What is Polluting India's Air?

The Need for an Official Air Pollution Emissions Database

Tanushree Ganguly, Adeel Khan, and Karthik Ganesan

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PM2.5, NO_x, SO_2 and CO emissions in India are on the rise.

Image: Alamy

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Council on Energy, Environment and Water
Sanskrit Bhawan, A-10 Qutab Institutional Area,
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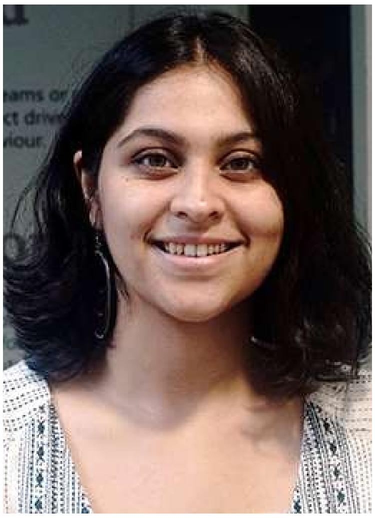
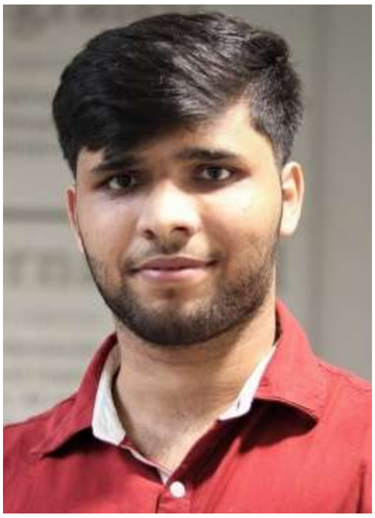
The authors



Tanushree Ganguly
tanushree.ganguly@ceew.in

A Programme Lead at The Council, Tanushree's research focuses on assessing potential alternative methods for monitoring air quality, and understanding and addressing current regulatory challenges for the effective implementation of clean air policies. She has a master's degree in environmental engineering from the Georgia Institute of Technology and is a certified engineer-in-training under California law.

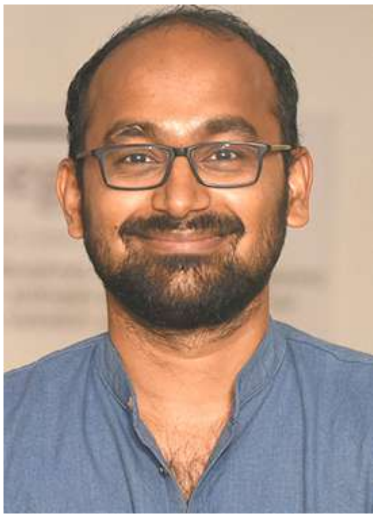
"The absence of a periodically updated national emission database is a significant lacuna in India's air quality management framework. The wide variation in existing estimates for India's criteria pollutant emissions highlights the need to standardize data collection and reporting protocols and develop a comprehensive database of representative emission factors."



Adeel Khan
adeel.khan@ceew.in

A Research Analyst at The Council, Adeel uses air quality data from monitoring stations, satellite retrievals, and model outputs, to recommend policy-making decisions. He holds a master's degree in environmental science and resource management from TERI School of Advanced Studies and a bachelor's degree in physical sciences from St Stephen's college, Delhi.

"Emission inventories play a crucial role in setting emission reduction targets and evaluating policy measures. In this study, we find there is a large variation across emission inventories due to underlying assumptions, use of different activity data and emission factors. Hence, there is a need for a centralized and up-to-date emission inventory for the country."



Karthik Ganesan
karthik.ganesan@ceew.in

Karthik is a Fellow and Director, Research Coordination, at The Council. He has been analysing energy and linkages to the economy for the past seven years, and his current work is focused on cost-effective power generation options for discoms, understanding the environmental impact of power generation, and the role of energy efficiency in industrial production. He has a BTech and an MTech in civil engineering from IIT Madras and a master's degree in Public Policy from the National University of Singapore.

"The focus on source apportionment, without a widely accepted emissions inventory does little to help gauge the dynamic nature of polluting sources. Egregious sources can be identified and their impact quantified, if there is a public and widely accepted emissions inventory."

China and India are the leading emitters of $PM_{2.5}$ in the world. While China's $PM_{2.5}$ emissions are declining, India's emissions are on the rise.

Image: iStock

Contents

Acronyms

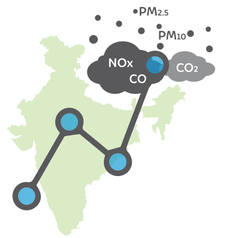
AWB	agricultural waste burning
BS	Bharat Stage
Caltrans	California Department of Transportation
CARB	California Air Resources Board
CEA	Central Electricity Authority
CMA	Cement Manufacturers Association
CO	carbon monoxide
CPCB	Central Pollution Control Board
ECLIPSE	Evaluating the CLimate and Air Quality ImPacts of Short-livEd Pollutants
EDGAR	Emissions Database for Global Atmospheric Research
EEA	European Environment Agency
EF	emission factor
EMEP	European Monitoring and Evaluation Programme
FAI	Fertilizer Association of India
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
HDT	heavy duty trucks
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IIT	Indian Institute of Technology
IRF	International Road Federation
LPG	liquefied petroleum gas
MARKAL	Market Allocation energy system model
MoC	Ministry of Coal
MoEFCC	Ministry of Environment, Forest and Climate Change
MoPNG	Ministry of Petroleum and Natural Gas
NAAQS	National Ambient Air Quality Standards
NCAP	National Clean Air Programme
NEC	national emission ceilings
NEMMP	National Electric Mobility Mission Plan
NIES	National Institute for Environmental Studies, Japan
NKN	National Knowledge Network
NSSO	National Sample Survey Office
OECD	Organisation for Economic Co-operation and Development
PM	particulate matter
PMUY	Pradhan Mantri Ujjwala Yojana
PPAC	Petroleum Planning & Analysis Cell
REAS	Regional Emission Inventory in Asia
RSD	relative standard deviation
SBM	Swachh Bharat Mission
SMoG	Speciated Multipollutant Generator
SO_2	sulphur dioxide
TERI	The Energy and Resources Institute
UCA	Unnat Chulha Abhiyan
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
UNSTAT	United Nations Statistics Division
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WEF	World Economic Forum

Formulation of a national emission inventory is one of the primary components of India's *National Clean Air Programme* (NCAP).

Image: Recreated from the NCAP

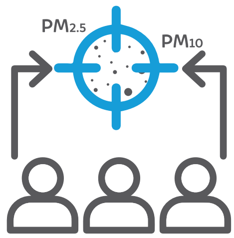
Executive summary

India has one of the highest burdens of emissions of particulate matter (PM), sulphur dioxide (SO_2), and carbon monoxide (CO) in the world; second only to China (Crippa et al. 2018). Multiple sources suggest that India's $PM_{2.5}$ emissions have grown significantly in the last three decades (Crippa et al. 2018, Venkataraman et al. 2018). In response to India's rising air pollution, the Indian Government has taken numerous interventions including the introduction of the Swachh Bharat Mission (SBM) to improve solid waste management, the Pradhan Mantri Ujjwala Yojana (PMUY) and Unnat Chulha Abhiyan (UCA) to promote improved cook stoves and clean fuel, the National Electric Mobility Mission Plan (NEMMP) to scale up the adoption of zero-emission vehicles, and the accelerated introduction of Bharat Stage (BS) VI fuel in the country (Swachh Bharat Urban 2021; PMUY 2021; Gulati 2012; Baggonkar and Modi 2016; PIB 2018). More recently, India's Ministry of Environment, Forest and Climate Change (MoEFCC) launched the National Clean Air Programme (NCAP) with the goal to ensure that India meets its National Ambient Air Quality Standards (NAAQS) within a stipulated time frame (Sundaray and Bhardwaj 2019).



While estimates for India's emissions exist, they vary significantly at both the aggregate level and for sectoral contributions

While numerous estimates have modelled pollutant emissions from India, there is a dearth of studies that capture the impact of the aforementioned interventions on India's emission burden. This could in part be attributed to the absence of an official air pollution emission inventory for India. While estimates for India's emissions exist, they vary significantly at both the aggregate level and for sectoral contributions. Notwithstanding the variations in estimates, the different assessments agree on the leading emitters and highlight the need for priority action on point sources like industries and power plants, while also highlighting the significant burden that households face by way of emissions originating from solid fuel use. The variability does not affect our ability to plan for achieving the *National Clean Air Programme* (NCAP) target for reducing particulate concentrations by 20 to 30 per cent by 2024. However, it increases the uncertainty in assessing impacts of various interventions and prioritising action for various parts of the country.



The variability does not affect our ability to plan for achieving the National Clean Air Programme target for reducing particulate concentrations by 20-30% by 2024

One of the major criticisms of the NCAP has been its failure to specify sectoral emission reduction targets. To set sectoral emission reduction targets it is crucial to understand the extent to which the different polluting sectors contribute to ambient air pollution. Given the variations in the existing estimates, it is difficult to conclusively determine the relative share of sources to India's emission burden. To illustrate the extent of variations across these estimates, we compared criteria pollutants ($PM_{2.5}$, PM_{10}, NO_x , SO_2 and CO) emission estimates from three global emission inventories, including EDGAR, ECLIPSE, REAS and two domestic inventories - SMoG and TERI. EDGAR, ECLIPSE, REAS and SMoG are multi-year inventories and 2015 is the latest year for which all of them provide estimates. The TERI inventory estimates emissions for 2016. Here's what we find in our study.

Total emissions vary within 25 per cent for all pollutants except PM10

The relative standard deviation (RSD)[1] for total emissions for all pollutants, except PM10, fall within 25 per cent (Table ES1). For PM10, the RSD was found to be 37 per cent, owing largely to the higher PM10 estimates in TERI's inventory. TERI's PM10 emissions are higher than the other inventories as it takes urban fugitive dust into account, while others do not. SMoG includes dust as a sector but does not report PM10 emissions.

Database	PM2.5	PM10	NOx	SO2	CO
EDGAR	6154	9645	10420	11480	73195
ECLIPSE	6747	8937	8772	7331	56709
REAS	4906	6960	9741	10866	62622
SMoG	7693	NA	7475	8366	71869
TERI	7316	16210	8500	10033	43132
RSD (%)	**17**	**37**	**12**	**18**	**21**

Table ES1
PM10 emission estimates (Kt/year) vary by 37 per cent across the five inventories

Source: Authors' analysis; Data from EDGAR, ECLIPSE, REAS, SMoG and TERI

Sectoral emission estimates are noticeably different

While the variations at an aggregate level are not too large, we observe significant variations in emission estimates across sectors and pollutants (Figure ES1). This level of variation can impact modelled concentration of pollutants through the use of chemical transport models, as the transformation and transport of pollutants from different sources will vary. Therefore, the observed variations in emission estimates call for a closer look at the underlying activity data and emission factors that were used to arrive at these estimates.

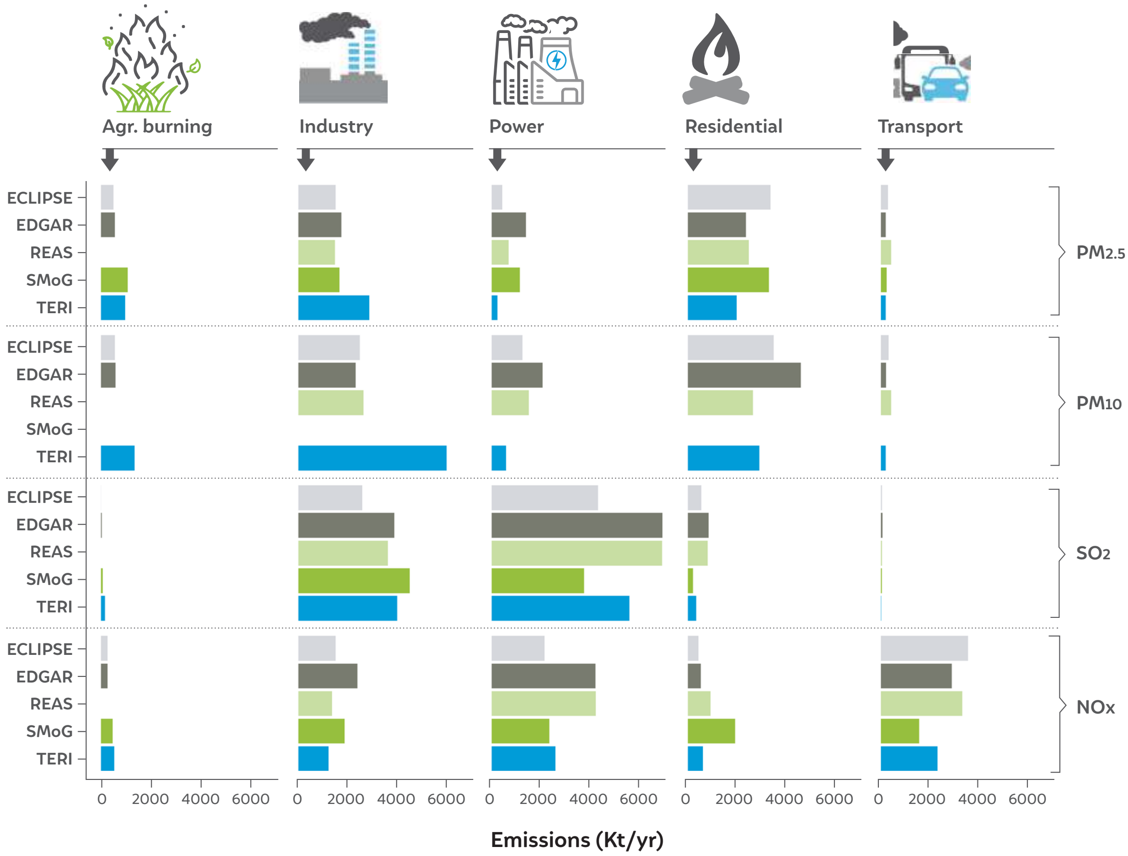


Figure ES1
Highest variations in estimated emissions from power plants, transport and agricultural residue burning

Source: Authors' analysis; Data from EDGAR, ECLIPSE, REAS, SMoG and TERI

1. RSD is defined as the ratio of standard deviation to the mean and is used to define the extent of variability in relation to the mean.

Sectoral contributions differ greatly

Across the different inventories, the residential sector is seen to be the leading emitter of $PM_{2.5}$ emissions, with contributions ranging from 27 to 50 per cent. The power sector is the leading emitter of SO_2 emissions across the five inventories, with contributions ranging from 44 to 62 per cent. This is on account of the significant share of coal that is consumed in power generation. The power sector is also the leading emitter of NO_x emissions, with its contribution ranging from 24 to 43 per cent. While the contribution of households to primary $PM_{2.5}$ emissions is highest, it must be noted that large point sources such as such as coal-based power plants and industrial units contribute a large share of $PM_{2.5}$ through secondary particulate matter, which is a result of the transformation of SO_x and NO_x emissions from gas form to particle form. A recent study estimates that the contribution of secondary particulate matter from coal-based power plants could be as high as 80% of total particulate matter attributable to power plants (Cropper et al. 2021).

Emissions from industries were found to be the second largest source of $PM_{2.5}$, PM_{10} and SO_2 emissions

Industrial production stands as the second largest source of most of the criteria pollutants that were assessed and when combined with power plants, represent a possibly the largest and most easily targeted source of emissions for policy makers and regulators to address. They are large point sources and finite in number. Particulate pollution arising from solid fuel use in households is distributed across the length and breadth of the country and much harder to abate, as it involves interventions that target both affordability of cleaner fuels and affecting behaviour change to move populations away from the use of free of cost biomass in many pockets.

Table ES2
Sectoral contributions to emissions vary significantly

Pollutant	Residences (%)	Power (%)	Industry (%)
$PM_{2.5}$	27-50	3-22	21-38
PM_{10}	18-46	3.5-21	23-37
NO_x	5-25	24-43	14-24
SO_2	2.5-7.5	44-62	32-53
CO	40-61	0.4-1.0	12-27

Source: Authors' analysis; Data from EDGAR, ECLIPSE, REAS, SMoG and TERI

Variations at the national level are also reflected at the state level

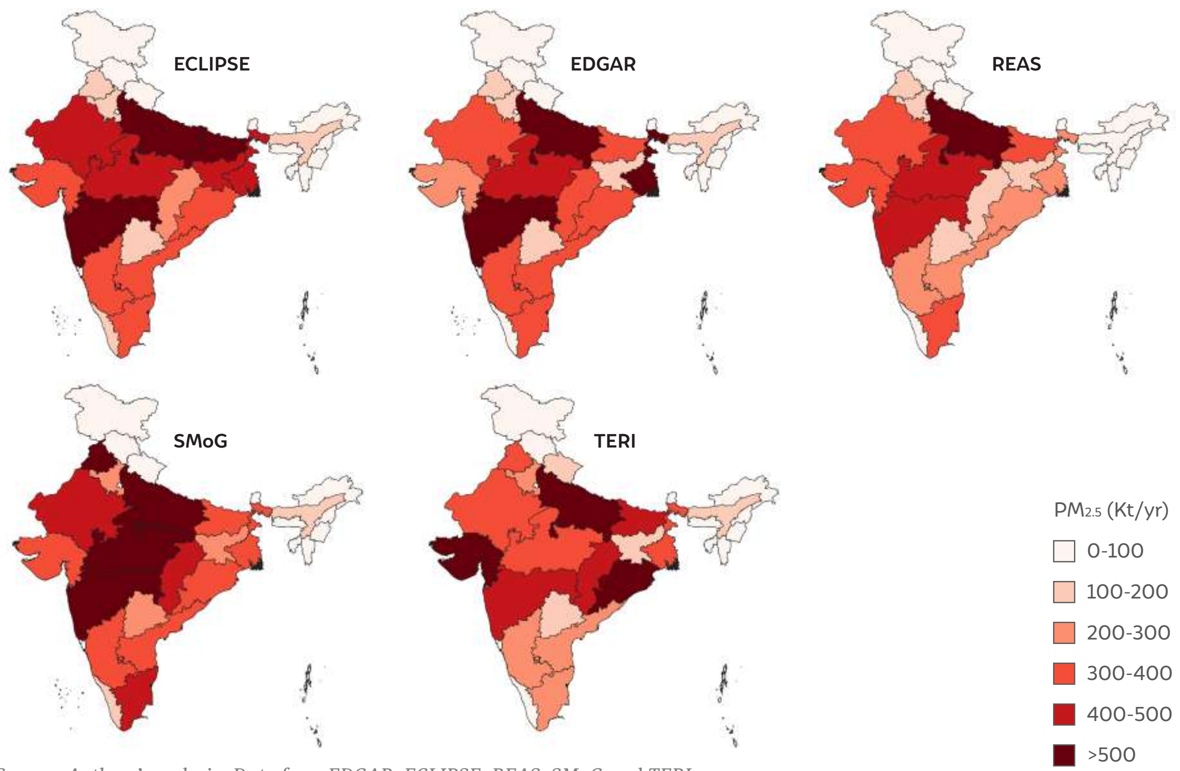
While all five databases find Uttar Pradesh (UP) to be the state with the highest $PM_{2.5}$ burden, the estimated emissions from the states were found to vary significantly (Table ES3). The estimated $PM_{2.5}$ emissions from the state range from 588 (REAS) to 976 (TERI) kilo-tonnes per year. The high emissions from the state of UP can be ascribed to a significant share of $PM_{2.5}$ emissions from solid fuel use in households and the prevalence of this to a much larger degree in India's most populous state (Mani et al. 2021). The leading $PM_{2.5}$ emitting states, as per the different databases, are listed in Table ES3. While Maharashtra is consistently in the top 5 emitting states, Madhya Pradesh features prominently in four out of the five databases (Figure ES2). The high emission burden in the states of Uttar Pradesh and Maharashtra also explains the presence of the highest number of non-attainment cities in both the states.

Table ES3
Top 5 polluted states based on $PM_{2.5}$ across the emission inventories

Source: Authors' Analysis; Data from EDGAR, ECLIPSE, REAS, SMoG and TERI

Inventory	Highest-emitting states	Emissions (Kt/yr)
EDGAR	Uttar Pradesh	661
	West Bengal	572
	Maharashtra	549
	Madhya Pradesh	450
	Odisha	369
ECLIPSE	Uttar Pradesh	887
	Maharashtra	549
	Bihar	520
	Madhya Pradesh	471
	West Bengal	438
REAS	Uttar Pradesh	588
	Maharashtra	415
	Madhya Pradesh	403
	Tamil Nadu	365
	Rajasthan	311
SMoG	Uttar Pradesh	816
	Punjab	776
	Maharashtra	592
	Madhya Pradesh	584
	Rajasthan	452
TERI	Uttar Pradesh	976
	Gujarat	586
	Odisha	525
	Chhattisgarh	495
	Maharashtra	429

Figure ES2 **Uttar Pradesh, Madhya Pradesh and Maharashtra emerge as the leading emitters of $PM_{2.5}$**



Source: Authors' analysis; Data from EDGAR, ECLIPSE, REAS, SMoG and TERI

Uncertainties in estimates should not delay action

The above findings highlight that there are considerable uncertainties in emissions estimates for India. However, these uncertainties should in no case delay action. Notwithstanding the variations in estimates, the industrial sector appears to be among the leading emitters for multiple pollutants including $PM_{2.5}$, SO_2 and NO_x. The power sector emerges as the leading emitter of both NO_x and SO_2 emissions in India. As mentioned above, SO_2 and NO_x react in the atmosphere to form secondary particulate matter, thereby increasing ambient particulate concentrations. The residential sector which accounts for the largest share of particulate emissions in India is also a leading cause of air-pollution mortality in India, and should therefore be addressed. This is particularly crucial for states like Uttar Pradesh, Bihar and Madhya Pradesh where a significant share of particulate emissions can be attributed to the households.

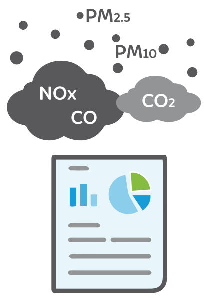
We find considerable uncertainties in emission estimates for India. However, these uncertainties should not delay action

India should formalise a periodically updated, national emission database

While action on addressing emissions from sources must continue, India should work towards formalising a regionally representative, periodically updated air pollution emission inventory. Such an emissions inventory is key to help model the dynamic nature of pollution sources and their impact on various areas and assess the implications of new policies and regulations to curtail emissions from specific sources. Despite an acknowledgment of the absence of a comprehensive national inventory in India's National Clean Air Programme, India is yet to formalise a national emission inventory (Sundaray and Bhardwaj 2019).

Emissions from any sector depend on sectoral energy consumption (or activity level) and emissions produced per unit of energy consumed (emission factors). Therefore, the disagreements in sectoral emission estimates and sectoral contributions can be attributed to differences in activity levels and/or emission factors. In our study, we find that data sources used for estimating sectoral energy consumption, emission factors, and the extent and efficiency of emission control technologies vary across the five inventories. This can explain the variations in sectoral emission estimates. While TERI and SMoG indicate that they rely on plant-level information and domestic data sets for computing sectoral energy consumption, EDGAR, ECLIPSE, and REAS use international databases like IEA, UNSTAT, FAOSTAT, etc. However, it must be noted that international databases also ultimately rely on statistics published by the Government of India - annual and periodic surveys, the Census, and other industry sources for various activities that consume energy. However, differences can arise in the way the sources are interpreted as India does not have an energy balance that has been built bottom-up, and one that allocates all fuel consumed to specific end-uses. In the absence of a clear description of activity levels and fuel consumption linked to that activity level, in each of the inventories, it also becomes difficult to compare and explain reasons for variation.

The choice of emission factors also varies from study to study. ECLIPSE and SMoG use technology-linked emission factors for all sectors. The TERI inventory uses fuel-wise emission factors for computing emissions from domestic fuel combustion and power plants and technology-linked emission factors for industries, brick kilns and transport. REAS used fuel-wise emission factors for estimating residential and power plant emissions, activity input-based emission factors for estimating industrial emissions and vehicle category-linked emission factors for calculating emissions from transport.



While action on addressing emissions from sources must continue, India should work towards formalising a periodically updated air pollution database emission inventory

How can the causes for uncertainties in estimates be addressed?

While absolute emission estimates are needed to determine emission reduction targets, estimates on sectoral emission contributions can determine the scale and pace of mitigation required across sectors. While the available information on India's emission estimates clearly identifies the sectors that need to be targeted, but, for determining the scale of action needed to achieve desirable emissions reductions, India needs a regionally representative emission inventory. Given uncertainties in emission estimates can be ascribed to assumptions on activity-levels and emission factors, we recommend the development of standardised emission reporting protocols for industries, vehicle registration - survival and deregistration, and waste handling reporting templates for urban local bodies. This would help improve data collection and reporting for the industrial and transport sectors, and ensure consistency in methods and data sources used for the preparation of city-level emission inventories. Further, we also recommend conducting periodic primary surveys to collect information on household fuel usage and data on energy use in informal sectors, at regular intervals. Finally, we recommend the development of a comprehensive database for representative, regional, process-specific, and technology-linked emission factors based on actual field measurements. Often, such data is not available in public databases which results in scientists and researchers making assumptions in their emission estimates. Therefore, such emission factors are essential for accurately computing emissions from different polluting sectors.

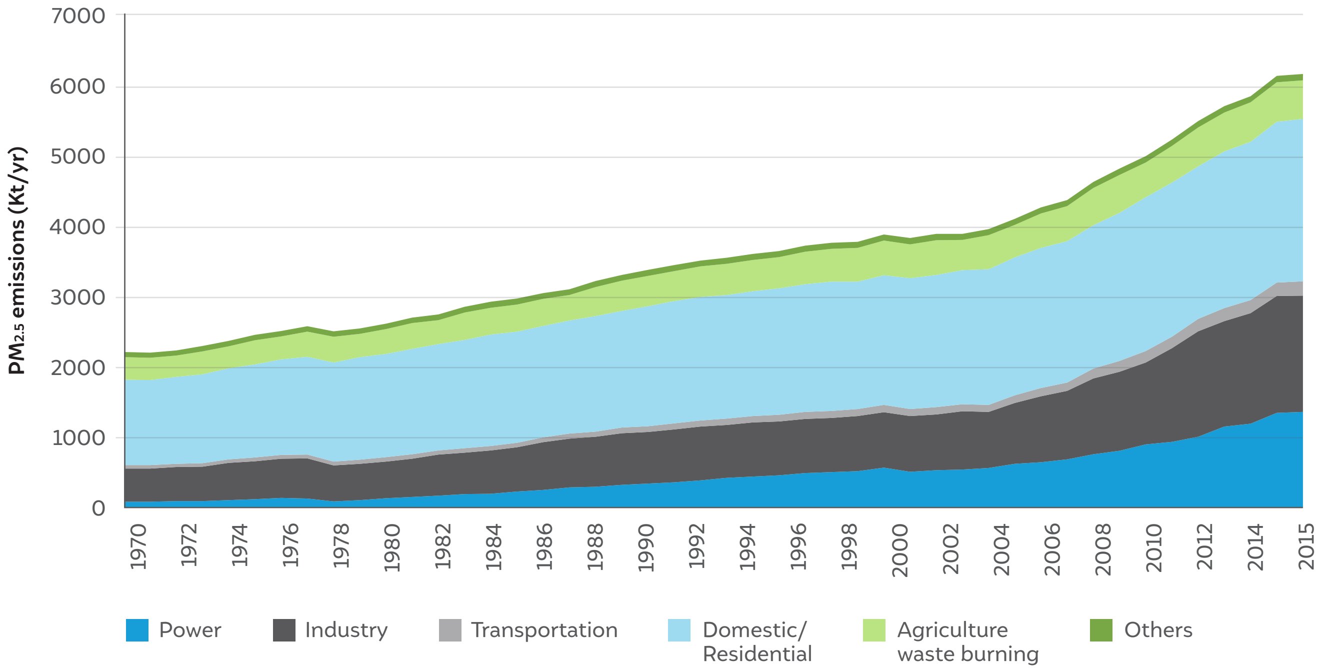
India needs an official, regionally representative emission inventory to determine the scale of action needed to meet the NCAP targets

1. Introduction: the case of multiple inventories

India is among the leading emitters of particulate matter (PM), sulphur dioxide (SO_2), and carbon monoxide (CO) in the world; second only to China (Crippa et al. 2018). Existing literature on India's emissions trajectory informs that emissions from power generation and industrial production have doubled between 1995 and 2015 (Chandra Venkataraman et al. 2018). Historical emission data from the Emissions Database for Global Atmospheric Research (EDGAR) suggests that India and China have always been the leading emitters of $PM_{2.5}$ across the globe. However, in recent years China's $PM_{2.5}$ emissions show a declining trend, but in India they continue to grow.

Emissions from large-scale combustion in power plants and industries are driving the $PM_{2.5}$ emission growth in India (Figure 1).

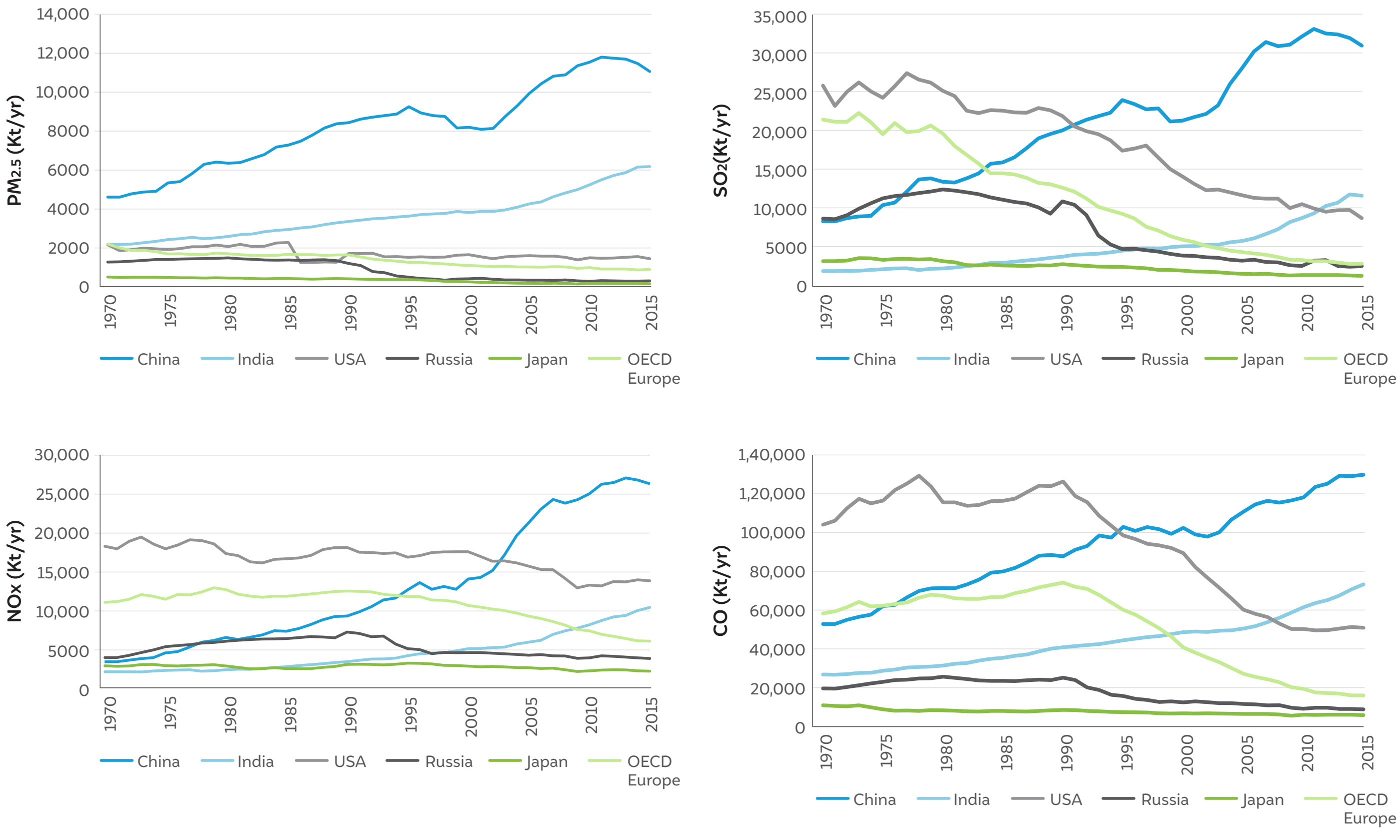
Figure 1 **Between 1970 and 2015, $PM_{2.5}$ emissions from large-scale combustion in India grew 5.5 times**



Source: Authors' analysis; Data from EDGAR

Global emission growth profiles also suggest that the United States (US) and Organisation for Economic Co-operation and Development (OECD) nations of Europe were the leading emitters of NOx, SO_2, and CO back in 1970. While emissions and the associated health burden for these regions have declined over the years, emissions in India are on the rise. The particularly drastic drop in emissions from the European Union (EU) nations can, in part, be attributed to the EU National Emission Ceilings (NEC) directive. The NEC directive is aimed at limiting emissions by setting legally mandated emission reduction commitments for all EU nations (UNECE 2009; Seddon, Cardenas, and Moses 2020). This highlights the need for sectoral emission reduction targets in a country's air pollution mitigation strategy (Figure 2).

Figure 2 Pollutant emissions in India are on the rise

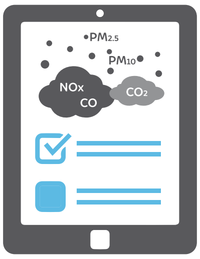


Source: Authors' analysis; Data from EDGAR

Since the notification of India's National Ambient Air Quality Standards (NAAQS) in 2009, the Indian Government has taken numerous steps to reduce air pollution. These interventions include the introduction of the Swachh Bharat Mission (SBM) to improve solid waste management, the Pradhan Mantri Ujjwala Yojana (PMUY) and Unnat Chulha Abhiyan (UCA) to promote improved cook stoves and clean fuel, the National Electric Mobility Mission Plan (NEMMP) to scale up the adoption of zero-emission vehicles, and the accelerated introduction of Bharat Stage (BS) VI fuel in the country (Swachh Bharat Urban 2021; PMUY 2021; Gulati 2012; Baggonkar and Modi 2016; PIB 2018). More recently, India's Ministry of Environment, Forest and Climate Change (MoEFCC) launched the National Clean Air Programme (NCAP) with the goal to ensure that India meets its NAAQS within a stipulated time frame (Sundaray and Bhardwaj 2019). The particulate concentration reduction target was set at 20-30 per cent by 2024. However, there is a dearth of studies that evaluate the impact of these interventions on India's emission burden.

Various studies have suggested different mitigation strategies to help India meet its NAAQS. Some of these strategies are: having a multi-sectoral strategy in place, hundred per cent adoption of clean cooking fuel in India's households and implementation of market mechanisms like the emission trading system for improving industrial compliance (Greenstone et al. 2018; Purohit et al. 2019; Chowdhury et al. 2019). While all the aforementioned solutions should certainly be a part of India's air pollution mitigation strategies, the resultant emission reductions can only be quantified vis-à-vis a comprehensive baseline emission inventory for all polluting sectors.

As the NCAP points out, India lacks a comprehensive emission inventory (Sundaray and Bhardwaj 2019). The Central Pollution Control Board (CPCB) released draft guidelines and common methodology for the development of emission inventories, back in 2010 (CPCB 2010b). While city-level inventories, following the guidelines, have been developed for a few cities like Delhi, Mumbai, Chennai, Kanpur, and Bengaluru, a periodically updated national inventory of criteria air pollutants is missing. National-level sectoral emission estimates are essential for setting emission reduction targets at the national and sub-national levels and tracking progress towards achieving them. A national emission inventory that is built ground up, from regional-, state-, and city-level inventories, can be helpful in understanding regional distribution of emissions. Further, it could also feed into a national-level air quality forecasting model and facilitate pan-India air quality alerts/forecasts.



India's air pollution mitigation strategies, the resultant emission reductions can only be quantified vis-à-vis a comprehensive baseline emission inventory for all polluting sector

While India does not have a formal air pollution emission database, a number of international and domestic institutions have estimated India's emissions burden. However, there are significant variations in these estimates - at the aggregate level and more specifically in sectoral contributions. While, the variability does not affect our ability to plan for achieving the National Clean Air Programme (NCAP) target for reducing particulate concentrations by 20 to 30 per cent by 2024, it increases the uncertainty in assessing impacts of various interventions and prioritising action for various parts of the country.

It is worth noting that reputed academic institutions across the country have been tasked with the responsibility of conducting source-apportionment studies for the non-attainment and million-plus urban agglomerations in the country, which is the focus of India's NCAP. Source-apportionment may be carried out by developing an emission inventory followed by dispersion modeling which provides a spatial distribution of pollutant concentration (S. Guttikunda 2011). An emission inventory serves as a baseline for a region's pollution load and can be periodically updated by accounting for change in activity levels due to policy interventions or other external factors.

Baseline information for developing emission inventories includes data on various parameters like regularly updated sectoral information such as vehicular fleet characteristics, fuel consumption in industries and power plants, primary cooking fuel distribution and extent of pollution control in industries. Additionally, process- and region-specific emission factors based on field measurements are also needed to accurately compute emissions from industries, agriculture, and municipal waste burning. Often, such data is not available in public databases. Therefore, scientists and researchers make assumptions in their emission estimates. These assumptions result in variations in inventories, even for limited geographies (Jalan and Dholakia 2019).

While various studies have compared national- and source-level emission estimates from available international and national global emission databases (Saikawa et al. 2017; Reddy and Venkataraman 2002; Pandey et al. 2014b; Crippa et al. 2018; Kurokawa and Ohara 2020; TERI 2021; Chandra Venkataraman et al. 2018; Pandey et al. 2014a; Zbigniew Klimont et al.

2017), these studies do not compare activity-level information or the emission factors that the different inventories employ.

In this study, we review and compare India-level emission estimates from three global and two national emission databases. Through this assessment, we try to explain the regional distribution of emissions in India and key drivers of pollution in the country. To explain the variations, we observe in the estimates, we also discuss the data sources for activity-level information and emission factors used by these inventories. With this study, we aim to inform MoEFCC, the National Knowledge Network (NKN) established under the NCAP and the CPCB, of the causes of variations in emission estimates, and recommend steps to reduce them.

NCAP points out, India lacks a comprehensive emission inventory

National-level sectoral emission estimates are essential for setting emission reduction targets at the national and sub-national levels and tracking progress towards achieving them.

Image: iStock

2. Methodology

In this study, we review and compare India-level emission estimates from three global and two national-level emission inventories to illustrate the extent of variation in the available emission estimates for India. As mentioned previously, while these variations do not affect our ability to execute interventions, it increases the uncertainty in assessing impacts of these interventions. The five inventories compared in this study are described in Table 1.

Table 1 Descriptions of five global and two national-level emission inventories used in this study

Emission Inventory	Description	Spatial resolution	Time period	Pollutants	Version used	Source
EDGAR	Emissions Database for Global Atmospheric Research (EDGAR) is maintained by the European Commission's Joint Research Centre	0.1° *0.1° (11.1 *11.1 km)	1970-2015	BC, CO, NH_3, NMVOC, NO_x, OC, PM_{10}, $PM_{2.5}$, SO_2	v5.0	European Commission 2021
ECLIPSE	Evaluating the Climate and Air Quality Impacts of Short-lived Pollutants (ECLIPSE) is maintained by the International Institute for Applied Systems Analysis (IIASA)	0.5° *0.5° (55.5 *55.5 km)	1990-2050	BC, CH_4, CO, NH_3, NO_x, OC, OM, PM_{10}, $PM_{2.5}$, SO_2, NMVOC	v6b	ECLIPSE 2021
REAS	Regional Emission Inventory in Asia (REAS) is maintained by the National Institute for Environmental Studies, Japan (NIES)	0.25° *0.25° (27.5 *27.5 km)	1950-2015	BC, CO, NMVOC, NO_x, OC, PM_{10}, $PM_{2.5}$, SO_2	v3.2	REAS 2021
SMoG	Speciated Multipolluter Generator (SMoG) is maintained by the Indian Institute of Technology (IIT Bombay)	0.25° *0.25° (27.5 *27.5 km)	1985-2015	$PM_{2.5}$, NMVOC, NO_x, SO_2, CO	v1	SMoG-India 2021
TERI	Spatially resolved pollution emission inventory for India maintained by The Energy and Resources Institute (TERI)	36 km *36 km	2016	CO, NH_3, $PM_{2.5}$, PM_{10}, NO_x, NMVOC, SO_2	NA	TERI 2021

Source: Authors' compilation

In Tables 1 and 2, we list the pollutant and sectoral coverage of each emission database. We find that except SMoG, all the other inventories estimate $PM_{2.5}$, PM_{10}, NO_x, SO_2, CO, NH_3, and NMVOC. SMoG does not compute emissions for PM_{10}. In this study, we compare emissions from residences, power plants, transport, and industries, as these are common to all the inventories. Given that four out of the five inventories cover agricultural waste burning (AWB), we also include emissions from AWB in our assessment. We only consider criteria pollutants ($PM_{2.5}$, PM_{10}, NO_x, SO_2, CO) in our assessment. It is important to note that EDGAR, ECLIPSE, REAS, and SMoG are multi-year inventories. 2015 is the latest year for which all of them provide estimates; the exception being the TERI inventory which provides estimates of emissions for 2016.

Table 2 All databases estimate emissions from residences, transport, power plants and industries

Source sector	ECLIPSE_v6b	EDGAR_v5.0	REAS_v3.2	SMoG_v1	TERI
Agriculture waste burning	✓	✓	✗	✓	✓
Agriculture (manure, fertiliser, etc.)	✓	✓	✓	✗	✓
Power	✓	✓	✓	✓	✓
Industry (manufacturing + others)	✓	✓	✓	✓	✓
Urban dust	✗	✗	✗	✓	✓
Domestic	✓	✓	✓	✓	✓
Transport (rail, road + others)	✓	✓	✓	✓	✓
Solvents	✗	✓	✓	✗	✓
Waste burning	✓	✓	✗	✗	✓

✓ YES ✗ NO

Source: Authors' compilation

As EDGAR, ECLIPSE, REAS and SMoG provide emission data as gridded datasets, we had to aggregate these estimates at the national and state levels. For EDGAR, ECLIPSE, REAS, and SMoG, we obtain national- and state-level estimates by summing grid-level values. Zonal statistics were used to sum the grid-level values to obtain a single value for each state and for the country. It is important to note that emission estimates obtained by spatial aggregation differ from absolute estimates found in literature by one to five per cent.

For assessing variations in the estimates, we compute the relative standard deviation (RSD) for total pollutant emissions and sector-wise pollutant emissions. The RSD is a statistical measure used to define relative variability and is computed by taking the ratio of standard deviation of data points to the mean of the data set.

Given that emissions from any sector are a function of sectoral activity/fuel consumption and sector-specific emission factors for different pollutants, in this study, we also explore how different data sources and emission factors used by the different emission inventories result in varying emission estimates.

Data sources used for estimating sectoral energy consumption, emission factors, and the extent and efficiency of emission control technologies vary across the inventories.

Image: iStock

3. Results and discussion

In this section, we compare the national and sectoral emission estimates for PM2.5, PM10, NOx, SO2, and CO. We also highlight how the sectoral contribution to PM2.5 emissions vary from state to state. Further, we explain the observed variations in emission estimates in the different inventories by comparing the activity information and emission factors that they use.

3.1 Variations in total emission estimates

We find that the RSD for total emissions for all pollutants except PM10 falls within 25 per cent. For PM10, the RSD was found to be 37 per cent. TERI's PM10 emission estimates are significantly higher than that of the other inventories because it considers emissions from urban fugitive dust while others do not. SMoG considers urban dust as a sector, but as mentioned previously, it does not compute PM10 emissions. Existing research on pollution sources in India suggests that dust is a significant contributor to PM10 pollution in the country (CPCB 2010a; S. K. Guttikunda and Jawahar 2012).

Database	PM2.5	PM10	NOx	SO2	CO
EDGAR	6154	9645	10420	11480	73195
ECLIPSE	6747	8937	8772	7331	56709
REAS	4906	6960	9741	10866	62622
SMoG	7693	NA	7475	8366	71869
TERI	7316	16210	8500	10033	43132
RSD (%)	**17**	**37**	**12**	**18**	**21**

Table 3
Total PM10 emission estimates (Kt/yr) vary by 37 per cent across the five inventories

Source: Authors' compilation; Data from EDGAR, ECLIPSE, REAS, SMoG and TERI

3.2 Variations in sectoral emission estimates

In this section, we examine the following:

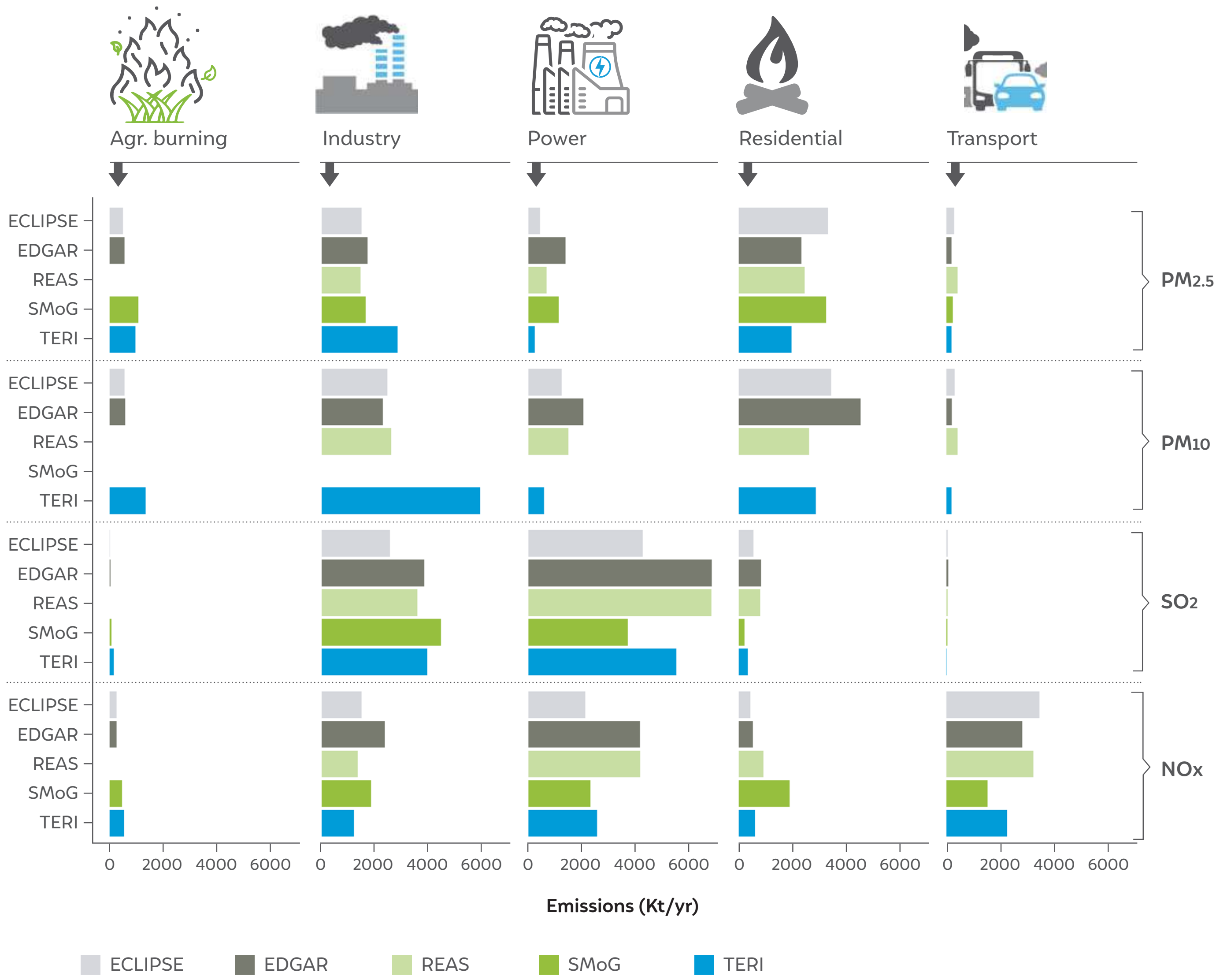
- How emission estimates for the same sector vary across inventories. (Figures 3 and 4)
- How sectoral contributions to emissions vary (Table 4)

We find that the sectoral emission estimates vary significantly across inventories. Figure 3 represents the emission estimates for all pollutants and sectors we compare in this assessment, and Figure 4 represents the relative standard deviation between emission estimates by various sectors.

We find that the overall variation in residential $PM_{2.5}$ emissions is less than 25 per cent. However, SMoG's residential $PM_{2.5}$ emission estimates are approximately 50 per cent higher than those estimated by TERI. The overall variation in SO_2 and NO_x emissions from power plants are found to be 27 and 30 per cent respectively. However, REAS and EDGAR's SO_2 estimates are almost twice that of SMoG and ECLIPSE's estimates.

We observe highest variations in estimated emissions from power plants, transport and agricultural residue burning. The observed variations in emission estimates call for a closer look at the underlying activity data and emission factors that were used to arrive at these estimates.

Figure 3 **Highest variations in estimated emissions from power plants, transport and agricultural residue burning**



Source: Authors' analysis; Data from EDGAR, ECLIPSE, REAS, SMoG and TERI

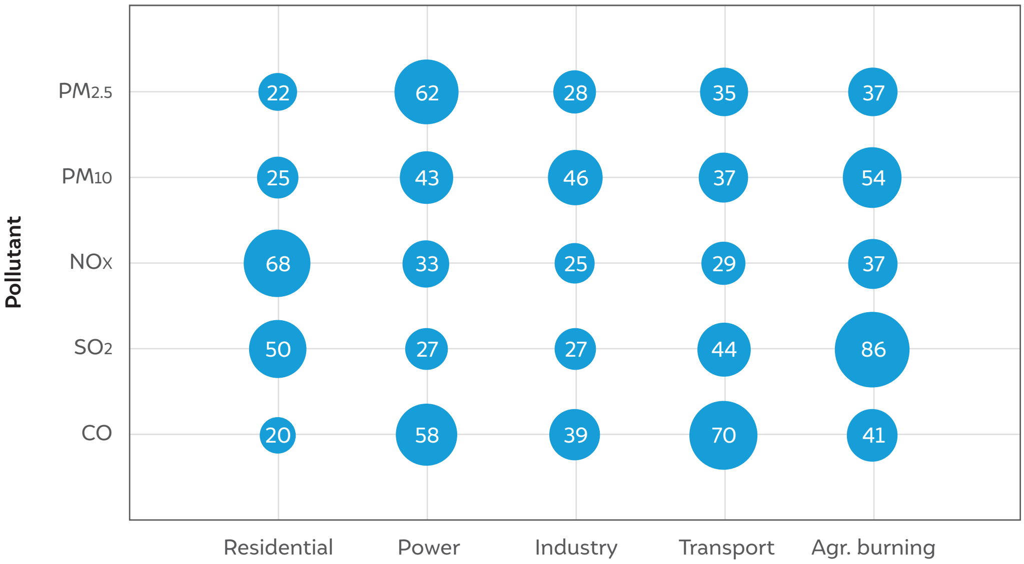


Figure 4
Highest RSD observed for estimated emissions from power plants, transport and agricultural residue burning

Source: Authors' analysis; Data from EDGAR, ECLIPSE, REAS, SMoG and TERI

Notwithstanding the significant variations in the emission estimates, the residential sector is seen to be the leading emitter of $PM_{2.5}$, across the five inventories with its contribution ranging from 27 to 50 per cent of the total $PM_{2.5}$ emitted in the country (Figure 5). Power plants are the leading emitters of SO_2 emissions, with their contribution ranging from 44 to 62 per cent of all SO_2 emitted in the country (Figure 6). This is on account of the significant share of coal that is consumed in power generation. While all inventories conclude that the power sector is the leading cause of NO_x emissions, ECLIPSE suggests that transport is the leading emitter of NOx emissions in India (Figure 7). In Table 4, we summarise how sectoral contributions to the different criteria pollutants are considerably varied.

While the contribution of households to primary $PM_{2.5}$ emissions is highest, it must be noted that large point sources such as such as coal-based power plants and industrial units contribute a large share of $PM_{2.5}$ through secondary particulate matter, which is a result of the transformation of SOx and NOx emissions from gas form to particle form. A recent study estimates that the contribution of secondary particulate matter from coal-based power plants could be as high as 80 per cent of total particulate matter attributable to power plants(Cropper et al. 2021).

Emissions from industries and power plants are the most easily targeted source of emissions for regulators and policy makers to address

Industrial production stands as the second largest source of most of the criteria pollutants that were assessed and when combined with power plants, represent a possibly the largest and most easily targeted source of emissions for policy makers and regulators to address. They are large point sources and finite in number. Particulate pollution arising from solid fuel use in households is distributed across the length and breadth of the country and much harder to abate, as it involves interventions that target both affordability of cleaner fuels and affecting behaviour change to move populations away from the use of free of cost biomass in many pockets.

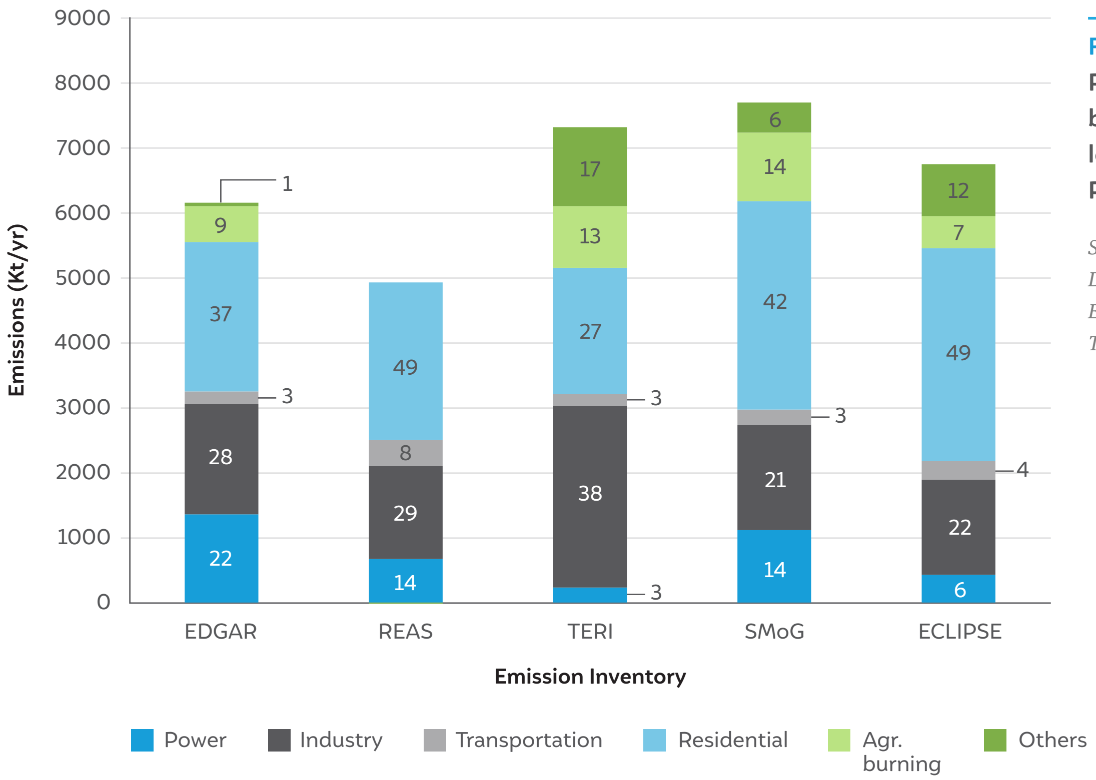


Figure 5

Residences, followed by industries, are the leading emitters of $PM_{2.5}$

Source: Authors' analysis; Data from EDGAR, ECLIPSE, REAS, SMoG and TERI

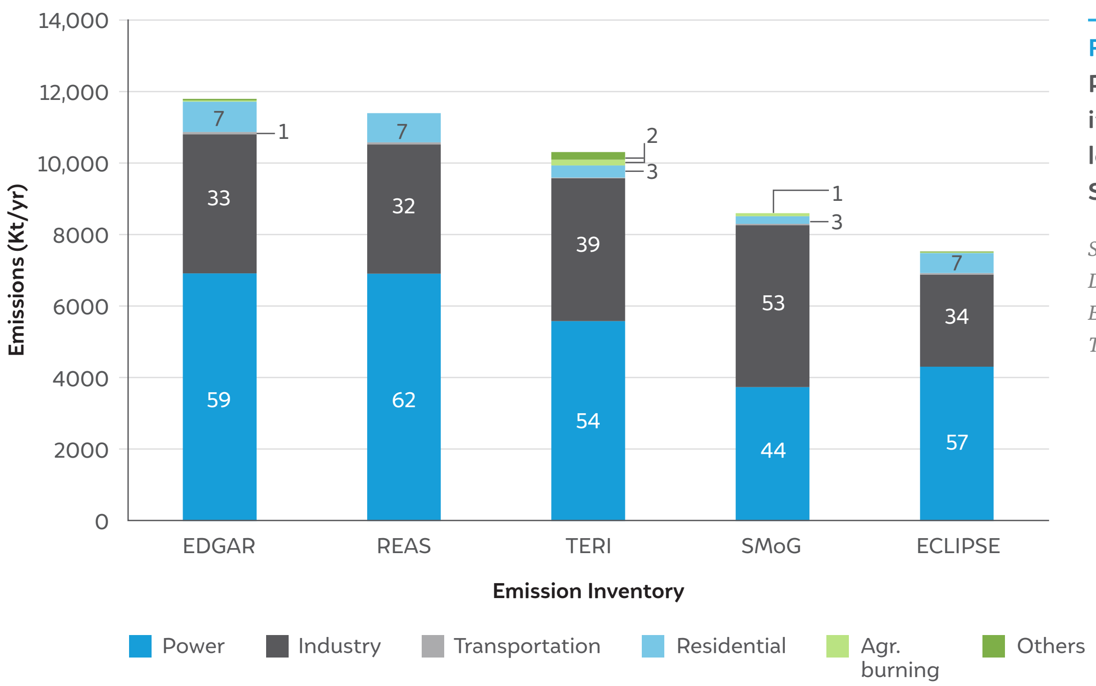


Figure 6

Power plants and industries are the leading emitters of SO_2

Source: Authors' analysis; Data from EDGAR, ECLIPSE, REAS, SMoG and TERI

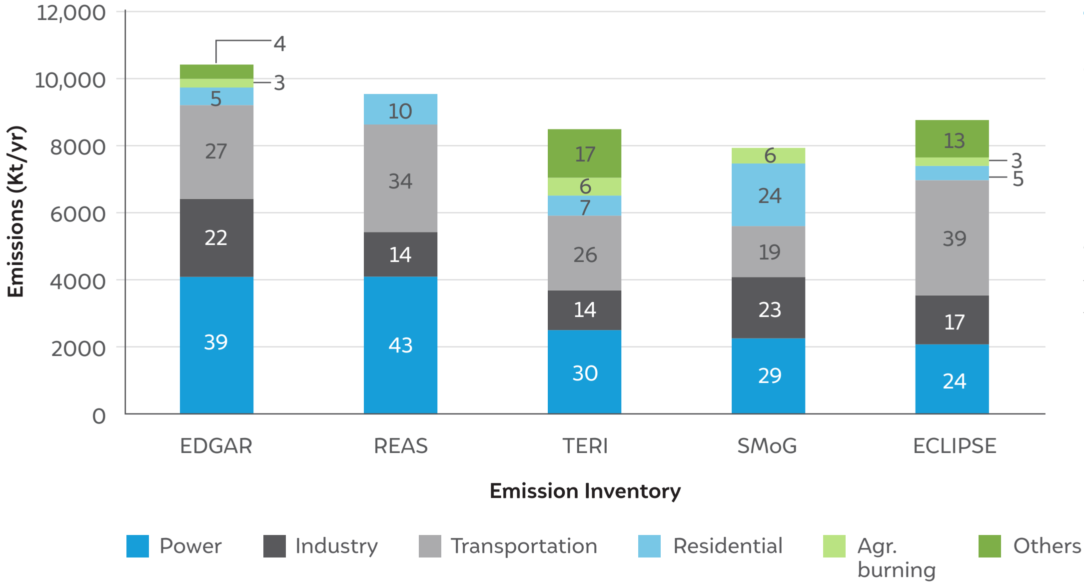


Figure 7
Transport and power plants are the leading contributors to NOx emissions

Source: Authors' analysis; Data from EDGAR, ECLIPSE, REAS, SMoG and TERI

Table 4
Sectoral contributions to emissions vary significantly

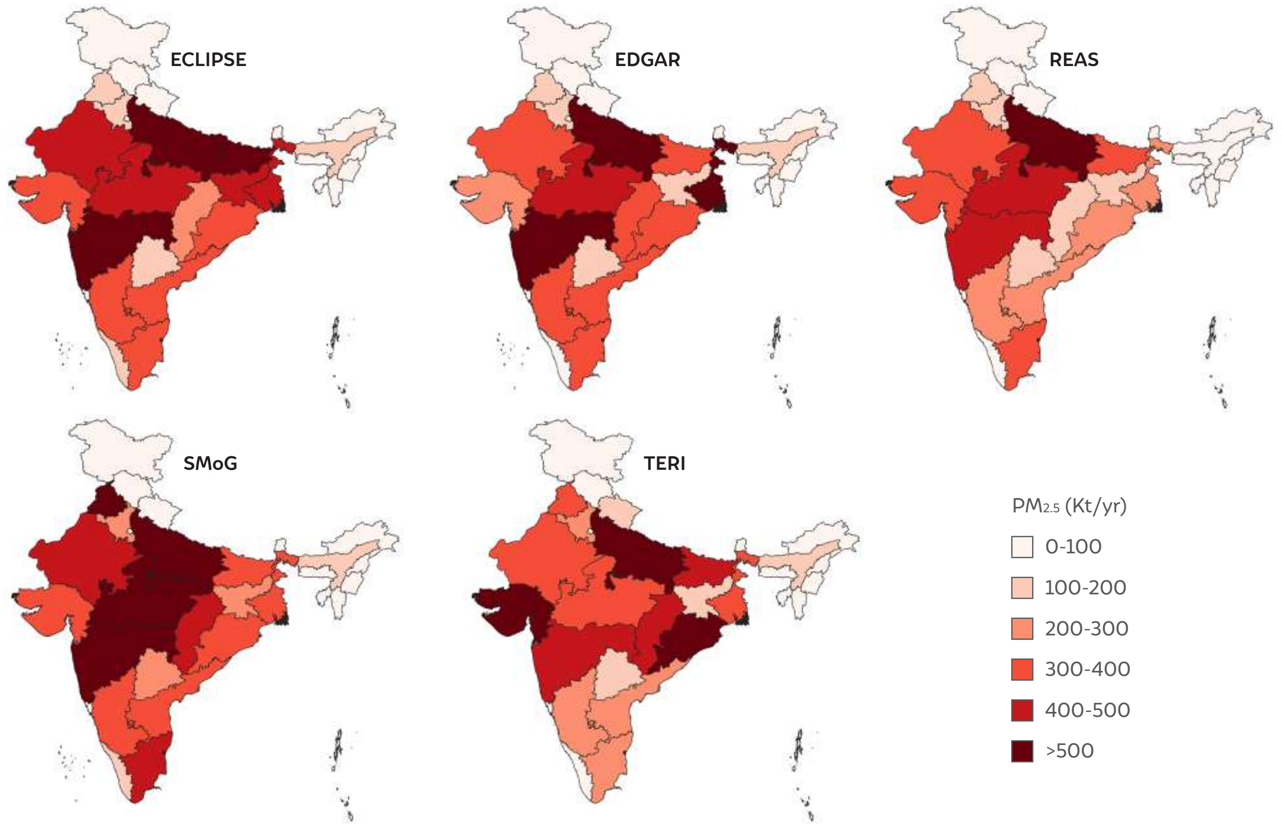
Pollutant	Residences (%)	Power (%)	Industry (%)
$PM_{2.5}$	27-50	3-22	21-38
PM_{10}	18-46	3.5-21	23-37
NO_x	5-25	24-43	14-24
SO_2	2.5-7.5	44-62	32-53
CO	40-61	0.4-1.0	12-27

Source: Authors' analysis; Data from EDGAR, ECLIPSE, REAS, SMoG and TERI

3.3 Regional distribution of emissions

As per CPCB's list of non-attainment cities, Maharashtra, Uttar Pradesh, and Punjab have the highest number of non-attainment cities with 18, 17, and 9 non-attainment cities, respectively. On averaging the gridded emissions at the state level, we find that Maharashtra and Uttar Pradesh also feature among the highest-emitting states across the five inventories (Figure 8).

Figure 8 **Uttar Pradesh, Maharashtra and Madhya Pradesh emerge as the leading emitters of $PM_{2.5}$**



Source: Authors' analysis; Data from EDGAR, ECLIPSE, REAS, SMoG and TERI

All five inventories agree on Uttar Pradesh being the leading emitter of $PM_{2.5}$ in the country, with emission estimates ranging from 588 (REAS) to 976 (TERI) kilotonnes per year (Table 5). The high emissions from the state of UP can be ascribed to a significant share of $PM_{2.5}$ emissions from solid fuel use in households and the prevalence of this to a much larger degree in India's most populous state (Mani et al. 2021) (Annexure 1). Maharashtra features among the highest-emitting states as per all inventories, except TERI's. Estimated $PM_{2.5}$ emissions from Maharashtra range from 415 Kt (REAS) to 549 Kt (ECLIPSE). The high emission burden in the states of Uttar Pradesh and Maharashtra also explains the presence of the highest number of non-attainment cities in both the states. Madhya Pradesh also features among the highest emitting states as per all inventories, except TERI's, with its emissions ranging from 403 Kt (REAS) to 584 Kt (SMoG). As per TERI's estimates, Gujarat, Odisha, and Chhattisgarh emit more than Maharashtra or Madhya Pradesh. The Himalayan states of J&K (now a union territory), Himachal Pradesh, Uttarakhand, and the North-eastern states of Arunachal Pradesh, Nagaland, Manipur, and Mizoram, were found to be the lowest emitters of $PM_{2.5}$.

Inventory	Highest-emitting states	Emissions (Kt/yr)
EDGAR	Uttar Pradesh	661
	West Bengal	572
	Maharashtra	549
	Madhya Pradesh	450
	Odisha	369
ECLIPSE	Uttar Pradesh	887
	Maharashtra	549
	Bihar	520
	Madhya Pradesh	471
	West Bengal	438
REAS	Uttar Pradesh	588
	Maharashtra	415
	Madhya Pradesh	403
	Tamil Nadu	365
	Rajasthan	311
SMoG	Uttar Pradesh	816
	Punjab	776
	Maharashtra	592
	Madhya Pradesh	584
	Rajasthan	452
TERI	Uttar Pradesh	976
	Gujarat	586
	Odisha	525
	Chhattisgarh	495
	Maharashtra	429

Table 5
Top 5 polluted states based on $PM_{2.5}$ across the emission inventories

Source: Authors' analysis; Data from EDGAR, ECLIPSE, REAS, SMoG and TERI

The variations in state-wise emission estimates and relative ranking of highest emitting states, further reinforces the need for a closer look at the proxies that the databases consider, to distribute the emissions regionally.

From the comparison presented in the previous sections, it is evident that the sectoral emission estimates vary significantly across the inventories compared in this assessment. These variations stem from various factors like activity information used for assessing sectoral energy consumption, choice of emission factors, and extent and assumptions on the effectiveness of pollution control technology.

The CPCB guidelines and conceptual methodology on emission inventory provides guidance on both activity data collection methods and choosing emission factors (CPCB 2010b). It recommends a combination of secondary data collection from government records and primary data collection from industrial facilities and representative localities.

On choice of emission factors, the guidelines say that while city-specific factors that take local characteristics and local prevailing technology into account are preferred, emission factors from secondary literature can also be used as long as the inventory developers can demonstrate that the chosen factors are representative of the local conditions.

In sections 3.4 and 3.5, we review the activity data and emission factors that the different inventories compared in this study have used.

3.4 Activity data

Global emission databases such as EDGAR, ECLIPSE, and REAS acquire energy consumption information from international databases described in this section. SMoG and TERI primarily rely on regional databases, and plant-level information on energy consumption and industrial production. Assumptions on the extent of adoption of pollution abatement technology are made on the basis of expert consultations.

EDGAR uses sectoral energy consumption data from the International Energy Agency (IEA) via energy balance statistics (IEA 2014). It obtains industrial production statistics from commodity statistics of UNSTAT , USGS, and data reported to UNFCCC (UNSTATS 2014; USGS 2014; UNFCCC 2014). It uses crop statistics from FAOSTAT (FAOSTAT 2014). EDGAR uses vehicular fleet distribution, reported by International Road Federation (IRF), and end-of-pipe control measures by Automobile India (IRF 2007; Automobile India 2009).

As in the case of EDGAR, primary energy statistics used in ECLIPSE are also from IEA databases. ECLIPSE enriches information from the IEA with regional information. For instance, in addition to domestic energy consumption from IEA statistics, data on domestic kerosene consumption is obtained from regional studies (Purohit and Michaelowa 2008; Mahapatra, Chanakya, and Dasappa 2009; Desai et al. 2010). ECLIPSE assumes 15 per cent of India's vehicular fleet to be comprised of high-emitting vehicles. To account for these high-emitters, amplification rates have been applied to emission factors for both light- and heavy-duty vehicles.

REAS uses fuel consumption statistics from IEA World Energy Balances (IEA 2017). Weighting factors for household fuel consumption are obtained from TERI (TERI 2019). Information on emission control in power plant emissions is obtained from the World Electric Power Plants Database (Platts 2018). Production rates for iron and steel are obtained from the Steel Statistical Yearbook (World Steel Association 2016). For regional distribution of crude steel production, data is obtained from the USGS Minerals Yearbook and IndiaStat (USGS 2014; IndiaStat 2021). Other industrial production statistics are obtained from USGS, and commodity statistics from UNSTAT (UNSTATS 2014; USGS 2014). For estimating emissions from transport, vehicular fleet distribution is obtained, and vehicle survival functions are obtained from existing literature (Baidya and Borken-Kleefeld 2009; TERI 2019).

ECLIPSE assumes 15% of India's vehicular fleet to be comprised of high-emitting vehicles

SMoG computes residential emissions by using state-wise food consumption data from the National Sample Survey Office data (NSSO 2014). It uses primary cooking fuel distribution and kerosene (for lighting) consumption data from Census data (Census 2011). Estimates of emission from large-scale combustion in heavy industries, including power plants, is based on plant-wise data on installed capacity, energy consumption and annual production. Energy consumption and industrial production statistics for light industries are taken from data records maintained by the Central Electricity Authority (CEA), Cement Manufacturers Association (CMA), Ministry of Coal (MoC), Ministry of Petroleum and Natural Gas (MoPNG) and Fertilizer Association of India (FAI) (MoC 2007; CEA 2010; FAI 2010; MoPNG 2012). To compute emissions from road transport, SMoG uses historical vehicular statistics and survival rates from existing literature (Sadavarte and Venkataraman 2014a). For emissions from railways, fuel consumption is obtained from the records of the Ministry of Railways(Ministry of Railways 2011).

Global inventories rely primarily on international energy consumption databases while national inventories rely on regional databases and information

TERI computes residential emissions from cooking and lighting by using primary cooking fuel distribution data from Census, village electrification data from CEA, LPG sales from Petroleum Planning & Analysis Cell (PPAC), and state level per capita consumption of different fuels, including firewood for water heating, from NSSO reports (Census 2011; CEA 2012; NSSO 2014; PPAC 2017). To calculate emissions from power plants, the TERI inventory uses plant-wise coal consumption data from CEA, and information on emission controls employed in power plants are based on expert consultations. It uses MARKAL, the Market Allocation energy system model,[2] to obtain energy consumption from the industrial and transportation sectors. India-level energy consumption values for the transport sector are downscaled to district levels, using district-level information on category-wise number of vehicles from the Directorate of Economics and Statistics of different states. Information on vehicle survival rates and vehicle vintage is obtained from parking lot surveys conducted in different cities and stakeholder consultations.

From the discussion above, it is evident that global inventories rely primarily on international energy consumption databases while national inventories rely on regional databases and information. However, even in the case of national inventories, the robustness of the emission factors and activity data needs to be clearly assessed. The details of the scope of local and facility-specific surveys, their geographic representativeness, periodicity and the underlying data that has been collected for these, need to be made available to clearly determine how much more accurate these are, as compared to the more 'generic' figures used in global databases. Fuel combustion in informal industries and residential settlements contribute significantly to India's emission burden. Fuel consumption in these sectors often go unreported and should be accounted for in the activity information that the emission inventories use. While this consumption is likely reflected in another sector, the emission factors and their impact on ambient air quality may be very different. Allocating fuel consumption to the respective sectors is crucial and having a consistent energy balance, at the country, regional, and sector levels, is a prerequisite to have good activity data.

3.5 Emission factors

Emission factors are key to developing national, regional, and local emission inventories, setting standards for emissions and developing pollution control strategies. The EPA defines an emission factor (EF) as "a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant" (EPA 2021b). Emission factors can be expressed in different ways, like mass of pollutant emitted divided by unit mass of fuel consumed or energy consumed by the polluting

2. MARKAL is a modelling system developed by the IEA to analyse economic, energy and environmental parameters at global, national and local levels.

activity or unit distance travelled, etc. In this study, we review the data sources that the five inventories use to obtain emission factors and illustrate how choice of emission factors impact emission estimates.

It is worth noting that in the five inventories compared in this study, the emission factors were reported in different ways. While TERI, SMoG, and REAS report emission factors as mass of emissions per unit fuel consumed, EDGAR and ECLIPSE report them as mass of pollutant per unit energy consumed. For the transport sector, EDGAR, REAS, and TERI report EF as mass of pollutant per unit distance travelled, ECLIPSE as mass of pollutant per unit energy consumed, and SMoG as mass of pollutant per unit mass of fuel consumed. Therefore, to compare the emission factors across sectors, we had to convert them to consistent units. For these conversions, we used calorific values from the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC 2006). The fuel density and mileage for different vehicle classes were obtained from existing literature and government reports. The conversion methodology, calculations and data sources for calorific values, fuel density and mileage are listed in Annexure 3.

For same source, emission inventories report emission factors in different ways

In addition to using different units to express the EFs, the emission inventories also use different types of emission factors. ECLIPSE, EDGAR, and SMoG use technology-linked emission factors for all sectors. The TERI inventory uses fuel-wise emission factors for computing emissions from domestic fuel combustion and power plants, and technology-linked emission factors for industries, brick kilns, and transport. REAS uses fuel-wise emission factors for estimating emissions from residences, power plants, and industrial combustion, factors based on clinker bricks produced per tonne for cement and brick production, and vehicle category-linked emission factors for calculating emissions from transport.

As in the case of activity information, the five inventories also use different data sources for emission factors. EDGAR uses emission factors based on the European Monitoring and Evaluation Programme (EMEP)/European Environment Agency (EEA) Guidebook (EEA 2013). REAS, ECLIPSE, TERI and SMoG borrow emission factors available in existing studies and databases like the US-EPA AP-42 (EPA 2021a). Additionally, for the TERI inventory, emission factors were developed for sectors like agricultural waste burning, refuse burning, road resuspension and certain industrial processes. The different data sources used by the inventories are summarised in Annexure 2.

To illustrate the differences in EFs used in the five emission databases, we compare the following emission factors:

- $PM_{2.5}$ emission factors for the residential sector (Table 6a)
- SO_2 emission factors for the power sector (Table 6a)
- NO_x emission factors for the transport sector (Table 6b)

Table 6a Emission factors for residences and power plants vary across the five emission databases

Pollutant	Leading emitter	Fuel	EDGAR (g/kg)	ECLIPSE (g/kg)	REAS (g/kg)	SMoG (g/kg)	TERI (g/kg)
$PM_{2.5}$	Residences	Wood	12.8	8.6	4.6	4.1	4.6
		Dung	5.2	3.5	9.8		4.4
		Biomass	8.6	5.6	5.7	5.6	5.7
		Kerosene (cooking)		6	0.3	0.6	3
		Kerosene (lighting)		84		93	91.3
		LPG	0.24	0.47		0.3	0.4
SO_2	Power	Coal	18.7-19.92	0.23-16.49	12.29	4.9-7.3	7.37

Source: Authors' compilation

Table 6b Transport sector emission factors for NOx indicate the greatest variations

	Vehicle	Fuel	EDGAR (g/kg)	ECLIPSE (g/kg)	REAS (g/kg)	TERI (g/kg)	SMoG (g/kg)
Passenger Private	2W	Petrol	0.03-0.39	0.08-0.12	0.2-0.3	0.03-0.1	
	4W	Petrol	0.044-2.68	0.03-1.88	0.98-2.70	0.04-0.95	0.12-1.6
		Diesel	0.069-1.10	0.13-1.11		0.47-1.7	
		CNG	0.044-0.084	0.04-1.79	2.1	0.07-0.53	0.62
Passenger Public	Bus	Diesel	0.30-67.18[3]	0.25-11.91	5.70-9.08	5.17-15.25	0.6-8.35
		CNG	4.83-16.5	0.96-13.81	5.7	6.21-15.15	7.70
Trucks	Heavy- Duty Trucks	Diesel	0.15-120.61[3]	0.29-12.94	5.22-12.80	8.35-12.85	0.83-10.39

Source: Authors' compilation

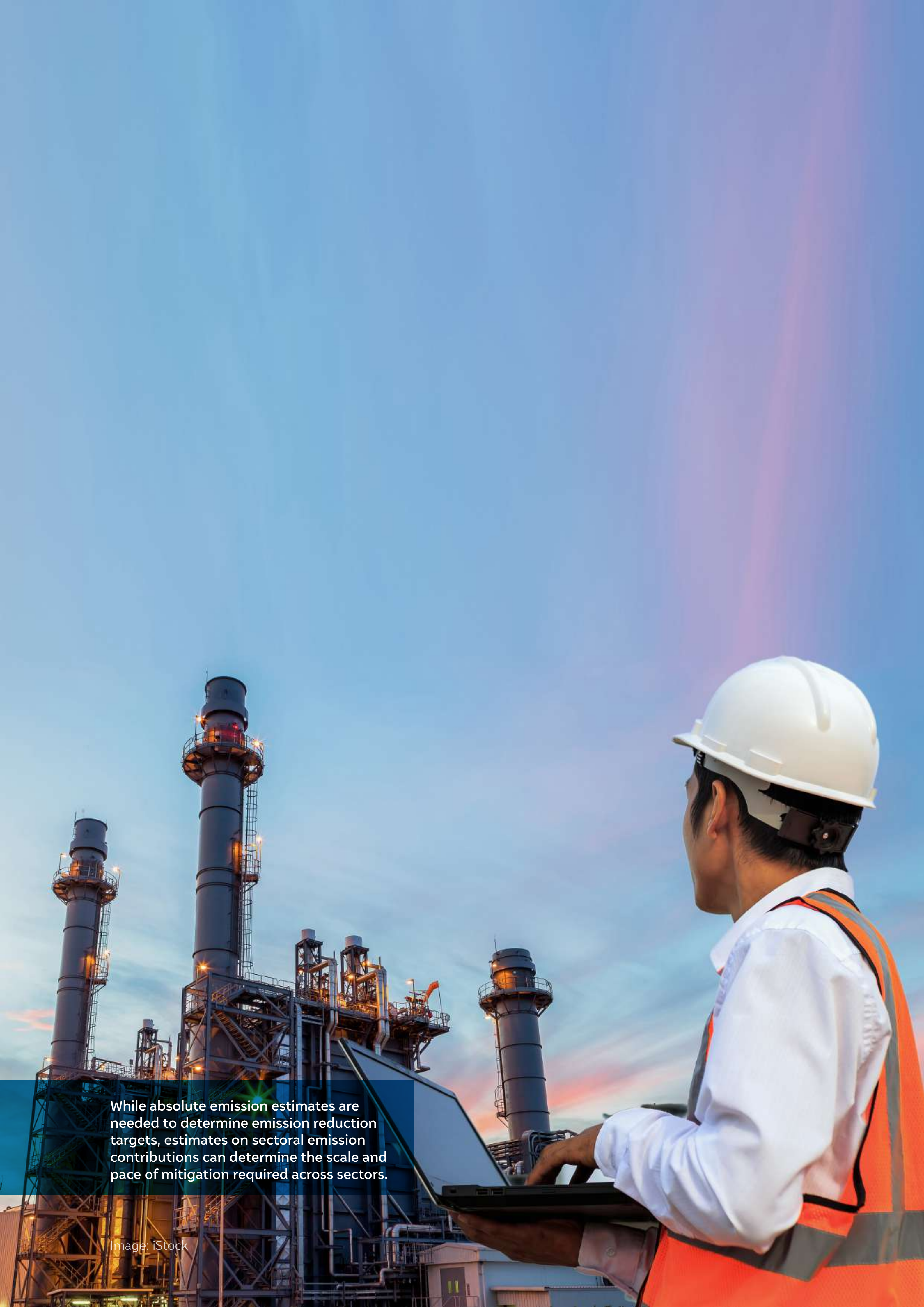
While $PM_{2.5}$ emission factors for dung and biomass are comparable across the five inventories, those for firewood range from 4.1 g/kg (SMoG) to 12.8 g/kg (EDGAR), across the five inventories. It is worth noting that despite employing similar emission factors and region-specific information on household fuel consumption, TERI's emissions are almost 50 per cent lower than those of SMoG's emissions. TERI's emission estimates account for growth in village electrification and households that use LPG, while SMoG's does not. This explains the lower emissions estimated by TERI.

Firewood range from 4.1 g/kg (SMoG) to 12.8 g/kg (EDGAR), across the five inventories

For computing SO_2 emissions from power plants, the SO_2 emission factors used in SMoG range from 4.9 to 7.3 g/kg of coal. The TERI inventory uses an SO_2 emission factor of 7.37 g/kg for all coal-based power plants.

In the case of NOx emissions from the transport sector, we observe significant variations in emission factors, particularly in the case of diesel passenger buses and heavy-duty trucks. As mentioned earlier, transport sector emissions show the greatest variations. This could partly be attributed to the wide range of emission factors that the inventories employ.

3. The EMEP guidebook reports a wide segment of vehicle technologies, resulting in a wide range of emission factors.



While absolute emission estimates are needed to determine emission reduction targets, estimates on sectoral emission contributions can determine the scale and pace of mitigation required across sectors.

Image: iStock

4. Recommendations

As indicated in the previous sections, with this study, we not only aim to highlight the variations in existing emission estimates for India, but also inform ways in which the discrepancies can be addressed. From our review, we infer that the lack of information on the extent of adoption of pollution control technology in industries, and region and process-specific emission factors are the two major challenges associated with the development of emission inventories. Further, global and regional databases rely on different data sources for information on activity levels. To ensure consistency in activity level information and emission factors used in emission inventories, we recommend the following:

Assessing representativeness of existing estimates

In this study, we have discussed variations in the existing emission estimates. However, assessing which inventory is more representative of the emissions scenario in India warrants a much closer look at emission calculation methodology. The NKN can play a critical role here in identifying ways in which these inventories could be improved/upgraded to reflect India's emission scenario. Further, the NKN could also promote cross-learning across various groups that have already developed inventories for India and those that are in the process of developing new ones. This would help eliminate discrepancies in sectoral contributions estimated by different inventories.

The National Knowledge Network can play a critical role here in identifying ways in which these inventories could be updated to reflect India's emission scenario

Periodic primary surveys to collect data from residential and informal sectors

Our review suggests that household energy use in India continues to be a significant source of $PM_{2.5}$. The latest available information on household primary cooking fuel usage is from 2011. While more recent data on the number of LPG connections is available from Government records, it is difficult to draw inferences on sustained usage of LPG as primary cooking fuel from these numbers alone. Periodic primary surveys to assess how fuel usage in households is changing over time would, therefore, be crucial in assessing trends in emissions from households. Equally, the lack of an established energy balance for the country also means that understanding the breakdown of fuel use between formal and informal entities is missing. A periodic and sustained assessment of use across different sectors, especially those not covered in formal statistical surveys is critical, to establish their contribution to local and regional pollution.

Data reporting and collection protocols

It is evident from our review that emission estimates are based on assumptions about sectoral activities and penetration of abatement technology. Further, the availability of information required for computing emissions varies from sector to sector and region to region. To address these data gaps and ensure consistency in availability of data across sectors and regions and to help scientists and environmental professionals with required data for developing emission inventories, government departments should develop reporting protocols for the polluting entities that fall under their jurisdiction. For instance, the California Air Resources Board (CARB) has mandated all industrial facilities, with annual criteria pollutant emissions exceeding 250 tonnes, to report their emissions annually. CARB collects and reports this data to the general public (CARB 2021). For computing emissions from vehicles and unpaved roads, CARB collects data from the California Department of Transportation (Caltrans). This also illustrates the need for inter-department coordination in data collection.

A periodic and sustained assessment of energy use across different sectors, especially those not covered in formal statistical surveys is critical, to establish their contribution to local and regional pollution

Development of a comprehensive emission factor database

In Section 3.5, we have explained how choice of emission factors contributes to variations in emission estimates. Uncertainty in emission estimates can arise from uncertainties in emission factors (Pandey et al. 2014b). Therefore, we recommend that the CPCB, along with NKN, should develop and publish a comprehensive emission factor database, consisting of region-, process-, and fuel-specific emission factors. For instance, the AP-42 Compilation of Air Pollution Emissions Factors has been published by the United States Environmental Protection Agency (USEPA) since 1972, and contains emissions factors and process information for more than 200 source categories (EPA 2021a). The EPA also regularly updates the emission factors in the database. Similarly, the European Environment Agency (EEA) regularly updates its emission factor database which consists of both emission factors and efficiencies of control technologies (EMEP 2021). These will require the conduct of specific studies to assess emissions factors and collate existing research, which when synthesised, would give a view of the diversity across the country.

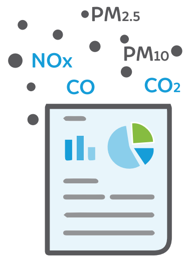
Ultimately, the availability of a periodically updated energy balance, spatial and sectoral resolution of energy consumed and consistent energy factors that are accepted and reviewed by the research community, would enable the environment regulator at the centre or in the state, to provide a consistent inventory for the policy and research community to use, in addressing sources of pollution, and according priority to their mitigation. Currently, the lack of a universally accepted emissions inventory brings into question the conclusions of various efforts to describe source contributions and is hindering concerted efforts against egregious sources of pollution.

5. Conclusion


Image: iStock

Our findings highlight that there are considerable uncertainties in emissions estimates for India. However, these uncertainties should not be an excuse to delay action. Notwithstanding the variations in estimates, the industrial sector appears to be among the leading emitters for multiple pollutants including PM2.5, SO_2 and NOx. The power sector emerges as the leading emitter of both NOx and SO_2 emissions in India. As mentioned above, SO_2 and NOx react in the atmosphere to form secondary particulate matter, thereby increasing ambient particulate concentrations. The residential sector which accounts for the largest share of particulate emissions in India is also a leading cause of air-pollution mortality in India, and should therefore be addressed.

While action on addressing emissions from sources must continue, India should work towards formalising a regionally representative, periodically updated air pollution emission inventory. Such an emissions inventory is key to help model the dynamic nature of pollution sources and their impact on various areas and assess the implications of new policies and regulations to curtail emissions from specific sources.



An emissions inventory is key to determine the dynamic nature of pollution sources and model their impact on ambient pollution levels

The formulation of the NKN to provide knowledge support under the NCAP, and the push towards conducting source apportionment studies across the non-attainment cities in the country are developments that signal that India is moving towards science-based air quality management. Given emission inventories are less resource-intensive than source apportionment studies, the NKN should prioritise the development of a database for representative emission factors. This would help improve data collection and reporting for the industrial and transport sectors, and ensure consistency in methods and data sources used for preparation of city-level emission inventories across the country.

Finally, data collection particularly for the informal and domestic sector could be significantly improved. Periodic primary data collection exercises for household fuel usage, penetration of clean cooking fuels or technologies, fuel usage and technology adoption in informal and micro, small and medium industries, etc., should be carried out at regular intervals.

Criteria pollutant emissions in India are on the rise. While the NCAP is an encouraging step towards reducing emissions in the country, it does not set sectoral emission reduction targets. A baseline inventory of sectoral emissions is critical for determining sectoral reduction targets which would then determine the scale and pace of action needed across sectors.

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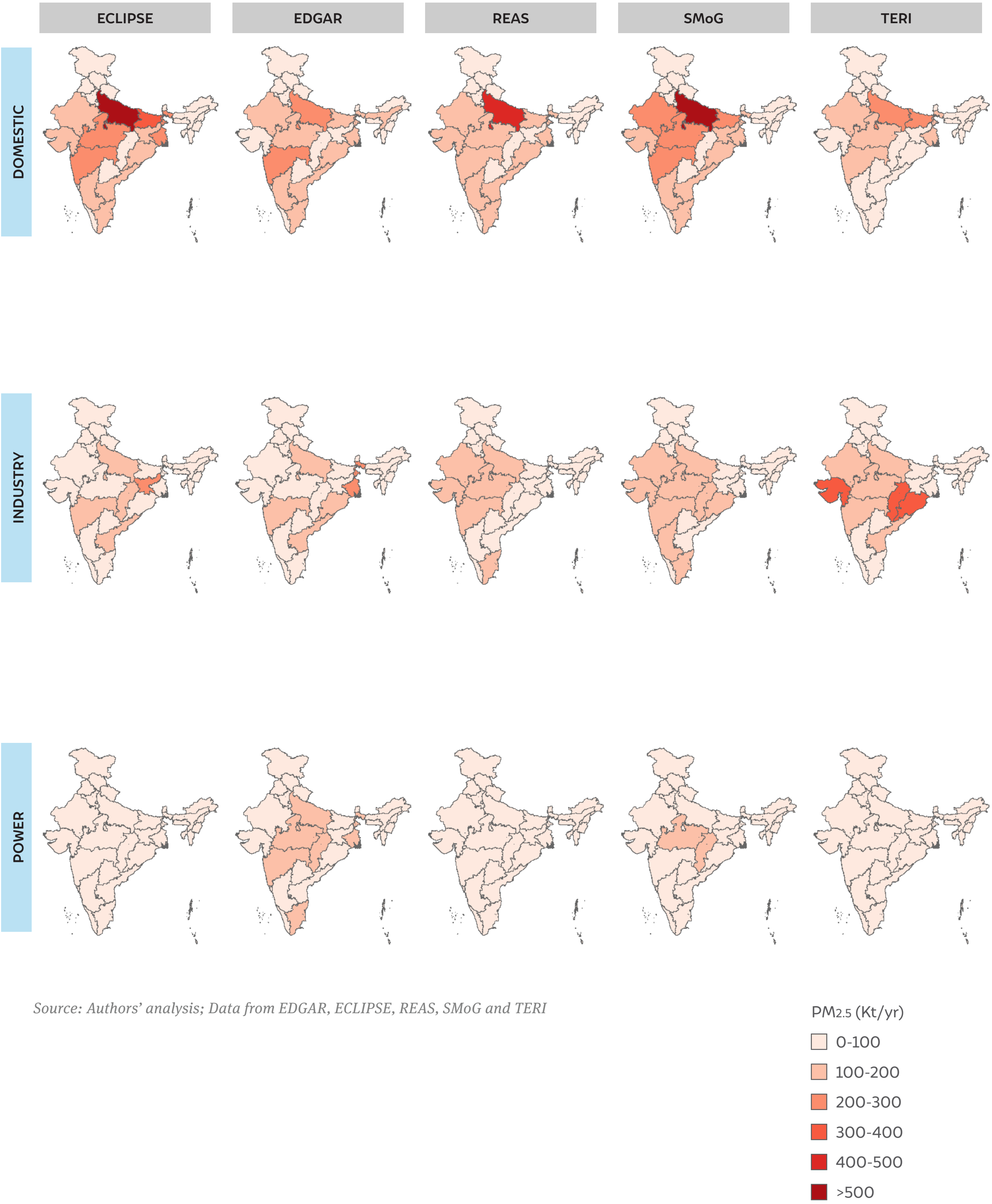
Annexures

Annexure 1 State-wise distribution of sectoral PM2.5 emissions



Source: Authors' analysis; Data from EDGAR, ECLIPSE, REAS, SMoG and TERI

Annexure 2 Summary of emission factors used in the inventories

Sector	EDGAR	REAS	ECLISPE	SMoG	TERI
Electricity generation	(EEA 2013, 2019)	(Kato and Akimoto 1992; Reddy and Venkataraman 2002)	(IIASA 2021)	(Chakraborty et al. 2008)	(Sharma and Kumar 2016; ARAI 2010)
Industry	(EEA 2013, 2019)	(Z. Klimont et al. 2002; Zbigniew Klimont et al. 2002; Kupiainen and Klimont 2004; Streets et al. 2006)	(IIASA 2021)	(Bond et al. 2004; Kupiainen and Klimont 2004; Zhang et al. 2009; Weyant et al. 2014)	(ILFS 2009; Rajarathnam et al. 2014; AP-42 1999; CPCB 2010b)
Transport	(D'Angiola et al. 2010; Schifter et al. 2005)	(Mishra and Goyal 2014; Sahu, Beig, and Parkhi 2014; Sadavarte and Venkataraman 2014b)	(IIASA 2021)	ARAI (2007) Mobile V6.2	(ARAI 2010)
Residences	(EEA 2013, 2019)	(Pandey et al. 2014a)	(IIASA 2021)	(Roden et al. 2006; Parashar et al. 2005; C. Venkataraman et al. 2005; Saud et al. 2012; Cao et al. 2008; Shen et al. 2010)	(Sharma and Kumar 2016)
Agricultural waste burning	(EEA 2013, 2019)	NA	(IIASA 2021)	(Turn et al. 1997; Andreae and Merlet 2001; Kim Oanh et al. 2011)	Developed for the study

Source: Authors' compilation

Annexure 3 Emission factor conversion

Conversion of g/GJ to g/Kg

g/Kg= value (g/GJ)* Net Calorific value (GJ/Kg)

Conversion of g/kg to g/km

g/km =(value (g/kg) * Density (Kg/m^3))/(1000(l/m^3)*Mileage(Km/l))

Conversion of Kg/GJ to g/Km

g/km =(value (Kg/GJ)*Net Calorific value (GJ/Kg)* Density (Kg/m^3)*1000(g/Kg))/(1000(l/m^3)*Mileage(Km/l))

Conversion of Kg/GJ to g/Km (For CNG vehicles, where mileage is given in Km/Kg)

g/km =(value (Kg/GJ)*Net Calorific value (GJ/Kg)*1000(g/Kg))/(Mileage*(Km/Kg))

Fuel	Net Calorific Value (TJ/Gg)	Net Calorific Value (GJ/Kg)
Wood	15.6	0.0156
Dung	11.6	0.0116
Biomass	11.6	0.0116
Kerosene (c)	43.8	0.0438
Kerosene (L)	43.8	0.0438
LPG	47.3	0.0473
Hard Coal	26.7	0.0267
Lignite	11.9	0.0119
Natural Gas	48	0.048
Gasoline	44.3	0.0443
Diesel	43	0.043

Table A1
Net Calorific Value of fuels

Source: IPCC. 2006

Segment	Fuel	Mileage	Unit	Source
2Ws	Petrol	57.4	Km/l	(Anup and Yang 2020)
	Diesel		Km/l	
	CNG		Km/kg	
4Ws	Petrol	15.8	Km/l	(Goel et al. 2016; NITI Aayog and Rocky Mountain Institute 2017)
	Diesel	14.9	Km/l	
	CNG	17.44	Km/kg	
Bus	Petrol		Km/l	(MoRTH 2017; NITI Aayog and Rocky Mountain Institute 2017)
	Diesel	4.5	Km/l	
	CNG	2.26	Km/kg	
Truck	Petrol		Km/l	(Malik et al. 2019)
	Diesel	3.78	Km/l	
	CNG		Km/kg	

Table A2
Mileage of different vehicle types

Source: Authors' compilation

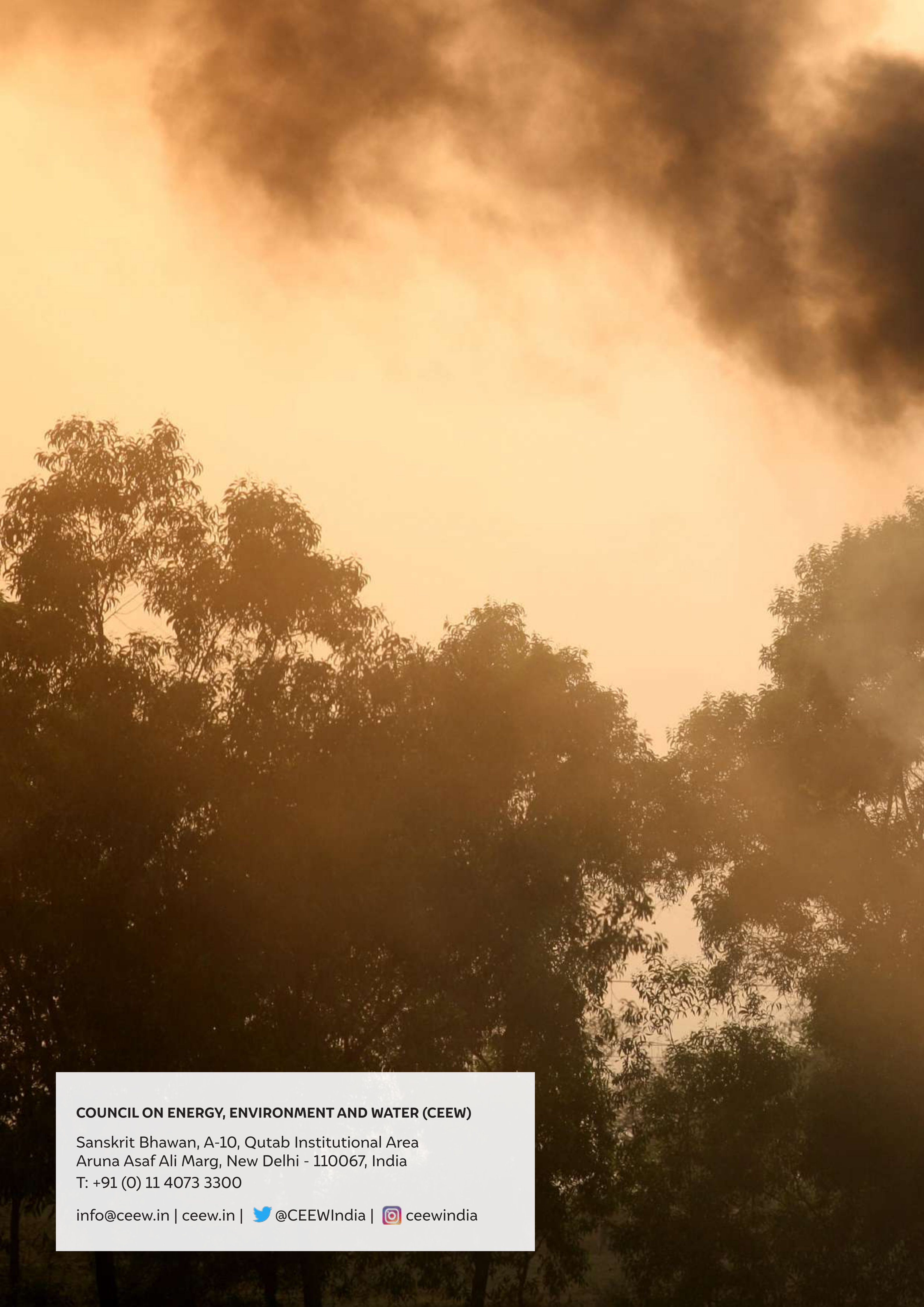
Fuel	Density	Unit	Source
Gasoline	747.5	kg/m^3	(BPCL 2021)
Diesel	832.5	kg/m^3	(BPCL 2021)
CNG	0.76	kg/m^3	(GAIL 2021)

Table A3
Fuel Density for mass conversion

Source: Authors' compilation

A publicly available, periodically updated national air pollution emission inventory is essential to evaluate how policy and technological interventions are getting translated into emission reductions.

Image: iStock



COUNCIL ON ENERGY, ENVIRONMENT AND WATER (CEEW)

Sanskrit Bhawan, A-10, Qutab Institutional Area
Aruna Asaf Ali Marg, New Delhi - 110067, India
T: +91 (0) 11 4073 3300

info@ceew.in | ceew.in | @CEEWIndia | ceewindia