IGP-HF airshed shares a common flow of air that can be (near)-uniformly polluted or stagnant. For AQM systems, the definition of airsheds for a region or country is fundamental since 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. This means 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. Solving regional problems in the context of local action requires regional coordination, analysis and assessment and ultimately can require regional harmonization of standards and policies. Continuing engagement and support for the IGP-HF process is an essential element of national AQM planning. As the chief air resource management agency for Nepal, the DoE must work collaboratively with other ministries and across levels of government within Nepal, but also across the airshed, which entails coordination with governments at the IGP-HF level. By forging partnerships with other IGP-HF countries—through future Science Policy and Finance Dialogues and other convenings—and using consistent, science-based methods to explore policy options and regulatory approaches for common airshed sectoral sources, the DoE must remain engaged in regional AQM coordination.

Raising awareness based on high quality air quality data is critical. In other countries of the Indo Gangetic Plains and Himalayan Foothills, such as India, Bangladesh and Pakistan, the recognition of air pollution as a critical problem has significantly advanced over the years, driven by growing scientific evidence, media coverage, and public advocacy. This acknowledgment has led to policy actions, large-scale awareness campaigns, and community involvement. In contrast, while Nepal faces serious air pollution issues, awareness and recognition of the problem remain limited (compared to these other countries), hindering the urgency and scope of action needed to address it effectively. A couple of steps for Nepal to improve awareness of the air pollution issue include:

1. **Public Awareness Campaigns:** Implementing widespread public awareness campaigns to inform the public about the health impacts of air pollution, open burning of garbage and the importance of air quality management. This will help generate public demand for clean air.
2. **Community Engagement:** Engaging local communities through workshops and seminars to foster a better understanding of air quality issues, enabling easy access of air quality data to the communities, supporting programs for local air monitoring by communities, building awareness on taking adaptive actions during the periods of air pollution spikes and encouraging community-driven solutions for local air quality management.
3. **Media Involvement:** Utilizing various media platforms, including social media, television, and radio, to disseminate information on air quality trends in the country/relevant cities, raise

awareness about air quality and its effects and potential mitigation and adaptation actions that each stakeholder can implement to address the issue of air pollution.

4. **School Programs:** Integrating air quality education into school curriculums to educate the younger generation about the importance of clean air and how they can contribute to improving air quality.
5. **Campaigns for Clean Technologies:** Beyond information on environmental benefits of clean technologies, awareness efforts should also focus on raising financial literacy i.e., educating individuals and firms about the costs, benefits, financing options, and long-term savings associated with adopting these technologies.

There are many sectoral data/information needs; the priorities are:

Develop a national digital vehicle database integrating registration, inspection, and emissions test results. To enhance the effectiveness of air quality management in the transportation sector, it is crucial to develop a national digital vehicle database. This database should integrate vehicle registration, inspection, and emissions test results, providing a comprehensive overview of the vehicle fleet's compliance with emissions standards. Such a system will facilitate better monitoring and enforcement of regulations, ensuring that vehicles on the road meet the required emissions standards and contribute to improved air quality.

Use remote sensing for emissions monitoring on key corridors. Implementing remote sensing technology for emissions monitoring on key transportation corridors can significantly enhance the ability to detect activity and address high-emission vehicles. Remote sensing allows for real-time monitoring of vehicle emissions, identifying non-compliant vehicles and enabling targeted enforcement actions. This technology can help reduce emissions from the transportation sector, contributing to cleaner air and improved public health.

Track adoption and usage rates of electric and improved biomass stoves. Tracking the adoption and usage rates of electric and improved biomass stoves is vital for assessing the effectiveness of interventions aimed at reducing household air pollution. By monitoring the uptake of these cleaner cooking technologies, policymakers can identify barriers to adoption and develop targeted strategies to promote their use. This will help ensure that households transition to cleaner cooking methods, reducing indoor and outdoor air pollution.

Use geospatial mapping to identify high-pollution-risk residential clusters. Utilizing geospatial mapping to identify high-pollution-risk residential clusters can help target interventions where they are needed most. By mapping areas with high levels of pollution exposure, policymakers can prioritize resources and actions to address the specific needs of these communities. This approach will enhance the effectiveness of air quality management efforts and improve public health outcomes.

Conduct satellite-based monitoring of agricultural burning across the Terai. Satellite-based monitoring of agricultural burning across the Terai region is essential for understanding the extent and impact of this practice on air quality. By tracking the location, frequency, and intensity of agricultural burning, policymakers can develop targeted interventions to reduce emissions from this source. This will help mitigate the impact of agricultural burning on air quality and public health.

Map spatial patterns of agricultural residue availability for cleaner fuel production. Mapping the spatial patterns of agricultural residue availability is crucial for promoting the use of cleaner fuels. By identifying areas with high availability of agricultural residues, policymakers can support the development of cleaner fuel production facilities and encourage the use of these fuels. This will help reduce reliance on traditional biomass and fossil fuels, contributing to improved air quality.

Track seasonal variations in residue burning practices. Tracking seasonal variations in residue burning practices is important for understanding the temporal dynamics of this pollution source. By monitoring when and where residue burning occurs, policymakers can develop targeted interventions to reduce emissions during peak burning periods. This

A forest fire burns in the Hattiban Forest, in the outskirts of Kathmandu. Fires like this can blanket the nearby urban area with acrid smog.
Source: AP Tolang / iStock.

will help mitigate the impact of residue burning on air quality and public health.

Develop early warning systems using forest dryness and fire risk indices. Developing early warning systems using forest dryness and fire risk indices is essential for preventing and managing forest fires. By monitoring these indices, authorities can predict and respond to fire risks more effectively, reducing the occurrence and impact of forest fires on air quality. This proactive approach will help protect public health and the environment.

Deploy remote sensing for real-time forest fire detection: Deploying remote sensing technology for real-time forest fire detection can significantly enhance the ability to detect and respond to forest fires. By monitoring forest areas in real-time, authorities can quickly identify and address fires before they spread, reducing their impact on air quality and public health. This technology will help improve the effectiveness of forest fire management efforts.

Map high-risk zones for preventive fire management interventions: Mapping high-risk zones for preventive fire management interventions is crucial for targeting resources and actions where they are needed most. By identifying areas with a high risk of forest fires, authorities can prioritize preventive measures, such as controlled burns and vegetation management, to reduce the likelihood of fires. This approach will help protect air quality and public health.

5.2 Rules: Strengthening air quality governance and enforcement

Proposed policies and action plans to address air pollution need the power of law and regulation to achieve their goals. While the recommendations identified in government 'action plans' set the stage for a more effective AQM and establish potential institutional arrangements for effective AQM monitoring and enforcement, this potential will only be achieved if the recommendations are enshrined in law giving relevant agencies the appropriate mandate via the EPA, and those agencies subsequently develop regulations and guidance to carry out the mechanisms identified. This sets the legal and regulatory framework for effective AQM.

Ambient standards could be strengthened, and an annual average fine particle standard added. The revised NAAQS mandates 24-hour average threshold levels for pollutants including $PM_{2.5}$ that are more than twice the WHO guideline value. 24-hour average PM_{10} standards are similarly far higher than WHO guidelines. More concerning, however, is that Nepal currently lacks annual average thresholds for these pollutants. Both annual and 24-hour standards are crucial for assessing air quality. For instance, the WHO recommends annual an average $PM_{2.5}$ concentration below 5 μg/m^3 and 24-hour average below 15 μg/m^3. However, without inclusion of annual average levels for $PM_{2.5}$ and PM_{10} NAAQS, Nepal misses an opportunity for compliance with indicators that are indicative of the largest burden of disease, chronic, long-term exposure to $PM_{2.5}$.

High-level support can put in place institutional arrangements that support effective AQM governance. World Bank analytics in multiple global regions have shown that the most effective AQM programs have (i) basic legislative and regulatory frameworks, (ii) national high-level champions (who ensure staffing and budget for basic functions as well as push line ministries to cooperate), (iii) decision-making based on high quality evidence, including data, analyses and knowledge, (iv) horizontal and vertical coordination of programs (i.e., federal, provincial and local alignment and coordination across ministries), and (v) accountability and transparency via the production and tracking of publicly-available information (See Figure 5.2). This framework provides a solid basis for restructuring Nepal's existing AQM framework. However, experience shows that it will require support beyond MOFE, including sectoral line ministries responsible for key pollution sources to ensure that recommendations take root across government. Defining a long-term AQM agenda and providing the necessary budget for it needs to be championed or endorsed by high-level officials, like the prime minister, within and across layers of government. This is particularly the case if the agenda's objectives and targets require multi-sectoral actions.

At the sectoral level, Nepali federalism presents a unique challenge to clarify AQM mandates and advance action. Given that the constitution guarantees that each level of government can establish their own Environment Protection Act and that all levels of government have a mandate for enforcing and delivering clean air, a series of technical-level dialogues—sanctioned at a high-level—are needed across all ministries and agencies to define effective implementation arrangements.

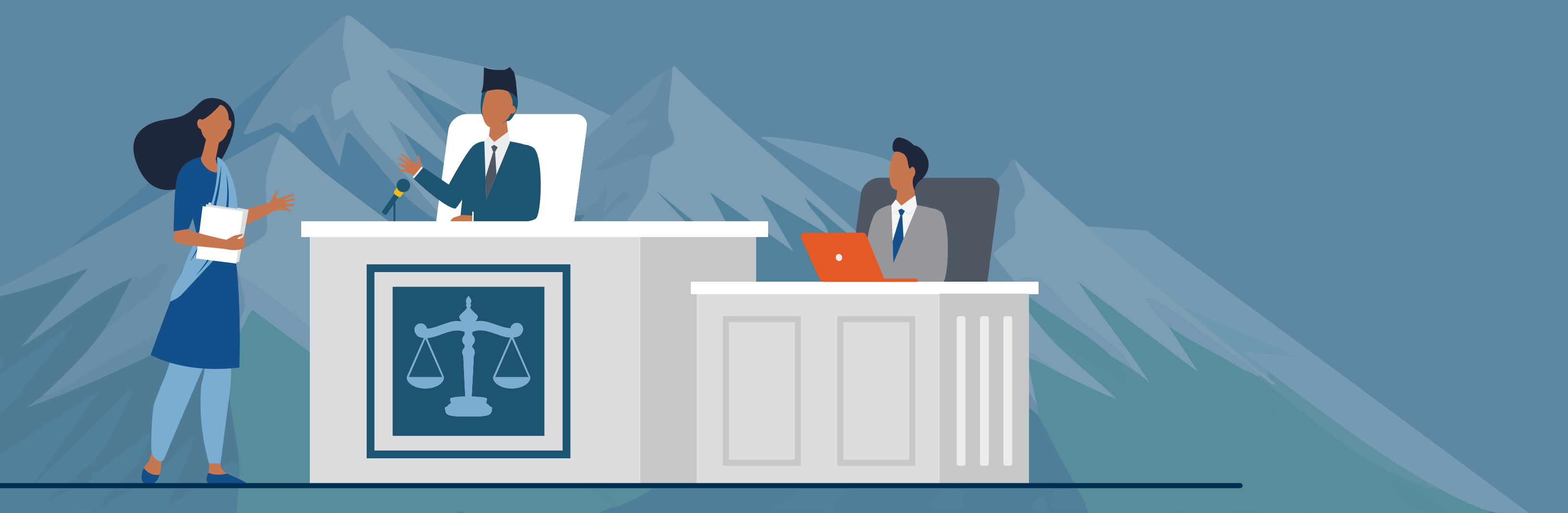
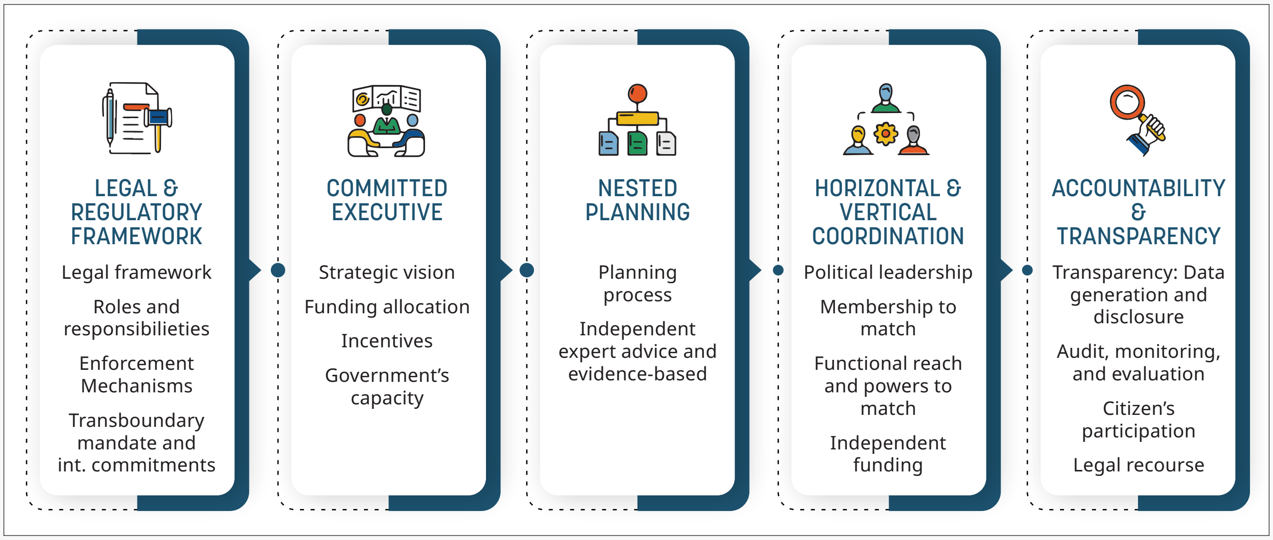


Figure 5.2: Governance and institutional framework for assessing AQM systems



Source: World Bank, 2024b. Air Quality Management in EU Member States: Governance and Institutional Arrangements: International Experience and Implications, Europe and Central Asia Region, Washington DC.

For each of the areas discussed below, the GoN can develop a blueprint for action including legislative principles and regulatory reforms with corresponding budget (including revenue generation and resource requirements) and accountability recommendations. Specific dialogues can follow a similar format to set clear goals, timebound targets and enforceable/ accountable outcomes targeting key AQM functions, including AQ monitoring (already described in Section 5.1), industrial enforcement, vehicle inspection enforcement, clean cooking technology testing and sales and forest fires management.

Enhancing regulations and enforcement for industrial facilities will require careful consideration of existing mandates, staffing and equipping appropriate agencies. Theoretically, existing industrial standards and requirements under the Industrial Enterprises Act for development of new industrial facilities requires compliance with standards and ensures that development will adhere to approved conditions and levels, preventing it from making a "significant contribution to control of pollution." However, the lack of inspectional human resources, equipment and procedures to ensure follow-through on plans or to conduct routine inspections prevents the GoN from effectively controlling emissions from the sector.

- **Mandates** - The registration of new industries is handled by the Department of Industry (DoI) or industry departments or offices from provinces. However, the industrial standards are set by the Ministry of Forest and Environment, which also reviews and approves EIAs and has the authority through the DoE to inspect the industrial facilities and verify that self-monitoring reports are in place and to ensure compliance with those industrial standards. Projects that are under provincial jurisdiction follow a different process with provincial authorities providing oversight. EIAs tend to utilize a self-monitoring process utilizing external consultants, making it very difficult for effective oversight to understand if industries are following requirements or not. Updated legislation should provide clear roles and responsibilities among federal, provincial and local level allocating the mandate to regulate and enforce specific categories of industries in specific geographic locations (including provinces, municipalities of various sizes and industrial zones).

- **Mechanisms** – Section 20 of the EPA requires industries making a significant contribution to receive a pollution control certificate (PCC). However, the process of issuing PCC stopped in

2002 due to unclear regulations between the DoI and the Ministry of Environment, Science, and Technology and now is a completely voluntary process with only clean industries tending to apply. A comprehensive system of permitting needs to be established that includes all industrial sources that emit specified pollutants above specific thresholds. Operating permits can be tied to emission charges that would provide funding for environmental permitting and inspections/audit staff. This can be complemented with routine reporting (e.g. emissions or activity data) to support AQ emission inventory work (see below), as well as a system of routine inspections using specified methodology and set fines for various specific violations (right now fines are extremely subjective and only for 'actions in contravention of the act'). The use of routine inspections would also call for a means of accrediting or certifying both public and private sector inspectors in the approved test methods.

- **Means** – A means of accomplishing the activities above would ensure that a clearly identified agency (with the established mandate, at the federal, provincial or municipal level) has resources (both human resources—in terms of authorization to hire staff—as well as financial resources – in terms of having adequate budget to pay staff, procure stack testing equipment, inspection vehicles and pay for training of staff) and capacity to carry out the mechanisms described. The DoE should prepare a roadmap for strengthening the enforcement of the regulator(s) (including e.g., DoI, DoE, and DOLOS at the federal and provincial level) that defines clear and escalating penalties, streamlines legal procedures, and defines mandates across all levels of government and/or the private sector. The DoE should also strengthen the enforcement capacity of its staff, including with training programs for emissions inspectors/auditors and technical professionals, and the procurement of monitoring and inspection equipment at the appropriate level of government and within the private sector.

- **Accountability** – To establish accountability for these programs, it is the responsibility of the federal DoE or DoI to train inspectors on procedures and to insist on rigorously following regulatory procedures for collecting data and performing inspections. However, it is also the responsibility of the inspection programs (whether at the federal, provincial or local level) to follow regulations or guidance in carrying out these duties. Failure to conduct inspections per requirements should automatically trigger corrective actions, loss of funding, and ultimately imposition of a federal inspection program until corrective actions are demonstrated. This provides the incentive for proper enforcement and compliance. For regulated industries, a non-negotiable system of fines for failure to comply with standards, including daily fines and ultimately sealing of industrial units after an established grace period elapses.

Industrial standards could be stricter and better enforced. To enhance environmental compliance and ensure accurate monitoring of industrial emissions, it is imperative to update regulations to mandate routine stack testing. Taking a sample of pollutants from a stack or vent is usually the most direct, and often the only, way of determining if a source's emissions comply with regulations or with the limits set in a permit. Emission, or "stack", testing should be required whenever a new piece of equipment is installed, or when a new or revised permit is issued, and certain facilities should be required to routinely perform emission testing every two or three years. Due to the difficulty of the procedures and expense of the equipment, stack tests would normally be performed by a professional consultant who specializes in this type of work and is hired by the facility doing the test. The DoE, DoI or other government (e.g., provincial or municipal) entities should serve in the role of auditor, ensuring that test procedures and equipment meet specifications detailed in testing regulations. Industrial standards that outline current emissions limits should be strengthened and amended to include written guidelines regarding the stack test requirements, procedures and data handling conventions. Such inspections will not only ensure compliance but also promote transparency and accountability in industrial operations, ultimately contributing to improved air quality and environmental protection. For industries with significantly higher emissions (such as Cement Plants), the feasibility of establishing Continuous Emission Monitoring Systems (CEMS) connected to the DoE's central office may also be explored (See Box 5.1). As discussed in Chapter 1, the use of these more sophisticated industrial monitoring systems may require significant training and skills development but should wait until capacity and expertise to conduct baseline ambient air quality monitoring is demonstrated per section 5.1.

Mandate third-party certification for industry inspections and emissions reporting. To ensure the accuracy and reliability of industry inspections and emissions reporting, it is essential to mandate third-party certification. Independent certification bodies can provide unbiased assessments, ensuring that industries comply with environmental standards. This approach will enhance transparency, build public trust, and improve the overall effectiveness of air quality management.

Delegate regulatory enforcement authority to provincial governments with clear accountability frameworks. This delegation can improve the efficiency and effectiveness of air quality management. Clear accountability frameworks should be established to ensure that provincial authorities are held responsible for enforcing regulations and achieving air quality targets. This decentralized approach will enable more localized and responsive enforcement actions.

Box 5.1: Successful implementation of Continuous Emission Monitoring System (CEMS) in China

Continuous Emission Monitoring Systems (CEMS) are automatic systems installed in highly polluting industries to measure emitted air pollutants in real-time. These systems facilitate governments to effectively monitor and enforce air pollution standards and control policies. In China, CEMS was pilot tested in various industrial facilities starting 1990s and by 2015, the government mandated large scale deployment of CEMs in coal-fired power plants. Under the 13th Five-Year Plan (2016-2020), the Ministry of Ecology and Environment (MEE) mandated real-time emission reporting for high-polluting industries including cement plants and steel industries. Industrial firms were required to install CEMS on their facilities, such as exhaust chimneys or stacks, to continuously monitor emissions of PM, SO_2, and NO_x. The collected hourly data is transmitted from the CEMS at industrial facilities to a central monitoring station for analysis and assessing compliance with specific emission standards for pollutants. Industrial firms are also required to upload the collected CEMS data to public online platforms which serve as repositories for environmental data and provide transparency to the public regarding industrial emissions.

Besides strengthening monitoring and enforcement mechanisms, CEMS are crucial for developing emission inventories, refining air quality models, and assessing the effectiveness of pollution control measures. For instance, the air quality in the Yangtze River Delta region was simulated using the Community Multiscale Air Quality (CMAQ) model that utilized emission inventories with and without CEMS data from coal-fired power plants. The findings indicated that incorporating CEMS data reduced biases between simulated and observed pollutant concentrations, leading to more accurate reflections of actual pollution sources (Y. Zhang et al., 2021). This suggests that the integration of CEMs data significantly improved the accuracy of emission inventories in China. Similarly, CEMS data can be used to assess the effectiveness of emission reduction policies. CEMS measurements have been compared with satellite observations to report that SO2 emission reduced by 13.9 percent after the implementation of stricter air pollution standards in 2014.[a] This alignment between CEMs and satellite data underscores the reliability of CEMS in tracking emission trends.

a MIT Energy Initiative. 2019. Tracking emissions in China. Accessed through: https://energy.mit.edu/news/tracking-emissions-in-china/.

Establish penalties for tampering with monitoring equipment or submitting false data: To maintain the integrity of air quality monitoring data, it is crucial to establish penalties for tampering with monitoring equipment or submitting data that is not representative of normal operating conditions. Strict penalties will deter individuals and organizations from interfering with monitoring devices, ensuring that accurate and reliable data is collected for decision-making and regulatory enforcement.

Strengthening vehicular emissions inspection and testing is important. As part of their environmental protection mandate, the DoE sets the standards for vehicular emissions. However, the Pollution Control Division of the Department of Transport Management (DoTM) under the Ministry of Physical Infrastructure and Transport (MoPIT) is responsible for overseeing vehicular pollution control. Since 1996, the DoTM has implemented an annual green sticker program and established emission testing procedures for vehicles in the Kathmandu Valley. It also conducts emission testing for three- and four-wheelers, even though most vehicles in the valley are two-wheelers,which are not tested.

- **Mandates** – While the mandate to set standards are clearly within MOFE and the DoE, the EPA's Chapter 3, Section 15 gives the DoE the authority to assess compliance with standards from various pollution sources, including vehicles, and Section 35, Clause 2 provides the authority for respective agencies to act on non-compliance including for the DoTM to collect revenues from emission testing and collect fines for non-compliance. Nevertheless, the current practice shows a duplication in duties between the DoE and the DoTM, especially in managing pollution from vehicular emissions, as well as gaps for specific technology classes like two-wheelers. Additionally, the implementation of the green sticker program in major metropolis other than the Kathmandu Valley would require defining and strengthening the roles of the provincial ministry and their respective environment and transport divisions. There may also be a need for municipal officials to step up enforcement of compliance by conducting random checks to reduce non-compliance and collect fines.
- **Mechanisms** – An expansion of the existing inspection and maintenance program is needed to ensure that all emitting vehicles (including two-wheelers) are included. Establishing such a system will require routine fee and fine collection (or potentially funding through dedicated vehicle fuel taxes) but can enable expansion and establishment of the provincial DOE or the DoTM offices primarily to train and regulate private sector vehicle inspection stations (via local garages and petrol stations). An expanded program should ensure that inspection schedules are adhered to (e.g., via random traffic stops with sticker checks) and establish a system of fines for various specific violations and system of accrediting private sector garages/inspectors.
- **Means** – To ensure effective AQM as well as to eliminate corruption via hand sales of green stickers, it is also crucial for all relevant agencies to have access to a digital data sharing/ green sticker program thereby highlighting the need for a centralized data-sharing government portal. Ensuring that the right agency (with the mandate) has resources, staffing, tailpipe testing equipment, vehicles or other equipment and capacity to carry out the job.
- **Accountability** – Criminal penalties should be imposed for illegal issuance of green stickers, but fines for operating a vehicle with an expired sticker can also contribute to financing the enhanced program. A hold on federal grants can ensure that provinces and municipalities hold up their mandates under federal regulations.

Strengthened Nepal Vehicular Mass Emission Standards (Euro-VI) with strict enforcement will reduce emissions from the transportation sector. Government action between 2000 and 2012 was significant and importing the Euro-6 standard petrol and diesel since 2020 sets the stage for further progress. However, Euro-VI standards—equivalent to Bharat Standard VI (BS VI) emission norms—for heavy-duty vehicles and passenger vehicles are needed to yield the air quality benefits that build on the foundation of these prior actions. Regulatory action should be complemented with enhanced enforcement, including enhanced vehicle testing through accreditation for vehicle testing centers and repair shops, increased random checks and fines for failure to comply and digital record keeping system for vehicle registrations and green sticker compliance. There is an urgent need for comprehensive infrastructure to support vehicle scrapping, including the establishment of Vehicle Fitness Testing Centers in all provinces to ensure regular inspections and proper decommissioning processes. Standards also need to be consistent across all types of vehicles, including heavy-duty vehicles, buses and two- three-wheelers.

Certify private inspection stations under strict federal standards. Stricter standards can expand the capacity for vehicle inspections and improve compliance with emissions regulations. By ensuring that private stations meet high standards, the government can enhance the effectiveness of vehicle inspection programs and reduce emissions from the transportation sector.

Mandate dust control and road cleaning as part of all public works contracts. To reduce dust emissions from construction and roadworks, it is important to mandate dust control and road cleaning as part of all public works contracts. Implementing these measures will minimize the release of particulate matter into the air, improving air quality and reducing health risks.

Support RETS to become the national testing and certification hub and introduce comprehensive clean cooking standards. Improving clean cooking options in Nepal will reduce household air pollution, which is one of the major contributors to $PM_{2.5}$ emissions and creates a high health risk from traditional smoke exposure. Presently, the safety and efficiency of clean cooking technologies are evaluated by the Renewable Energy Test Station (RETS) against interim standards for biomass cookstoves (Nepal Interim Benchmark for Solid Biomass Cookstoves, NIBC). However, comprehensive national standards for electric stoves and biomass pellets are still lacking. These national standards, consistent with international protocols, will also be necessary for wide-scale adoption of clean cooking technologies in Nepal.

Strengthening local governments' role in monitoring household energy programs. This will improve the implementation and effectiveness of these initiatives. Local authorities can provide valuable insights and support for promoting clean energy technologies, ensuring that programs are tailored to the specific needs of their communities.

Institutionalize a crop residue management system through public-private partnerships: This system will help address the issue of agricultural burning. By involving both public and private sectors, the government can develop sustainable solutions for managing crop residues, reducing emissions, and promoting cleaner agricultural practices.

Assign local government roles in enforcing seasonal burning bans: Assigning local governments this responsibility will enhance the effectiveness of these regulations. Local authorities are better positioned to monitor and enforce bans, ensuring that agricultural burning is minimized, and air quality is improved.

Strengthen coordination between forestry departments, fire services, and disaster management agencies. This is crucial for effective forest fire management. By improving communication and collaboration, these agencies can respond more quickly and effectively to forest fires, reducing their impact on air quality and public health.

Formalize rapid response protocols for peri-urban forest fire management. These response protocols will ensure that fires are detected and addressed quickly, minimizing their impact on air quality. These protocols should include clear roles and responsibilities for all involved agencies, as well as guidelines for coordination and communication.

Establish fire prevention units at local level. This will enhance the capacity to prevent and manage forest fires. These units can conduct regular patrols, engage with local communities, and implement preventive measures to reduce the risk of fires and their impact on air quality.

"Graded Response" programs are effective for managing episodes with acutely high air pollution levels. Targeted short-term measures may be needed to reduce emissions—and thus population exposure—to air pollution by imposing restrictions on activities that bring about immediate short-term results even while they may be unsustainable over the long run. Managing acute air pollution episodes requires a robust monitoring network (see recommendations above to credibly inform when air quality thresholds are exceeded) along with a pre-agreed publicly disseminated and accepted plan that details which restrictions will be imposed when air quality exceeds certain thresholds, who will enforce those restrictions, and the penalties associated with non-compliance. In addition, because most episodes of acute air quality in Nepal are a result of emissions from domestic forest fires, large-scale open burning of crop- residue in Nepal, or large-scale crop residue burning in nearby countries, special attention needs to be paid to (a) ways to reduce forest fires and crop residue burning in Nepal, (b) opportunities for temporary reduction of emissions from other domestic sources during bad episodes and (c) strengthening of regional coordination and cooperation to reduce emissions beyond Nepal's borders.

Box 5.2: International experience in responding to heavy air pollution episodes

Many cities have established a system in which pre-agreed measures are triggered when air pollution reaches harmful levels. Unlike ad hoc emergency decisions, these systems activate specific actions when air pollution crosses certain thresholds.

New Delhi:

The Graded Response Action Plan (GRAP) was introduced by the Ministry of Environment, Forest and Climate Change (MoEF&CC) in 2017 and is implemented in the National Capital Region (NCR) of India, which includes Delhi and its surrounding cities. GRAP outlines a set of predefined measures and actions to be taken at four stages of air quality deterioration, based on the Air Quality Index (AQI). In the event of Stage I, 'Poor' air quality conditions, the contingency plan includes measures such as road sweeping, traffic management, preventing garbage burning, monitoring thermal power plants, dust control in construction, ban on firecrackers, and public awareness campaigns through media. Similarly, Stage II, 'Very Poor' air quality conditions, prompt actions such as halting diesel generators, increasing parking fees, and enhancing public transportation with additional buses. During Stage III, 'Severe' air quality conditions, GRAP mandates shutting industries such as brick kilns and stone crushers, maximizing natural gas-based power generation, and promoting off-peak travel with differential rates in public transport, as well as intensifying road cleaning in high dust areas. In Stage IV- 'Severe+' air quality conditions, measures include restricting truck entry, suspending construction, implementing an odd-even scheme for vehicles, and empowering a Task Force for additional actions.

Beijing:

The Beijing "Heavy Air Pollution Contingency Plan" outlines a three-tier alert system (yellow, orange, and red) based on forecasted daily mean air quality index levels. The plan involves educating the public and organizing medical services based on the severity of forecasted air pollution. Each alert level triggers specific emission reduction measures. A yellow alert involves street cleaning, dust control on construction sites, increased public transport use, and emphasize providing health protection guidance. An orange alert introduces extra rounds of street cleaning, reduced outdoor activities like barbecues, and a ban on transport vehicles carrying construction waste. A red alert imposes more stringent measures, including production restrictions, increased electricity transmission from other cities to reduce local power generation load, and enforcement of odd-even rules that allows the vehicles to operate on alternate days. The contingency plan is integrated into the city's health emergency system, overseen by the Municipal Heavy Air Pollution Emergency Headquarters and a dedicated Health Emergency Response Branch.

Managing acute air pollution episodes requires a robust monitoring network along with a pre-agreed publicly disseminated and accepted plan.

Box 5.3: Indoor Air Pollution: Case studies of protective and preventive measures

South Korea has implemented a series of emergency measures to combat high levels of PM2.5 originating from domestic emissions. In 2018, the government mandated the installation of air purifiers in all classrooms nationwide, equipping schools and public daycare centers with government-funded filtration systems and air quality monitoring devices that automatically adjust purification levels based on pollution levels.[a] Studies show that the installation of one and two air purifiers reduced the average PM2.5 levels of classrooms by 67 percent and 81 percent, respectively (Han et al., 2022). Similarly, Singapore deployed air purifiers in all primary and secondary schools and established protocols to suspend classes when the 24-hour Pollutant Standard Index (PSI) exceeded 300.[b] Additionally, real-time air quality alerts were issued to advise schools to cancel outdoor activities and elderly care centers to keep residents indoors during severe pollution episodes. During the 2019 Southeast Asian haze crisis, the Malaysian government distributed around half a million face masks to residents in heavily affected areas and temporarily closed schools to minimize children's exposure to hazardous air quality.[c] In Bangladesh, 350 households received free air purifiers, but their usage was inconsistent suggesting that alongside financial support, awareness campaigns and behavioral change incentives are needed to scale up their adoption (Chowdhury, 2024).

While protective measures such as use of air purifiers and masks help reduce short-term health risks, they do not address the root causes of indoor pollution, such as reliance on polluting fuels. In India, the Pradhan Mantri Ujjwala Yojana (PMUY) has provided 80 million free LPG connections to low-income households, reducing reliance on biomass fuels and indoor smoke exposure.[d] Likewise, China's Coal-to-Gas and Coal-to-Electricity program have rapidly replaced coal stoves with cleaner energy alternatives, significantly lowering indoor pollution in rural areas (J. Zhang et al., 2022). In summary, a comprehensive approach is needed to tackle indoor pollution- combining immediate protective measures with long-term solutions that transition households away from highly polluting fuels.

a Ministry of Education. 2018. *Announcement of countermeasures against high concentrations of fine dust in schools.* Accessed through: https://english.moe.go.kr/boardCnts/view.do?boardID=265&boardSeq=74120&lev=0&m=03&opType=&page=11&s=english&searchType=S&statusYN=C.

b National Environment Agency (NEA). 2019. *Singapore Government Agencies Implement Measures to Mitigate Impact of Haze.* Accessed through: https://www.todayonline.com/singapore/moe-deploy-25000-air-purifiers-primary-secondary-schools.

c Reuters. 2019. *Malaysia sends half a million face masks to haze-hit state, shuts schools*. Accessed through: https://www.reuters.com/article/world/malaysia-sends-half-a-million-face-masks-to-haze-hit-state-shuts-schools-idUSKCN1VV0C2/.

d Ministry of Petroleum and Natural Gas. India. 2016. *Pradhan Mantri Ujjwala Yojana 2.0*. Accessed through: https://pmuy.gov.in/about.html.

5.3 Economics: Using pricing and markets to create the economics of cleaner air

To accelerate the adoption of clean technologies in Nepal, a strategic combination of macro-fiscal and pricing policies is essential. These policies must align with Nepal's development priorities, ensuring economic growth while addressing environmental concerns such as air pollution and climate change. The proposed recommendations in this section build on the stocktaking of existing environmental fiscal policies in section 2.2.3 of this report and the gaps identified there.

Recently taken initiatives by the GoN to reduce import duties for electric vehicles (EVs) and electric stoves have shown how fiscal policy accelerates the adoption of clean technology. In July 2022, the Nepal government issued significant reductions in import duties for EVs. Import duties were reduced to as low as 10 percent from as high as 80 percent, depending on the types and capacities of the EVs. As a result, the share for newly registered electric two-wheelers increased from below one percent in 2021 to seven percent in 2024, electric three-wheelers surged from 15 percent to 88 percent, while four-wheeled EVs jumped from four percent to 81 percent during the same period. This growth reflects the market's responsiveness to the incentive provided. The government also promoted clean cooking adoption by reducing import costs for electric cookstoves. The import duty on electric cookstoves was reduced from 30 percent to 15 percent, in addition to offering VAT exemptions on select models. To further promote renewable energy and clean technologies, the government introduced the Green Tax in July 2024, under GRID DPC-2 whereby NPR 1 per liter for diesel/gasoline and NPR 0.5 per kg of coal was introduced. Overall, fiscal and pricing policies under the GRID-DPC series together illustrate the importance of a conducive economic environment for the adoption of clean technologies.

The government could consider a reformulation of the existing environmental fiscal policies to strengthen emission reduction and to benefit the low-income households. The following recommendations might help to accomplish this objective:

1. **Streamlining different environmental taxes, into one improved Green Tax.** A number of separate taxes are imposed on petroleum, particularly gasoline and diesel in Nepal. These include the pollution tax, the infrastructure levy, and the road maintenance fees. The government could consider integrating these taxes into the revised Green Tax. It would streamline the environmental tax system in Nepal and reduce administrative costs.

2. **The Green Tax could be applied to fossil fuels based on their emissions/pollution content.** The existing Green Tax has two limitations. First, its rate on coal and coal products (NPR 0.5/kg) is smaller compared to petroleum products (NPR 1/liter), but coal has much higher emissions and pollution intensity. Second, the current Green Tax is also applied to petroleum products that are used for non-energy purposes (e.g., lubrication) and do not produce emissions, which could easily be adjusted. Adjustments to alleviate these

two limitations could strengthen the Green Tax's effectiveness to reduce emissions of local air pollutants as well as CO_2.

3. **Increasing the Green Tax rates.** Integrating existing environmental taxes and infrastructure levies into single Green Taxes based on the polluter-pay principle would raise the rates and broaden the base. However, it might seem like merely renaming the existing taxes despite the increased coverage. Moreover, the current Green Tax rate is one of the lowest in the world, amounting to less than USD2 per ton of CO_2. The rate may gradually increase to assist its effectiveness to promote the green transition of the economy. Studies suggest that Nepal will benefit from green taxation because it helps substitute imported fossil fuels with domestic hydropower (Timilsina et al., 2024a).

4. **The Green Tax revenue could be used to finance emissions reduction initiatives such as promoting cleaner technologies and enhancing energy efficiency.** Currently the GoN uses the Green Tax and the pollution tax revenue as general revenue in the consolidated budget of the government. Existing studies suggest that allocating these funds towards environmental objectives, including emission reduction initiatives and subsidizing cleaner technologies, would be a better strategy to amplify the benefits of the tax. For instance, in Japan, the revenue generated from carbon tax introduced in 2012 is allocated to climate change mitigation measures, such as promoting renewable energy and energy-efficient technologies. These investments are expected to reduce both energy costs and emissions over time (Arimura & Matsumoto, 2020). In Singapore, the carbon tax revenue is reinvested into

Box 5.4: Singapore's Carbon Tax and Revenue Recycling Initiatives

In 2019, Singapore emerged as the first country in Southeast Asia to implement a policy aimed at charging carbon tax. The tax system was established to discourage heavy greenhouses gas (GHG) emitters from discharging pollutants into the environment. The tax rate was set at USD 5 per tonne of CO_2 equivalent (tCO_2e) from 2019 to 2023, providing transitional period for enterprises to adjust. The government has announced its plan to increase the tax rate to USD 25 per tonne by 2024 and 2025, targeting USD 50 per tonne to USD 80 per tonne by 2030.[a]

The revenue generated from carbon tax is reinvested into programs that help enterprises transition to cleaner technologies and improve energy efficiency. For instance, the Energy Efficiency Fund (E2F) and the Resource Efficiency Grant for Energy (REG(E)) programs which assist industries financially to adopt cleaner and energy efficient technologies are funded through revenue from carbon tax.[b] As of 2024, the E2F offers up to 70 percent co-funding to firms investing in energy efficient technologies and the REG(E) provides up to 50 percent co-funding to manufacturing firms investing in emission reduction measures that lead to carbon abatement of at least 250 tonnes per annum.[c] Funds have also been earmarked under the Research, Innovation and Enterprise 2025 plan for the development of sustainable urban solutions, as well as emerging low-carbon technologies.

Singapore's implementation of the carbon tax exemplifies how environmental tax, coupled with revenue recycling, could work as an effective tool to decrease pollution as well as promote sustainable industrial development.

a Based on information provided by the National Climate Change Secretariat (NCCS), Singapore on Carbon Tax. Accessed through: https://www.nccs.gov.sg/singapores-climate-action/mitigation-efforts/carbontax/.

b Ministry of Sustainability and the Environment. 2021. Written Reply to Parliamentary Question on Carbon Tax. Accessed through: https://www.mse.gov.sg/latest-news/written-reply-to-parliamentary-question-on-carbon-tax-by-ms-grace-fu--minister-for-sustainability-and-the-environment.

c Based on information provided by the Singapore Economic Development Board (EDB) on Resource Efficiency Grant for Emissions (REG(E). Accessed through: https://www.edb.gov.sg/content/dam/edb-en/how-we-help/incentive-and-schemes/Information%20-%20Resource%20Efficiency%20Grant%20for%20Emissions.pdf.

co-funding programs that help industries adopt cleaner technologies (see Box 5.4). A similar tax recycling strategy can be developed in Nepal to boost the environmental and social benefits. In Nepal's brick industry, tax revenues from environmental fiscal policies could be channeled into adopting cleaner technologies or alternative fuels, thereby reducing coal consumption and associated emissions (Timilsina et al., 2024b).

5. **The government could design a revenue scheme that prioritizes low-income households to rectify its potential regressive impacts on vulnerable population.** Levying taxes often disproportionately impacts low-income households, as they spend a higher share of their income on essentials like energy. To address this, compensation mechanisms for poor households could be implemented prior to introducing the taxes. This proactive approach ensures that vulnerable populations are not adversely affected during the transition. Effective compensation can take the form of direct cash transfers or rebates that can help offset increased costs of energy and goods, ensuring that the transition toward sustainability does not exacerbate existing inequalities. Additionally, revenues can be recycled into programs like educational grants, health insurance, and social security contributions, which improve access to essential services and uplift low-income communities over the long term. For instance, using green tax revenues to provide affordable public transportation options can create long-term benefits for vulnerable populations while simultaneously addressing environmental goals.

Box 5.5: Is Nepal ready for an Emissions Trading System (ETS)?

The ETS in Gujarat represents a pioneering effort in India to control industrial air pollution through market-based mechanisms. Introduced as a pilot program, the ETS targets particulate matter emissions among 317 high-polluting plants in a major industrial city within the state. This system establishes an airshed-level cap on total emissions and allows participating firms to trade emission permits, thereby providing flexibility and economic incentives for reducing pollution. A critical component of the ETS is the robust monitoring system installed in the participating firms, which ensures accurate measurement and reporting of emissions. Evaluated through a randomized control trial, the pilot ETS in Gujarat has demonstrated 20-30 percent reductions in emissions at a lower cost compared to other approaches (Greenstone et al., 2023). However, the ETS cannot be transferred to other IGP HF jurisdictions including Nepal in the short or medium term, primarily due to differences in industrial structure, measurement capacity, regulatory and institutional capacity, market size and diversity, and cost and complexity. Nepal's industrial facilities are mainly micro, small, and medium enterprises (MSMEs), whereas Gujarat's scheme focuses on large industries. The monitoring and evaluation system for an effective ETS should be robust and requires a well-functioning Continuous Emissions Monitoring System (CEMS). Nepal's existing capacity is insufficient to start a CEMS. Gujarat's ETS benefits from many participating industries, fostering a robust market for emissions trading permits with competitive pricing and liquidity. In contrast, Nepal's smaller industrial base would likely result in low market liquidity and price instability, potentially leading to system failure. Furthermore, setting up an ETS involves high administrative and operational costs, adding to the complexity and financial burden for regions with limited resources and capacity.

5.4 Incentives: Private sector adoption of clean technologies and practices

Government-provided incentives are critical for galvanizing the private sector to adopt cleaner technologies. The private sector often needs a 'nudge' to shift to cleaner technologies, as has been shown the world over (World Bank, 2023). While incentives can take many forms, the GoN should specifically consider how tax incentives (such as tax breaks), technology subsidies, concessional terms on lending, and risk guarantees, among others, can incentivize firms to adopt cleaner technologies. Experience in other countries has shown that these programs can help to overcome fear of the unknown among first movers and encourage behavior change in sectors where dirtier technologies are prevalent (IEA, 2024). Voucher programs, which enable the government to target subsidies, have also been effective in encouraging individuals to adopt new technologies that may be unfamiliar or not in common use (e.g., clean cooking options) (Spiesberger & Schönbeck, 2019; Shankar et al., 2020). Creating the right incentives for firms, farms, and households to adopt cleaner technologies should be explored with care, as there are also drawbacks associated with subsidies (including financial strain on public resources, market distortion, misallocation, and transaction costs) but is necessary to nudge these actors toward novel technologies needed to clean the air.

Nepal has successfully introduced incentives for the adoption of cleaner production technology. Industrial energy efficiency and cleaner production have been a focus since the 1980s and several Development Partners have supported initiatives. In 1994, the World Bank implemented a program in collaboration with the GoN to establish an Office of Energy Efficiency Service (OEES) that focused on energy audits and energy-saving options in industrial boilers, industrial equipment, and hotel lighting (World Bank, 2008). In 1998, the Danish International Development Agency (DANIDA) started the Environment Sector Programme Support (ESPS) to support cleaner production in industries of Nepal, mostly from Hetauda and Balaju Industrial Districts. By 2005, the ESPS interventions were carried out in 322 industries whereby loans and grants were provided to industries adopting cleaner production (PACE Nepal, 2011). The program also conducted energy audits and extended technical assistance to industries to implement energy efficient practices (DANIDA, 2017). By drawing upon the results from ESPS, a German development agency—Gesellschaft für Internationale Zusammenarbeit (GIZ)—implemented the Nepal Energy Efficiency Programme (NEEP) in 2010 to further advance industrial energy efficiency efforts in Nepal. The implementation of NEEP led to the establishment of an Energy Efficiency Centre (EEC) which facilitated energy audits, offered training to energy auditors, collaborated with local banks to encourage investment in energy efficient practices, and overall provided energy efficiency services to large industries as well as small scale enterprises.[51] From 2016-2021, a German Development bank- Kreditanstalt für Wiederaufbau (KfW) funded Energy Efficiency Financing Program in Nepal to support industries like steel, cement, and hospitality to adopt efficient and cleaner technologies (Adephi, 2021). In partnership with Rastriya

51 NEEP. *Promotion and Realization of Energy Efficiency*. Accessed through http://energyefficiency.gov.np/resource.php.

Banijya Bank Limited (RBBL), a state-owned commercial bank, this program offered grants covering up to 39 percent of the investment (capped at NPR 10 million) for adopting energy-efficient technologies (USAID, 2021). Another program managed by RBBL is the GIZ's Renewable Energy and Energy Efficiency Programme-Green Recovery and Empowerment with Energy in Nepal (REEEP-GREEN), aimed at promoting broader adoption of energy efficient practices from 2021-2024.52 Through this program, industries and enterprises with high energy saving potential received grants to implement energy-saving measures identified through certified energy audits (EU Nepal, 2023). Similarly, AEPC leads the Nepal Renewable Energy Programme (2019–2025) that supports the scaling up the use of renewable energy technologies such as mini-grid, solar, and biogas.

Private sector firms require financial incentives to adopt cleaner technologies. For Nepal, such a financing mechanism may include: (a) grants for a part of the technology costs; (b) loans at favorable terms (e.g. rates and tenors); and/or (c) offering partial risk guarantees through the Deposit and Credit Guarantee Fund (DCGF) to Financial Intermediaries for the financing of cleaner technologies/fuels. The GoN will have to explore which sort of mechanism would draw the demand of potential clean technology adopters to undertake the desired on-lending and reduce emissions. This can demonstrate the viability of and reduce the perceived risk of financing/installing cleaner technologies, demonstrate the demand for scaling up clean technology interventions, and establish a financing model for future technology/ fuel switches and clean air interventions with private sector involvement. Financial incentives should be complemented by raising awareness campaigns and strong enforcement of emission standards.

Reducing taxes on clean technology lowers costs by allowing businesses to deduct a portion of their investment from their tax liabilities, improving the return on investment and reducing perceived risks. Adopting or switching to cleaner technologies requires capital investment, often posing a financial burden to industries and enterprises. Incentives such as tax exemptions, reduced import duties, or tax rebates help alleviate the financial strain by reducing the cost of purchasing these technologies and making them more affordable.

To accelerate the transition toward cleaner industrial technologies in Nepal, the government should introduce accelerated terminal depreciation for firms retiring polluting equipment such as inefficient boilers and furnaces. Terminal depreciation allows businesses to claim a tax deduction for the unrecovered value of an asset when it is scrapped or replaced—effectively compensating for early retirement losses. By offering an enhanced depreciation rate (e.g., 100 percent of the remaining book value) for certified polluting assets that are replaced with verified clean technologies, this policy would reduce the financial burden of switching and incentivize faster turnover of high-emitting capital stock. This measure would be particularly impactful in pollution-intensive sectors like brick manufacturing, cement, textiles, and food processing, where firms often hesitate to invest in cleaner technologies due to sunk costs in legacy equipment.

Alongside financial incentives, effective enforcement and awareness within the industry are needed to stimulate the uptake of cleaner production technologies. Nepal has introduced incentives for the adoption of clean and energy efficient solutions through the Industrial Enterprises Act (IEA) 2020 and Industrial Enterprises Regulation (IER) 2021. The IEA 2020 and IER 2021 provide provisions for tax reduction and customs duty exemption to industries adopting eco-friendly technologies. Industries investing in pollution abatement technologies, such as energy efficient machinery and emission control equipment, are eligible for tax deduction of up to 50 percent of their taxable income for expenditures incurred to install these control systems. The import duties are further reduced or waived, encouraging the industries to adopt cleaner solutions. Despite these provisions by the government, their implementation and industry awareness remain uncertain. Therefore, in addition to such incentives, a strong mechanism is required to ensure not only effective implementation but also monitoring and promotion of these incentives to maximize their benefits and encourage widespread adoption of clean production practices.

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52 MoEWRI. *REEP-GREEN*. Accessed through: https://reeep.gov.np/page/about-us?utm.

Incentives are needed to encourage behavior change in adopting new cooking methods. Transitioning to modern, efficient technologies such as electric stoves, biogas systems, and improved biomass cookstoves reduces pollution and public health burden. In Nepal, various efforts have been made to disseminate improved cookstoves and biogas systems; however, due to their high up-front costs and lack of financing mechanisms, the adoption of such technologies has been limited. Subsidies, tax exemptions, and collaboration with microfinance institutions will be crucial in making these technologies more affordable. Other feasible approaches to ensure affordability include bulk procurement of the clean cooking stoves to reduce the capital costs and results-based financing, where payments are disbursed only after verifiable results are achieved, like successful delivery, installation, and use of clean cooking stoves.

To promote sustainable agricultural practices and reduce emissions, various financial incentives and support programs are essential. Subsidizing the purchase of happy seeders and rice straw balers will encourage farmers to adopt sustainable residue management practices, thereby reducing agricultural burning, improving air quality, and promoting cleaner agricultural practices. Supporting farmer cooperatives in offering residue collection services will facilitate sustainable management of crop residues, further reducing agricultural burning and enhancing air quality. Additionally, providing incentives for low-emissions fertilizer technologies will encourage the use of environmentally friendly fertilizers, which will help reduce emissions from agricultural activities, improve air quality, and support sustainable farming practices.

Provide incentives for community-based forest fire management initiatives. Providing grants will support local efforts to prevent and manage forest fires. This financial assistance will enhance the capacity of communities to address forest fire risks, improving air quality and public health. Offering incentives for the early detection and reporting of wildfires will encourage individuals and organizations to take proactive measures and will improve the effectiveness of forest fire management efforts, reducing their impact on air quality.

A fleet of electric buses charge at the Sajha Yatayat depot in Kathmandu. *Source: Narendra Shrestha/World Bank.*

5.5 Infrastructure: Putting in place infrastructure that enables adoption of clean air technologies and practices

Public infrastructure such as a reliable electricity grid and good roads plays a crucial role in enabling the adoption of clean technologies across multiple sectors. In Nepal, improving electricity infrastructure is particularly important, as electricity supports the clean transitions in sectors contributing the most to pollution, such as manufacturing, cooking, and mobility (see section 4.1). Strengthened electricity infrastructure means increased reliability in the generation, transmission, and distribution system, all of which are essential to displace fossil fuels and reduce air pollution. Provided there is a stable and uninterrupted power supply, industrial facilities reliant on traditional fuel systems can conveniently switch to electric alternatives, which drastically reduce emissions. Similarly, to reduce household emissions, electric/induction stoves, rice cookers, and other household appliances are ideal solutions to biomass-based cooking that leads to indoor air pollution. However, the large-scale adoption of e-cooking solutions depends on improving electricity reliability across both urban and rural areas.

One of the key constraints in transitioning to cleaner technologies is the reliability of electricity supply. More than 75 percent of firms in Nepal experience regular outages (typically 13 outages per month) (World Bank, 2023b). Approximately 10 percent of boilers are located within Industrial Districts (IDs), which benefit from dedicated feeder lines, ensuring consistent electricity reliability. For enterprises situated outside of IDs, backup solutions are necessary such as the installation of a dedicated feeder line for larger enterprises, solar panels for smaller boilers, and/or use of the original (pre-existing) fuel-based technologies.

To ensure electricity reliability, it is important to strengthen electricity infrastructure through investments in storage, modernization, and stabilization of electrical grid, including integration of renewable energy. Large-scale Battery Energy Storage Systems (BESS) are a feasible and scalable solution, already being implemented globally[53] to stabilize grids, store excess energy from renewable sources, and release it during peak demand hours. Furthermore, cross-border transmission line development with neighboring countries like India can play a crucial role in strengthening supply security. This interconnected grid system reduces dependence on a single energy source, mitigates risks of power shortages, and ensures a more stable and reliable electricity supply, particularly during peak demand or emergencies. Ensuring dedicated, reliable electric feeder lines to major industrial parks will support the adoption of electric production technologies. This infrastructure investment will provide industries with a stable and sufficient power supply, promoting cleaner production methods.

Beyond electricity infrastructure, improvement of public transport, non-motorized transport, and land use planning are critical strategies to enhance mobility while reducing emissions. There is an absence of organized mass transit system in Nepal, with no Bus Rapid Transit (BRT) or Light Rail Transit (LRT). In the Kathmandu Valley, around three percent of 1.75 million registered vehicles fall under the category of public transport, accounting for 28 percent of all trips made using public transportation.[54] While there are plans for modernizing public transport with the adoption of electric buses and smart transport management systems[55], broader policy

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53 In South Asia, India is scaling up BESS to manage energy fluctuations through government-backed investments and private sector participation. For instance, Kadapa Ultra Mega Solar Park is a large-scale initiative integrating solar energy with BESS, featuring a planned capacity of 1000 MW, of which 250 MW is currently operational.

54 National Policy Forum. 2024. *Why does Kathmandu's public transport need a complete revamp? A perspective from Mass Rapid Transit promoting efficient urban mobility.* Accessed through: https://www.nationalpolicyforum.com/posts/why-does-kathmandus-public-transport-need-a-complete-revamp-a-perspective-from-mass-rapid-transit-promoting-efficient-urban-mobility/.

55 Initiatives include deployment and operation of electric public buses in the Kathmandu valley by Sanjha Yatayat, expansion of electric public microbuses and minibuses through collaborations with organizations like GIZ and ADB, and widespread adoption of electric rickshaws in cities of the Terai. Additionally, the Sustainable Urban E-Mobility Project aims to integrate smart transport management systems in Kathmandu and Pokhara.

support, financing, and integration with urban planning are needed. To complement improvement of public transport, infrastructure for non-motorized transport such as cycling lanes and pedestrian friendly road networks must be prioritized. Additionally, integration of transport infrastructure with land use planning through higher Floor Area Ratios (FAR), mixed use zoning, and transit-oriented development (TOD)[56] can promote densification around transit points, with easy access to public transport and reduced urban sprawl (World Bank, 2024a). These long-term structural interventions, alongside electrification and clean energy adoption, are necessary to achieve emission reduction and improve air quality in Nepal.

In the context of Nepal and similar countries, the "Improve" dimension of the Avoid-Shift-Improve (ASI) paradigm is the most relevant for reducing air pollution. With growing urbanization and increasing reliance on motorized transport, a wholesale shift to public transit or non-motorized modes is unlikely in the short term. Similarly, avoiding trips altogether is constrained by economic and infrastructural realities. However, improving vehicle technology—such as transitioning from diesel and petrol to electric or cleaner fuel vehicles—is a more feasible and impactful strategy. Nepal has already committed to increasing EV adoption, supported by hydropower-based electricity, fiscal incentives, and an expanding charging network. Strengthening fuel quality standards, enforcing emissions regulations, and modernizing public and freight transport fleets with cleaner alternatives will yield significant air quality benefits. While "Shift" strategies, such as improved public transport, can complement these efforts, "Improve" remains the most pragmatic and scalable solution for reducing transport-related air pollution.

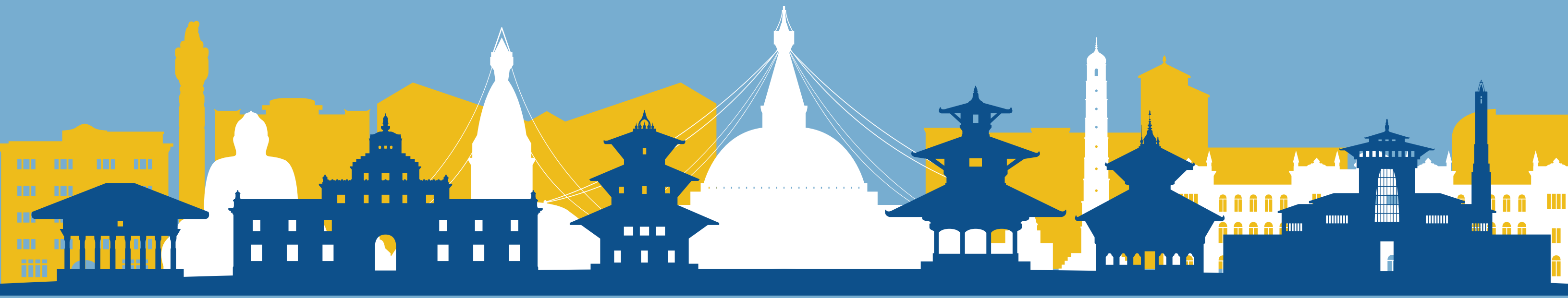
In the transport sector, the "Improve" strategy presently incorporates an increasing emphasis on the adoption of EVs, which relies on the availability of proper public charging infrastructure. Nepal has over 400 charging stations, of which 62 are installed by the Nepal Electricity Authority (NEA), a governmental body, while the remaining 300+ are privately owned and operated (ICT Frame, 2024). The charging stations are concentrated across main highways to facilitate long-distance travel between major cities. A national plan for EV infrastructure is crucial to systematically build a network of charging stations, with a focus on underserved areas. Additionally, standards should be introduced to ensure that the stations are safe to use and compatible with all vehicle types. To strengthen access to charging facilities, the private sector can collaborate with the government to install solar or hybrid charging stations at key locations such as malls, hotels, and office complexes. The charging stations can explore creative business models, such as subscription plans, to attract more users. While two- and three-wheelers can be charged from residential charging, the rapid adoption of EVs will put extra load on the local electricity network. In such a scenario, substantial investment will be required to improve the condition of the local distribution network, upgrading transformers, and thereby ensuring stability in the electricity supply to meet household requirements and additional charging of vehicles.

Public infrastructure has been a key factor in promoting clean technologies in South Asia. For example, in India, the FAME scheme of the government has supported the development of charging stations through subsidies combined with public investment for the promotion of EVs. During Phase-I, the government sanctioned 520 charging stations while in FAME's Phase-II, 2,877 EV charging stations were sanctioned.

Additionally, the government of Bangladesh has implemented several policies to enhance public infrastructure for clean technology adoption. Bangladesh has adopted ambitious goals of achieving 15 percent of total electricity generation from renewable sources by 2030[57], and the construction of solar parks has been a significant step toward this goal. In Pakistan, the Alternative Energy Development Board (AEDB) has been actively involved in promoting renewable energy projects and has facilitated the installation of wind and solar energy projects, which are crucial for reducing reliance on fossil fuels.

56 FAR is the ratio of a building's total floor area to its land size where a higher FAR allows for tall and compact buildings; mixed-use zoning allows residential, commercial, and recreational spaces to coexist in the same area; and TOD focuses on creating dense, walkable neighborhoods around public transport hubs to reduce car dependency and improve accessibility.

57 Ministry of Power, Energy, and Mineral Resources. Bangladesh. 2023. *Integrated Energy and Power Master Plan (IEPMP).*



CONCLUSION

Air pollution is a major health and economic crisis in Nepal. The average $PM_{2.5}$ concentration in the Kathmandu Valley and the Terai is seven to eight times higher than WHO guidelines, causing over 25,000 premature deaths annually and reducing average life expectancy by more than three years. If no additional action is taken, $PM_{2.5}$ levels are projected to rise even further by 2035, leading to tens of thousands of additional premature deaths and deepening economic losses, currently estimated at over six percent of GDP annually. Therefore, investing in clean air is essential for ensuring a healthier and more sustainable environment for future generations.

To address this crisis, Nepal has set an ambitious goal of achieving 35 µg/m^3, similar to its neighboring countries with which it shares the Indo-Gangetic Plains and Himalayan Foothills (IGP-HF) region. While challenging, reaching this target is possible, as shown by examples from other cities such as Mexico City, Beijing, and Ulaanbaatar. These nations have achieved improvements in air quality through strict regulations, effective enforcement, environmental fiscal policies, investments in clean technology, and public-private partnerships. Their experiences demonstrate that with a combination of political will, public engagement, and technical innovation, progress is achievable.

Three high-impact pollution abatement measures have been identified:

1. Cleaner industrial boilers with effective post-combustion technologies (baghouse, wet scrubbers, or electrostatic precipitators)
2. Electric or fan-assisted improved cookstoves for cleaner household energy
3. Inspection and maintenance programs for heavy-duty and light-duty vehicles, with scrappage and Euro-4 upgrades

Achieving the 35 µg/m^3 target requires coordinated action across all three sectors, supported by five enabling foundations: robust data systems, effective governance, supportive economic policies, targeted incentives, and adequate infrastructure. Several priority actions, also outlined in Table 0.1, include the following:

- Scaling up the Green Tax and linking revenues to clean technology incentives
- Establishing real-time emissions monitoring (CEMS) for major industries
- Subsidizing household clean energy adoption
- Installing fast-charging EV infrastructure
- Strengthening enforcement for seasonal crop burning bans

Artwork: Aarya Bajracharya, 'Where's My Blue Sky?' Live Art Challenge.

Air pollution does not respect borders. Addressing air pollution requires collaboration across different levels of government- local, national, and regional.

Air pollution does not respect borders. Addressing air pollution requires collaboration across different levels of government- local, national, and regional. Coordinated policies and regulations, along with shared resources and data, will enable a more effective response to air quality challenges. Cross-border cooperation with neighboring countries can further strengthen these efforts by addressing transboundary pollution and sharing best practices.

A whole-of-government approach is crucial in driving the necessary changes. Various government bodies must collaborate to offer incentives, establish regulations, enforce these regulations, and implement economic policies that promote clean technologies and practices. Subsidies, tax exemptions, and favorable financing mechanisms can make clean energy solutions more accessible and affordable. Additionally, public awareness campaigns and educational programs can foster societal support for these initiatives.

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ANNEX

Towards Clean Air in Nepal:
Benefits, Pollution Sources, and Solutions

Annex A: Detailed Assessment of Air Quality in Nepal

Knowledge about Nepal's air pollution problem has increased significantly over the past two decades and there is now sufficient data to understand the broad picture. Although, as early as the 1980s the Kathmandu Valley's air pollution problem was part of public discourse (Kanak Dixit, 1987) and one study reported a handful of measurement datapoints (Davidson et al., 1986), it was not until the early 2000s that multi-month data sets were collected while several doctoral studies laid out elaborate hypotheses about how physical factors and human activities together affected air quality in the Kathmandu Valley (Aryal et al., 2008, 2009; Kitada & Regmi, 2003; Panday et al., 2009; Panday & Prinn, 2009; R. P. Regmi et al., 2003).

The 2010's saw the International Centre for Integrated Mountain Development (ICIMOD) hosting several international field campaigns on air pollution in Nepal as well as collaborating with the Government of Nepal's (GoN) Department of Environment (DoE) to establish an air pollution monitoring network around the country. This network has grown to 27 stations (Doe, 2024), and is complemented by two stations in Kathmandu run by the US State Department (Becker et al., 2021). Research and monitoring over the past decade have revealed that Nepal's air pollution problem is not confined to the Kathmandu Valley, affects most of the country's population, and is particularly severe in the Terai (Rupakheti et al., 2017).

A.1 Spatial and temporal patterns of air quality in the Kathmandu Valley

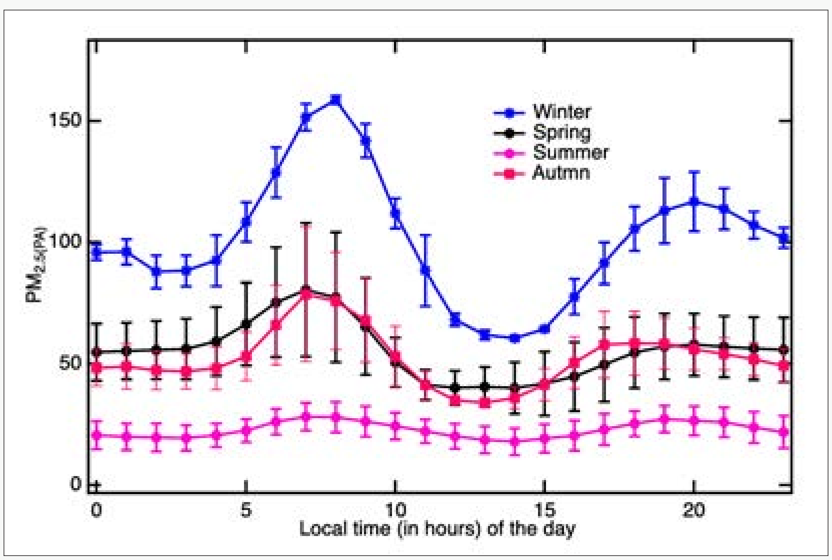
Pollutant levels follow a diurnal cycle, dropping rapidly at midday when vertical mixing allows winds from the western passes to reach the surface (Figure A.1). Pollution is lowest in the afternoons due to ventilation by these winds. However, after sunset, cold air pooling at the valley bottom restricts ventilation, causing pollution to accumulate. Overnight, down-slope winds bring cleaner air, lifting the polluted cold pool until early morning, when it mixes back down, adding to rush-hour emissions.

Pollutant levels follow a diurnal cycle, dropping rapidly at midday when vertical mixing allows winds from the western passes to reach the surface.

Places in the valley bottom have a distinct pattern with a morning and an evening peak in air pollution. This diurnal cycle has been observed on precipitation-free days in multiple locations and across a variety of pollutants. Measurements in October 1995 found condensation nuclei in Kathmandu to have a morning peak from around 6 am to after 9 am, and again from around 8 pm to around 10 pm (Hindman & Upadhyay, 2002). Continuous measurements of carbon monoxide (CO) and PM_{10} in *Bouddha*, northeast of Kathmandu city, from September 2004 to June 2005 found distinct repeating patterns of morning and evening peaks on all clear days (Panday & Prinn, 2009). The same pattern was later observed in CO concentrations at other locations around the valley (Mahata, Rupakheti, et al., 2017) as well as in black carbon concentration at *Paknajol*, in central Kathmandu (Putero et al., 2018). A more recent study of $PM_{2.5}$ measurements at the two US Embassy stations (Becker et al., 2021) found the same basic pattern, but with consistently higher morning peaks than evening peaks. The same pattern also occurred in $PM_{2.5}$ measurements using a Purple Air low-cost sensor at the Institute of Engineering in 2020 (Regmi et al., 2023). The morning and evening peaks remain clearly visible in each valley-bottom station when hourly data is averaged together for an entire year (DoE, 2024). These peaks are explained in Figure A.1 below. The one pollutant with a very different diurnal cycle at the bottom of the Kathmandu Valley (Putero et al., 2018) is ozone, which has a day-time maximum and very low values at night (Bhardwaj et al., 2018a; Panday & Prinn, 2009; Singh Mahata et al., 2018).

Beyond the Kathmandu Valley's flat valley bottom the daily air pollution patterns are quite different. In simultaneous sampling in Spring 2005 at Pullahari Monastery on a little hill and at *Bhimdhunga* pass on the western edge of the valley (both ~150-200 meters above the valley bottom), CO was found to gradually increase after midnight, while the valley bottom had its night-time low (Panday & Prinn, 2009). *Nagarkot* (700 meters above the valley floor, on the eastern rim), experiences day-time peaks in CO (Panday et al., 2009) and consistently high ozone levels throughout the night (Mahata, Rupakheti, et al., 2017).

Figure A.1: Diurnal cycle of $PM_{2.5}$ in Pulchowk, Kathmandu Valley, for each season



Source: Regmi et al., 2023.

Occasionally the seasonal patterns are affected by other factors, such as in Spring 2021. More days in the last week of March and first week of April that year were classified as "very unhealthy" compared to in January (Doe, 2024). Those days coincided with the occurrence of unusually high numbers of forest fires and wildfires upwind of Kathmandu (Kuikel et al., 2024).

Ozone and aerosol optical depth have different seasonal patterns from particulate matter. Ozone has peak values in Spring, unlike in many mid-latitude places where its peak values occur in summer. This makes sense, given the need for sunlight in the production of ozone, but the frequent cloud cover during the summer monsoon (Bhardwaj et al., 2018a; Singh Mahata et al., 2018). A 2012-2013 study measuring ozone at multiple locations around the Kathmandu Valley found WHO's 8-hour standard of 50 ppb exceeded 132 times in a year in Paknajol, in the city center, and 102 times in the Bode, downwind of Kathmandu. It exceeded 159 times at the hilltop station in Nagarkot, at 2000 meters altitude, indicating polluted regional air (Mahata, Rupakheti, et al., 2017). Most of these exceedances occurred in the Spring, but there were also a few between September and December. Meanwhile, aerosol optical depth (AOD), a measure of the total particulate matter in a column of air above a location, is affected by regional air masses. AOD scales quite closely with visibility, but it may not be a good proxy for ground-level air quality: Becker et al, 2021, pointed out the contrast between ground level $PM_{2.5}$, which peaks in winter, and AOD over the Kathmandu Valley, which peaks in the pre-monsoon.

There are very few analyses of multi-year air pollution trends in Nepal. Measurements of daily average PM_{10} measurement in Bhaktapur (in the brick kiln region in the eastern Valley) showed a wintertime decrease after 2003, when the most polluting moving chimney bull's trench brick kilns were banned (Aryal et al., 2008). A plot of annual average $PM_{2.5}$ measurements at four DoE stations and two US embassy stations over six years found inter-annual fluctuations of 5-10 μg/m³ (Kim Oanh et al., 2024).

Decade-scale air quality trends in the Kathmandu Valley are unclear due to limited surface-data availability and inconsistent findings. Mahapatra et al. (2019) observed a 35 percent increase in AOD over the Kathmandu Valley from 2000 to 2015. While AOD has one of the longest consistent datasets, because it is a measure of pollution levels over the entire atmospheric column rather than at the surface, it predominantly reflects regional rather than local influences. Two studies that have attempted to reconstruct $PM_{2.5}$ levels for the Kathmandu Valley using global datasets and models show conflicting results: Becker et al. (2021) observed a steady increase in $PM_{2.5}$ levels at a rate of 2 μg/m³ from 2003 to 2019, with the most pronounced increases occurring during winter and post-monsoon periods. Meanwhile, Bhatta & Yang (2023) showed fluctuating $PM_{2.5}$ levels[1], with a gradual increase from 46 mg/m³ to 56 mg/m³ in 2005 followed by a gradual decrease to 52.5 mg/m³ by 2017 (Figure A.2). However, these reconstructions lack details on changing human activities within the valley, so any results prior to 2017 need to be taken with a grain of salt.

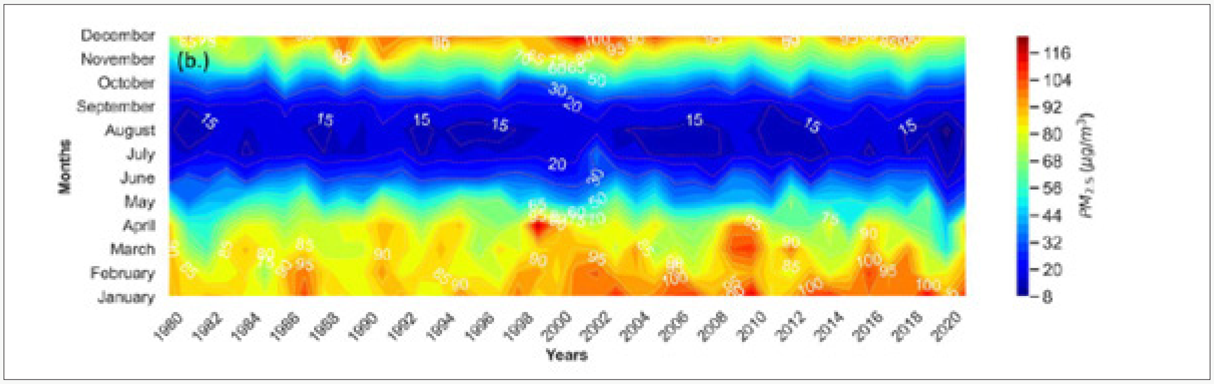
In summary, particulate matter and carbon monoxide show consistent patterns in the Kathmandu Valley on daily and seasonal time scales. They are higher in the city center and the eastern valley than elsewhere. They have morning and evening peaks. (See Box A.1). Peak and trough values are higher in the winter and lowest during the summer monsoon. Long-term trends are not clear.

A.2 Spatial and temporal patterns of air quality outside the Kathmandu Valley

There are fewer peer-reviewed studies of air pollution from the entire rest of Nepal than from the Kathmandu Valley. Our current understanding is limited by the availability of past research results.

1 In this study the Kathmandu Valley's monthly average $PM_{2.5}$ concentration was reconstructed from 1980 to 2021 by first using machine learning to correct MERRA2 global meteorological reanalyses using US Embassy measurements of $PM_{2.5}$ from March 2017 onwards.

Figure A.2: Monthly average $PM_{2.5}$ for the Kathmandu, reconstructed for the period 1980 to 2021



Source: Bhatta & Yang, 2023.

Only two places, Lumbini in the west-central Terai, and Nepal Climate Observatory – Pyramid station, near Mt. Everest Basecamp, have hosted research that has resulted in more than a dozen journal publications each. Their results, plus a few studies from elsewhere in Nepal, along with data from recent Department of Environment monitoring stations in 2021, provide an understanding of the air quality situation outside of the Kathmandu Valley in Nepal.

The column of air above the Terai also has a far higher aerosol optical depth than elsewhere in Nepal. The high AOD levels observed from the ground in Lumbini (Rupakheti et al., 2018a, 2020) and by satellite over the entire Terai region (Kim Oanh et al., 2024). It is also reflected in the worsening visibility data collected at airports in the Terai (Kathayat et al., 2023). AOD over the Terai is affected by the regional pollution haze that sits over the IGP during the dry season; higher altitude locations such as Kathmandu have a thinner layer of haze over them, leading to lower AOD (Mahapatra et al., 2019).

Few studies and less air quality data exist for hilly areas of Nepal outside of the Kathmandu Valley. Carbon monoxide (CO) measurements in *Chanban*, Makwanpur, southwest of the Kathmandu Valley, showed smaller diurnal variations in CO compared to stations within the valley. Interestingly, each day's CO levels in *Chanban* closely corresponded to that day's low values observed in the Kathmandu Valley (Singh Mahata et al., 2017); this suggests that, while the Kathmandu Valley's pollution peaks may be determined by local emissions, the levels of its afternoon low values were largely influenced by the quality of the regional background air. *Dhankuta* and Gandaki Boarding School (GBS) had the least gaps in their air quality records and reported annual mean $PM_{2.5}$ concentrations of 37.7 μg/m³ and 58.64 μg/m³ in 2021 (DoE, 2024). *Dhankuta's* diurnal cycle resembled that of the Kathmandu Valley stations with an early morning and post-sunset peak, while GBS showed an unusual late morning[2] and evening peaks (DoE, 2024). Both stations showed tall single-day peaks during March-April, coinciding with forest fire activity. Meanwhile a 2020 study with portable samplers found lower winter-time $PM_{2.5}$ levels in *Pokhara*[3] compared to *Pulchowk* in the Kathmandu Valley in 2020 (Regmi et al., 2022). Once Covid lockdowns started in March 2020, $PM_{2.5}$ levels dropped at both sites, but *Pokhara* consistently had cleaner air than Kathmandu. Several studies of AOD over *Pokhara* using ground-based AERONET observations found AOD peaking in the

2 Between 9 am and noon.

3 The annual mean $PM_{2.5}$ recorded in Pokhara was 61.1 μg/m³ compared to 99.7 μg/m³ in *Pulchowk*.

Spring[4] (Ramachandran & Rupakheti, 2020, 2021; J. Regmi et al., 2020; Xu et al., 2014), with exceptionally high levels in 2016, attributed to increased forest fires (Ramachandran & Rupakheti, 2021).

Despite high mountain areas' reputation for pristine blue skies, there are times when pollution plumes reach high altitude locations. At the DoE's Rara Lake station, 3,120 meters above sea level, the annual mean $PM_{2.5}$ concentration is 16.8 µg/m^3, but unhealthy air quality was observed on numerous days in March and April 2021, exceeding the NAAQs on 32 out of 294 days (DoE, 2024). At the Yala Glacier black carbon observatory (4,900 meters), set up by ICIMOD and the GoN, surprisingly high peaks of black carbon were observed in April 2017, driven by up-valley winds carrying air from regions with forest fires (Rai et al., 2019). Black carbon, usually a minor constituent of $PM_{2.5}$, contributes to the melting of Himalayan glaciers both by darkening surfaces and by warming the air on contact with glaciers (Gertler et al., 2016; Panday, 2022; Rai et al., 2019). Elsewhere too, pollutants have also been observed arriving in the afternoons at high mountain sites, including at Lukla and Hotel Everest View (Hindman & Upadhyay, 2002). PM_{10} levels exceeding 80 µg/m^3 were recorded at the Nepal Climate Observatory – Pyramid (NCO-P) near Mt Everest Base Camp during Spring afternoons (Decesari et al., 2010). The NCO-P also had ozone maxima in the Spring and minima in July (Cristofanelli et al., 2010a). Records from an ice core on the north side of Mt. Everest since 1995 show significant increases in black carbon (Ming et al., 2008a), suggesting a rise in air pollution reaching high altitudes in the Himalaya.

A.3 Physical processes that affect air pollution in Nepal

Air pollution concentrations in any given location are a result of two very different types of processes: The quantity of emissions taking place–from both anthropogenic and natural sources–and the physical and chemical processes that transport, transform or remove pollutants from the atmosphere. This section first discusses the relevant physical processes, followed by the human activities and emissions.

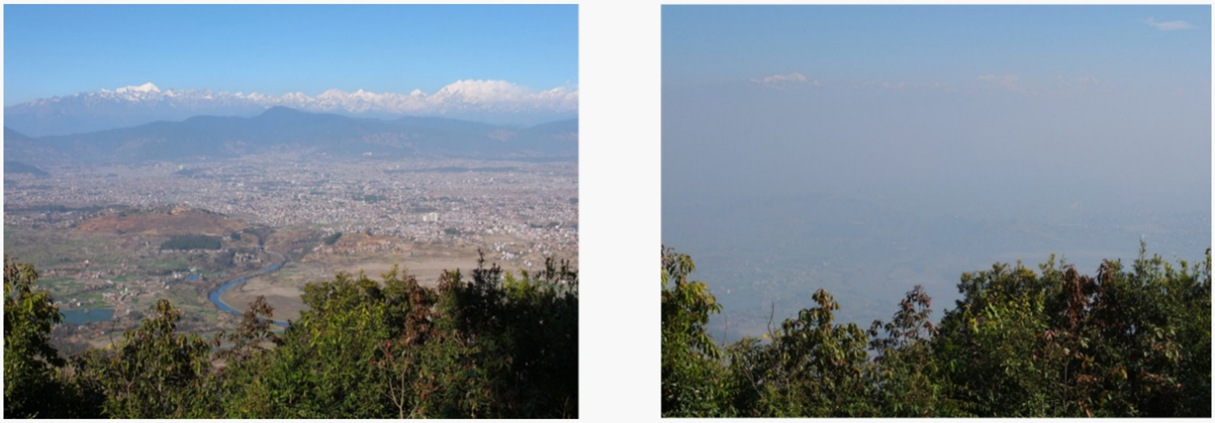
The concentration of most of Nepal's rains during the summer monsoon period has a strong impact on air quality. The impact is two-fold. First, rain washes out particles from the atmosphere, reducing their atmospheric lifetime, the distance they can travel from the source, and the concentrations to which they can accumulate. Lower particulate pollution levels have consistently been observed during the monsoon season in Nepal across all studies. Second, by having most of the year's rainfall concentrated during a three-month period, that leaves the rest of the year much very dry and dusty. Rainfall during the winter and spring, when brick kilns are operating across vast regions of South Asia and when more open fires take place, has decreased significantly and may decrease further with climate change (Hamal et al., 2021).

In recent years the Terai has experienced increases in winter fog that appear to be connected to air pollution. Visibility data from airports around the Terai going back to 1980 show an increase both in the number of foggy days and in the frequency of dense fog (Kathayat et al., 2023; Shrestha et al., 2023). While fog can be a purely natural phenomena, when sharp temperature gradients can lead to natural condensation of water vapor into droplets that obscure visibility, air pollution particles can significantly affect how condensation occurs resulting in a pollution/water mixture and droplets of different sizes than would occur naturally. Just like in other parts of the IGP, fog patterns in the Terai have changed starting in the late 1990s. The worsening visibility data collected at airports in the Terai (Kathayat et al., 2023) is consistent with observations of regional pollution haze (pollution-impacted fog) at all levels of the atmosphere sitting over the IGP during the dry season (Rupakheti et al., 2018a, 2020; Kim Oanh et al., 2024).

During the dry season, air pollution levels in Nepal are affected by weather patterns, resulting in day-to-day variations. Kathmandu on two otherwise identical days, with identical local emissions, might

4 Mean levels exceeded 60 ppb in Spring.

Figure A.3: View of Kathmandu from Hattiban (1775m) on the southern valley rim, on 28 Feb. 2013 (L) and 2 March 2013 (R)



Photos: Arnico Panday.

have clear skies on one day and very hazy conditions on the other (See Figure A.3). Episodes of transport of high pollution loads from the IGP across Nepal's width and across the high Himalaya to the Tibetan Plateau have been found to depend on synoptic weather conditions, with the passing of southwesterly flows over central and northern India leading to transport pollutants to the high Himalaya (Lüthi et al., 2015).

Ozone levels over Nepal are determined by different processes compared to particulate matter. Ozone is photochemically produced in the atmosphere, and thus its control requires both a detailed understanding of the transport and chemistry, as well as of the sources of a diverse set of precursors (Sillman et al., 1990). Due to its need for sunlight, ozone levels in Nepal peak in the pre-monsoon spring instead of in the summer as is more common at mid-latitudes. At high altitudes there is another source of ground-level ozone: stratospheric intrusions raised ozone levels on 14.1 percent of observed days at Nepal Climate Observatory-Pyramid, (Cristofanelli et al., 2010b).

A.4 Impacts of human activities on air quality in Nepal

While physical processes transport around and affect the accumulation and ventilation of pollutants, reducing air pollution requires addressing the anthropogenic emissions sources and the activities responsible for them. The anthropogenic sources of air pollution are discussed in chapter 4.

The sources contributing to particulate air pollution in Nepal vary seasonally (Kim et al., 2021; Saikawa et al., 2019). Their relative contributions depend on the time and place. The concentration of $PM_{2.5}$ at any given location is the sum of contributions from local sources and from far-away sources transported over. Some of these sources are year-round and some are seasonal. The biggest year-round sources in Nepal are cooking with biofuels, vehicles (particularly diesel-powered ones), and, in some parts of the country, industries. Brick kilns are big sources in some parts of the country (primarily in the Tarai and near the Kathmandu Valley) between December and May, while agricultural residue burning and forest fires occur at specific times in the Autumn and the Spring. In addition, garbage burning is a big source that tends to occur more in the dry season than in the monsoon.

Secondary particles are formed through chemical reactions in the atmosphere. They typically require gaseous emissions of ammonia from agriculture (fertilizer or manure) plus either sulfur dioxide or nitrogen oxides gases to form ammonium sulfate or ammonium nitrate particles. Gas-to-particle conversion in the formation of new, secondary particles has been observed in detail a number of places in the Indian Himalaya (Mönkkönen et al., 2005; Ram et al., 2008; Venzac et al., 2008) but has not been studied in detail in Nepal. Regional GAINS model runs, however, do show substantial contributions to $PM_{2.5}$ load over Kathmandu by secondary particles originating from gases emitted elsewhere in Nepal and in other nearby countries (World Bank, 2023).

The concentration of a pollutant measured at a particular location is influenced by a few processes operating on different scales. It is influenced by a variety of sources located at different distances from the site, with air flow between the source and the measurement site varying in time. Small sources repeated across a landscape, such as cooking with biofuel in the IGP, influence the air quality and climate of entire regions (Praveen et al., 2012). Weekday versus weekend differences have been observed in many places including Kathmandu (Pudasainee et al., 2010). As we have seen earlier, seasonal variations in polluting human activities, such as brick kilns and agricultural residue burning, also play a major role in determining the levels of air pollution at any given time and place. Sometimes impacts of events in one place can be observed across a broad region: Agricultural fires in northwestern India have been found to lead to simultaneous increases in ozone and CO in both Nainital and in Bode in the Kathmandu Valley (Bhardwaj et al., 2018b).

A major cause for concern in Nepal is trans-boundary transport of pollutants that adds onto the pollution levels due to locally emitted pollutants. Regional pollution originating from sources outside Nepal contribute an additional 20-25 percent of particulate matter in the Kathmandu Valley (Mahapatra et al., 2019), and as much as two-thirds of CO in Lumbini (Rupakheti et al., 2016). Biomass burning in the northwestern IGP region has been identified as a major source of ozone and CO in Nepal (Bhardwaj et al., 2018a). Model back trajectories have found that high pollution episodes in Chitwan may be caused both by nearby and far-away fire burning (Mehra et al., 2018). During the post-monsoon period, Lumbini is affected by biomass burning from western India and eastern Pakistan (Wan et al., 2017), while during the pre-monsoon period, it experiences significant influence from air masses originating in the western IGP (Rupakheti et al., 2018b). While local emissions playing a role in diurnal pollution peaks, their levels are affected by the time-varying background regional air pollution originating from far-away sources onto which they are added. Evidence for increased regional background pollution can be found in ice cores from high mountain areas high (Kaspari et al., 2011; Ming et al., 2008b), while recent real-time stations at the height of glaciers provide insights into the processes bringing the BC to those altitudes. For instance, at NCO-P station near Mr. Everest, clean background conditions were observed 55 percent of the time, but there were episodes when PM levels 50 times the background concentration (Marinoni et al., 2010) and included dust from the Middle East.

The use of models to study air pollution in Nepal is limited by the quality of the input data, but this is improving. There have been some attempts to improve both the activity data, and the emissions factor that describes the amount of each pollutant emitted per unit of activity. The Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE) conducted in 2015 and 2018, sponsored by the US National Science Foundation and ICIMOD, aimed to improve emission data by measuring pollutants from various sources not well represented in global databases (Goetz et al., 2018; Islam et al., 2019; Jayarathne et al., 2018; Stockwell et al., 2016). It found significant discrepancies between older emission factors and actual emissions, particularly from vehicles and brick kilns in the Kathmandu Valley. It found that the older HTAP_v2.2 emissions inventory underestimated emission of particulates by vehicles in Kathmandu Valley by more than a factor of one hundred (Zhong et al., 2019).

Field based source apportionment studies give us insights into the relative contributions of different sources of pollution, particularly in the Kathmandu Valley. One study found the major sources of PM_{10} to be motor vehicles (31 percent), soil dust (26 percent), biomass/garbage burning (23 percent) and brick kilns (15 percent); the major sources of BC to be brick kilns (40 percent), motor vehicles (37 percent), and biomass/garbage burning (22 percent) (B. M. Kim et al., 2015a).Non-methane volatile organic compounds (NMVOCs) were traced to industries (32 percent), traffic (16.8 percent), residential biomass burning (10.9 percent), brick kilns (10.4 percent), and biogenic sources (10.0 percent) (Sarkar et al., 2017). More than 37 percent of toxic NMVOCs such as benzene were found to be from brick kilns. Another study at the same site found the main sources particulate bound mercury to be brick kilns, diesel engines and biomass burning (Guo et al., 2017). Furthermore, brick kilns, diesel engines, and biomass burning were found to be major sources of particulate-bound mercury (Guo et al., 2017). Anthropogenic combustion sources, including garbage burning (18 percent), biomass burning (17 percent), and fossil fuel combustion (18 percent) have been identified as the largest contributors to $PM_{2.5}$ pollution in Nepal (Islam et al., 2019). A field campaign[5] conducted in 2018 revealed that resuspended dust contributes significantly to $PM_{2.5}$ and PM_{10} levels in central Kathmandu during winter (Islam et al., 2021).

Several changes in human activities affect emissions in Nepal, ranging from changes in industrial operations to transportation preferences and agricultural practices. The start of operations of brick kilns in the Kathmandu Valley on January 3rd, 2013, shows a clear jump in air pollution (Kim et al., 2015b). Major changes in emissions from the brick sector occurred when Nepal banned moving chimney bull's trench kilns in 2003, and again starting in 2015 when many kilns started converting to zig-zag. The Kathmandu Valley's largest pollution point source, the state-owned Himal Cement Factory shut down in 2002; its former location in Chobhar is now a dry port. During several pre-Covid years all of Kathmandu's streets were dug up for new water pipes, resulting in extreme dust emissions that disappeared again after the streets were re-paved. Until 2017 Nepal experienced severe power shortages, leading to the operation of diesel gensets with an installed capacity of over 600 MW. Those are mostly idle since power cuts have ended. In certain districts of the Nepali Tarai, the switch from hand harvesting to machine harvesting of rice and wheat, followed by the burning of taller stubble that is left behind, has become a major source of pollution. Meanwhile, changes in firewood consumption, combined with drier spring weather is contributing to more severe forest fires (Hamal et al., 2021; Kuikel et al., 2024). Meanwhile, over the past year, the Nepali automobile market has seen a rapid increase in the sale of electric passenger cars and vans.

Lockdown measures implemented during COVID-19 in Nepal temporarily resulted in substantial reduction in emissions, thereby impacting air quality. Several studies have looked at the impacts of Covid on air quality in Nepal, when the country imposed a strict lockdown from 24 March 2020 to 11 June 2020, followed by several phases of partial openings and shorter lockdowns (Bhandari et al., 2023). The first lockdown coincided very closely with India's lockdown, leading to a rare reduction in industrial and transport emissions both within and upwind of Nepal, and the largest fraction of pre-monsoon days within WHO and NAAQS limits on record (Bhandari et al., 2023). The city of Nepalganj saw $PM_{2.5}$ levels drop by more than 80 percent (Baral & Thapa, 2021). The Kathmandu Valley saw a 38.1 percent decrease in $PM_{2.5}$ and 38 percent decrease in aerosol optical depth while the country overall saw a 27.7 percent decrease in AOD when compared to multi-year mean values (Dhital et al., 2022). At the US monitoring station at Phora Durbar, $PM_{2.5}$ was found to be 46.7 percent lower during the first lockdown compared to the average over the same period in the previous three years (Edwards et al., 2021).

Oftentimes pollution levels in Nepal are a result of a complex interplay between when and where human activities take place, and the physical processes resulting from the mountainous topography. Box A.1 illustrates one such example.

5 The study found that in wintertime in central Kathmandu, 11 percent of $PM_{2.5}$ and 34 percent of PM_{10} were from resuspended dust and that 28-30 percent of $PM_{2.5}$ was made up of organic carbon, which originated from garbage burning (15-21 percent), biomass burning (10-17 percent) and fossil fuel combustion (14-26).

Box A.1: Interplay between human activities and physical processes: The morning and evening pollution peaks in the Kathmandu Valley.

A detailed study of morning and evening peaks in carbon monoxide and particulate matter in the Kathmandu Valley during the dry season using modeling, simultaneous sampling around the valley and on nearby hills, and detailed analysis of special occasions (festivals, evenings with bonfires), found the valley's pollution pattern to result from a close interplay between topography and emissions patterns (Panday et al., 2009; Panday & Prinn, 2009):

During the afternoon (when pollution levels are low) the valley is well ventilated by winds entering through the western passes and exiting through the eastern passes, with a smaller inflow also occurring up the Bagmati Valley from the South (Kitada & Regmi, 2003; Regmi et al., 2003). Post-sunset cooling begins the formation of a pool of cold air in the valley bottom that isolates the valley bottom from winds aloft while suppressing ventilation of ongoing emissions. During wintertime this happens before the evening rush hour, so a larger fraction of evening emissions is trapped compared to in other seasons, when emissions from the evening rush hour can easily leave the valley. Later at night, air quality in the valley bottom improves, as emissions decrease, while down-slope winds bringing cleaner air from the surrounding mountains that pushes underneath the polluted layers, which rise overnight, leading to increased pollution levels after midnight on the smaller hills in the valley. In the morning the ground heats up, vertical mixing resumes, and polluted layers mix down again, creating a morning peak in pollution that begins shortly after sunrise and includes both down-mixed pollutants from the evening before and new emissions taking place in the morning. Pollutant levels drop rapidly once vertical mixing is sufficient for winds entering through the western passes to sweep down to the surface level again – the timing of this is not dependent on emissions patterns, but on meteorology.

Measurements of carbon monoxide carried out in 2012-2013 in Bode, in the eastern Valley, found a much smaller night-time dip in CO levels during those months when nearby brick kilns operated all night – the nighttime dip was much more during July to October when the brick kilns were not operating (Singh Mahata et al., 2017). The same study also ran a second CO instrument at Chanban, a background site outside of the valley, for two months, and found that the daily minima of CO in Bode coincided with the levels observed in Bode, and these fluctuated depended on regional inflow of polluted air. A complementary study (Mahata, Rupakheti, et al., 2017) found that Bhimdhunga Pass on the western end of the valley did not experience an evening peak in pollution in the Spring – this makes sense given the prevailing westerly winds, and the isolation of site from valley bottom air.

A.5 Details on air quality monitoring network

Table A.1 provides details on air quality monitoring stations along with the information on air pollution sources near these stations, as compiled from the annual report published by the DoE on the Status of Air Quality in Nepal.

Figure A.4 shows the annual average concentrations of PM_{10} for ten monitoring stations across Nepal for the year 2023. All stations exceeded WHO's standard for PM_{10} of 15 μg/m^3 of annual average exposure.

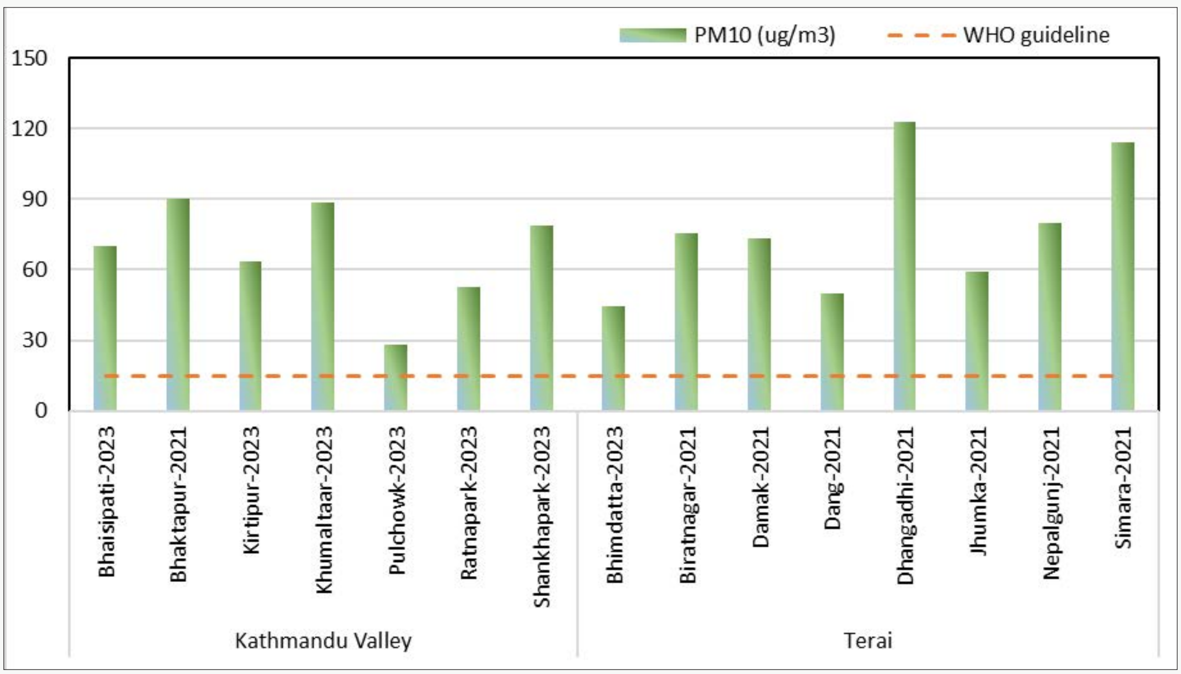
Table A.1: Information on air quality monitoring stations of Nepal

Names	District	Longitude	Latitude	Location information	Sources of air pollution
Achaam	Achaam	81.28	29.14		
Bhaisipati	Kathmandu	85.30	27.65	• Lies inside the premises of Bhaisepati Housing office • urban area	• Vehicles and commercial activities
Bhaktapur	Bhaktapur	85.42	27.67	• Lies inside the premise of Sainik Awasiya Mahavidyalaya (school) • semi-urban area	• Vehicles and commercial activities
Bharatpur	Chitwan	84.44	27.67		
Bhimdatta	Kanchanpur	80.18	28.96	• Lies adjacent to the northern boundary of Bhimdatta municipality office • urban area	• Vehicles and commercial activities
Biratnagar	Morang	87.27	26.45	• Lies inside the premises of Mahendra Morang Campus premises • urban area	• Vehicles and commercial activities
Damak	Jhapa	87.70	26.67	• Lies inside the premises of Saraswati Madhyamik Bidyalaya (school) • Urban flat land	• Local or pollutants transported from other places
Dang	Dang	82.53	27.99	• Lies near Ghorahi Rampur road • semi-urban area	• Local or pollutants transported from other places
Deukhuri Dang	Dang	82.71	27.84		
Dhangadhi	Kailali	80.60	28.70	• Lies in the center of Dhangadhi city • Urban area	• Burning of agricultural residue during pre-monsoon season. • Since this is near to border trans boundary air pollution is also an issue of this location.
Dhankuta	Dhankuta	87.34	26.98	• Lies in the premises of Dhankuta metropolitan city office • Small town	• Forest fire, agriculture residue burning, vehicles or pollutants transported from other regions

Names	District	Longitude	Latitude	Location information	Sources of air pollution
Dhulikhel	Kavre	85.55	27.61		
Hetauda	Makwanpur	85.03	27.42		
Ilam	Ilam	87.84	27.04		
Janakpur	Dhanusha	85.93	26.74	• Lies inside the premises of office chief minister of Madhesh province • Urban area	• Vehicles and industries • Agricultural residues burning • Near to border trans boundary air pollution
Jhumka	Sunsari	87.20	26.66	• Lies inside a Regional Agriculture Training Centre • Urban area	• Vehicles and commercial activities
Khumaltar	Lalitpur	85.32	27.65		
Kirtipur	Kathmandu	85.29	27.68	• Lies inside premises of Tribhuvan University • Background area	• Agriculture residue burning
Lumbini	Rupandehi	83.28	27.50		
Nepalganj	Banke	81.62	28.05	• Lies inside district office of Banke • Urban area	• Vehicles and commercial activities
Phora Durbar	Kathmandu	85.32	27.71	• Lies in the premises of US club at the heart of Kathmandu	• Vehicles and commercial activities
Pokhara DHM	Kaski	83.97	28.21		
Pokhara GBS	Kaski	83.97	28.26	• Lies in the premises of Gandaki Boarding School that is situated in Pokhara Metropolitan City • Urban area; recently heavily urbanized	• Vehicles • Emissions from fires in the other regions is also transported to pokhara.
Pokhara University	Kaski	84.09	28.14	• Lies inside premises of girls' hostel of Pokhara University • Urban area	• Vehicles and commercial activities
Pulchowk	Lalitpur	85.32	27.68	• Lies at the top floor terrace of Pulchowk Engineering Campus	• Vehicles and commercial activities
Rara	Mugu	82.09	29.51	• Lies inside the premises of Rara national park • High Mountain	• Either forest fire or pollutants transported
Ratnapark	Kathmandu	85.32	27.71	• Lies inside a park near Rani Pokhari • Heart of Kathmandu, urban area.	• Vehicles and commercial activities
Sauraha	Chitwan	84.50	27.57		
Shankapark	Kathmandu	85.34	27.73	• Lies within the premises of a park close to the road	• Vehicles and commercial activities

Names	District	Longitude	Latitude	Location information	Sources of air pollution
Simara	Bara	85.00	27.16	• Lies inside premises of armed police force • Semi-urban area	• Industries as it lies near bara-parsa industrial corridor • Trans-boundary pollution
Surkhet	Surkhet	81.62	28.60		
US Embassy	Kathmandu	85.34	27.74	• Lies in the premises of US embassy	• Vehicles and commercial activities
Yala	Rasuwa	85.61	28.21	• Lies near the Yala glacier, approx. 4900 m above sea level • High mountain	• Trans-boundary sources

Figure A.4: Annual average PM_{10} for the Kathmandu Valley and the Terai, for the period 2021 and 2023



Source: World Bank based on DoE's annual reports on Status of Air Quality in Nepal, 2021 and 2023.

Note: For stations where the latest PM1 data were not reported, 2021 data is included to ensure broader representation. By 2023, DoE has reported data from a total of sixteen stations within the Kathmandu Valley and the Terai, stations which had minimal gaps.

A.6 Improving air quality monitoring

The Department of Environment (DoE) may choose to increase the reliability and accessibility of data from existing stations. The DOE has long-term plans to expand their monitoring network for a total of 56 stations that would provide reliable and continuous air quality information across the country. With more than half of their eventual target number of stations in place, there is need to shore up the existing stations with reliable power supply and communication infrastructure at all air monitoring stations in Nepal. The GoN needs to identify and support an appropriate mechanism for hiring of agencies to provide continuous operation, maintenance and management (supply of spare parts and attending to repairs) for monitoring stations, even across fiscal years, which currently presents an issue due to complex procurement rules. The GoN needs to build capacity of federal and provincial officials in air quality monitoring (analysis and interpretation of data, operation and maintenance of stations, development of action plans, etc.), to develop Standard Operating Procedures (SOPs) and Quality Assurance/Quality Control (QA/QC) protocols for various functions of the monitoring stations, procure hardware and software for monitoring data processing and management and begin to establish a source apportionment network. These activities include implementing data quality control protocols and enhancing public data availability, which are all severely lagging. Once those problems have been addressed, there is also a need to add more measurement parameters to existing stations such as Sulfur Dioxide (SO_2), Nitrogen Oxide (NOX) and Ozone (O_3). Particulate matter is not the only pollutant of concern in Nepal. Already in 2013-2014, ozone exceeded the WHO's 8-hour standard of 50 ppb on 159 out of 357 days in Nagarkot on the Kathmandu Valley's eastern valley rim, and on 132 out of 354 days in Paknajol in Kathmandu's city center and on 102 out of 353 days in Bode, east of Kathmandu city center (Mahata et al., 2018). DoE's stations have been measuring ozone since 2016 in Chitwan and 2017 in Lumbini and around Kathmandu, but the DoE has yet to report ozone data to any audience.

Given the severity of air pollution in Nepal it is imperative to bring in newer monitoring technologies. There is a need to produce multi-day pollution forecasts. Running models well over the Himalaya is not easy: Models using global input data tend to systematically underestimate the pollution in the Kathmandu Valley, as seen in WRF-CHEM simulations of black carbon (Mues et al., 2018), MERRA2 reanalyses of $PM_{2.5}$ (Becker et al., 2021; Bhatta & Yang, 2023). While it may take time for Nepal to have systems and human resources in place to reliably run pollution forecasts, the Indian Institute of Tropical Meteorology in Pune, India, already does so over the entire South Asian region. Currently, for domestic Indian consumption they apply a "cookie cutter" onto the map to only display forecasts over India, but with the right agreements they would easily be able to supply the DoE and other government agencies in Nepal with forecasts as well. There is also a need to integrate into daily use in Nepal satellite observations, such as the Korean GEMS satellite, which United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP) is trying to connect to decisionmakers around Asia.

To establish accurately $PM_{2.5}$ trends for multiple stations, consistent data across all seasons for multiple years is needed. For the analysis to be meaningful, at least 70 percent of data should be available for each season every year. Figure A.5 shows that only three stations of the Kathmandu Valley (*Bhaisepati, Ratnapark, Pulchowk*) have more than 70 percent data availability across all seasons for only three years. All other stations fall below this threshold and have less data. Due to these limitations in data availability, the current dataset is insufficient to establish clear and meaningful air quality trends.

Figure A.5: Percentage of $PM_{2.5}$ data available across air quality monitoring stations in the Kathmandu Valley and the Terai (2016-2023).

		2016				2017				2018				2019				2020				2021				2022				2023			
		JJA	MAM	SON	DJF	JJA	MAM	SON	DJF	JJA	MAM	SON	DJF	JJA	MAM	SON	DJF	JJA	MAM	SON	DJF	JJA	MAM	SON	DJF	JJA	MAM	SON	DJF	JJA	MAM	SON	DJF
Kathmandu Valley	Bhaisipati	0	0	0	0	21	0	100	34	100	88	100	98	93	82	96	100	98	100	96	100	92	100	69	69	0	0	0	0	96	75	100	77
	Bhaktapur	0	0	0	0	16	0	87	34	68	97	100	96	73	100	74	80	95	39	71	30	88	72	54	100	0	0	0	0	0	0	0	0
	Dhulikhel	0	0	36	32	63	99	45	99	100	95	96	100	23	100	20	99	85	100	0	79	0	0	0	0	0	0	0	0	0	0	0	0
	Khumaltar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	92	91	62	100	99	100	97	93
	Kirtipur	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	99	91	96	96	55	100	84	62	98	93	52	34
	Pulchowk	0	0	45	30	92	100	77	99	100	99	71	82	100	91	100	96	0	0	0	57	0	0	0	0	0	0	0	0	62	0	100	34
	Ratnapark	4	0	85	33	100	88	88	92	95	53	100	100	76	83	95	98	85	88	0	79	96	97	48	97	89	43	79	62	100	96	80	80
	Shankhapark	0	0	12	0	73	34	38	37	40	78	96	91	75	30	95	99	37	44	0	0	0	0	0	0	89	23	54	97	69	90	0	0
Terai	Bharatpur	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	92	0	95	84	0	0	0	0	0	66	1	38	0	0	0	0
	Bhimdatta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	93	34	0	25	38	50	0	0	0	0	61	0	100	62
	Biratnagar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	64	0	92	30	82	68	76	69	0	0	0	0	0	0	0	0
	Damak	0	0	0	0	0	0	0	0	0	0	0	0	17	0	0	34	0	92	5	75	93	66	22	77	0	0	0	0	0	0	0	0
	Dang	0	0	0	0	0	0	0	0	0	0	68	20	97	95	100	88	98	100	100	43	74	98	31	96	12	17	42	34	0	0	0	0
	Dhangadhi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	100	26	23	100	58	49	0	0	0	0	0	0	0	0
	Janakpur	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	99	100	98	94	0	0	0	0	0	0	0	0
	Jhumka	0	0	0	0	0	0	0	0	0	0	0	12	52	32	100	90	0	0	0	36	0	98	0	64	0	0	0	0	0	0	0	0
	Lumbini	0	0	9	13	99	95	46	99	100	100	8	69	35	49	13	16	0	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Nepalgunj	0	0	0	0	0	0	0	0	20	0	88	20	100	65	100	88	98	100	82	62	0	38	0	67	0	98	0	66	0	0	0	0
	Sauraha	0	0	0	0	89	91	97	82	100	35	100	41	20	67	42	93	67	65	0	45	0	0	0	0	0	0	0	0	0	0	0	0
	Simara	0	0	0	0	0	0	52	0	100	34	100	100	96	100	0	0	0	0	15	67	36	43	0	0	0	0	0	0	0	0	0	0

Note: The seasons are categorized as JJA (June-July-August, Monsoon), MAM (March-April-May, Summer), SON (September-October-November, Autumn), and DJF (December-January-February, Winter). Stations with at least 70 percent data availability across all seasons are highlighted in grey, indicating more reliable datasets for trend analysis.

Annex B: Air Quality Standards

B.1 Standards for the industry sector

Table B.1: Standard on emission and stack height for brick kilns

Types of Kiln	Suspended Particulate Matter (mg/Nm^3)	Height of Stack (meter)
Bull's Trench Kiln, Forced Draft (Fixed Chimney)	350	17
Bull's Trench Kiln, Natural Draft (Fixed Chimney)	500	30
Hoffmann Kiln, Forced Draft	350	17
Hoffmann Kiln, Natural Draft	500	30
Vertical Shaft Brick Kiln (VSBK)	250	15
Hybrid Hoffmann Kiln (HHK)	200	7
Tunnel Kiln	100	10

Table B.2: Standard on emission and sampling method for cement plants

Category	Emission Limit	
Total Suspended Particulate Matter	Less than 500 $\mu g/Nm^3$	
Sample Collection Method	**Testing Method**	**Reference**
The sampling point must be located at a position in the cement industry where the emissions are carried in the direction of the airflow, at 300-500 meters from the source.	Gravimetric	IS 11255 (Part One)

Table B.3: Standard on emission and sampling method for crusher plants

Category	Emission Limit	
Total Suspended Particulate Matter	Less than 600 $\mu g/Nm^3$	
Sample Collection Method	**Testing Method**	**Reference**
The sampling point must be located 10-40 meters away from the controlled point of crusher industry. Screening should be performed at the controlled point, and it is considered central for sampling.	Gravimetric	IS 11255 (Part One)

Table B.4: Emission limits for new diesel generators (g/kWh)

Category (kW)	CO	HC + NO_x	PM
kW < 8	8.00	7.50	0.80
8 = kW < 19	6.60	7.50	0.80
19 = kW < 37	5.50	7.50	0.60
37 = kW < 75	5.00	4.70	0.40
75 = kW < 130	5.00	4.00	0.30
130 = kW < 560	3.50	4.00	0.20

Table B.5: Emission Limits for in-use diesel generators (g/kWh)

Category (kW)	CO	HC	NO_x	PM
kW < 8	8.00	1.30	9.20	1.00
8 = kW < 19	6.60	1.30	9.20	0.85
19 = kW < 37	5.50	1.30	9.20	0.85
37 = kW < 75	5.00	1.30	9.20	0.70
75 = kW < 130	5.00	1.30	9.20	0.54
130 = kW < 560	5.00	1.30	9.20	0.54

Table B.6: Standard on emission and sampling method for industrial boilers

Steam Generation Capacity of Boiler (Kg/hour)	Pollutant	Emission Limit (mg/Nm^3)
Less than 2000	Particulate Matter	1200
2000 to less than 10000		800
10000 to less than 15000		600
15000 and above		150
Sample Collection Method	**Testing Method**	**Reference**
Sampling point located at a height of one-third of the stack's height from the ground.	Gravimetric	IS 11255 (Part One)

Standard on chimney height for industrial boilers

The chimney height for industrial boilers using solid or liquid fuels must comply with the following formula:

$$H = 14Q^{0.3}$$

Where:

- **H** = Total height of the chimney above ground level (in meters).
- **Q** = Emission rate of sulfur dioxide (SO_2) in kilograms per hour (kg/hr).

Additionally, under no circumstances should the chimney height be less than **11 meters**.

B.2 Standards for the mobility sector

The NVMES guidelines stipulated that carbon monoxide (CO) emissions for four-wheelers registered prior to 1980 must not surpass 4.5 percent of their overall emissions, with a hydrocarbon (HC) limit set at 1000 ppm. Similarly, the CO emission cap for two-wheelers is also 4.5 percent of total emissions, but with a stricter hydrocarbon threshold of 7800 ppm or less. In 2012, the NVMES was revised to include the adoption of Euro-III standards. By then, 1.37 million registered vehicles in Nepal supposedly adhered to Euro-I or Euro-II standards (Shrestha, 2020). The permissible limits for various pollutants as mandated by NVMES are provided in the Table B.7 to Table B.9.

Table B.7: Emission standards as per NVMES, 2000[6]

Fuel	Vehicle type	CO (% by volume)	HC (ppm)
Petrol	Four-wheelers 1980 or older	4.5	1000
	Four-wheelers 1981 onwards	3	1000
	Three-wheelers	4.5	7800
	Two-wheelers (two stroke)	4.5	7800
	Two-wheelers (four-stroke)	4.5	7800
Gas	Four-wheelers	3	1000
	Three-wheelers	3	7800
Diesel	Older than 1994	-	75
	1995 onward	-	65

Table B.8: Emission standards for petrol vehicles, as per the revised NVMES of 2012 (MOFE, 2019)

Vehicle Type	Limit Values (Grams per Kilometer, g/km)		
	CO	HC	NO_x
Passenger Cars	2.3	0.2	0.15
Light Commercial Vehicles (LCVs)			
RM <= 1305 kg	2.3	0.2	0.15
1305 > RM <= 1760 kg	4.17	0.25	0.18
RM > 1760 kg	5.22	0.29	0.21
Two-Wheelers			
Class I (displacement < 150 cc)	2.0	0.8	0.15
Class II (displacement >= 150 cc)	2.0	0.3	0.15
Three-Wheelers	1.0	0.15	0.65

Note: RM signifies Reference Mass that represents unloaded vehicles with no driver and passengers but having full tank fuel with tools and spare tire adding another extra 100 kg weight or relative weight.

6 Air Quality Standard. Accessed through https://www.scribd.com/document/466521849/Air-Quality-Standard-docx.

Table B.9: Emission standards for diesel vehicles, as per the revised NVMES 2012 (MOFE, 2019)

Vehicle Type	Limit Values (Grams per Kilometer, g/km)			
	CO	NO_x	$HC+NO_x$	PM
Passenger Cars	0.64	0.56	0.50	0.05
Light Commercial Vehicles (LCVs)				
RM <= 1305 kg	0.64	0.56	0.50	0.05
1305 > RM <= 1760 kg	0.80	0.72	0.65	0.07
RM > 1760 kg	0.95	0.86	0.78	0.10
Vehicle Type	**Limit Values (Grams per Kilometer, g/km)**			
	CO	**NO_x**	**$HC+NO_x$**	**PM**
Heavy Duty Vehicles (HDVs) RM > = 3.5 ton	2.1	0.10-0.13	0.66	5.0

Annex C: Literature on Health Impacts from Air Pollution and Air Q+ Health Analysis Methodology

C.1 Air Quality-related health impact research

There is evidence of negative health outcomes of air pollution in Nepal. While more research is needed, several studies have been conducted in Nepal and show, for example, that a 10 μg/m³ increase in $PM_{2.5}$ level was associated with increased risks of hospitalization of 1.00 percent, 1.70 percent and 2.29 percent for total, respiratory and cardiovascular admissions, respectively (Gurung et al., 2017).

A study examining the health effects on individuals residing near a brick kiln in the Bhaktapur district found that 50 percent of respondents faced health problems, particularly respiratory illnesses, allergies, and eye irritation, confirming that both short-term and chronic exposure to air pollution is associated with an increased risk of non-communicable diseases (NCDs) in Nepal (Pariyar et al., 2013). Outpatient data from the Department of Health Services (DoHS) in Nepal show that respiratory diseases are the top reason for outpatients' consultations with both upper and lower respiratory tract infections being within the top 4 and COPD being the top cause of mortality among inpatients (Kurmi et al., 2016). Many studies have confirmed the association of high levels of household air pollution (HAP) in Nepal and negative health outcomes (Budhathoki et al., 2020; Acharya et al., 2021; Devakumar et al., 2015).

Globally, PM2.5-associated preterm births were estimated at 2.7 million in 2010, with South Asia having the highest percentage (Malley et al., 2017). In China, exposure to air pollutants like $PM_{2.5}$, PM_{10}, SO_2, and O_3 was linked to preterm births and low birth weight (Zhou et al., 2022; Liu et al., 2009). In Nepal, 15.7 percent of total deliveries were premature among women exposed to indoor air pollution from cooking with solid fuels (Acharya et al., 2021; Koirala & Bhatta, 2015). Pre-term births and their role in contributing to neo-natal deaths as a risk factor associated with air pollution were included in the Global Burden of Disease calculations for the first time in 2019 and are no longer left out of such calculations.

Emerging research has shed light on the link between air pollution and childhood stunting in South Asia, particularly in regions with high baseline levels of PM2.5. Prolonged exposure to air pollutants during critical developmental stages, such as pregnancy, can lead to stunting, and reduced cognitive development, with lifelong consequences (e.g., stunting leads to lower productivity later in life). The prevalence of childhood stunting in South Asia is approximately 38 percent of children under five years of age affected (World Bank, 2022). In South Asia, for each 1 μg/m³ increase in $PM_{2.5}$ during pregnancy, childhood stunting increases by 0.5 percent (Heft-Neal et al., 2024). Stunting effects are most severe between ages 1 and 3, disproportionately affecting children from socioeconomically disadvantaged households that are frequently exposed to higher pollution levels.

Emerging research also suggests that air pollution may have adverse neurological effects. These effects on the nervous system can potentially increase the risk of neurodegenerative diseases such as Alzheimer's and Parkinson's. Impacts associated with air pollution include cognitive decline (Power et al., 2016; Peters et al., 2018) and dementia in later life (Carey et al., 2018).

Studies have documented negative impacts of air pollution on cognitive and learning outcomes across various age groups. Exposure to $PM_{2.5}$ can impair basic cognitive abilities such as attention, memory, and problem-solving, with the largest effects among prime working age adults (La Nauze & Severnini, 2021). Acute exposure to fine particulate matter can alter brain cells found in the hippocampus, a region of the brain critical for learning and memory processes (Davis et al., 2013). Chronic exposure is associated with declines in episodic memory (ability to recall past events) and dementia risks, especially among older adults (Ailshire & Clarke, 2015). In children, air pollution can impair academic achievement by disrupting their learning potential (Ebenstein et al., 2016). This, in turn, affects their earning potential in the future as children exposed to air pollution are more likely to achieve lower educational outcomes that limit their lifetime earnings.[7]

C.2 AirQ+ health analysis methodology

The AirQ+ tool is designed to estimate the short-term and long-term health impacts of indoor and ambient air pollution, particularly PM2.5 pollution. The short-term effects are quantified by impact assessment and long-term effects by the burden of disease.

AirQ+ uses the Integrated Exposure-Response (IER) function from the Global Burden of Disease (GBD) study to calculate the health impacts of prolonged exposure to $PM_{2.5}$. By inputting the average annual $PM_{2.5}$ concentration, AirQ+ quantifies the number of deaths or cases attributable to $PM_{2.5}$ exposure through the Population Attributable Fraction (PAF). This links $PPM_{2.5}$ exposure to specific health outcomes, such as chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), acute lower respiratory infections (ALRI), and lung cancer. The PAF is a key metric used to indicate the fraction of deaths from these diseases caused by long-term exposure to $PM_{2.5}$. PAFs also indicate how much of a particular health issue could have been prevented if the harmful exposure to air pollution had been eliminated.

A detailed analysis of the burden of disease attributable to ambient PM2.5 exposure was conducted for both Kathmandu and Terai in 2021 and 2035. In Kathmandu, $PM_{2.5}$ concentrations in 2021 was at 37 μg/m³, but by 2035, this concentration is projected to rise to 51 μg/m³. This increase in exposure will result in higher PAF for various diseases, indicating a greater burden of mortality linked to air pollution. By 2035, the burden of all diseases in Kathmandu is projected to increase, with lung cancer showing the largest growth in attributable proportions. The PAF for lung cancer increases from 16 percent (PAF 0.1566) in 2021 to 20 percent (PAF 0.1984) in 2035 reflecting a 27 percent increase in lung-cancer related deaths. COPD (19.4 percent), IHD (7.8 percent), and ALRI (17.5 percent) will also see significant increases.

7 Harvard T.H. Chan. 2024. *Air pollution exposure in infancy may limit economic mobility in adulthood.* Accessed through: https://hsph.harvard.edu/news/air-pollution-exposure-in-infancy-may-limit-economic-mobility-in-adulthood/.

The Terai region had slightly lower $PM_{2.5}$ concentration in 2021 (39 μg/m^3), which is expected to rise to 42 μg/m^3 by 2035. While the concentration increase is less dramatic than in Kathmandu, the health burden still increases across all diseases. By 2035, the Terai region is expected to face a higher burden of disease from $PM_{2.5}$ exposure, with lung cancer experiencing the most significant increase.

The PAF for lung cancer increases from 16 percent (PAF 0.1598) in 2021 to 17 percent (PAF 0.1723) in 2035, with lung cancer related deaths rising by 7.8 percent. Similarly, COPD (5.8 percent) and ALRI (5.3 percent) show moderate increases in their attributable burdens between 2021 and 2035, and IHD (2.7 percent) shows a slight increase.

Annex D: The GAINS modeling tool

D.1 Introduction

To provide air quality management in Nepal with a good understanding of where pollution is currently coming from and how pollution can be reduced most effectively in the future, the analysis employs a version of the well-established GAINS model framework that has been tailored to the Kathmandu Valley and the Terai.

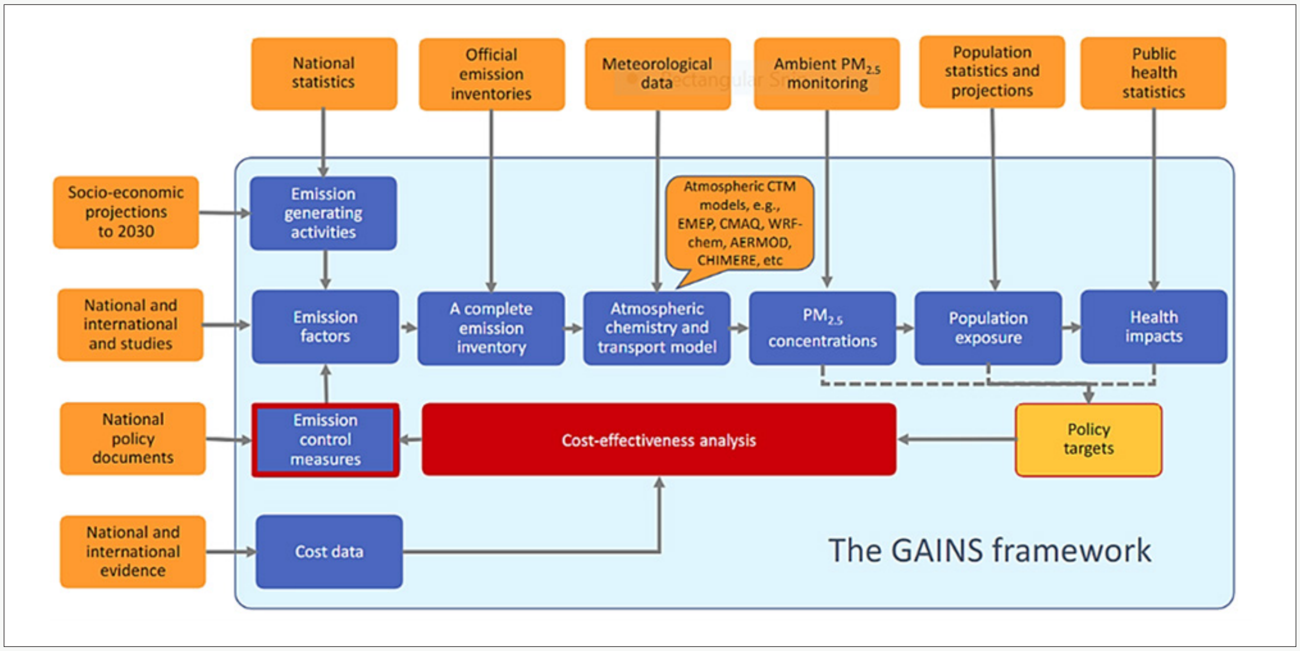
The GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model, developed by the International Institute for Applied Systems Analysis (IIASA), brings together information on the sources of emissions and their socio-economic drivers with advanced modeling of atmospheric chemistry and transport of pollution (Amann et al. 2011). It quantifies the spatial distribution and origins of observed pollution concentrations in ambient air. Based on given projections of future economic, energy and agricultural development, GAINS estimates the future improvements in air quality and population exposure that are offered by 1,100 proven emission control options and the costs that would occur to the overall economy (the blue boxes in Figure D.1). To inform decision making about the cost-effectiveness of alternative policy intervention options, GAINS explores cooperative multi-sectoral portfolios of measures that achieve given air quality and/or climate policy targets at least cost (the red boxes in Figure D.1).

Building on robust scientific understanding and quality-controlled local data, GAINS analyses have informed decision makers and stakeholders in the selection of measures that delivered the effective air quality improvements around the world. Local versions have been implemented and applied for policy analyses in, inter alia, China, South Africa, Vietnam, the European Union, and the parties to the Convention on Long-range Transboundary Air Pollution (LRTAP). Over the last years, a special version of the GAINS model has been developed for the airshed of the Indo-Gangetic Plain and Himalayan Foothills (IGP-HF) and applied for air quality management planning in IGP States in India, Punjab province in Pakistan and the Greater Dhaka Area in Bangladesh.

D.2 The GAINS implementation for the Kathmandu Valley and the Terai

For Nepal, the GAINS model has been implemented for two regions, i.e., Kathmandu Valley and Terai. Starting from the GAINS model for South Asia that has been developed by IIASA for the World Bank report on airshed management in South Asia (World Bank 2023a), these localized versions capture the characteristic emission sources in Nepal and assess ambient air quality in the two regions with a 1 km x 1 km resolution. Input data (the orange boxes in Figure D.1) have been compiled from a host of local statistics, measurement data and policy documents that were provided by local experts (Table D.1). The project team brought together international experts on the GAINS modeling from the IIASA and Iowa State University, and local experts on emission inventories, air quality monitoring and atmospheric chemistry from the Centre for Energy Studies (CES), Institute of Engineering (IoE) and the Central Department of Environmental Science of Tribhuvan University as well as the Department of Chemical Science and Engineering of Kathmandu University.

Figure D.1: Information flow in the GAINS-IGP model analysis



Source: International Institute for Applied Systems Analysis (IIASA).

Table D.1: Key approach and data sources employed for the GAINS implementations for the Kathmandu Valley and the Terai

Sectoral emission inventory of $PM_{2.5}$ precursors
Compiled from local activity statistics and GAINS-South Asia emission factors
Downscaled to 1*1 km using plant locations, population density, road maps, land use data
Monthly variation for brick kiln and forest fire emissions
Dispersion calculations
Local dispersion of primary $PM_{2.5}$: Iowa Urban Dispersion/HySplit model 1*1 km resolution
Long-range transport of primary PM into KV: EMEP dispersion model, 0.1°* 0.1°, 15 min calculations, monthly results, 2018 meteorology
Formation of secondary $PM_{2.5}$: EMEP dispersion model, 0.5°* 0.5°, 15 min calculations, monthly results for KV, downscaled to KV
Monitoring data
Daily observations of DoE 2018-2023
Daily observations of the low-cost sensor network for 2023
Daily observations of US-EPA for US-Embassy and Durbar Square
Missing daily observations assimilated (interpolated to match the overall station trend relative to all KV observations)

D.3 Estimates of current and future precursor emissions of $PM_{2.5}$

The GAINS model distinguishes about 400 emission source categories, for which it estimates the annual quantities of precursor emissions that generate secondary $PM_{2.5}$ in ambient air. These include primary $PM_{2.5}$, sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) and volatile organic compounds (VOC) and the six Kyoto greenhouse gases. For each source category, annual emissions of a pollutant are estimated as a function of the level of economic activity, (uncontrolled) emission factors that reflect typical conditions in the area without any emission controls, as well as the removal efficiencies and application shares of applied control measures. Activity rates (i.e., the quantities of emission-generating activities) are compiled from relevant local statistics or, if unavailable, estimated based on experience from other countries/states with comparable conditions.

Emission factors are primarily derived from local measurements that are deemed representative for the specific sources in the region (i.e., in South Asian countries), and local emission inventories to the extent they are available. The plausibility and robustness of local data is validated with international literature. In total, GAINS-IGP-HF considers about 1,100 proven emission control options for which the emission removal efficiencies are derived from world-wide literature considering the local conditions in Nepal and other regions in South Asia with similar characteristics.

Total emissions of a given source category in an administrative unit are spatially distributed based on statistics for large point sources and using appropriate surrogate data for distributed sources (e.g., maps of population distribution, road networks, land-use data, agricultural statistics) (Table D.2). Region-specific diurnal and seasonal time profiles as well as the heights at which emissions occur are considered for the emissions of each source category.

Table D.2: Data sources for the implementations of the GAINS model for the Kathmandu Valley and the Terai

Sector	Activity statistics	Spatial pattern	Observations
Residential	• For provinces 1, 2, 3: Fuel consumption by district provided by the energy statistics of Water and Energy Commission (WEC) 2019 • For the other provinces: Energy consumption per household reported for the 3 provinces (distinguishing Terai and the hilly/ mountainous rest of the country) applied to census household statistics	• Household census (dominant cooking fuel) 2021 by districts, municipal, wards • Further distributed by population density 1km*1km	• Less consumption of fuel wood than in national energy statistics • GAINS emission factors
Commercial	• For provinces 1, 2, 3: Fuel consumption by district provided by the energy statistics of Water and Energy Commission (WEC) 2019 • For the other provinces: Residual fuel consumption to National energy statistics	• Population density 1km*1km	• GAINS emission factors
Brick kilns	• Inventory of brick kiln types provided by Amico • Average brick production, fuel consumption, emission factors by type	• Inventory of brick kiln locations provided by Amico	
Cement plants	• Inventory of cement plants (clinker production provided in CemNet.com 2023)	• Locations of cement plants provided in CemNet.com 2023	• GAINS specific fuel consumption and emission factors
Other industry	• For provinces 1, 2, 3: Fuel consumption by district provided by the energy statistics of Water and Energy Commission (WEC) 2019 • For the other provinces: Residual fuel consumption to National energy statistics	• For Kathmandu: polygons of industrial areas provided by Amico • For other areas in the 3 provinces: district data distributed by population density • Other areas: Population density 1km*1km	• GAINS emission factors

Data for the 2020 baseline year have been corrected to represent actual emission levels and fuel consumption from 2021, which was not impacted as significantly by COVID lockdowns. These estimates serve as input for simulating ambient $PM_{2.5}$ concentrations in 2021.

Figure D.2: Primary emissions of $PM_{2.5}$ from the various source sectors in the Kathmandu Valley in 2021 (tons/cell)

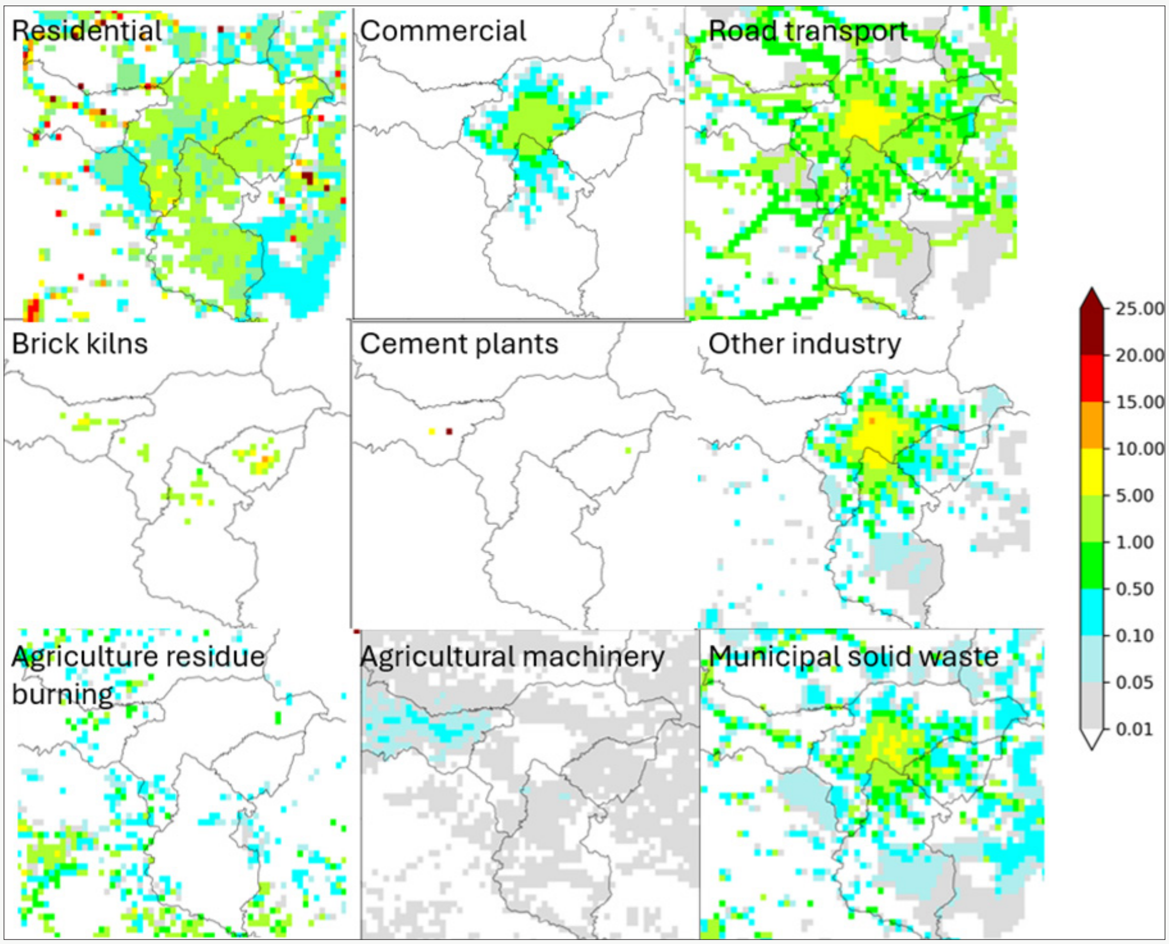


Figure D.3: Total primary $PM_{2.5}$ emissions in the Kathmandu Valley in 2021 (tons/cell)

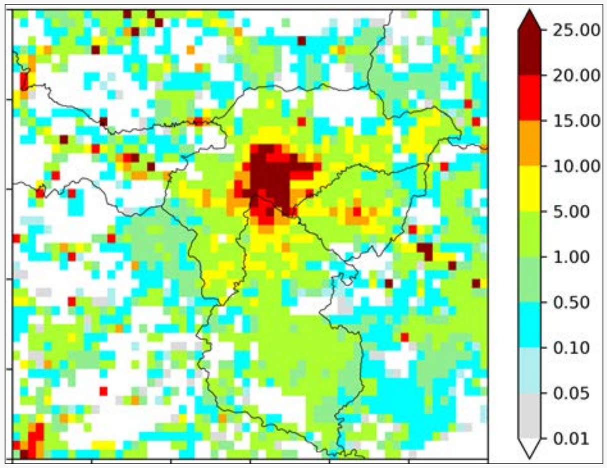
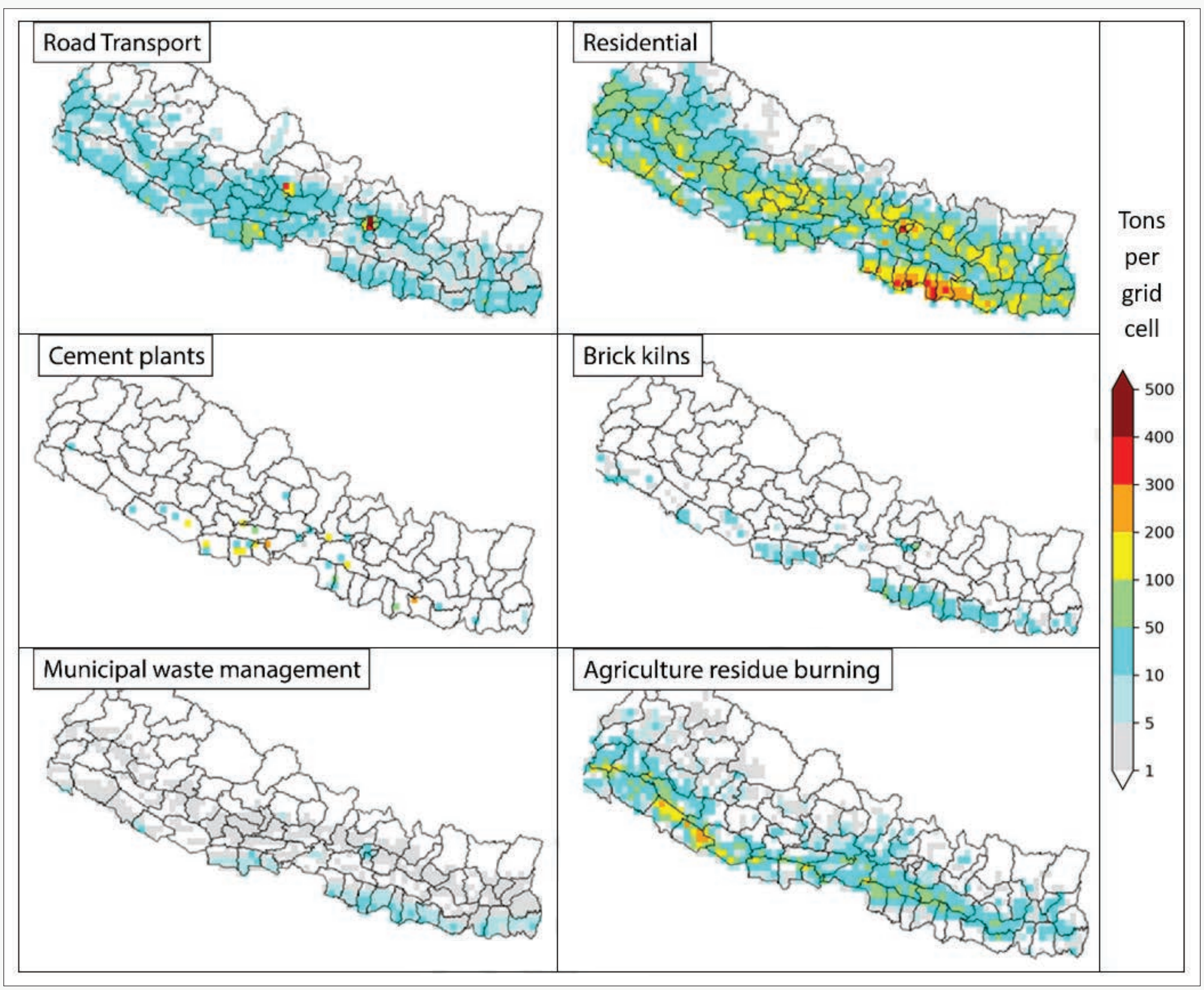


Figure D.4: Density of primary $PM_{2.5}$ emissions from the various sectors in Nepal, 2021



D.4 $PM_{2.5}$ concentrations in ambient air

With the resulting emission fields of all $PM_{2.5}$ precursor emissions, annual mean concentrations of $PM_{2.5}$ in ambient air are computed at a 1 km x 1 km spatial resolution for the Kathmandu Valley and 10 km x 10 km for the Terai. For this purpose, the GAINS-Nepal model combines dispersion characteristics of (i) local primary $PM_{2.5}$ emissions, (ii) the long-range transport characteristics of primary $PM_{2.5}$emissions from all of South Asia into the Kathmandu Valley, and (iii) the formation and transport of secondary $PM_{2.5}$ emitted throughout South Asia. The atmospheric dispersion of primary $PM_{2.5}$ emissions within the Kathmandu model domain is derived at a 1 km x 1 km spatial resolution from the Iowa Urban Dispersion model. These calculations are based on hourly forwards trajectories of air movements for all of 2018 computed by the HySplit model (https://www.arl.noaa.gov/hysplit/), a three-dimensional Lagrangian model that utilizes open access global meteorological inputs to study dispersion. The dispersion of all primary $PM_{2.5}$ in the Terai, the import of primary $PM_{2.5}$ into the Kathmandu Valley and the Terai, and the formation and transport of secondary $PM_{2.5}$ is derived from the EMEP atmospheric chemistry model (Simpson et al., 2012) for entire South Asia using a 0.1° longitude x 0.1° latitude (11 km x 11 km) spatial resolution. The underlying computations of the EMEP model have been performed at hourly time steps for the full year, employing the meteorological conditions of 2018 and considering for all emission sources the characteristic seasonal and diurnal time patterns and distinguishing three emission heights.

Although public attention and legislative air quality management focuses on episodic concentration peaks at pollution hot spots, worldwide epidemiological evidence indicates long-term exposure to $PM_{2.5}$ as the most powerful predictor for adverse health impacts. With a focus on public health, hourly results are aggregated to annual mean concentrations as the most relevant metric associated with public health impacts. Annual mean concentrations of $PM_{2.5}$ computed for the Kathmandu Valley and the Terai are shown in Figure D.5 and Figure D.6, respectively.

Figure D.5: Computed annual average concentrations of $PM_{2.5}$ in the Kathmandu Valley (μg/m³), 2021

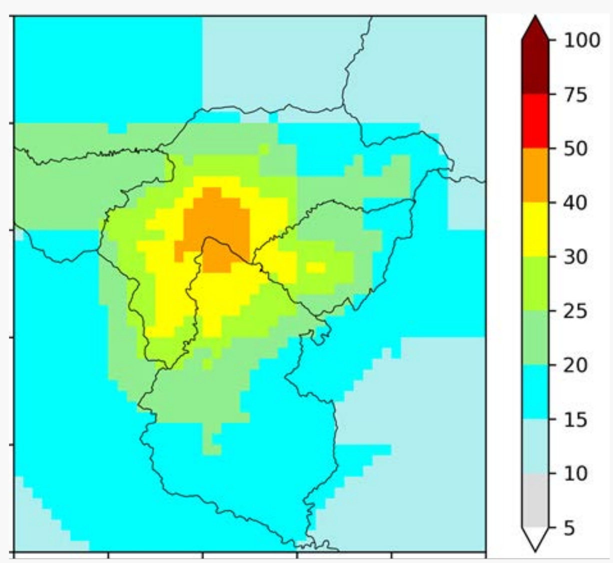
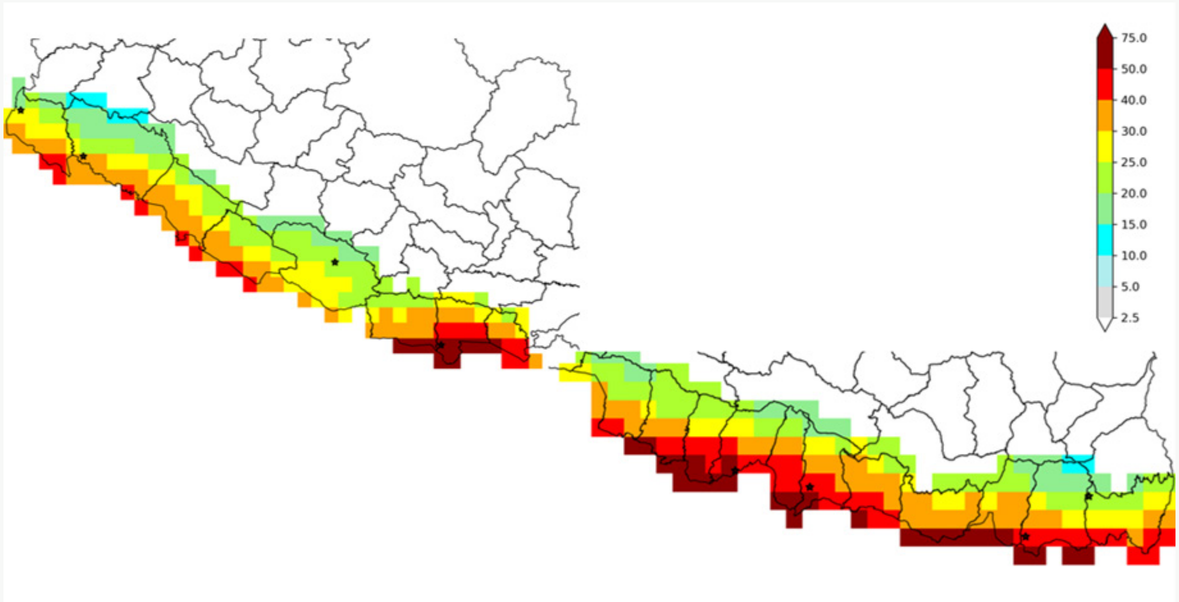
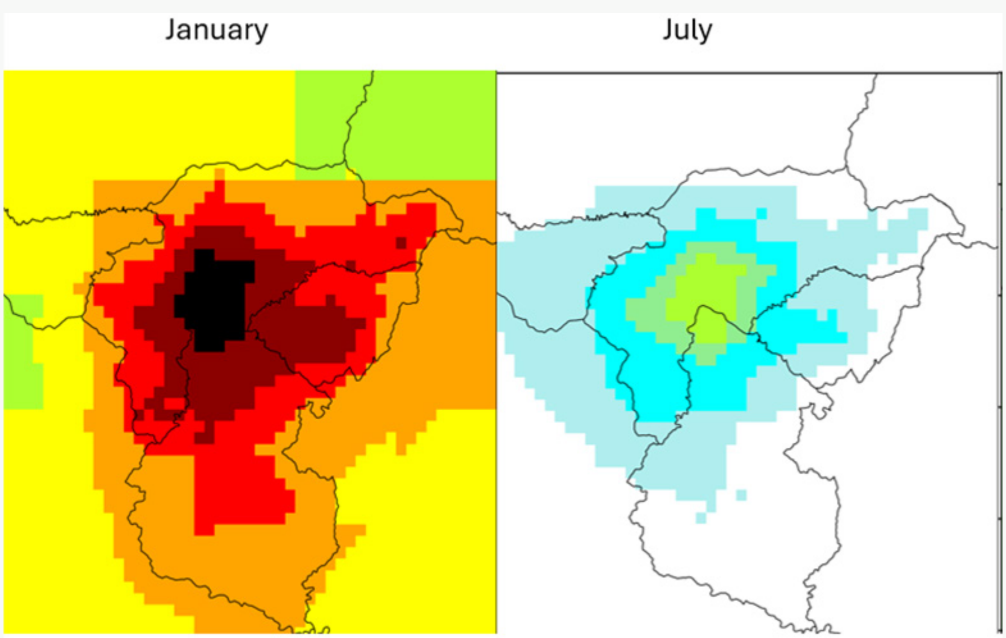


Figure D.6: Computed annual average concentrations of $PM_{2.5}$ in the Terai (μg/m³), 2021



However, as clearly shown by the monitoring data (see Figure 1.4 and Figure 1.5 in the main report), Nepal's air quality is characterized by strong seasonal variations of pollution due to meteorology (dry season, monsoon periods) and the seasonality of some emission sources (e.g., forest and agricultural fires, brick kilns). The model calculations capture this seasonality well as shown by the results for January and July 2021 for the Kathmandu Valley (Figure D.7).

Figure D.7: Computed monthly average $PM_{2.5}$concentrations for January and July 2021 in Kathmandu (μg/m³)



D.5 Model validation with ambient air quality data

Although Nepal's AQM monitoring network has grown significantly over the last years, there is only a limited number of Stations available that enable a robust assessment of annual average $PM_{2.5}$ concentrations (see Section 1.4 in the main report). To this end, model results have been compared for stations for which valid observations are available for more than 15 days in each month (in order to capture the seasonal variations). Missing data have been assimilated, i.e., interpolated to match the overall ratio between the average of the available observations of the given station in the year and the average of the measurements of all stations in model domain Valley on the same days. Following these criteria, for the Kathmandu Valley 24 annual averages could be established for the period 2020-2023, composed of eight stations from the DoE monitoring network, 14 stations from the low-cost sensor network, and two stations operated by the US-Embassy (Figure D.9). The locations of the stations are shown in Figure D.8. For the Terai, 22 annual averages could be established for eight DoE stations, although some of them with rather poor data coverage (Figure D.10, Figure D.11).

Figure D.8: Locations of the monitoring stations with sufficient data coverage in the Kathmandu Valley. Figures refer to recent measurements of annual average $PM_{2.5}$ concentrations (µg/m^3)

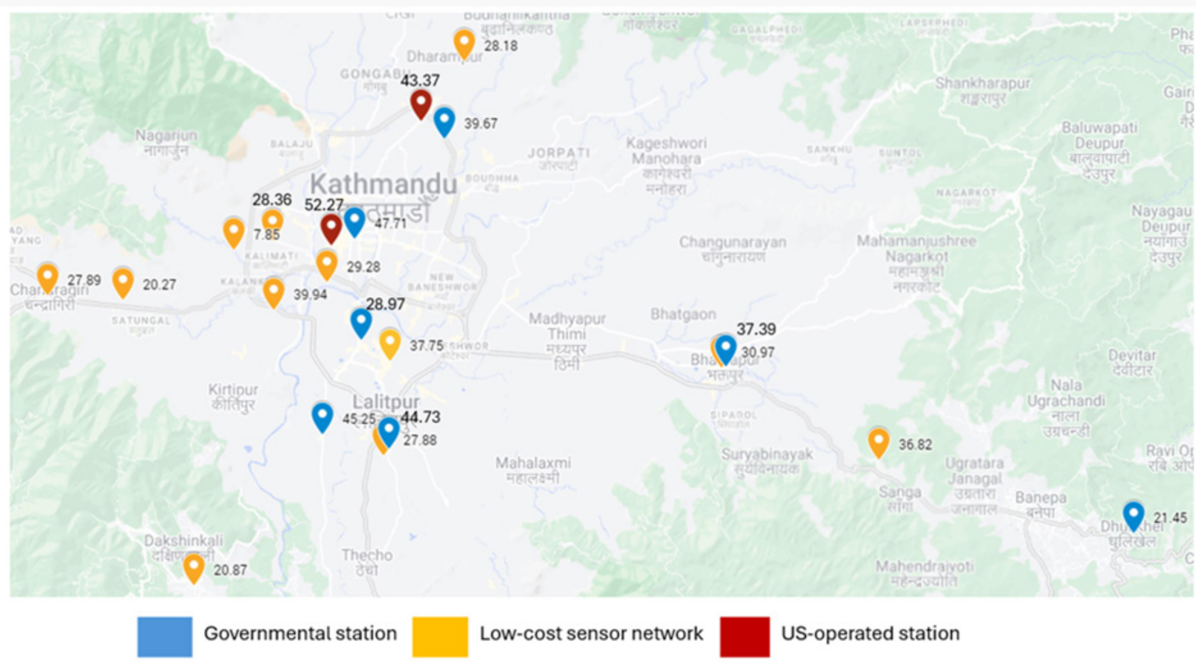


Figure D.9: Annual average concentrations of $PM_{2.5}$ measured at monitoring stations in the Kathmandu Valley

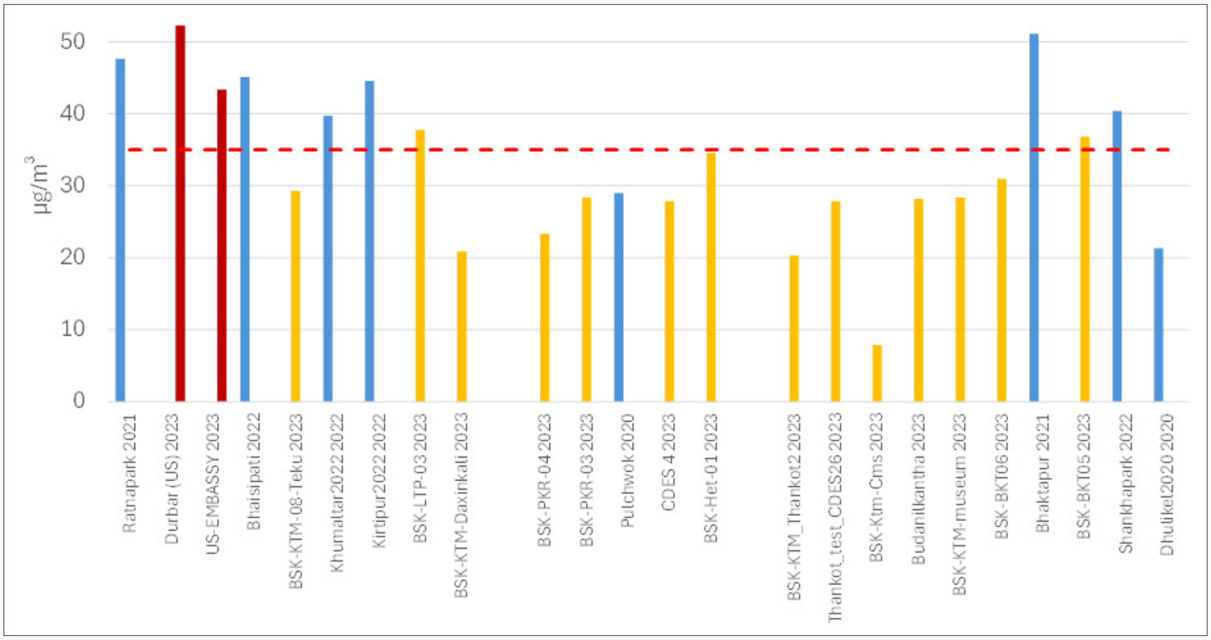
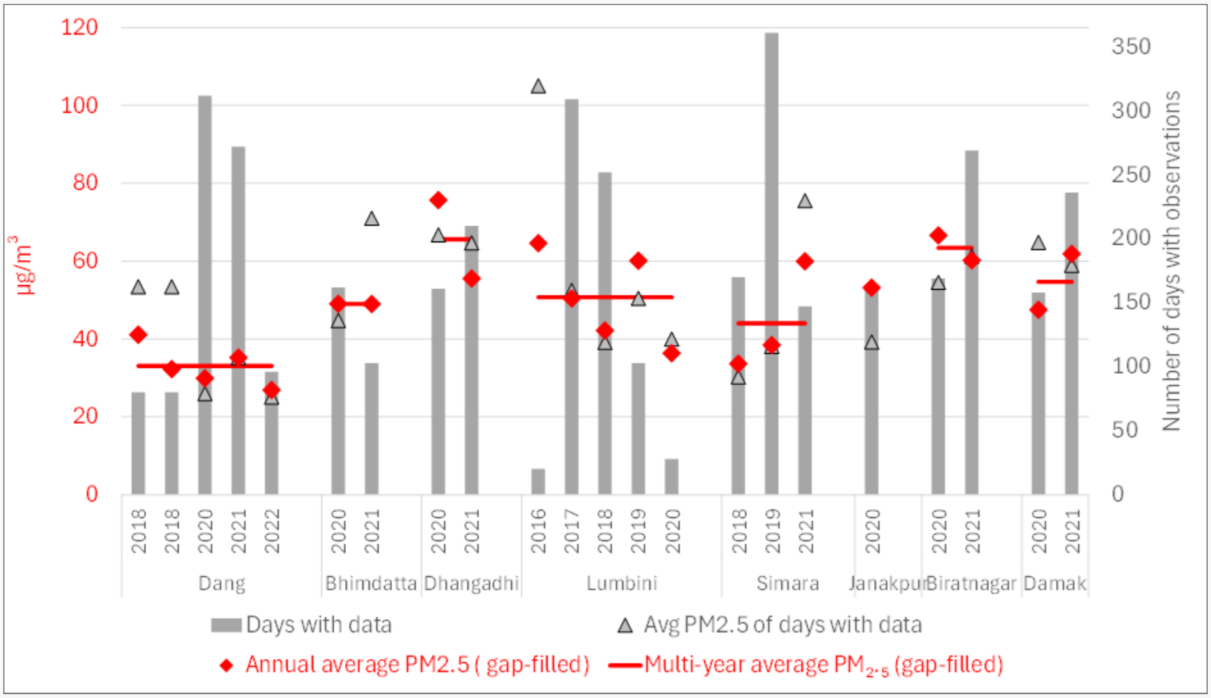


Figure D.10: Locations of the monitoring stations with sufficient data coverage in the Terai

Figure D.11: Annual average concentrations of $PM_{2.5}$ measured at monitoring stations in the Terai



The comparison of monitored and modelled $PM_{2.5}$ concentrations reveals a reasonable fit given the prevailing multiple uncertainties. The average $PM_{2.5}$ concentrations that have been determined for these stations were then compared against the GAINS estimates of the average concentration of the 1 km x 1 km grid cell in which the stations are located (Figure D.12). Discrepancies are mainly due to the significant uncertainties in the monitoring of annual average $PM_{2.5}$ concentrations, the systematic differences between point measurements and the variability of$PM_{2.5}$ concentrations within the surrounding 1 km x 1 km grid cell, the uncertainties in the spatial patterns of the estimated emissions, and general uncertainties in the atmospheric dispersion calculations.

Figure D.12: Validation of estimated annual mean $PM_{2.5}$ concentrations at specific locations in the Kathmandu Valley against modelled $PM_{2.5}$concentrations in the surrounding 1 km x 1 km grid cells.

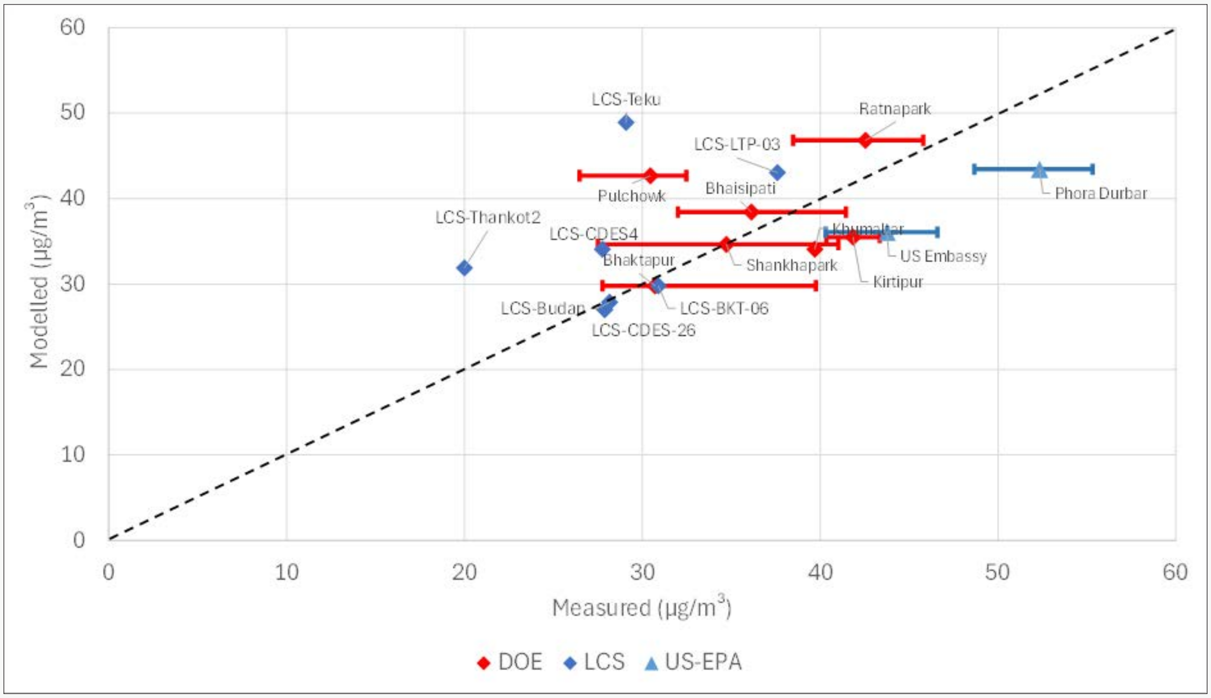
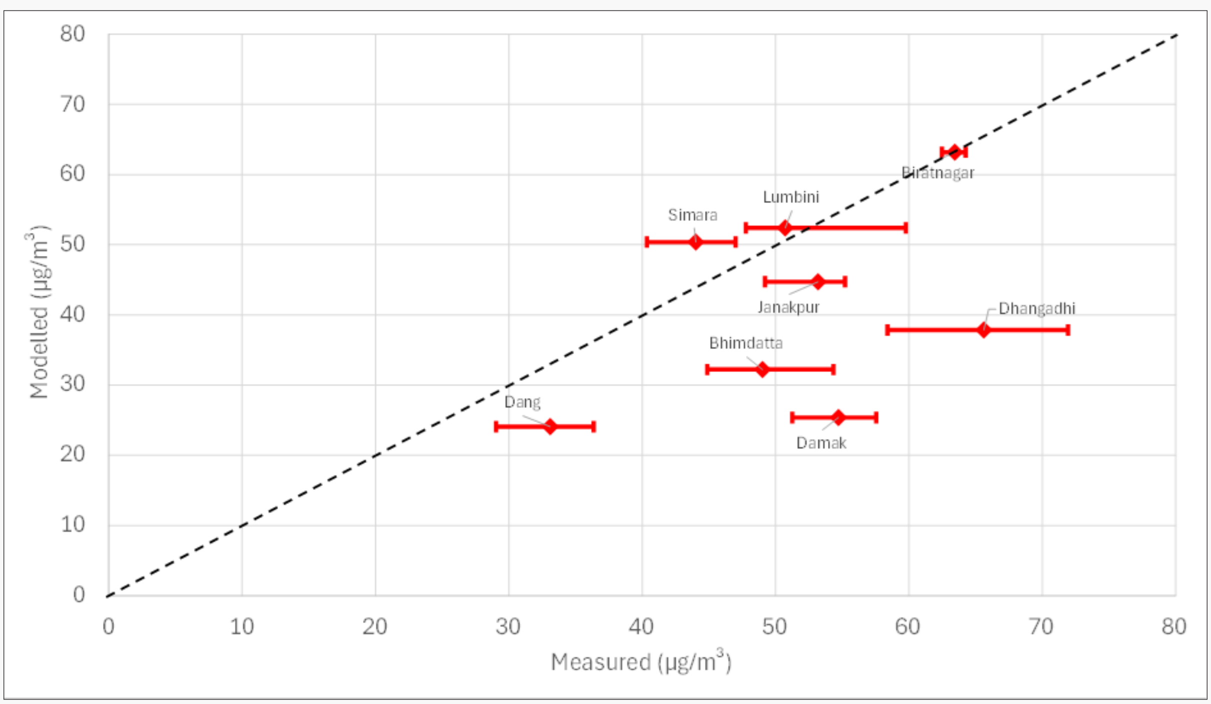


Figure D.13: Validation of estimated annual mean $PM_{2.5}$ concentrations at specific locations in the Terai against modelled $PM_{2.5}$ concentrations in the surrounding 1 km x1 km grid cells.



D.6 Source apportionment of population exposure to $PM_{2.5}$

The geo-physical approach of the GAINS model enables a tracking of the contributions from individual emission sources within the airshed to total $PM_{2.5}$ concentrations in ambient air at a given location or region. For the Kathmandu Valley, the contributions to $PM_{2.5}$ concentrations from the key sectors are shown in Figure D.14. Note that $PM_{2.5}$ in ambient air is composed of primary and secondary $PM_{2.5}$, whose contributions are shown in Figure D.15.

Figure D.14: Contributions of the various emission source sectors to annual mean $PM_{2.5}$ concentrations in the Kathmandu Valley in 2021 (µg/m³)

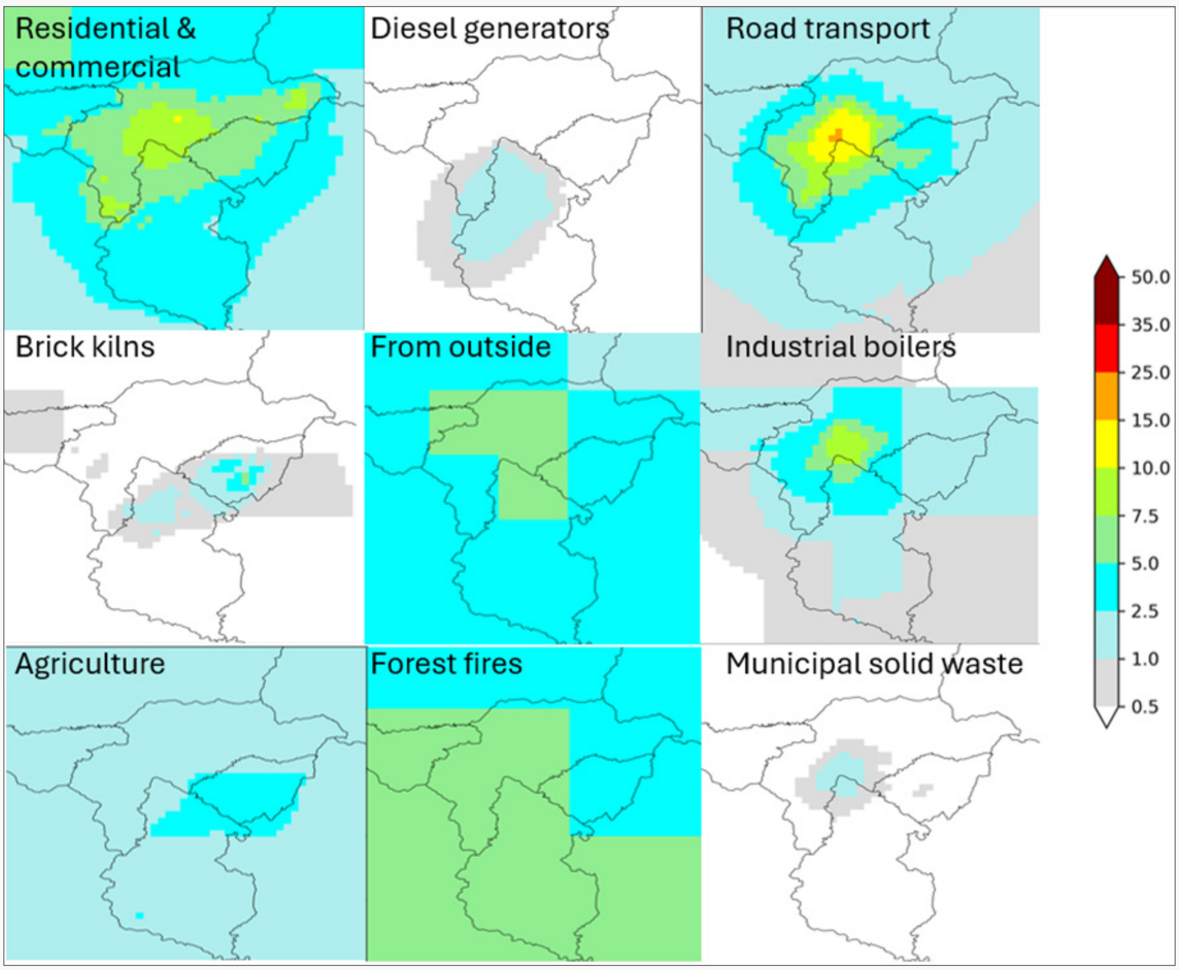
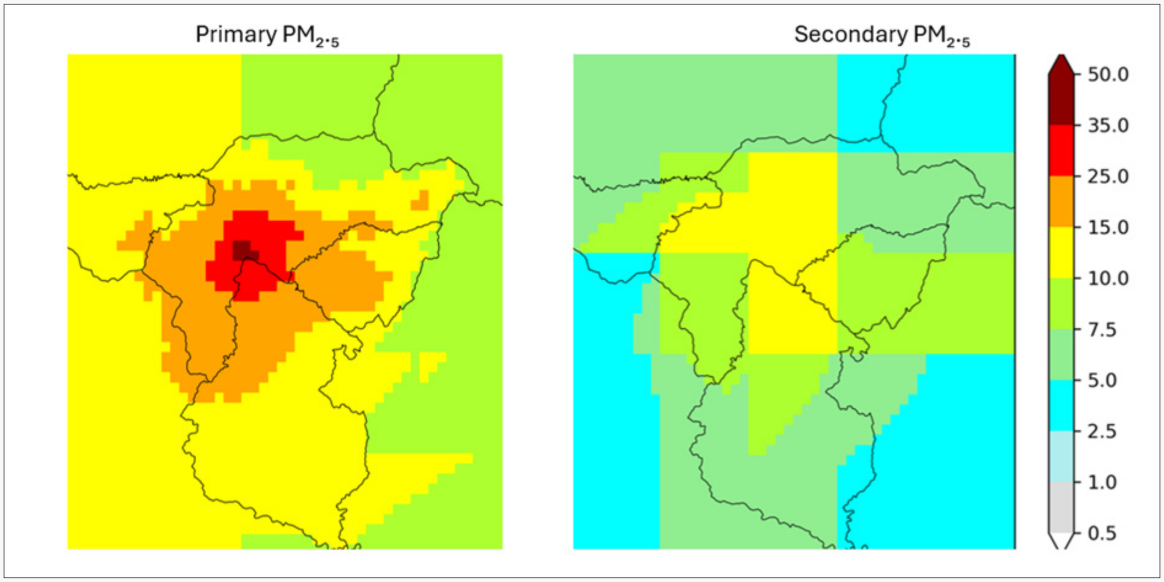
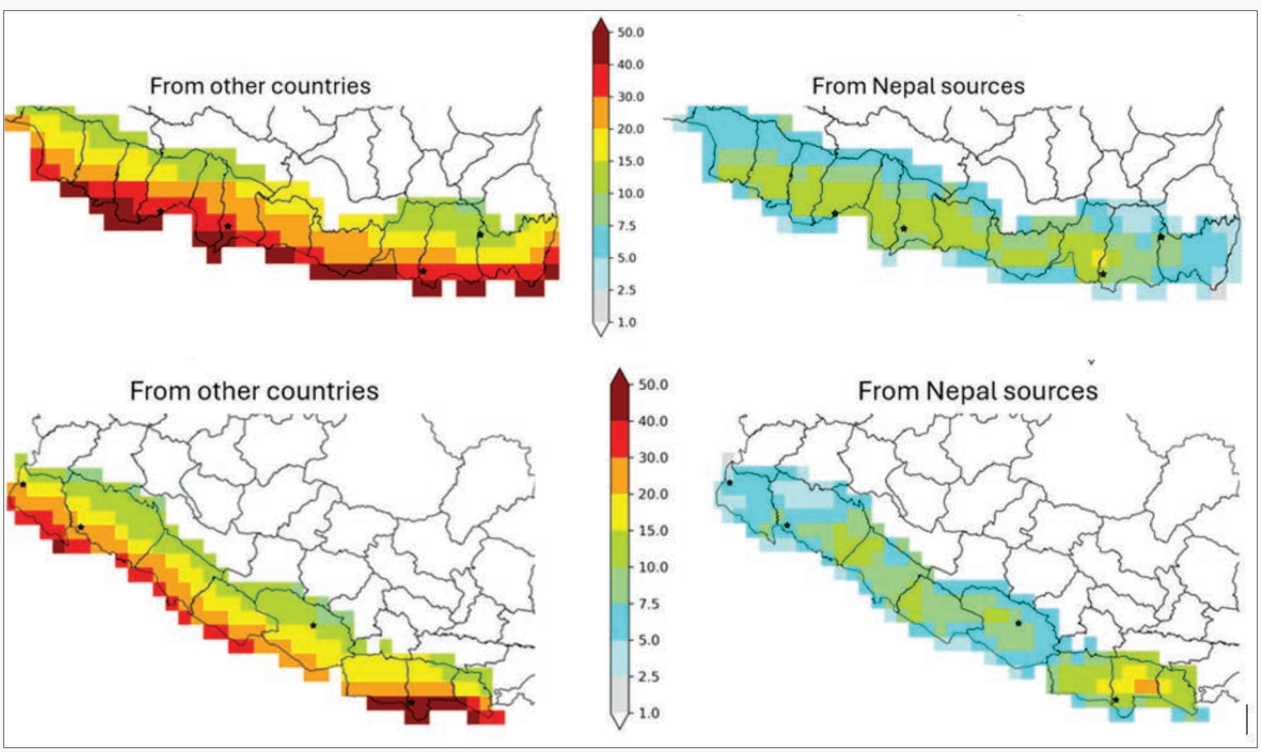


Figure D.15: Annual mean concentrations of primary and secondary $PM_{2.5}$ in Kathmandu 2021 (µg/m³)



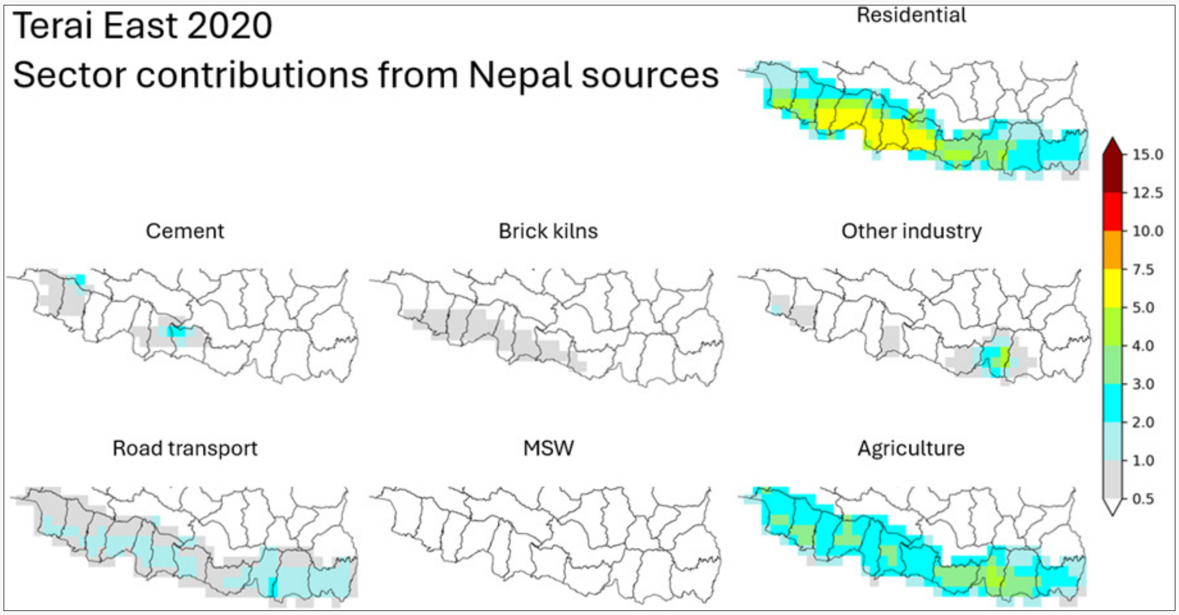
Due the narrow shape of the Terai and its location in the IGP with very high emissions, a significant share of $PM_{2.5}$ in its ambient air originates from outside regions, especially from India (Figure D.16).

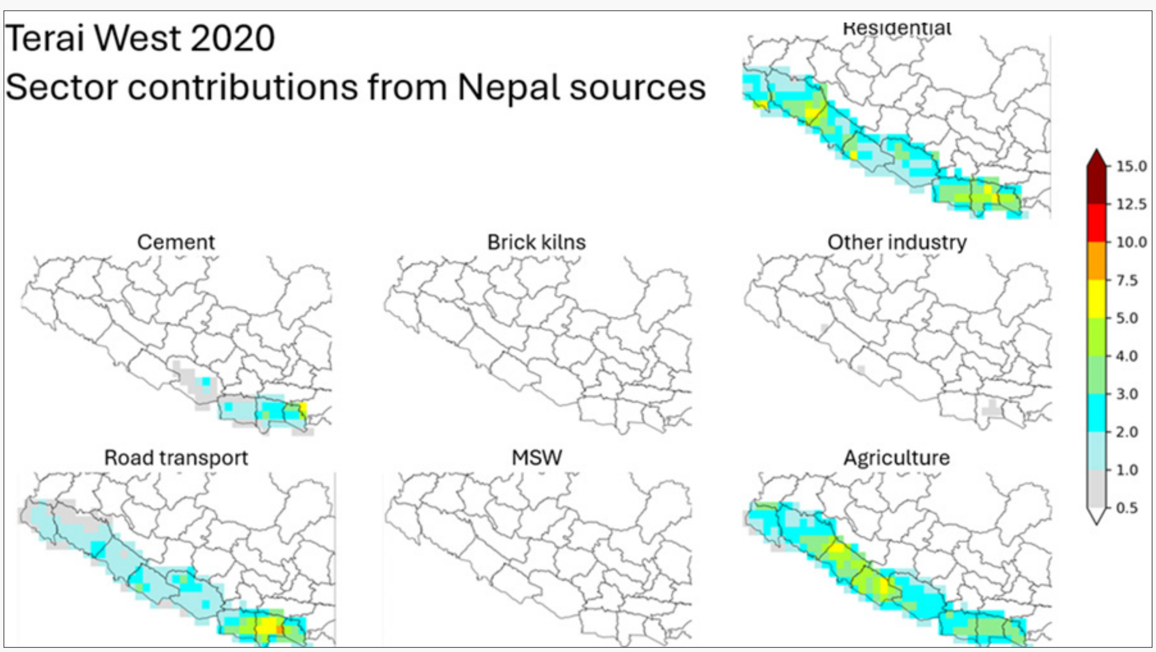
Figure D.16: The spatial origin of $PM_{2.5}$ concentrations in the Terai East (upper panel) and the Terai West (lower panel) in 2021 (µg/m³)



The contributions to ambient $PM_{2.5}$ in the Terai from the different source sectors in the Terai are shown in Figure D.17.

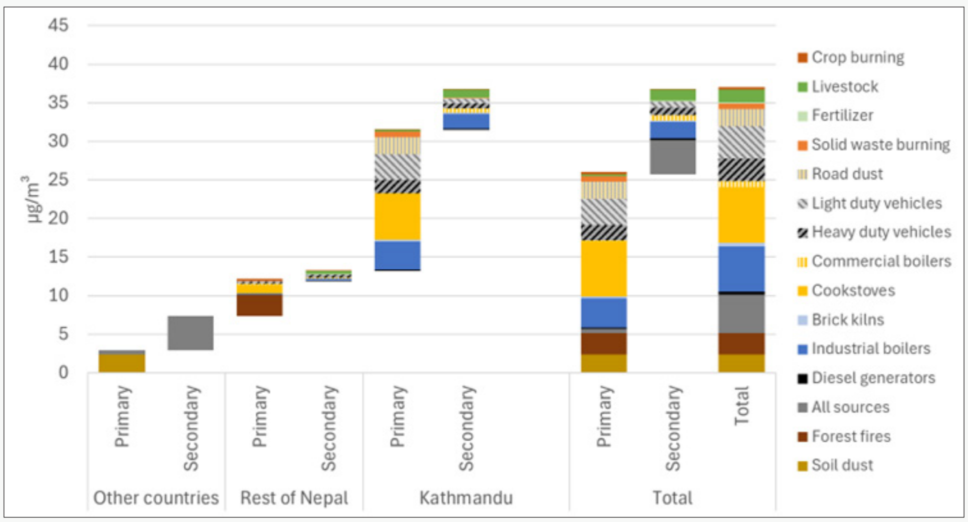
Figure D.17: Contributions of the various emission source sectors to annual mean $PM^{2.5}$ concentrations in the Terai in 2021 (μg/m³)





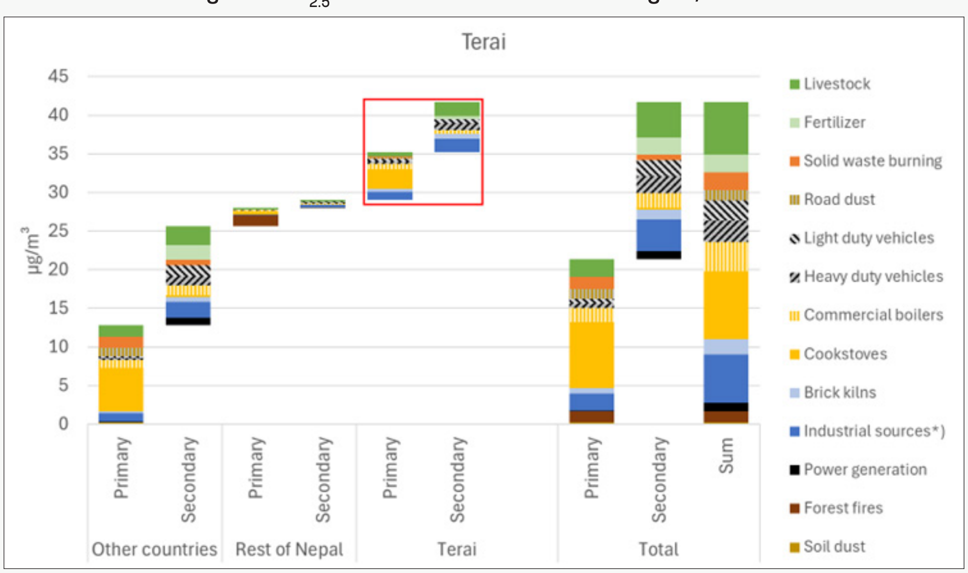
While the maps above provide valuable insights into the spatial diversity of the sectoral contributions to $PM_{2.5}$ concentrations throughout a region, aggregated metrics that summarize contributions in a larger region or at specific locations are more informative to address the burden of air pollution on public health and to maximize health benefits from pollution control interventions. The spatial and sectoral origins of population exposure in a region or at a location can be illustrated by so-called source apportionment diagrams. The situation in the Kathmandu/Terai in 2021 is depicted in Figure D.18 and Figure D.19, respectively. These graphs indicate the contributions to population-weighted $PM_{2.5}$ exposure that originate from (i) from other countries and natural sources (soil dust), (ii) from other regions in Nepal except the Kathmandu/Terai, and from the Kathmandu/Terai itself. Furthermore, the graphs distinguish the contributions of primary and secondary $PM_{2.5}$.

Figure D.18: Spatial and sectoral origin of $PM_{2.5}$ in ambient air in the Kathmandu Valley, 2021



Source: GAINS-Nepal, developed for this report.

Figure D.19: Spatial and sectoral origin of $PM_{2.5}$ in ambient air in the Terai region, 2021



Source: GAINS-Nepal, developed for this report.

D.7 Cost-effectiveness analysis

To inform decision making about the cost-effectiveness of alternative policy intervention options, the GAINS-Nepal model explores cooperative multi-sectoral portfolios of measures that achieve given air quality and/or climate policy targets at least cost to the economy. This cost-effectiveness analysis considers the specific costs of the measures and their impact on air quality/population exposure and/or greenhouse gas emissions.

The GAINS-Nepal model estimates the economic or resource costs of about 1,100 emission control options that would occur to the overall economy of Nepal, with the aim to quantify the value of resources that would be diverted from other productive purposes. Considered resource costs include, inter alia, upfront investments, costs of capital, as well as operating costs for labor and material input, waste disposal, costs for domestic energy extraction and energy imports, and revenues from the sale of by-products. However, markups charged over production costs by manufacturers or dealers are ignored in the economic analysis as they do not represent actual resource use of the society. Similarly, transfer payments such as taxes and subsidies are excluded.

The focus of the analysis on the overall economy is different from the perspectives of private and public firms driven by profits or at least cost recovery and for households on the ground. Firms and households operate within financial settings where costs, prices as well as investment and behavioral decisions are affected by taxes, subsidies, regulations, profit expectations and individual risks. A recent extension to the GAINS model explores transfer payments (taxes and subsidies) that would make measures that emerge as cost-effective for societies financially attractive for profit-oriented enterprises and private households and estimates their impact on government budgets. However, this extension is not yet available for South Asia.

Cost data for each option are based on international literature and market statistics and adjusted to local conditions in Nepal considering local wage rates and purchasing power parities. Technology-specific data, such as removal efficiencies, unit investment costs, and non-labor operating and maintenance costs, are derived from international literature and experience, to represent the conditions in a competitive world market. However, local circumstances lead to justifiable differences in the actual costs at which a given technology removes pollution at different sources. Country- and region-specific parameters considered in the cost calculation include, inter alia, labor costs, energy prices, size distributions of plants, plant utilization, fuel quality, animal fodder prices, paper collection rates, composting rates, the state of technological development, and the extent to which emission control measures are already applied. The analysis for Nepal draws primarily on local information collected for these factors. Data gaps have been filled with information from countries with comparable conditions provided by the global GAINS database and adjusted to local conditions considering, inter alia, local labor costs, fuel quality, age of plants, operating hours, etc. The feasible and cost-effective measures are then ranked by their marginal costs, and the resulting sequence of measures is presented in the form of a marginal cost curve (see Chapter 4.4 in the main report).

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