AIR QUALITY ANALYSIS AND TOOLS FOR POLICY

Siddarth Durga, Steven J. Smith, Meredydd Evans, Jon Sampedro, and Sha Yu
Pacific Northwest National Laboratory

January 2022

A product of the South Asia Group for Energy

AIR QUALITY ANALYSIS AND TOOLS FOR POLICY

Siddarth Durga, Steven J. Smith, Meredydd Evans, Jon Sampedro, and Sha Yu
Pacific Northwest National Laboratory

January 2022

A product of the South Asia Group for Energy

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
email: orders@ntis.gov <https://www.ntis.gov/about>
Online ordering: http://www.ntis.gov

Abstract

South Asia is home to some of the most significant air quality challenges in the world. More than 99% of the region's population is exposed to unhealthy fine particulate matter ($PM_{2.5}$) concentrations, as defined by the World Health Organization. Recent policy initiatives in South Asia show that air quality policy is a priority, given the health impacts of air pollution. At the same time, capacity and data to assess and address air pollution remains limited in many areas.

The main objective of this report is to outline a set of publicly available tools that can be used to inform policies to improve air quality in South Asia. The report primarily focuses on tools such as emission inventories and integrated modeling systems with country-level resolution and illustrates their air quality assessment capabilities through examples and brief technical summaries. The report (1) focuses on the Community Emissions Data System that provides historical emissions of key pollutants for all countries in South Asia, and (2) profiles an analysis of Indian air pollution and policy scenarios using several integrated modeling tools. Both of these examples draw on recent research and data that outlines the scale of the challenge as well as the policy options for reducing air pollution in the region. The report concludes with key recommendations for regional stakeholders working toward mitigating air pollution in South Asia.

Acknowledgements

The authors would like to thank the United States Agency for International Development and the Alliance for Sustainable Energy, LLC, which is the managing and operating contractor for the National Renewable Energy Laboratory, for funding this research.

Acronyms and Abbreviations

AP	Air pollution
BC	Black carbon
CEDS	Community Emissions Data System
EDGAR	Emission Database for Global Atmospheric Research
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
GCAM	Global Change Analysis Model
GFED	Global Fire Emissions Database
GHG	Greenhouse gas
IAM	Integrated assessment model
OC	Organic carbon
OM	Organic matter
RCO	Residential, commercial, and other

Table of Contents

List of Figures

1.0 Introduction

South Asia records some of the worst air pollution in the world, containing 84% of Asia's most polluted cities. Particulate and gaseous emissions from various anthropogenic and natural sources contribute to poor air quality in the region, adversely affecting human health and the environment. Of these emissions species, fine particulate matter with diameters less than 2.5 microns (also called $PM_{2.5}$) have the greatest impacts on human health, causing serious health conditions when exposed over the long term. Over 99% of South Asia's urban population is currently exposed to unhealthy $PM_{2.5}$ concentrations exceeding the World Health Organization's air quality guideline level of 5 $\mu g/m^3$ (micrograms/cubic meters) (IQ Air 2020).[1]

In 2019, India recorded the highest $PM_{2.5}$ concentrations in the region (83.3 $\mu g/m^3$), followed by Nepal (82.8 $\mu g/m^3$), Bangladesh (63.5 $\mu g/m^3$), and Bhutan (40.4 $\mu g/m^3$) (OECD 2022). The geospatial distribution of the $PM_{2.5}$ concentrations varied significantly across the region, with hazardous air quality levels recorded in the Indo-Gangetic plains and moderate air quality levels in Peninsular India (Figure 1). Meanwhile, the two island nations of South Asia—Sri Lanka and the Maldives—recorded relatively low mean $PM_{2.5}$ concentrations (20 and 10.9 $\mu g/m^3$, respectively); however, recent reports suggest that air pollution has increased in the urban centers of these countries (UNEP 2019, Nandasena et al. 2012).

The severe air pollution experienced in the region has wide-ranging impacts on human health and the environment. Long-term exposure to ambient and household air pollution poses a significant risk to public health. It is strongly associated with premature mortality and increased disease burden from respiratory infections, chronic obstructive pulmonary disease, stroke, cardiovascular disease, diabetes, and dementia (Yamamoto et al. 2014, Krishna et al. 2017, Balakrishnan et al. 2019, Murray et al. 2020, Priyankara et al. 2021). In addition, air pollution has major impacts on cities and agriculture, causing corrosion of building materials and cultural monuments (Natarajan et al. 2021), as well as reduction of crop yields (Burney et al. 2014). Furthermore, air pollution has detrimental effects on natural ecosystems, contributing toward loss of biodiversity and ecosystem instability (Lovett et al. 2009). Air pollution is also a key contributor to climate change, with some pollutants such as black carbon and ozone causing increased warming of the Earth's surface, whereas other pollutants such as sulfur dioxide have a cooling effect (Von Schneidemesser et al. 2015).

In this report, we provide details on several existing open-source tools that can inform policies for improving air quality in South Asia. Drawing on recent analyses, this report also highlights the policy options for reducing air pollution and its health impacts in the region. We highlight the air quality assessment capabilities of publicly available country-scale integrated assessment tools and emission inventories through examples and technical summaries. Integrated modeling tools analyze complex interactions between energy, economic, and climate systems and provide quantitative evidence for effective decision-making. These tools also inform important air quality policy questions such as how various future polices might alter $PM_{2.5}$ concentrations and associated health impacts. Emission inventories, meanwhile, provide detailed information on various pollution sources in a geographical region. This information can be used to identify high-impact sectoral interventions and prioritize the implementation of specific policies. Together, these tools provide support to researchers and policy makers in understanding the linkages between critical issues, such as air pollution and climate change, while also guiding future policy development through assessing alternative development pathways and policies.

---

[1] "Air quality guideline level … [is] a particular form of a guideline recommendation consisting of a numerical value expressed as a concentration of a pollutant in the air and linked to an averaging time. It is assumed that adverse health effects do not occur or are minimal below this concentration level." (WHO, 2021)

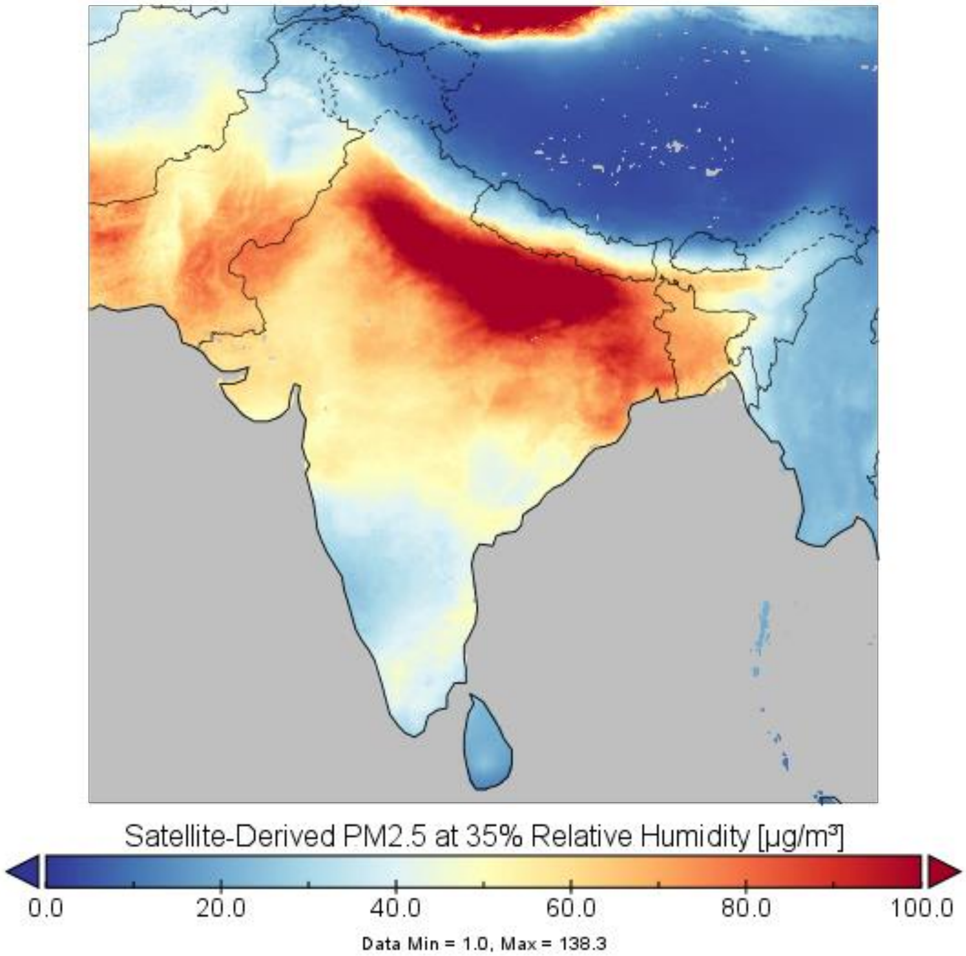

Figure 1. Annual surface $PM_{2.5}$ concentrations in South Asia for 2019. These $PM_{2.5}$ values were derived at 0.5° (~55 km) resolution from a combination of satellite data and modeling and include contributions from human activities, wildfires, dust, and sea salt (Hammer et al. 2020).

Section 2.0 of this report briefly discusses the importance of emissions inventories and their application in air quality assessment and planning. We use the Community Emissions Data System (CEDS)—an open-source global emission inventory—as an example to identify the key air pollutant sources for countries in South Asia. CEDS is one of the few country-level emission inventories that provide information about air pollution sources for all countries in the region. Section 3.0 outlines integrated modeling tools, which link policy analysis and air quality assessment models. We use a recent analysis of India as an example to illustrate the application of such tools for assessing linkages between policy, energy systems, climate, and air quality. Finally, Section 4.0 provides key recommendations for regional stakeholders aiming to improve air quality in South Asia.

2.0 Emission Inventories in South Asia

In this section, we provide an overview of emission inventories and their applications, along with a brief description of some commonly used global emission inventories. Subsequently, we explore the air quality assessment capabilities of emission inventories in detail using CEDS as an example (Section 2.1) for South Asian countries.

Emission inventories are datasets that contain detailed information on the amount of air pollutants produced by different sources (sector, fuel) within a specified geographical region (country, state, region). Comprehensive emission inventories play an important role in air pollution modeling, analysis, and policy formulation. Methodologies for developing inventory data range from the use of regional or global default assumptions to the extensive reporting and estimation systems in place for some countries.

Inventories provide a comprehensive breakdown of emission estimates, which is crucial in identifying targeted sectoral interventions and priority policy measures. In addition, emission inventories provide key input data to comprehensive integrated assessment models (IAMs)[2], Earth system models, and air quality dispersion models,[3] which are commonly used by policy makers and researchers to understand human exposure and risks, regional and local air quality implications of the current and proposed policies, and potential future energy and emissions developments (EPA, 2021).

International research and modeling projects utilize several global emission inventories for policy analysis. The Emission Database for Global Atmospheric Research (EDGAR) is a commonly used inventory that provides independent emission estimates of anthropogenic greenhouse gas (GHG) emissions (1970 to 2019) and air pollutants (1970 to 2015) at both national and global levels (EDGAR, 2021). Additionally, the ECLIPSE emissions inventory, derived largely from the GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model, estimates historical GHG and air pollutant emissions from 165 global regions and states/provinces in India and China at 5-year intervals (IIASA, 2021). The Global Fire Emissions Database (GFED) is also extensively used to obtain gridded emission estimates (1997 to 2016) attributed to forest and grassland fires and agricultural waste burning on fields. The GFED estimates are derived from a fusion of satellite data with models and provide information at 0.25^{o} (~27.75 km) global spatial resolution (GFED, 2021).

In this report, we highlight CEDS global emission inventory and identify the key sources of air pollution in South Asia. The CEDS emission inventory is publicly available as open-source data and software and is updated annually. The most recent release has published emission estimates from 1750 to 2019. The tool covers many air pollutants with the greatest health impacts and has a high level of sectoral detail. The CEDS emission estimates have been successfully validated against other existing global and regional emission inventories and is widely used (Hoesly et al. 2018, McDuffie et al. 2020, O'Rourke et al. 2021).

---

[2] IAMs are widely used to assess the feasibility of mitigation targets. These tools combine knowledge from multiple domains such as energy, food and agriculture, water, climate, economics, and policy to understand the linkages between human–Earth systems. Examples of IAMs include GCAM (Calvin et al. 2019), GAINS (Amann 2012), and AIM/CGE (Fujimori et al. 2017).

[3] Earth System Models are used to produce historical and long-term projections of climate change by modeling the interactions between atmosphere, ocean, and land systems (Heavens et al. 2013). Meanwhile, air quality dispersion models are used to estimate the dispersion pathway of air pollutants from point emission sources. These models find applications in evaluating the compliance to air quality standards by industrial facilities and power plants.

2.1 Community Emissions Data System

CEDS provides historical, gridded emissions for key pollutants for all countries in South Asia (Box 1). This data provides a comprehensive, open-source starting point to help countries understand their emission sources. It can also allow researchers in the region to conduct faster and more robust analysis of emission reduction options. Although the tool is global in scope, it provides detailed estimates for South Asian countries of interest, namely Bangladesh, Bhutan, India, Nepal, the Maldives, and Sri Lanka.

CEDS covers a range of air pollutants including sulfur dioxide (SO_2), nitrogen oxide (NO_x), black carbon (BC), organic carbon (OC), and ammonia (NH_3). This information can be readily used to estimate effective $PM_{2.5}$ emissions, which would otherwise be very time consuming to obtain from other sources. Figure 2 illustrates the relationship between effective $PM_{2.5}$ emissions and key air pollutants.

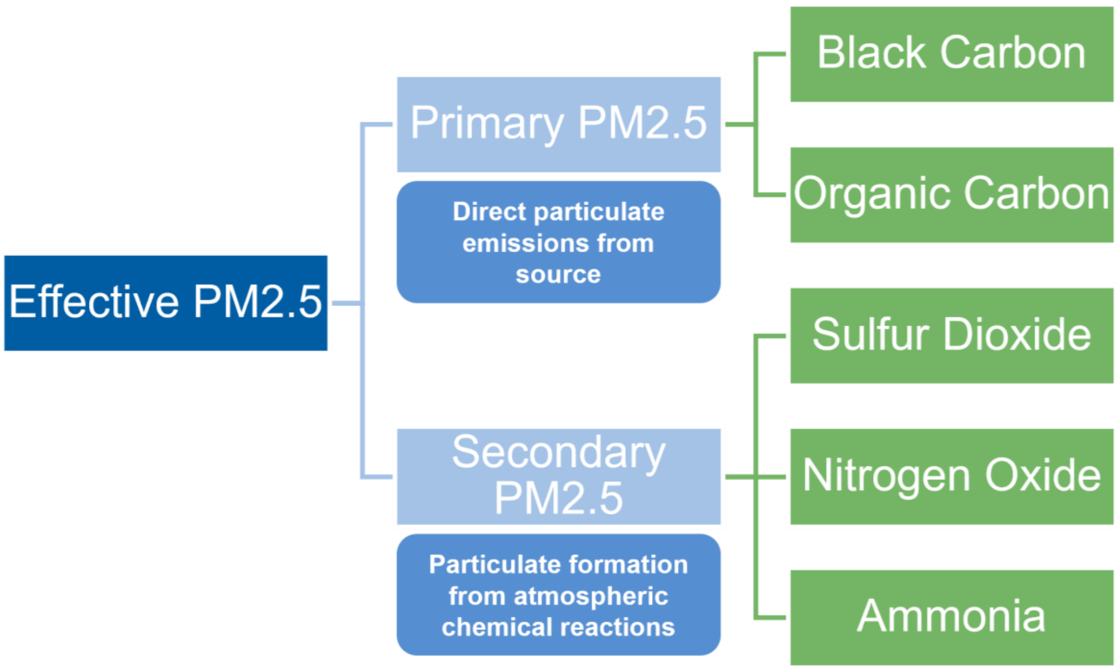

Figure 2. Derivation of the effective $PM_{2.5}$ emissions metric from precursor air pollutant emissions. Effective $PM_{2.5}$ is a metric that gives an indication of the total $PM_{2.5}$ in the atmosphere that would result from air pollutant emissions in a region. These emissions are a combination of primary $PM_{2.5}$ emissions (BC and OC) plus an estimate of the secondary $PM_{2.5}$ formed from precursor emissions (SO_2, NO_x, NH_3).

In this section, we use air pollution data from CEDS to identify the key sectors and fuels contributing to emissions in South Asia.[4] The air pollutants contributing to primary $PM_{2.5}$ (BC and OC) are discussed first, followed by the air pollutants contributing to secondary $PM_{2.5}$ (SO_2, NO_x, and NH_3). Finally, we discuss the effective $PM_{2.5}$ emissions estimated using CEDS air pollutant data and briefly discuss the policy options for mitigating these emissions.

[4] We use air pollutant data from the 2021 version of CEDS, specifically CEDS v2021_4_21. The data can be accessed from http://doi.org/10.5281/zenodo.4509372 (O'Rourke et al. 2021).

2.1.1 Black Carbon and Organic Carbon

BC and OC are small particles that make up much of the direct $PM_{2.5}$ in the atmosphere. These particulate aerosols are formed due to incomplete combustion of fuel and are directly emitted into the atmosphere (which is also called primary emission). Long-term exposure to BC and OC is detrimental to human health and causes respiratory infections, cardiovascular disease, lung damage, and premature death.

Biomass combustion from the residential sector is the largest source of BC and OC emissions in South Asia (Figure 3 and Figure 4). In particular, the use of traditional biomass for cooking and heating accounts for the largest share of BC and OC emissions in several countries of the region (India, Bangladesh, Nepal, and Bhutan). BC and OC emissions show a strong upward trend in Bangladesh and Nepal due to estimated increases in biomass consumption, and a steadily increasing trend is observed in Sri Lanka and Bhutan. Meanwhile, a gradual decline has been observed in India's BC and OC emissions since 2010, which is likely a result of Indian government initiatives focused on improving access to clean fuels and technologies for cooking. Nevertheless, there is significant scope to further reduce OC and BC emissions in the region.

The other important sources of BC and OC include road transport, industries, waste combustion, and open biomass burning.[5] Residential waste combustion and solid waste incineration are estimated to contribute a significant share of OC emissions in several South Asian countries (Sri Lanka, Bangladesh, the Maldives, and Bhutan). Similarly, BC emissions associated with road transportation are growing, especially in the Maldives, Bhutan, Sri Lanka, and Bangladesh. Over the last decade, OC and BC emissions from the power and industry sector have been growing in India and Sri Lanka.

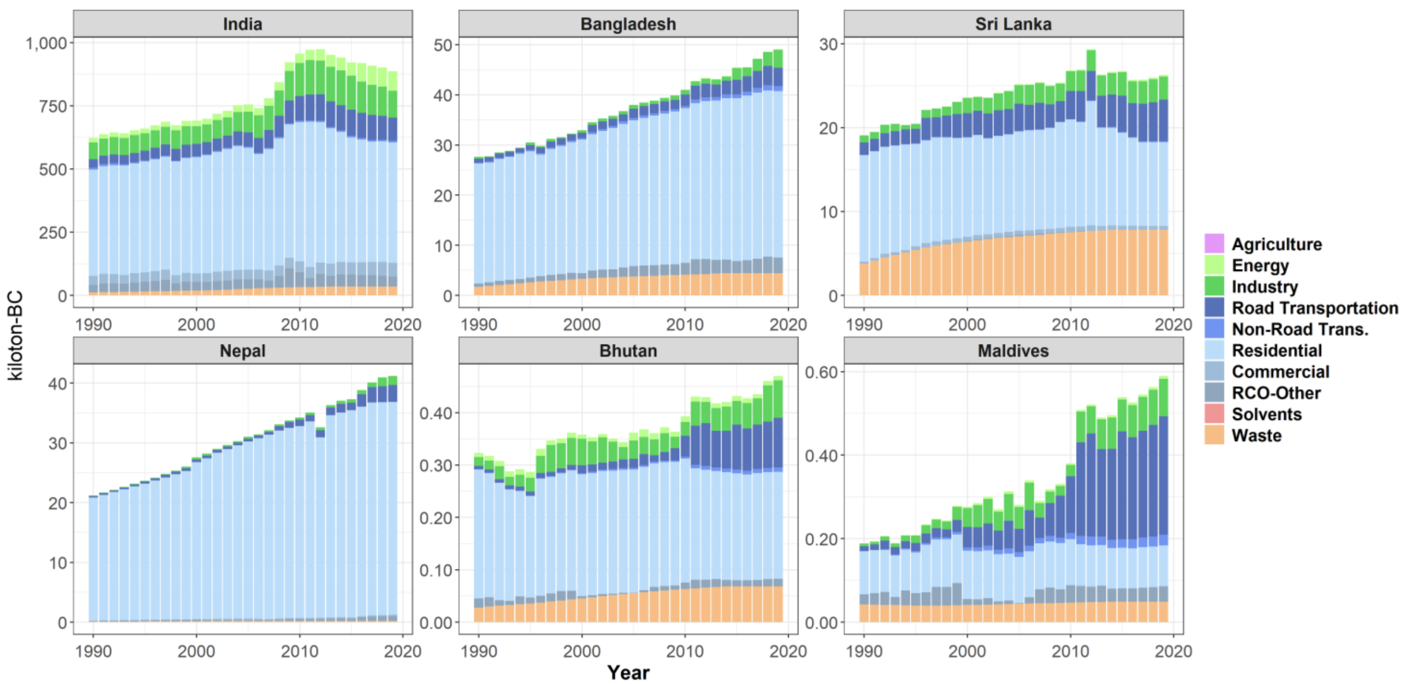

Figure 3. South Asia BC anthropogenic emissions by sector (1990 to 2019). In this figure, "residential and commercial – other" is abbreviated as the RCO-Other sector.

[5] Emissions from natural and human-induced biomass burning (forests, grasslands, agricultural residues) are an important additional source of OC and BC in South Asia. In 2015, these sources contributed to 10% and 20% of the total OC and BC in the region. Emissions from these sources are not included in CEDS, however, their contributions to total $PM_{2.5}$ can be obtained from GFED and van Marle et al (2017), and is illustrated in Figure 8.

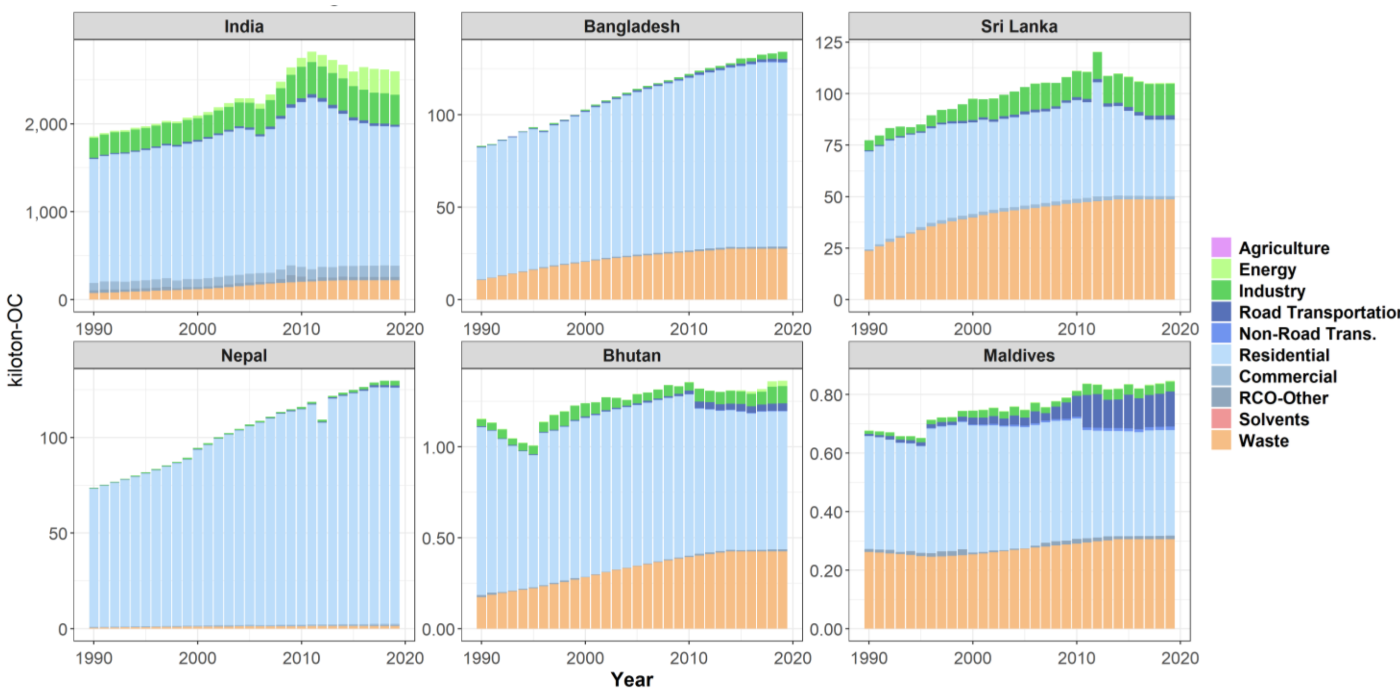

Figure 4. South Asia OC anthropogenic emissions by sector (1990 to 2019). The detailed breakdown of the aggregated CEDS sectors (as shown in the legend) is illustrated on page 373 of Hoesly et al. (2018).

2.1.2 Sulfur Dioxide

Elevated sulfur dioxide (SO_2) concentrations can cause burning in the nose and throat, breathing difficulties, airway obstruction, and lung damage, especially for sensitive populations (ATSDR, 2021). In addition, SO_2 undergoes chemical transformation in the atmosphere (along with NO_x and NH_3) and contributes to the formation of secondary $PM_{2.5}$. SO_2 also contributes to the formation of acid rain, which causes damage to the environment.

Over the last two decades, South Asian countries have experienced a rapid growth in SO_2 emissions, which occurred in parallel to economic development and industrialization (Figure 5). In 2019, the energy sector was the primary source of SO_2 emissions in India, Sri Lanka, and the Maldives. Meanwhile, Nepal, Bangladesh, and Bhutan had multiple important sources that changed in recent years. The industrial sector was one of the largest contributors in Nepal and Bangladesh and also accounted for a significant portion of SO_2 emissions in India. Within Bangladesh's industrial sector, SO_2 emissions were mainly attributed to non-metallic mineral manufacturing, such as brick and cement, whereas India's industrial emissions were largely from metal production (40%).

The fuel sources contributing to these emissions varied across South Asia. Hard-coal combustion was the single largest source of SO_2 emissions in India and Nepal, whereas hard coal and heavy oil together contributed to the majority of emissions in Bangladesh and Sri Lanka. In recent years, SO_2 emissions from diesel combustion in the transportation sector may have contributed to an increasing amount of SO_2 emissions in several South Asian countries (Bhutan, Nepal, Bangladesh, and Sri Lanka), although updated local information is needed to improve estimates.

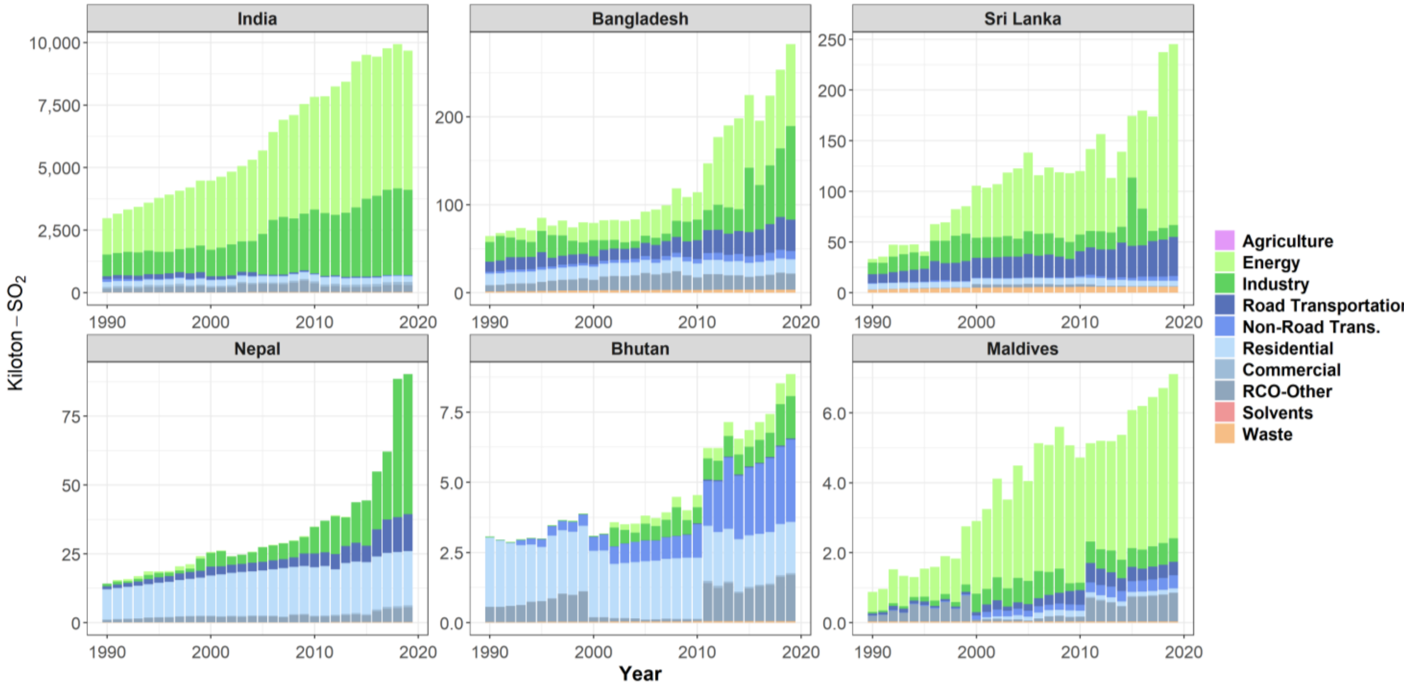

Figure 5. South Asia SO_2 emissions by sector (1990 to 2019).

2.1.3 Nitrogen Oxide

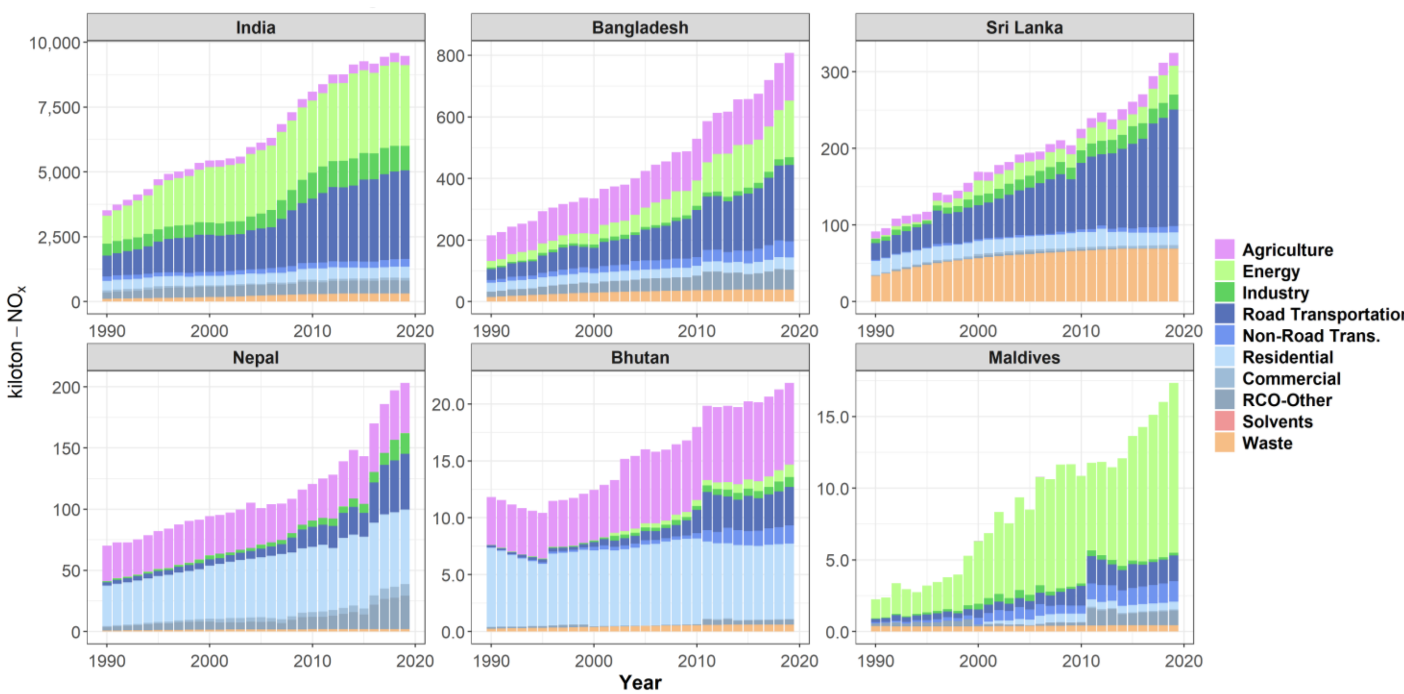

Figure 6. South Asia NO_x emissions by sector (1990 to 2019).

Long-term exposure to elevated nitrogen oxide (NO_x) concentrations increases the population's vulnerability to lung cancer, asthma, and respiratory infections. Furthermore, NO_x also contributes to the formation of acid rain and plays a role in the formation of tropospheric ozone (which is an air pollutant and a greenhouse gas). In 2019, NO_x emissions sources varied across individual countries in South Asia (Figure 6). In Nepal and Bhutan, biomass combustion from the residential sector and process emissions from the agricultural sector contributed to the majority of the NO_x emissions. In India, hard-coal combustion from the energy sector and diesel combustion from the road transportation sector accounted for the largest share of the country's NO_x emissions. Similarly, in the Maldives, the power and transport sectors were the leading NO_x emitters, with heavy oil combustion being the primary fuel source. Meanwhile, in Sri Lanka and Bangladesh, NO_x emissions from road transport accounted for over 40% of the total emissions, with remaining NO_x sources varying between these countries. While municipal waste combustion was a leading additional source in Sri Lanka, agriculture process emissions and gas-powered electricity generation both played an equal and important role in Bangladesh. Overall, South Asian countries' NO_x emissions have been on an upward trajectory since the year 2000, with emissions from road transport increasing in recent years.

2.1.4 Ammonia

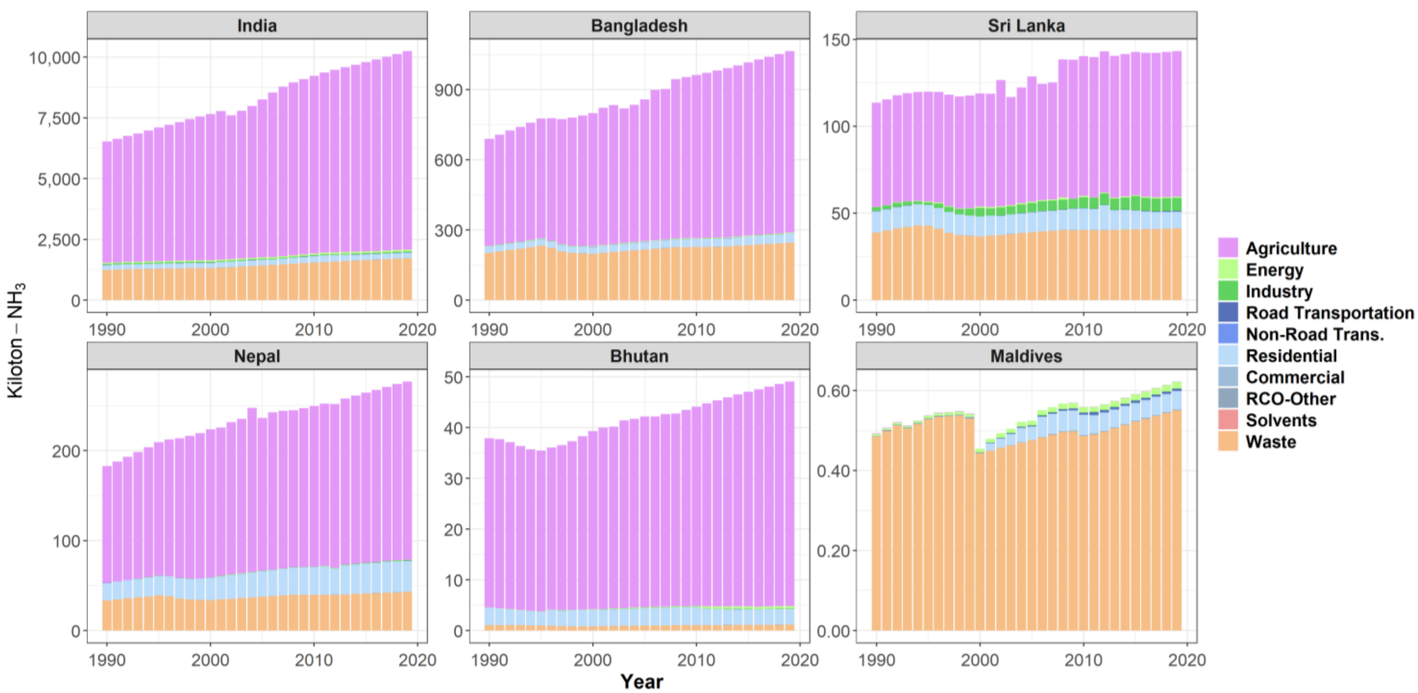

Figure 7. South Asia NH_3 emissions by sector (1990 to 2019).

Atmospheric NH_3 emissions contribute to the nutrient pollution of water bodies and to secondary $PM_{2.5}$ formation. Overall, NH_3 emissions are increasing substantially across South Asian countries (Figure 7). The agricultural sector is by far the largest source of NH_3 emissions in the region, with the majority of emissions coming from non-combustion processes associated with nitrogen-fertilized soils, cattle grazing, and manure management. In addition, wastewater handling (domestic and industrial) and untreated sewage contribute to a considerable portion of NH_3 emissions in India, Bangladesh, Sri Lanka, the Maldives, and Nepal, accounting for over 16% of the total NH_3 emissions in 2019.

2.1.5 Effective $PM_{2.5}$ Emissions

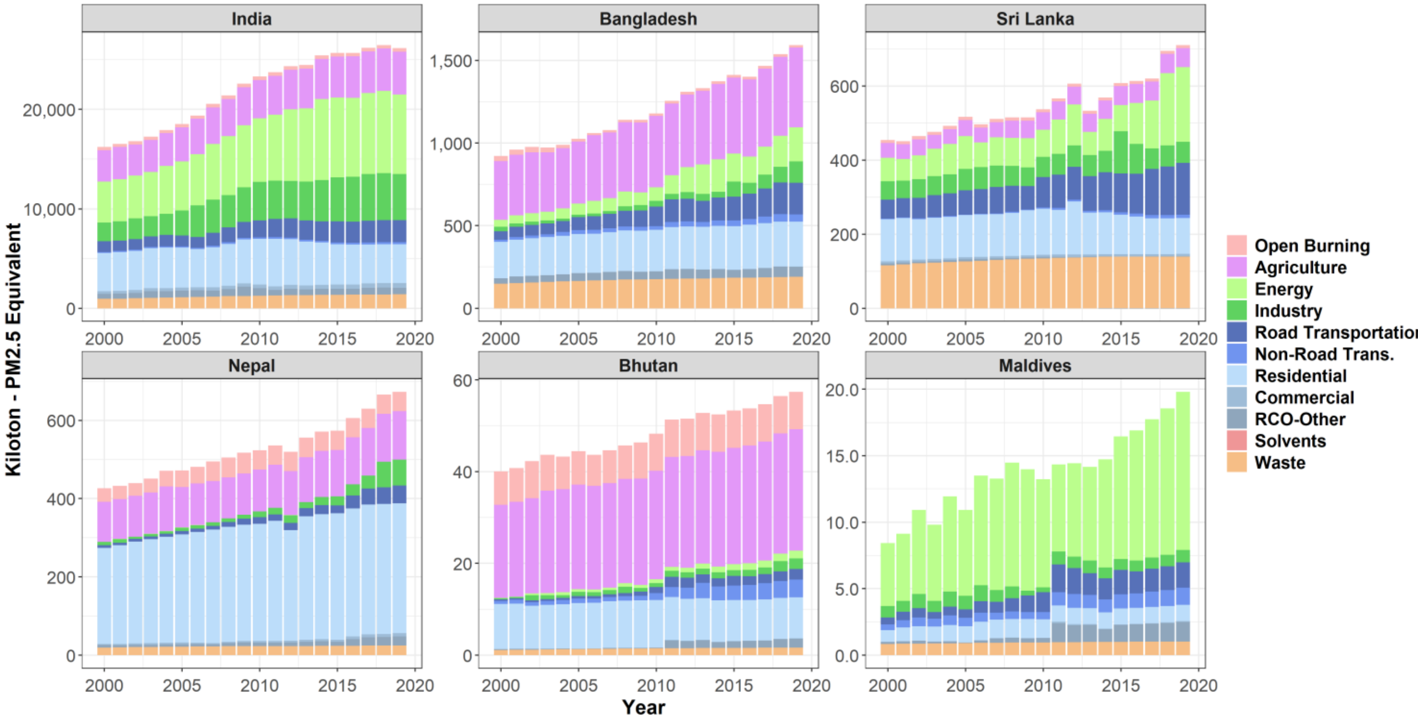

Figure 8. South Asia effective $PM_{2.5}$ emissions by sector (2000 to 2019). The effective $PM_{2.5}$ measure illustrates the relative contribution of different air pollutants that lead to the formation of $PM_{2.5}$ in individual countries. The effective $PM_{2.5}$ emissions are shown by sector for anthropogenic sources and for open biomass burning (which consists of a mix of natural and anthropogenic fires, including agricultural waste burning).

$PM_{2.5}$ is one of the most important pollutants from a human health perspective. However, understanding the $PM_{2.5}$ we breathe requires understanding the chemical precursors to $PM_{2.5}$. $PM_{2.5}$ in the atmosphere results from primary aerosol emissions plus secondary aerosol production. Primary emissions are particles directly emitted into the atmosphere, the main anthropogenic sources of which are which BC and OC. Secondary particles are formed from precursor gases such as SO_2, NO_2, and NH_3, which react in the atmosphere to form small particles. We use an equivalent $PM_{2.5}$ emissions metric (see Figure 2) to obtain a holistic view of the regional sources of $PM_{2.5}$ concentrations in the atmosphere.

Figure 8 illustrates the effective $PM_{2.5}$ emissions by sector calculated using information from CEDS and GFED (Smith et al. 2021). Effective $PM_{2.5}$ emissions are estimates of the total particulate matter that results from air pollutant emissions. This data provides insights into the air pollutant sources that contribute to high $PM_{2.5}$ concentrations in individual South Asian countries.

The figure highlights the important role of secondary emissions in the formation of $PM_{2.5}$. Overall, policy measures targeting the reduction of traditional biomass use in the residential sector can drastically lower direct $PM_{2.5}$ emissions of BC and OC, which are major contributors to air pollution across most South Asian countries. In addition, policies focused on reducing or regulating hard-coal combustion in the power and industrial sectors and diesel combustion in the transportation sector could drastically lower $PM_{2.5}$ concentrations in India and Sri Lanka. In Bangladesh, NH_3 emissions from agricultural processes and NO_x emissions from diesel-based road transport, agriculture, and natural gas power plants are significant $PM_{2.5}$

sources. Finally, in Nepal and Bhutan, policies focused on reducing traditional biomass consumption and agricultural process emissions could provide significant benefits. These countries could also undertake policy measures to reduce the growing SO_2 and NO_x emissions associated with industrialization and fossil fuel dependence.

Box 1: Community Emissions Data System

CEDS produces historical emission estimates for carbon-rich aerosols (BC and OC), anthropogenic air pollutants (CO, NH_3, NO_x, SO_2, and NMVOCs), and greenhouse gases (CO_2, CH_4, and N_2O) from the mid-18th century to the contemporary period (from 1970 for CH_4 and N_2O). CEDS emission estimates provide in-depth insights into national emission trends and can be used to identify key sectors and fuel sources of air pollution. The inventory data is also used to drive IAMs and energy-economy models, both of which play an integral role in air quality and climate change mitigation policy analysis (O'Rourke et al. 2021).

CEDS historical emissions are evaluated for 221 countries and territories across 55 sectors. The eight CEDS fuel types are hard coal, brown coal, coal coke, light oil, diesel oil, heavy oil, natural gas, and biomass. The 55 sectors are aggregated for display here into energy production; industry; solvents; transportation; residential, commercial, and other (RCO); agriculture; and waste. The principal output of CEDS are the annual average emission estimates of individual air pollutant species across countries, sectors, and fuel types, which are further processed to produce gridded emissions at 0.5^{o} resolution (~55 km) (Hoesly et al. 2018, McDuffie et al. 2020, JGCRI 2021).

The emission inventory system is publicly available (https://github.com/JGCRI/CEDS), and its emissions estimates are updated annually. The latest CEDS release (CEDS v2021_4_21, http://doi.org/10.5281/zenodo.4509372) provides emission estimates from 1750 to 2019. Although the tool is global in scope, it provides data for all the South Asian countries (O'Rourke et al. 2021).

We note that the energy consumption data used in CEDS can be uncertain, incomplete, or inconsistent across time for many of the countries considered in this report. This results in some discontinuities in emission estimates seen in some places in the figures. CEDS is built to allow users to amend or substitute improved, locally derived data, the use of which could improve estimates for the countries we focus on in this report.

3.0 Integrated Modeling Tools in South Asia: Linking Air Quality Assessment and Policy Analysis Tools

In this section, we briefly review the linkages between air pollution, sustainable development, and climate change mitigation policies and describe the importance of integrated modeling tools in addressing these complex multi-sectoral interactions. We then briefly highlight a study that uses integrated modeling tools to conduct policy analysis focusing on India (Section 3.1).

Air pollution, climate change, and sustainable development are complex environmental issues with synergies and trade-offs, requiring policy analysis that spans multiple economic sectors. Although certain policies such as SO_2 emissions control might be beneficial for improving the air quality of the region, they can lead to increased warming (because SO_2 contributes to cooling). Similarly, when not combined with other welfare policies, climate change mitigation policies such as an economy-wide carbon tax may contribute to the continued usage of traditional biomass for cooking and heating, exposing the population to harmful indoor air pollution. At the same time, certain air pollution control policies may have synergies with climate change mitigation policies and, in combination, could improve the total benefit across environmental domains. Understanding these advantages and disadvantages is one role of integrated modeling tools.

A common approach for integrated modeling of emissions and air quality is to link IAMs that conduct economy-wide system's analysis with air quality assessment models. These tools quantify the relationship between multiple human and environmental outcomes, such as air pollution, energy system transitions, climate change, human health, and sustainable development. These tools can support effective decision-making by allowing researchers and policymakers to better understand the synergies, trade-offs, and co-benefits of the interlinked outcomes. They can also help avoid policy outcomes that are counterproductive to, for example, either air pollution abatement or climate change mitigation.

Several historical studies have used integrated modeling tools to explore the linkages between energy, climate, air quality, and public health. Sampedro et al. (2020) combined an integrated assessment model (the Global Change Analysis Model [GCAM]) with the air quality assessment tool (Fast Scenario Screening Tool, TM5-FASST, Box 2) to assess the air pollution reductions and health co-benefits for different energy system pathways consistent with global climate targets. Similarly, Chafe et al. (2014) combined another integrated assessment model (GAINS) with TM5-FASST to estimate the concentrations of $PM_{2.5}$ and associated health impacts in several global regions, including South Asia.

The next section summarizes recent research conducted by Yarlagadda et al. (2021) focused on examining the "climate and air pollution implications of potential energy infrastructure and policy measures in India." This study serves as an example of how country-scale analyses can be conducted with available open-source data and tools.

3.1 Climate and Air Pollution Implications of Potential Energy Infrastructure and Policy Measures in India

Air pollution control and climate change mitigation policies when implemented together can significantly improve the overall air quality in South Asia. These policies are typically implemented across multiple parts of the energy sector (Section 2.2) and require a comprehensive assessment to understand the policy impacts on technology transitions, emission pathways, and public health. Integrated modeling tools play an important role in analyzing these relationships and provide useful information to stakeholders.

Yarlagadda et al. (2021) conducted an Indian climate change and air pollution analysis using publicly available integrated modeling tools. The study investigated the linkages between air pollution control and climate change mitigation by analyzing several policy scenarios with different levels of ambition and policy focus and the interaction between policies. The study used a scenario approach, which is a common method for exploring the potential future impact of sectoral policies and technological developments. The study demonstrated that both climate change and air pollution benefits can be maximized when GHG mitigation and air quality abatement policies are implemented together.

The analysis uses three modeling tools: (1) GCAM, which quantifies the energy system transitions and the associated GHG and air pollutant emissions in response to specific sectoral policy interventions; (2) Hector 2.0 (a simple climate model) integrated with GCAM, which evaluates the global warming outcomes for various policy scenarios; and (3) TM5-FASST (an air quality assessment tool), which was also coupled with GCAM emission estimates to calculate mean $PM_{2.5}$ and surface ozone concentrations at the country level. These tools could potentially also be used to conduct similar analyses for other South Asian countries.

Table 1. Policies implemented across policy dimensions (air pollution and GHG cases) and scenarios.

Policy Dimension	Reference Scenario	Ambitious Scenario
Air Pollution Controls (AP case)	Existing emission reduction plans are executed with some delay and partial implementation.	Ambitious emission reduction policies are executed across economy-wide sectors.
- Electricity Generation	Existing NO_x and SO_2 regulations are implemented with a decade of delay.	Existing NO_x and SO_2 regulations are implemented with 3 years of delay and are subsequently tightened.
- Transport	Low compliance of Bharat-VI vehicle emission standards (92% new vehicles).	High compliance of Bharat-VI vehicle emission standards (97% new vehicles).
- Industry	Delayed industry modernization.	Enhanced industry modernization and emission controls.
- Buildings	Slower access to clean cooking technologies.	Phase out of traditional biomass usage by 2050, and increase in the market penetration of liquified petroleum gas (LPG), and improved cookstoves.
Greenhouse Gas Pricing (GHG case)	No carbon price.	Economy-wide carbon price increasing steadily at 5% per year (53 $/t$CO_2$e by 2050).

Yarlagadda et al. (2021) developed “reference” and “ambitious” scenarios (based on the policy ambition) for air pollution control (AP case) and greenhouse gas reduction (GHG case) policy dimensions (Table 1). The policies in the AP case included several assumptions about technology, fuel, and emission standards across key sectors of the economy, including electricity generation, industry, transport, buildings, and agriculture. Meanwhile, the policy in the GHG case comprised an economy-wide carbon tax. The impact of the policy dimensions (AP and GHG cases) were analyzed both individually and in combination (the latter in another scenario called the GHG_AP case).

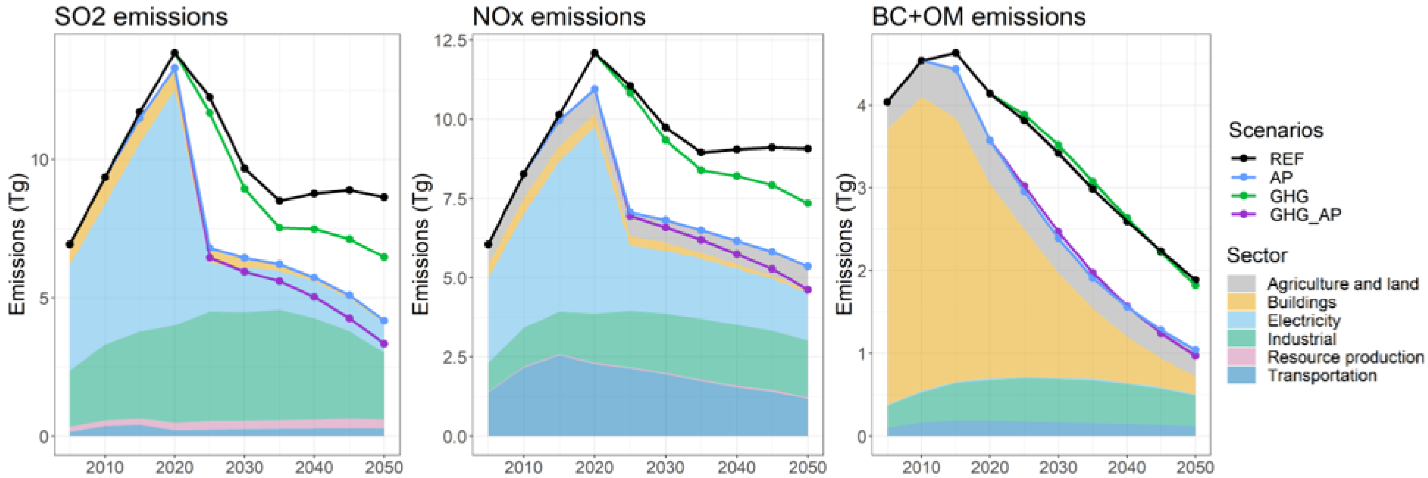

Figure 9. India's air pollutant emissions across policy scenarios. Significant reductions in SO_2, NO_x, and BC + organic matter (OM) emissions were observed in the AP case (blue line) relative to the GHG (green line) and reference cases (black line). When the GHG and AP cases were jointly implemented (GHG_AP case, purple line), the SO_2 and NO_x reductions increased further (Yarlagadda et al. 2021).

Considering conventional air pollution, emissions decrease even in the reference case under the assumption that current policies are implemented, albeit with some delay, and trends, such as shifts away from traditional biomass, continue. With enhanced stringency and implementation of policies as represented in the AP scenario, however, larger reductions in SO_2, NO_x, BC, and organic matter (OM)[6] were observed by 2050 (Figure 9). The reductions in SO_2 (64%) and NO_x (46% from 2015) were primarily driven by the immediate implementation and high compliance of the existing emission regulations in the Indian power sector. The significant decrease in BC and OM emissions was due to several factors, including uptake of clean cooking technologies in the residential sector, a transition away from coal in the commercial sector, and lower-emission coal-fired boilers in the industrial sector.

As a result of these air pollutant reductions, the mean $PM_{2.5}$ concentrations (estimated from TM5-FASST) decreased by 26% when compared to the reference. However, the net global warming impact (estimated from Hector) increased due to the drop in SO_2 and OM emissions, which otherwise would have contributed to cooling of the Earth's surface (Figure 10, blue dot).

Under the "ambitious" GHG policy scenario, major transformations occur in India's electricity and industrial sectors due to the application of an economy-wide carbon tax. A significant amount of coal generation is replaced by low-carbon technologies such as solar photovoltaics, wind, nuclear, and carbon capture and storage by 2050. In addition, there is wide-spread electrification of India's industrial sector and decreasing reliance on coal. Consequently, reductions in SO_2 (45%) and NO_x (28% from 2015) emissions are observed by 2050; however, these reductions are lower than those in the "ambitious" AP case. We note that a comprehensive GHG policy in isolation can slightly slow the phase out of traditional biomass as the cost of other energy sources increases. This leads to higher OM emissions in the short and medium terms and impedes access to modern energy, which is an important sustainable development indicator.

[6] OM is the total weight of primary organic particulate emissions. It is also common to report these emissions as OC (including elsewhere in this report), which are denominated in terms of the weight of carbon in the particle.

Overall, the "ambitious" GHG case has positive effects on both air quality and climate (Figure 10, green dot). However, the air quality benefits are lower than in the "ambitious" AP case. Although the net global warming impact decreases significantly due to drops in CO_2 emissions from coal use, mean $PM_{2.5}$ concentrations decrease by only 10% in the GHG case (compared to 26% in the AP case).

Finally, combining the AP and GHG scenarios leads to a larger reduction in air pollution than either scenario in isolation (Figure 10, purple dot). This is because the greenhouse gas policy measures help reduce a broad range of sources of $PM_{2.5}$ and its precursors. While the air pollution policies largely mitigate emissions attributed to traditional biomass in the residential and industry sectors, GHG policies also reduce emissions from coal usage in all sectors.

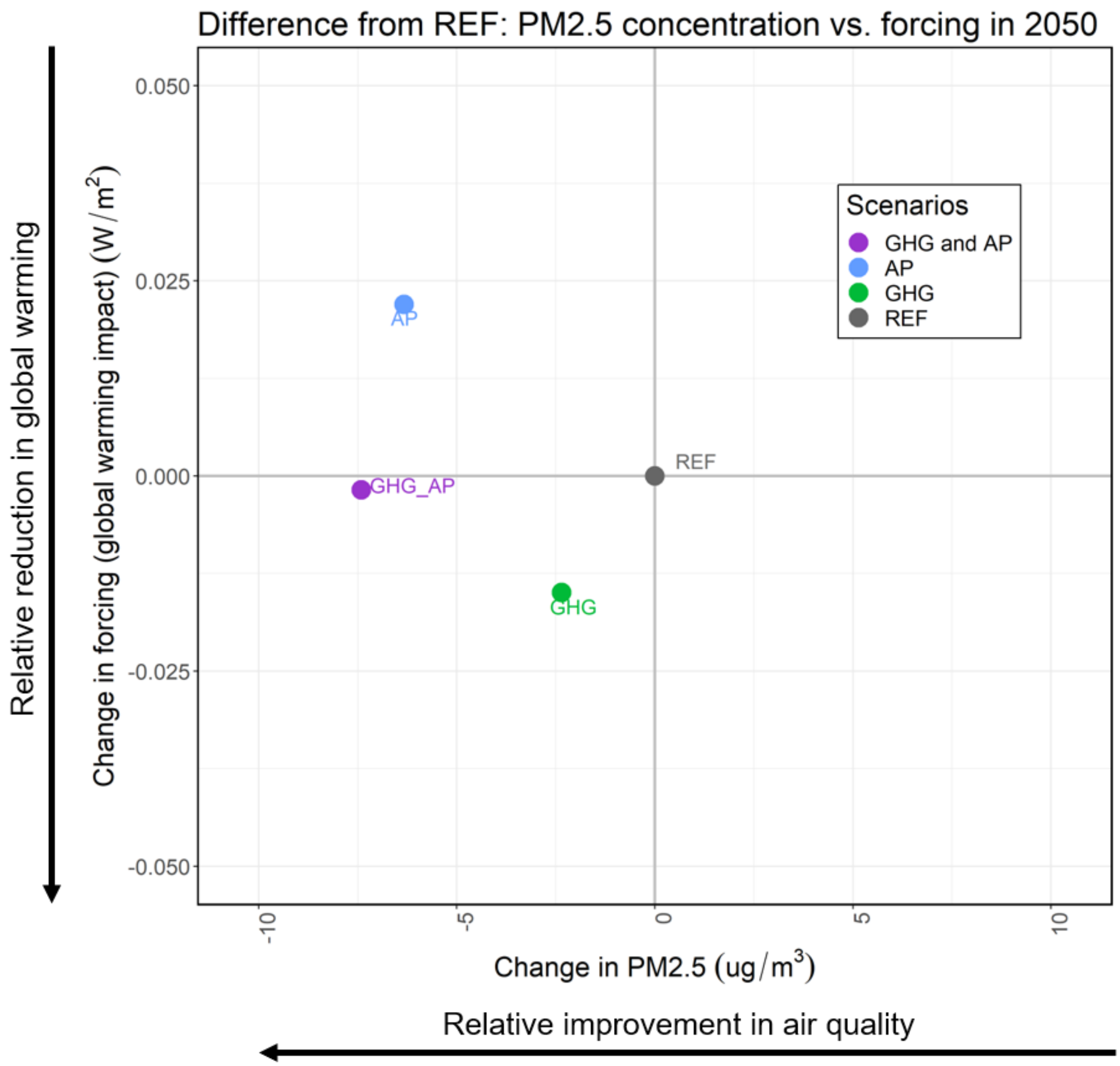

Figure 10. Air quality and climate implications of Indian policy scenarios. X-axis represents India's average $PM_{2.5}$ concentration (population-weighted) in 2050, and the Y-axis corresponds to radiative forcing (global warming impact) attributed to India in the same year, both relative to the reference scenario (REF). The results for the single AP and the GHG cases are shown in light blue and green respectively, whereas the results for the GHG and AP combination case (GHG_AP) are illustrated in purple.

Box 2: TM5-FASST

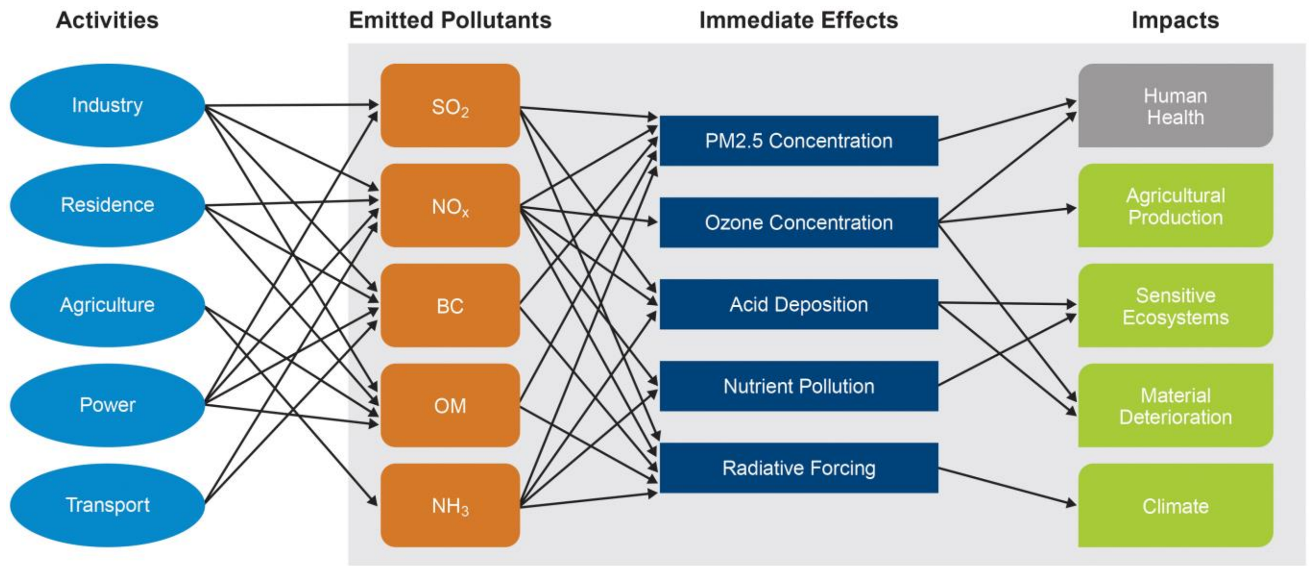

Figure 11. TM5-FASST model structure overview.

TM5-FASST is a global air quality assessment tool developed by the European Commission's Joint Research Centre. It estimates the concentrations of $PM_{2.5}$ and ozone in a geographical region, driven by the emissions of different precursors (SO_2, NO_x, OM, BC, NH_3) from different sources. Based on these concentration levels, the model also calculates the health impacts (premature mortalities) attributable to exposure of both $PM_{2.5}$ and ozone for five causes of death including ischemic heart disease, chronic obstructive pulmonary disease, stroke, lung cancer, and acute lower respiratory infection (Jerrett et al. 2009, Burnett et al. 2014, Forouzanfar et al. 2015).

TM5-FASST is specifically designed to compare different scenarios (emission pathways) in terms of pollutant concentrations and human health impacts at a global level in a flexible way without expensive computational requirements. Therefore, it can be easily applied to estimate the health co-benefits of reducing air pollutant emissions associated with a given global or regional climate policy.

Box 3: rfasst

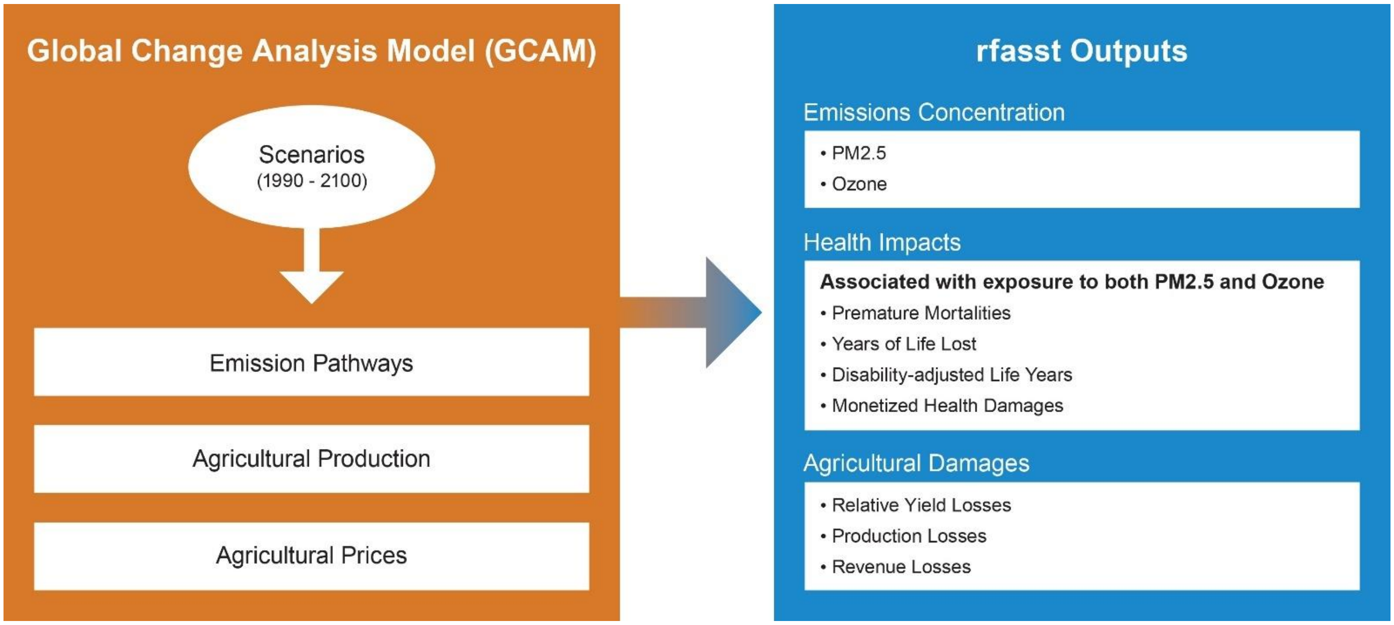

Figure 11. rfasst model framework. GCAM emission outputs (orange box) are processed using additional input information to estimate $PM_{2.5}$ and O_3 concentrations, along with health and agricultural indicators (blue box).

rfasst is an open-source R package that mimics the calculations of TM5-FASST (see Box 2) to estimate future human health and agricultural damages attributable to air pollution for any scenario run by GCAM. The package adds a new capability to the existing GCAM modeling framework, enabling estimation of co-benefits associated with different what-if scenarios, including socioeconomic narratives, air quality policies, or system-wide decarbonization strategies. The geographical (global and regional) and temporal (up to 2100) scales make the package potentially useful for a range of stakeholders, particularly those involved in the design of energy and environmental policies.

The package is divided in four modules that are easily modifiable, making the tool flexible for use in different modeling frameworks. rfasst is continually being developed to address different research objectives, and the documentation paper is under review in the *Journal of Open Source Software* (Sampedro et al., in review).

4.0 Recommendations

In this section, we provide recommendations for regional stakeholders aiming to improve air quality in South Asia. These recommendations focus on the applications of existing air quality tools, followed by important regional policy insights gathered from the prevailing air quality analyses. We also briefly discuss the importance of robust infrastructure to solve key data challenges and promote future research.

The several existing tools described in this brief can be used by policy makers and researchers to inform planning and to develop strategies for improving air quality in South Asia. Global emission inventories such as CEDS can provide valuable insights into historical air pollution sources and fuel contributions of individual countries in the region. This information can guide policy makers in identifying the high-impact sectoral strategies and air pollution abatement options across all South Asian countries. Meanwhile, integrated modeling tools such as GCAM and TM5-FASST can examine energy, air quality, and public health outcomes for a range of multi-sectoral policies in both the short and long term. These policies include vehicle and fuel emission standards, clean cooking initiatives, waste burning regulations, and air quality standards in the industrial and power sectors, among others. The findings from these tools can provide quantitative evidence to policy makers for understanding the impacts of mitigation policies at different levels of ambition and how they may lead to technology transitions.

Comprehensive policies across multiple sectors of the economy are required to improve air quality in South Asia. The sectors with the highest pollution abatement potential vary across individual countries in the region, as shown by CEDS emissions data (Section 2.0). Policies focused on reducing traditional biomass consumption for cooking and heating could substantially reduce the direct $PM_{2.5}$ emissions across all South Asian countries. Additionally, policies reducing or regulating coal usage in electricity generation and industry and diesel usage in road transportation can significantly reduce the total $PM_{2.5}$ emissions in India and Sri Lanka. Bangladesh could benefit greatly by reducing emissions from multiple important sectors (agriculture, electricity generation, and transportation). Nepal and Bhutan can attain substantial air quality improvements through targeted policies in the residential and agricultural sectors, along with preemptive policy measures to reduce fossil fuel dependence in the long term.

Combining air pollution and GHG mitigation policies can maximize the air quality benefits of South Asia while reducing the region's contribution to climate change. Currently, air pollution control policies largely focus on “end-of-the-pipe” solutions (e.g., SO_2 emissions standards in coal-fired power plants), whereas decarbonization strategies focus on low-carbon transitions in different sectors of the economy (e.g., increased share of renewable generation). Although countries across the world are taking actions to reduce air pollutants and GHG emissions concurrently, these actions are not always coordinated. Yarlagadda et al. (2021) shows that these issues are fundamentally connected, and when implemented together can provide maximum air quality benefits (Section 3.0). The study uses integrated modeling tools to assess the synergies and trade-offs between air quality and decarbonization policies, with the aim of coordinating and maximizing the benefits from both of these policy priorities.

Robust infrastructure is needed to set up future research and support policy making in South Asia. Enhanced data management efforts initiated by individual countries in the region would play an important role in improving the existing data and tools. Although the existing data and tools are well capable of conducting comprehensive policy analysis for South Asian countries, detailed information on local energy consumption and non-combustion processes would be helpful in improving the robustness of the current estimates. In parallel, policy makers could support initiatives for building stakeholder capacity in the region, with a focus on using existing data and tools for conducting future research. These initiatives could provide numerous prospects for investigating the future energy, climate, air pollution, agriculture, and public health implications of a suite of multi-sectoral policies whose findings could be incorporated into policy making.

5.0 Conclusions

South Asia records some of the highest air pollution levels globally, contributing to wide-ranging impacts on human health and the environment. A large portion of the region's population is exposed to high concentrations of $PM_{2.5}$ and precursor gases (SO_2, NO_x, NH_3), causing significant health issues upon long-term exposure. Reducing these harmful air pollution levels is one of the top regional priorities, which requires strategic planning and policy formulation.

Several publicly available tools can be used to conduct analyses and inform policy making for improving air quality in South Asia. These tools include emissions inventories such as CEDS and integrated modeling tools such as GCAM and TM5-FASST, which can be used obtain detailed policy insights at a country level. In particular, regional stakeholders can use emissions inventories to identify the major sources of air pollution in South Asian countries. Additionally, the stakeholders can apply integrated modeling tools to understand the impacts of potential policies on future energy infrastructure, air pollution, and climate change trends.

Existing air quality analysis also provides important policy insights for regional stakeholders. The CEDS emissions data highlights the need for comprehensive policies across multiple sectors of the economy in order to achieve substantial air pollution reduction. Combining these policies with climate change mitigation policies can further improve the overall air quality benefits in the region.

Finally, there is considerable scope to conduct future air quality and climate change analyses for South Asian countries. Policy makers may consider supporting capacity building efforts to utilize the existing tools and conduct robust air quality research for evidence-based policy making. In addition, policy makers may wish to support enhanced data management efforts, which will be crucial to improve the available data and analyses for future research.

6.0 References

Amann, Markus. "The GAINS Integrated Assessment Model." (2012).

ATSDR. "Agency for Toxic Substances and Disease Registry ToxFAQs". Accessed November 11, 2021. https://www.atsdr.cdc.gov/toxfaqs/tfacts116.pdf

Balakrishnan, Kalpana, Sagnik Dey, Tarun Gupta, R. S. Dhaliwal, Michael Brauer, Aaron J. Cohen, Jeffrey D. Stanaway et al. "The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: the Global Burden of Disease Study 2017." The Lancet Planetary Health 3, no. 1 (2019): e26-e39.

Burnett, R.T., Pope III, C.A., Ezzati, M., Olives, C., Lim, S.S., Mehta, S., Shin, H.H., Singh, G., Hubbell, B., Brauer, M. and Anderson, H.R., 2014. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. Environmental health perspectives, 122(4), pp.397-403.

Burney, Jennifer, and V. Ramanathan. "Recent climate and air pollution impacts on Indian agriculture." Proceedings of the National Academy of Sciences 111, no. 46 (2014): 16319-16324.

Calvin, Katherine, Pralit Patel, Leon Clarke, Ghassem Asrar, Ben Bond-Lamberty, Ryna Yiyun Cui, Alan Di Vittorio et al. "GCAM v5. 1: representing the linkages between energy, water, land, climate, and economic systems." Geoscientific Model Development 12, no. 2 (2019): 677-698.

Chafe, Zoë A., et al. "Household cooking with solid fuels contributes to ambient PM2. 5 air pollution and the burden of disease." Environmental health perspectives 122.12 (2014): 1314-1320.

EDGAR. "Emissions Database for Global Atmospheric Research." Accessed October 12, 2021. https://edgar.jrc.ec.europa.eu/.

EPA. Environmental Protection Agency. Accessed October 12, 2021. https://www.epa.gov/air-quality-management-process/managing-air-quality-emissions-inventories.

Forouzanfar, M.H., Afshin, A., Alexander, L.T., Anderson, H.R., Bhutta, Z.A., Biryukov, S., Brauer, M., Burnett, R., Cercy, K., Charlson, F.J. and Cohen, A.J., 2016. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. The lancet, 388(10053), pp.1659-1724.

Fujimori, Shinichiro, Toshihiko Masui, and Yuzuru Matsuoka. "AIM/CGE V2. 0 model formula." In Post-2020 Climate Action, pp. 201-303. Springer, Singapore, 2017.

GFED. "Global Fire Emissions Database." Accessed October 12, 2021. https://www.globalfiredata.org/.

Hammer, Melanie S., Aaron van Donkelaar, Chi Li, Alexei Lyapustin, Andrew M. Sayer, N. Christina Hsu, Robert C. Levy et al. "Global estimates and long-term trends of fine particulate matter concentrations (1998–2018)." Environmental Science & Technology 54, no. 13 (2020): 7879-7890.

Heavens, Nicholas G., Daniel S. Ward, and M. M. Natalie. "Studying and projecting climate change with earth system models." Nature Education Knowledge 4, no. 5 (2013): 4.

Hoesly, Rachel M., Steven J. Smith, Leyang Feng, Zbigniew Klimont, Greet Janssens-Maenhout, Tyler Pitkanen, Jonathan J. Seibert et al. "Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS)." Geoscientific Model Development 11, no. 1 (2018): 369-408.

IIASA. "Global Emission Fields of Air Pollutants and Ghgs." Accessed October 12, 2021. https://iiasa.ac.at/web/home/research/researchPrograms/air/Global_emissions.html.

IQ Air. "2019 WORLD AIR QUALITY REPORT", 2020. Retrieved from https://www.iqair.com/world-most-polluted-cities/world-air-quality-report-2019-en.pdf

Jerrett, M., Burnett, R.T., Pope III, C.A., Ito, K., Thurston, G., Krewski, D., Shi, Y., Calle, E. and Thun, M., 2009. Long-term ozone exposure and mortality. New England Journal of Medicine, 360(11), pp.1085-1095.

JGCRI. "A Community Emissions Data System (CEDS) for Historical Emissions." Joint Global Change Research Institute. Accessed October 12, 2021. http://www.globalchange.umd.edu/ceds/.

Krishna, Bhargav, Kalpana Balakrishnan, Amna R. Siddiqui, Bilkis A. Begum, Damodar Bachani, and Michael Brauer. "Tackling the health burden of air pollution in South Asia." bmj 359 (2017).

Lovett, Gary M., Timothy H. Tear, David C. Evers, Stuart EG Findlay, B. Jack Cosby, Judy K. Dunscomb, Charles T. Driscoll, and Kathleen C. Weathers. "Effects of air pollution on ecosystems and biological diversity in the eastern United States." Annals of the New York Academy of Sciences 1162, no. 1 (2009): 99-135.

McDuffie, Erin E., Steven J. Smith, Patrick O'Rourke, Kushal Tibrewal, Chandra Venkataraman, Eloise A. Marais, Bo Zheng, Monica Crippa, Michael Brauer, and Randall V. Martin. "A global anthropogenic emission inventory of atmospheric pollutants from sector-and fuel-specific sources (1970–2017): an application of the Community Emissions Data System (CEDS)." Earth System Science Data 12, no. 4 (2020): 3413-3442.

Murray, Christopher JL, Aleksandr Y. Aravkin, Peng Zheng, Cristiana Abbafati, Kaja M. Abbas, Mohsen Abbasi-Kangevari, Foad Abd-Allah et al. "Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019." The Lancet 396, no. 10258 (2020): 1223-1249.

Nandasena, Sumal, Ananda R. Wickremasinghe, and Nalini Sathiakumar. "Respiratory health status of children from two different air pollution exposure settings of Sri Lanka: A cross-sectional study." American journal of industrial medicine 55, no. 12 (2012): 1137-1145.

Natarajan, Narayanan, Mangottiri Vasudevan, Senthil Kumar Dineshkumar, Sivakkumar Shiva Nandhini, and Pandiyan Balaganesh. "Effects of air pollution on monumental buildings in India: An overview." Environmental Science and Pollution Research (2021): 1-10.

OECD, Organization for Economic Co-operation and Development. "Exposure to PM2.5 in Countries and Regions - OECD Statistics." Accessed January 4, 2022. https://stats.oecd.org/Index.aspx?DataSetCode=EXP_PM2_5.

O'Rourke, P. R, Smith, S. J., Mott, A., Ahsan, H., McDuffie, E. E., Crippa, M., Klimont, S., McDonald, B., Z., Wang, Nicholson, M. B, Feng, L., and Hoesly, R. M. (2021, April 21). CEDS v-2021-04-21 Emission Data 1975-2019 (Version Apr-21-2021). Zenodo. http://doi.org/10.5281/zenodo.4509372.

Priyankara, Sajith, Mahesh Senarathna, Rohan Jayaratne, Lidia Morawska, Sachith Abeysundara, Rohan Weerasooriya, Luke D. Knibbs, Shyamali C. Dharmage, Duminda Yasaratne, and Gayan Bowatte. "Ambient PM2. 5 and PM10 Exposure and Respiratory Disease Hospitalization in Kandy, Sri Lanka." International journal of environmental research and public health 18, no. 18 (2021): 9617.

Sampedro, J., Khan, Z., Vernon, C.R., Smith, S.J., Waldhoff, S., Van Dingenen, R. rfasst: An R tool to estimate air pollution impacts on health and agriculture. Journal of Open Source Software. Under review.

Sampedro, Jon, et al. "Health co-benefits and mitigation costs as per the Paris Agreement under different technological pathways for energy supply." Environment international 136 (2020): 105513.

Smith S.J., E. McDuffie, and M.M. Charles. 2021. "Accounting for Emissions: Inventories for Climate Forcers and Air Pollutants." (in prep for submission to Atmospheric Chemistry and Physics).

UNEP. “Maldives Gets out Ahead of Air Pollution.”, 2019. Retrieved from https://www.unep.org/news-and-stories/story/maldives-gets-out-ahead-air-pollution.

Van Marle, Margreet JE, Silvia Kloster, Brian I. Magi, Jennifer R. Marlon, Anne-Laure Daniau, Robert D. Field, Almut Arneth et al. "Historic global biomass burning emissions for CMIP6 (BB4CMIP) based on merging satellite observations with proxies and fire models (1750–2015)." *Geoscientific Model Development* 10, no. 9 (2017): 3329-3357.

Von Schneidemesser, Erika, Paul S. Monks, James D. Allan, Lori Bruhwiler, Piers Forster, David Fowler, Axel Lauer et al. "Chemistry and the linkages between air quality and climate change." Chemical Reviews 115, no. 10 (2015): 3856-3897.

WHO – World Health Organization. Global air quality guidelines. “Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide”. 2021. License: CC BY-NC-SA 3.0 IGO.

Yamamoto, S. S., R. Phalkey, and A. A. Malik. "A systematic review of air pollution as a risk factor for cardiovascular disease in South Asia: Limited evidence from India and Pakistan." International journal of hygiene and environmental health 217, no. 2-3 (2014): 133-144.

Yarlagadda, Brinda, Steven J. Smith, Bryan K. Mignone, Dharik Mallapragada, Cynthia A. Randles, and Jon Sampedro. "Climate and air pollution implications of potential energy infrastructure and policy measures in India." Energy and Climate Change (2021): 100067.

Monali Hazra
U.S. Agency for International Development
Email: mhazra@usaid.gov

Meredydd Evans
Pacific Northwest National Laboratory
Email: m.evans@pnnl.gov

The South Asia Group for Energy (SAGE) is a consortium comprising USAID, the United States Department of Energy and three national laboratories: the Pacific Northwest National Laboratory (PNNL), the Lawrence Berkeley National Laboratory (LBNL), and the National Renewable Energy Laboratory (NREL). The consortium represents excellence in research and international development in the energy sector to advance the Asia Enhancing Development and Growth through Energy (Asia EDGE) priorities in the South Asia region.