Non-CO_2 Emission Reduction Pathways for Madhya Pradesh: A Multi-Sectoral Assessment

Prepared by

Gateway Research,
Institute for Governance & Sustainable Development (IGSD)
&
The Energy and Resources Institute (TERI), New Delhi

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For more information

Environmental Planning and Coordination Organisation (EPCO)
Paryavaran Parisar, E- 5, Arera Colony,
Bhopal 462016 Madhya Pradesh, India
https://epco.mp.gov.in/

and

Gateway Research & Institute for Governance & Sustainable Development (IGSD)

Contributions

Environmental Planning and Coordination Organisation (EPCO), Department of Environment, Government of Madhya Pradesh

Supported by:

Shri Aniruddhe Mukerjee, *Additional Chief Sceretary (Environment)*
Shri Harshal Pancholi, *Executive Director*

Core Team:

Lokendra Thakkar (Retd.)
Ramratan Simaiya
Ravi Shah

GRI Team

Bhhavya Kapoor
Nehal Sharma
Akshat Patni
Ravleen Kaur
Rishi Bakshi
Asad Ali

GRF Team

Aman Kumar
Pranjali Chowdhary
Atharva Deshmukh

IGSD Team

Zerin Osho
Shivang Agarwal
Jahnavi Shah

TERI Project Team

Nimish Singh *(Principal Investigator)*
Justin Jacob *(Co-Principal Investigator)*
Shivani Sharma
Prabhat Sharma
Dheeraj Mehra
Hafiz Rahman
Arindam Dutta
R Suresh
Shweta Gautam
Krishnapriya Nair
K Sai Dinesh
Sneha Kashyap
Ashmeet Kaur Alang
Suruchi Bhadwal (Advisor)
Manish Kumar Shrivastava (Advisor)
Anju Goel (Advisor)

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दिलीप अहिरवार
राज्यमंत्री
मध्यप्रदेश शासन
वन, पर्यावरण विभाग

मंत्रालय : कक्ष क्र. 541, पंचम तल
वल्लभ भवन, क्र-1, भोपाल
दूरभाष : 0755-2550084 (कार्या.)
ई-मेल : dileepahirwar414@gmail.com

क्रमांक 534

भोपाल, दिनांक 2/9/26

Message

Madhya Pradesh has consistently demonstrated the economic growth, industrial advancement, and climate responsibility that can progress together. As one of India's fast growing and industrialising states, we are also increasingly exposed to the impacts of climate change, facing rising temperatures and heat stress, and mounting air pollution challenges across our urban and industrial centres. These realities demand governance that is forward-looking, science-driven, and people-centric.

The state has emerged as a national reference point for integrated climate and environmental governance, recognised for its leadership in renewable energy expansion, sustainable agriculture, waste management innovation, and clean mobility. Through pioneering initiatives such as the Indore Municipal Corporation's success in waste management, the institutionalisation of the State Action Plan on Climate Change (SAPCC), and the state's position as home to 27% of India's organic farming area, Madhya Pradesh has demonstrated that climate resilience must be embedded within the broader development pathway of the state.

This report marks an important step in strengthening Madhya Pradesh's climate leadership by providing a first-of-its-kind evidence base on Short-Lived Climate Pollutants and non-CO_2 emissions across key sectors of the state economy. By integrating climate and air quality considerations, it offers critical insights to support Madhya Pradesh's long-term development vision and public health priorities.

This report reflects the collaborative efforts of various experts, government departments, and institutions committed to addressing the climate crisis. By providing valuable data and evidence-based recommendations, this report informs policy decisions and ensures alignment with sustainable development goals. These insights should be instrumental in shaping Madhya Pradesh's climate resilience initiatives.

The Government of Madhya Pradesh remains committed to accelerating clean energy transition, sustainable mobility, resilient agriculture, circular economy approaches, and improved air quality management. Madhya Pradesh has long demonstrated that environmental responsibility and economic progress need not be pursued separately. The task ahead is to deepen that integration with precision, scale, and urgency, and this report seeks to contribute meaningfully to that process.

(Dileep Ahirwar)
राज्यमंत्री
मध्यप्रदेश शासन,
वन, पर्यावरण विभाग

Shri Aniruddhe Mukerjee
Additional Chief Secretary
Environment Department
Government of Madhya Pradesh

Message

Governing climate action at the state level is less about ambition and more about architecture, the institutional wiring that connects scientific evidence to departmental decision-making and to on ground implementation. Madhya Pradesh's development trajectory presents a specific and pressing configuration of pressure of rising temperatures, extreme heat events, urban and rural pollution due to dense populations and proximity to major emission sources.

In this context, what is needed is granular, sector-specific intelligence that can advise departments on plans and actions. This inventory of Short-Lived Climate Pollutants (SLCPs) does exactly that. It maps, with methodological rigour, the sectoral emission profiles of super-pollutants like methane, black carbon, and associated air pollutants. It includes both top-down and bottom-up approaches. The report makes a strong case for district-level emissions inventories and target setting by combining an independent assessment of the state's emissions using satellite remote-sensing observations with a detailed, sector-wise analysis of SLCP and other non-CO_2 effluents, besides identifying the relative contribution of key sectors across the state.

What makes this work particularly valuable is not just its scientific content, but its administrative utility. It identifies where targeted interventions will yield the highest returns across climate, public health, and resource efficiency simultaneously. The convergence of air quality and climate outcomes is not incidental. For Madhya Pradesh, it represents a practical governance opportunity. Interventions that reduce black carbon from combustion sources or methane from waste/agriculture are investments that pay across multiple policy objectives at once. That kind of co-benefit logic must increasingly shape how we design programmes and direct resources. I commend this report to departments, local bodies, and planning agencies as a working instrument and decision support system. Its findings can support departments and local administrations in identifying high-impact interventions, improving resource allocation, and strengthening monitoring and accountability frameworks.

Madhya Pradesh continues to advance its development and climate objectives. Evidence based planning and institutional coordination will remain central to building a resilient, competitive, and sustainable future for the state.

Aniruddhe Mukerjee

Shri Harshal Pancholi
Executive Director
Environmental Planning & Coordination Organisation (EPCO)

Message

Environment Pollution and Climate Change in India has long operated through a framework built around point sources, threshold limits, and consent conditions. While that framework remains foundational, short-lived climate pollutants present a distinct challenge. Methane, black carbon, and tropospheric ozone precursors emerge from diffuse sources and impact warming and pollution at varying scales.

Madhya Pradesh's climate change challenge is not uniform. The rising temperatures exacerbate vulnerabilities, especially in districts like Dindori, Bhind, and Sidhi, where adaptive capacities are low, compounding risks to livelihoods, public health, and ecosystem. In Madhya Pradesh, particularly in urban areas of the state, exposure to SLCPs and other harmful air pollutants, including PM_{10}, $PM_{2.5}$, SO_2, CO, and ozone precursors, is particularly high due to dense populations and proximity to major emission sources such as transport, and industry. However, Madhya Pradesh has demonstrated strong performance in other sectors, offering replicable models and approaches that can be adapted to address similar challenges. The state's climate finance initiatives in waste management made the Indore Municipal Corporation the first civic body in India to generate revenue through carbon credit trading. MP presently leads in organic farming, with 0.76 million hectares, accounting for 27% of India's total organic cultivation area. As of 2023, the state has a capacity of 3022 MW of energy generation from solar plants and has mandated biomass blending in coal-based power generation, introducing a 5% blending requirement in 2024.

This report *"Non-CO_2 Emission Reduction Pathways for Madhya Pradesh: A Multi-Sectoral Assessment"* is, to my knowledge, one of the more systematic attempts to quantify that picture for the state. It draws together emission estimates across sectors where mandate intersects with those of industries, municipalities, transport authorities, and agricultural agencies. The report establishes a credible baseline from which monitoring can be strengthened and mitigation designed. It also makes a case for integrating SLCP considerations into developmental frameworks going forward. I acknowledge the contribution of TERI, IGSD, and all participating departments and experts in preparing this report.

Harshal Pancholi

Message from the Director, IGSD

On behalf of the Institute for Governance & Sustainable Development (IGSD), I am pleased to present this report, 'Non-CO_2 Emission Reduction Pathways for Madhya Pradesh: A Multi-Sectoral Assessment'. As climate impacts intensify, it is increasingly clear that long-term decarbonisation alone is insufficient. Alongside sustained CO_2 reduction, rapid action on Short-Lived Climate Pollutants (SLCPs) such as methane and black carbon is essential to curb near-term warming, improve air quality, and reduce climate risks. Efforts to mitigate non-CO_2 pollutants hold special resonance for a state like Madhya Pradesh that sits at the intersection of rapid urbanisation, industrial growth, and a large agricultural and livestock economy.

The state's forests, rivers, and agricultural landscapes, including the Narmada river system, sustain livelihoods, biodiversity, and downstream water security well beyond the state's boundaries. Yet, the state is already experiencing significant increases in heat stress, with average temperatures projected to rise sharply by the 2030s. Rising pressures from urbanisation, transport, industrial and mining activity, biomass use, waste, and changing agricultural practices are intensifying these risks. SLCPs directly exacerbate these vulnerabilities, worsening heat stress and extreme weather, and affecting public health. The science is clear: reducing SLCPs can slow near-term warming and deliver immediate air quality and climate resilience benefits within this decade.

Against such a backdrop, this report assumes significance by quantifying challenges and offering actionable policy solutions. It establishes a robust 2019 emissions baseline and evaluates Alternative policy pathways through 2047, offering an evidence-based roadmap across transport, residential energy, industry and mining, power, livestock, agriculture, and waste. The report identifies interventions that are technologically feasible, economically viable, and crucially, aligned with the Madhya Pradesh State Action Plan on Climate Change (MP-SAPCC). The analysis highlights a major opportunity for Madhya Pradesh to achieve near-term emissions reductions while generating green jobs, improving public health, and strengthening long-term climate resilience.

At IGSD, we support governments in advancing science-based climate action through policy design, capacity building, technology enablement, and access to finance. We believe subnational leadership will shape the next phase of climate action in India, and Madhya Pradesh, already a frontrunner in areas such as waste management, is well-positioned to emerge as a leader in integrated clean air and climate strategy.

We thank the Government of Madhya Pradesh, the Environment Planning and Co-ordination Organisation (EPCO), TERI, and all contributing experts for their collaboration. IGSD stands ready to support the state in translating analyses into implementation and impact at the last mile.

Strengthening climate resilience in Madhya Pradesh is not only a state priority, it is a meaningful contribution to India's broader clean air and climate goals. Acting decisively on SLCPs today brings us closer to a cleaner, healthier, and more climate-resilient future for Madhya Pradesh and beyond.

Zerin Osho
Director, Institute for Governance & Sustainable Development (IGSD)

Message from the Director General, TERI

Madhya Pradesh, with its diverse geography, growing urban centres, extensive agricultural base, industrial activities and rich natural resources, occupies an important position in India's development trajectory. As the State continues to pursue economic growth and improve the well-being of its people, addressing the interconnected challenges of air pollution and climate change is essential to building a more resilient, healthier, and sustainable future.

The Government of Madhya Pradesh has demonstrated its commitment to sustainable development through initiatives aligned with the Madhya Pradesh State Action Plan on Climate Change (MP-SAPCC) and the National Clean Air Programme (NCAP).

The report, Non-CO_2 Emission Reduction Pathways for Madhya Pradesh: A Multi-Sectoral Assessment, provides a comprehensive assessment of opportunities that can be explored for Air Quality benefits alongside GHG reduction co-benefits.

The Government of Madhya Pradesh has made significant progress in air quality management. The state has focused on controlling vehicular emissions, reducing road dust, strengthening industrial pollution monitoring, improving waste management practices, and expanding air quality monitoring networks in major cities such as Bhopal, Indore, Gwalior, Jabalpur, Ujjain, Dewas, and Sagar. The Madhya Pradesh Pollution Control Board (MPPCB) has also undertaken scientific studies to identify major pollution sources and develop targeted mitigation strategies. These coordinated efforts, supported by regular monitoring, inter-departmental collaboration, and community participation, have contributed to measurable improvements in air quality in several urban centers and demonstrate strong commitment of the State Government to building a cleaner and healthier environment for its citizens.

On behalf of The Energy and Resources Institute (TERI), I appreciate the constructive collaboration and technical support extended by the Institute for Governance and Sustainable Development (IGSD) during the preparation of this report. I also acknowledge the valuable contributions of the Environmental Planning and Coordination Organization (EPCO), government departments, researchers, scientists, and other stakeholders whose insights have enriched and strengthened this work.

I am confident that the findings and recommendations presented in this report will serve as a valuable reference for policymakers, planners, and practitioners. By translating scientific evidence into actionable mitigation pathways, the study will support informed decision-making and guide the prioritisation of policies, programmes, and investments in Madhya Pradesh, advancing towards a cleaner, healthier, climate-resilient and sustainable future.

Vibha Dhawan

Vibha Dhawan
Director General
The Energy and Resources Institute (TERI)

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Glossary

Baseline Scenario (BAU): A Business-as-Usual (BAU) scenario represents the sectoral growth projections for the state of Madhya Pradesh under existing conditions, without considering the implementation of any specific mitigation actions or interventions to address SLCP emissions.

Alternate Scenarios (ALT): These scenarios assume the successful implementation of additional interventions aimed at reducing SLCP emissions. They assess the impact of these measures on both short-term (2030) and long-term (2047) policy targets. The interventions include specific sectoral policies planned by the state or similar measures being implemented in other parts of the country.

Global Warming Potential (GWP): An index to measure the potency of greenhouse gases to absorb infrared thermal radiation over a given time frame after their addition to the atmosphere.

Short-lived climate pollutants (SLCPs): Gases and pollutants that contribute to global warming with a relatively short atmospheric lifespan as compared to long-lived greenhouse gases like carbon dioxide. They include substances like black carbon, methane, tropospheric ozone, and some hydrofluorocarbons (HFCs).

Emission Factors: A coefficient representing the amount of a specific pollutant emitted per unit of activity or fuel consumed in a sector.

Emission Inventory: A comprehensive dataset that estimates emissions of different pollutants from various sources within a defined region and time period.

Urban Heat Island (UHI) effect: This refers to the phenomenon of urban areas experiencing significantly higher temperatures compared to the surrounding rural areas. This difference in temperature is primarily due to human activities and urban development, which alter land surfaces and environments.

Natural Farming in Rice Cropping: A sustainable agricultural practice that minimizes chemical inputs by relying on natural soil processes, organic matter, and microbial activity to enhance soil fertility.

Direct Seeded Rice (DSR): It is a rice cultivation method where seeds are sown directly into the main field instead of transplanting seedlings from a nursery. This can be done in either dry or wet conditions, with dry DSR involving sowing into a well-prepared, non-puddled seedbed, and wet DSR involving sowing into puddled soil.

Heat Stress: A condition resulting from prolonged exposure to high temperatures, often exacerbated by climate change and urbanization. It can lead to adverse health effects such as dehydration, heat exhaustion, and heatstroke, particularly among vulnerable populations.

Co-benefits: Additional advantages gained from implementing climate and air pollution mitigation policies, such as improved public health, food security, and economic benefits.

List of Abbreviations

APCDs	Air Pollution Control Devices
AQI	Air Quality Index
BAU	Business-As-Usual
BC	Black Carbon
CAAQMS	Continuous Ambient Air Quality Monitoring Stations
CAFE	Corporate Average Fuel Efficiency
CAGR	Compound Annual Growth Rate
CCN	Cloud Condensation Nuclei
CEA	Central Electricity Authority
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPCB	Central Pollution Control Board
DMS	Dimethyl sulphide
DSR	Direct Seeded Rice
FAME	Faster Adoption and Manufacturing of (Hybrid) and Electric Vehicles
FGD	Flue Gas Desulfurization
GHG	Greenhouse Gas
GWP	Global Warming Potential
H-CNG	Hydrogen-Compressed Natural Gas
HAMP	Heat Action Management Plan
HFCs	Hydrofluorocarbons
ICAP	India Cooling Action Plan
IPCC	Intergovernmental Panel on Climate Change
ITMS	Integrated Traffic Management system
LPG	Liquefied Petroleum Gas
MNRE	Ministry of New and Renewable Energy
MoEFCC	Ministry of Environment, Forest and Climate Change
MoPNG	Ministry of Petroleum & Natural Gas
MoRTH	Ministry of Road Transport & Highways
NAAQS	National Ambient Air Quality Standards
NAMP	National Air Monitoring Programme
NCAP	National Clean Air Programme
NDDB	National Dairy Development Board
NH_3	Ammonia
NMVOCs	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
NRRI	National Rice Research Institute
NSSO	National Sample Survey Office
O_3	Tropospheric Ozone
OH	Hydroxide
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter 2.5 microns
PM_{10}	Particulate Matter ≤ 10 microns
SAPCC	State Action Plan on Climate Change
SCR	Selective Catalytic Reduction
SDGs	Sustainable Development Goals
SLCPs	Short-lived Climate Pollutants
SO_2	Sulphur Dioxide
SRI	System of Rice Intensification
UNEP	United Nations Environment Programme
VOCs	Volatile organic compounds

Executive Summary

This report presents a comprehensive and first-of-its-kind emission inventory of non-CO_2 pollutants for the state of Madhya Pradesh, using 2019 as the baseline year. It highlights the critical need to sharpen focus on non-CO_2 pollutants especially Short-Lived Climate Pollutants (SLCPs)—including methane (CH_4), black carbon (BC), hydrofluorocarbons (HFCs), and tropospheric ozone (O_3) in order to mitigate shorter term climate impacts, while maintaining the long-term momentum on CO_2.

To work towards this holistic strategy, the report analyzes the projected trends in SLCPs and other non-CO_2 pollutants under a Business-As-Usual (BAU) scenario through 2047. The report also evaluates a set of policy-driven alternative scenarios (ALT) across sectors, identifying pathways to achieve maximum emission reductions. Two key insights emerge from this study:

1. It offers a sector-wise breakdown of SLCP and other non-CO_2 pollutant emissions, highlighting the relative contributions of key sectors across the state. This consists of a bottom-up activity-based quantitative emission inventory and an independent top-down assessment of the state's pollution burden using satellite remote sensing observations, which demonstrate the spatial distribution of atmospheric column burdens of SLCPs and air pollutants across districts in the state.
2. It identifies priority sectors and policy interventions that are essential for integrating climate and air quality action, based on scenario-based analysis. This scenario analysis feeds into a pathway for reduction of targeted non-CO_2 pollutants.

With rising global temperatures and increasing pollution, Madhya Pradesh is vulnerable to the effects of climate change and air pollution.

Madhya Pradesh is experiencing significant increases in heat stress and rising temperatures. Climate projections indicate that average annual maximum temperature in Madhya Pradesh is projected to rise by 1.3°C-1.6°C by mid-century and 2.0°C-4.3°C by end-century compared to 1981-2010 baseline levels. Minimum temperature is projected to rise by about 1.4°C-1.8°C by mid-century and 2.6°C-5.3°C by end-century compared to 1981-2010 baseline levels. These changes align with trends in extreme heat events, such as longer warm spells and more frequent warm days/nights, as highlighted in climate exposure indicators. The rising temperatures exacerbate vulnerabilities, especially in districts like Dindori, Bhind, and Sidhi, where adaptive capacities are low, compounding risks to livelihoods, public health, and ecosystems. Such trends underscore the critical need for targeted strategies to mitigate heat stress and enhance resilience across Madhya Pradesh.

Madhya Pradesh serves as an important case study for state-level SLCP mitigation. Focusing on short-lived climate pollutants allows the state to address air quality and manage unpredictability of weather in the short & medium term.

The state experiences a mix of urban and rural pollution sources, with BC from biomass burning, CH_4 from agriculture and waste, and industrial emissions contributing to air quality and climate challenges. In Madhya Pradesh, particularly in urban areas of the state, exposure to SLCPs and other harmful air pollutants—including PM_{10}, $PM_{2.5}$, SO_2, CO, and ozone precursors—is particularly high due to dense populations and proximity to major emission sources such as transport, industry, agriculture, and household combustion. This pollution burden is further compounded by rising temperatures and increased heat stress, which disproportionately affect vulnerable groups and elevate the risk of heat-related illnesses. Thus, targeted SLCP mitigation efforts not only serve to improve air quality and protect public health but also contribute meaningfully to urban climate resilience by cooling cities and reducing heat stress impacts on vulnerable populations.

Madhya Pradesh has proactively implemented measures to tackle air pollution and climate change while aligning with national policies and initiatives, particularly having positioned itself as a trend setter in mitigation of waste sector emissions.

Madhya Pradesh has pioneered climate finance initiatives in waste management. The Indore Municipal Corporation (IMC) became the first civic body in India to generate revenue through carbon credit trading, earning ₹50 lakh from the sale of 1.70 lakh tonnes of CO_2 under the Verified Carbon Standard (VCS) programme of the UNFCCC. MP presently leads in organic farming, with 0.76 million hectares, accounting for 27% of India's total organic cultivation area. Madhya Pradesh has implemented several initiatives to reduce emissions and transition toward cleaner energy sources. As of 2023, the state has a capacity of 3022 MW of energy generation from solar plants and has mandated biomass blending in coal-based power generation, introducing a 5% blending requirement in 2024. In the Mining sector, the Mineral Policy of Madhya Pradesh emphasises the need for sustainable mining practices by balancing economic development with environmental conservation. Under the SMART Cities Mission, cities like Bhopal, Indore, Ujjain, Gwalior, Jabalpur, Satna, and Sagar are developing intelligent transport systems, expanding Bus Rapid Transit Systems (BRTS), and introducing metro rail networks to improve urban mobility and air quality. Aligning air quality initiatives with broader climate action will enable Madhya Pradesh to advance a sustainable, low-carbon development trajectory, improving public health, environmental resilience, and long-term climate mitigation efforts.

This study establishes a baseline for short-lived climate pollutants (SLCPs) and other non-CO_2 air pollutant emissions in Madhya Pradesh and assesses their near-term and long-term trajectories under alternative policy scenarios. By doing so, it highlights the emission-reduction potential of targeted, sector-specific policy interventions that align with the state's development and climate priorities.

Two key assessments have been undertaken in this study. First, a baseline inventory of SLCP and other non-CO_2 pollutant emissions was established for 2019 using data from various government sources, complemented by academic literature. Second, emissions scenarios were developed, including a Baseline Scenario and Alternate Scenarios aligned with the state's policy direction and vision. These scenarios feature quantifiable targets for 2030, 2040, and 2047, in line with the state's and India's developmental goals. The study identifies the contribution of each sector towards SLCPs and air pollutants. Further, the report projects the emission reduction potential of existing strategies during 2030 and 2047.

A satellite-based spatial assessment complements the bottom-up quantitative inventory, confirming that Madhya Pradesh's pollution burden is geographically concentrated and sectorally differentiated, further underscoring the need for district-level rather than uniform state-level policy targeting.

An independent top-down analysis was conducted using multi-sensor satellite observations for 2019 (Sentinel-5P/TROPOMI, MODIS MAIAC, VIIRS, FIRMS, and SEDAC). Reading the NO_2, SO_2, CH_4, and aerosol layers together reveals four spatially distinct pollution regions across the state, each with a dominant atmospheric signature reflecting underlying differences in land use, economic activity, and population distribution (outlined in the table below). This heterogeneity provides the observational basis for the district-level prioritisation embedded in the sectoral recommendations that follow in subsequent sections.

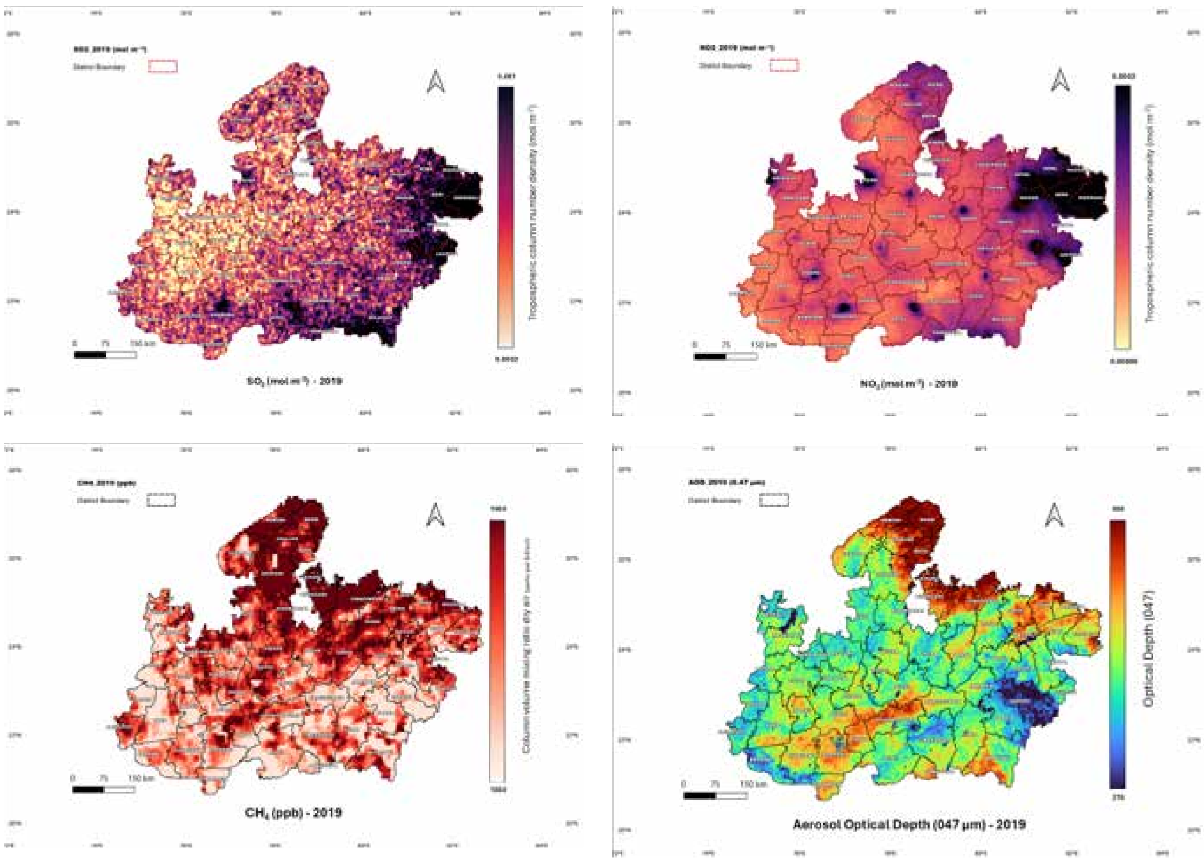

Figure 1: Individual Pollutant Column Composites, Madhya Pradesh 2019

((a) Sentinel-5P/TROPOMI annual mean composites for SO_2 and (b) NO_2, (c) column-averaged CH_4, and (d) MODIS MAIAC aerosol optical depth, for 2019. Each panel is displayed on its own physical scale and unit; layers have not been normalised or combined across different measurement units. Madhya Pradesh district boundaries overlaid.)

Table 1: Sectoral Satellite Atmospheric Evidence and Emission Inventory Requirements, Madhya Pradesh 2019

Sector	**What Satellite Detects**	**Key Hotspot Districts (Satellite-Derived)**	*Specific Limitation: Why Emission Inventory Is Required*
Power	SO_2 + NO_2 dominance in eastern belt; VIIRS confirms TPP asset locations as bright point-source nodes	Singrauli, Sidhi, Mauganj, Anuppur, Rewa, Gadarwara corridor	*Satellite confirms the eastern belt as the dominant combustion zone but cannot disaggregate asset-level contributions (e.g., individual TPP plants) needed to prioritise end-of-pipe controls such as FGD and SCR installation.*
Agriculture & Biomass Burning	CH_4 column in northern belt; FIRMS active fire detections (FRP 5–10 MW) on kharif cropland mask (Oct–Nov)	Morena, Bhind, Gwalior, Tikamgarh, Chhatarpur; Narmadapuram, Chhindwara, Narsinghpur (fires)	*Satellite cannot separate CH_4 from rice cultivation from that of co-located livestock and residential sources in the same northern belt. Inventory is required to model distinct interventions such as DSR adoption and residue-burning bans.*

Sector	**What Satellite Detects**	**Key Hotspot Districts (Satellite-Derived)**	*Specific Limitation: Why Emission Inventory Is Required*
Livestock	No independent satellite signal detectable; CH_4 in northern belt is a composite of multiple co-located sources	Spatially co-located with agriculture belt; not independently attributable	*Livestock — the state's single largest CH_4 source — is entirely invisible as an independent signal in satellite column retrievals. Quantification and scenario modelling (fodder management, breed composition) depend entirely on the activity-based inventory.*
Residential	Per-pollutant population-weighted exposure layers (NO_2, CH_4, CO, HCHO) highest across northern belt; urban nodes identifiable on NO_2 and CO layers	Entire northern belt (Sheopur to Singrauli); Indore, Bhopal, Jabalpur, Gwalior urban cores	*Population-weighted column layers cannot distinguish a household using LPG from one using fuelwood. They cannot identify biomass-dependent households targeted by clean cooking ALT scenarios. Fuel-use disaggregation requires household survey data and fuel-specific emission factors.*
Industry	Diffuse AOD + UVAI aerosol signal; Satna-Maihar-Katni belt and Indore-Ujjain-Dewas corridor identifiable	Satna, Maihar, Katni; Indore, Ujjain, Dewas, Bhopal, Sagar, Dhar	*AOD cannot separate industrial PM from road dust or construction emissions. Fuel-switching and process-change ALT scenarios require fuel consumption data and technology-specific emission factors.*
Mining	AOD + UVAI composite on 5 km mine buffers; CH_4 composite separately; Singrauli signal partly masked by adjacent TPP plume	Singrauli-Anuppur (coal), Balaghat (manganese), Satna-Maihar (limestone)	*Coal seam CH_4 is inseparable from the TPP plume in the satellite raster. Dust abatement ALT scenarios are formulated in activity-level terms — overburden removal volumes, transport distances, road surface type — that satellite aerosol proxies cannot provide.*
Waste	Persistent CH_4 co-located with VIIRS urban nightlights and landfill point layer at four major cities	Indore, Bhopal, Jabalpur, Gwalior (primary); Ujjain, Rewa (secondary)	*Satellite supports waste attribution at urban nodes but cannot differentiate CH_4 from open landfills, composting, anaerobic digestion, or waste combustion — the distinct treatment pathways around which ALT scenarios are structured.*
Transport	NO_2 + VIIRS radiance aligned with NH corridors; urban nodes visible only via spatial overlay with road network	Indore, Bhopal, Gwalior, Jabalpur; NH-44, NH-46, NH-30 corridors	*Transport NO_2 is not independently detectable at the state level — it is dominated by the eastern power sector and only visible through overlay with road network and VIIRS data. EV adoption and scrappage scenarios require vehicle fleet composition, fuel type, and vehicle-km data from transport demand modelling.*

Source: *Satellite analysis for this study (Sentinel-5P/TROPOMI, MODIS MAIAC, VIIRS, FIRMS, SEDAC, 2019). All satellite signals reflect atmospheric column burdens, not surface emission rates. Individual pollutant composites are presented on their own physical scales; no cross-species normalisation or combination is applied. Sectoral attribution is based on spatial co-location with known source types and is indicative.*

Key findings indicate that while the satellite-based analysis validates the spatial pattern of the pollution burden substantiated in subsequent sections on detailing findings from the activity-based emission inventory, it cannot disaggregate co-located sources (e.g., separating livestock, agricultural, and residential CH_4 in the northern belt, or coal-mine fugitive emissions from adjacent TPP plumes in the east), nor can it quantify sector-specific emission reduction potential under alternative policy scenarios. This structural limitation establishes the necessity of the bottom-up, activity-based inventory and scenario framework that follows.

Key Findings

The report takes a deep dive into a wide spectrum of SLCPs and other non-CO_2 pollutants that stand as a barrier to MP's clean air goals. It also provides viable policy solutions for the state, which can be implemented for reducing SLCPs and other non-CO_2 pollutants.

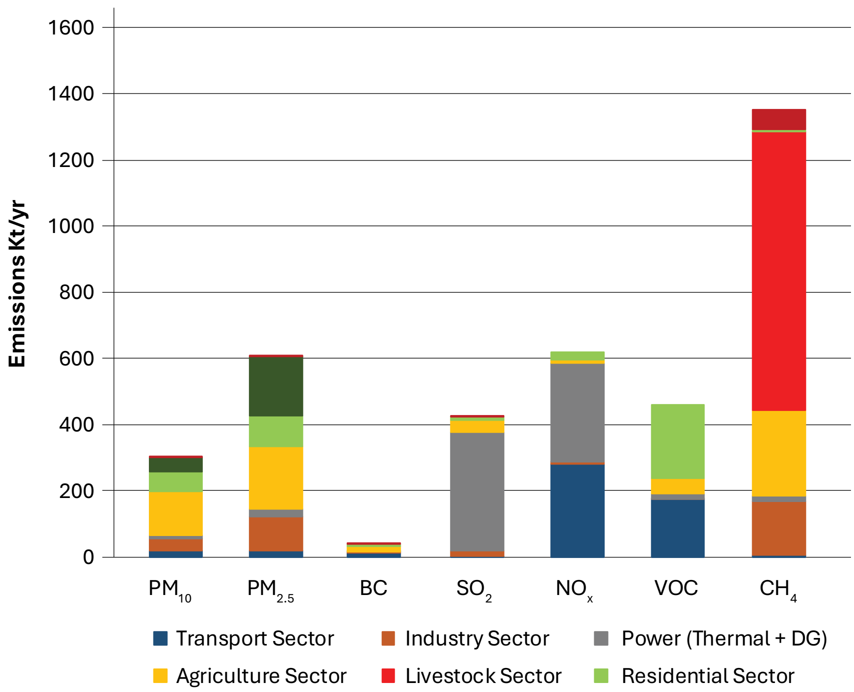

Figure 2: Sectoral contribution in 2019 for different pollutants in Madhya Pradesh in absolute numbers

Table 2: Sector-wise emissions (kt/year) of different pollutants in Madhya Pradesh

	PM_{10}	$PM_{2.5}$	BC	SO_2	NO_x	NMVOCs	CH_4
Transport Sector	19.2	18.6	13	3	281	174	5
Residential Sector	92	60	5	10	23	223	4
Industry and Mining Sector	102	35	0.4	14	7	1	163
Power (Thermal + DG)	24	10	1	358	297	16	18
Agriculture Sector	188	132	18	38	12	46	257
Livestock Sector	-	-	-	-	-	-	843
Waste Sector	4	4	0.1	0.4	-	-	61
Road dust re-suspension	181	43	-	-	-	-	-
Construction	18	3	-	-	-	-	-
Crematoria	3	2	0.1	0.1	0.4	9	1
Total	**631**	**308**	**38**	**424**	**620**	**470**	**1352**

As can be seen from the Table 1, methane emissions are the highest in the state followed by PM_{10} and NO_x. A substantial proportion of methane emissions can be attributed to the livestock sector, making it the single largest source of CH_4 in Madhya Pradesh, followed by agriculture. Open burning of agricultural residue remains a major concern, contributing to PM_{10} emissions along with re-suspension of road dust. The power sector, primarily comprising coal-fired thermal power plants, emerged as the largest emitter of NO_x in the state. NO_x emissions from transport account for 45% of total NO_x emissions, making it a critical contributor to ozone formation and secondary particulate matter, both of which significantly impact air quality and human health.

Transport Sector

The transport sector in Madhya Pradesh is a significant contributor towards NO_x (second highest contributor at 281 kt/yr) and NMVOC emissions (second highest contributing sector at 174 kt/yr) with cascading repercussions for ozone formation. Industrially developed districts in the state like Indore, Bhopal, Gwalior and Jabalpur, particularly show elevated emissions.

BAU and ALT Scenario:

The vehicle fleet in Madhya Pradesh is assumed to grow at an annual rate of approximately 9.79%, Under the BAU scenario, PM_{10} emissions are expected to increase by 27%, reaching 24.4 kt in 2047, while $PM_{2.5}$ emissions are projected to grow by 19%, reaching 22.1 kt. NO_x emissions are estimated to rise by 28%, from 280.9 kt in 2019 to 359.6 kt in 2047. CO emissions are likely to witness the most significant increase of 83%, reaching 409.9 kt by 2047. CH_4 emissions are projected to surge by 165%, while BC emissions are expected to rise by 22%. SO_2 emissions are expected to more than double, increasing by 115%, and VOCS emissions are projected to rise by 14%. Despite these increases, the implementation of BS-VI norms is expected to moderate the rate of emission growth.

Table 3: Descriptions of the Alternative Scenarios Assessed in the Transport Sector

Scenarios	Description
ALT-1 (Faster EV Adoption)	✓ By 2030, 40% of all new two-wheeler registrations and 100% of new commercial two-wheeler fleet will be EVs. 70% of all new three-wheeler registrations (passenger and freight) will be EVs. 15% of all new four-wheeler registrations and 40% of all new bus registrations will be EVs. ✓ By 2040, 50% of all vehicle fleets will transition to EVs. ✓ By 2047, 70% of all vehicle fleets in all districts will be converted to EVs..
ALT-2 (Vehicle Scrappage Policy)	✓ By 2030, 30% of all 20-year-old petrol and 15-year-old diesel vehicles will be scrapped. ✓ By 2040, 60% of all 20-year-old petrol and 15-year-old diesel vehicles will be scrapped. ✓ By 2047, 80% of all 20-year-old petrol and 15-year-old diesel vehicles will be scrapped..
ALT-3 (Biodiesel Blending)	✓ By 2030, 5% biodiesel blending will be achieved. ✓ By 2040, biodiesel blending will be increased to 10%. ✓ By 2047, biodiesel blending will reach 20%.

Results and Inference:

Table 4: Change in Transport Emissions Under Alternate Scenarios, compared to 2047 Emissions

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: Faster EV Adoption	-52%	-41%	-43%	-76%	-41%	-36%	-80%
ALT 2: Vehicle Scrappage Policy	-31%	-16%	-25%	-44%	-20%	-24%	-58%
ALT 3: Biodiesel Blending	-11%	-15%	-15%	-16%	-9%	-39%	-28%

Given the emission trends and spatial patterns observed, it is recommended that the government pursue statewide implementation of all three mitigation strategies—electric vehicle (EV) adoption, vehicle scrappage, and cleaner diesel interventions. District-level prioritization is essential. Urban centers such as Bhopal, Indore, Gwalior, and Jabalpur, where gasoline and CNG vehicle usage is high, should focus on EV deployment and scrappage policy implementation, supported by robust infrastructure and enforcement. Conversely, districts with high freight density and significant diesel consumption—such as Dewas, Dhar, Katni, and Rewa—should prioritize cleaner diesel strategies under ALT3. Strengthening institutional capacity through targeted training, integrating air quality and emission mitigation goals into state transport and urban planning frameworks, and leveraging public-private partnerships will be essential to ensure sustained and technically robust implementation across Madhya Pradesh.

Industry and Mining Sector

The industrial sector in MP remains a significant source of PM_{10} (102 kt/yr) emissions. CH_4 emissions from coal mining, estimated at 163 kt/year, remain a key concern in districts like Singrauli highlighting the need for effective emission control strategies. Indore emerges as a pre-dominant emitter, due to the presence of numerous small- and medium-scale industries using high-emission fuels. Dewas, Sagar, Dhar, Barwani, and Raisen are also key hotspots.

BAU and ALT Scenario:

Under the BAU scenario, emissions from the industrial sector and mining activities are expected to increase at a Compound Annual Growth Rate (CAGR) of 5% and 7%, respectively. By 2047, industrial emissions of PM_{10}, $PM_{2.5}$, SO_2, NO_x, NMVOCs, BC, and CH_4 are projected to be four times higher than their levels in 2019. Similarly, emissions from the mining sector, particularly PM_{10}, $PM_{2.5}$, and CH_4, are estimated to be six times higher than their 2019 levels.

Table 5: Descriptions of the Alternative Scenarios Assessed in the Industry Sector

Scenarios	Assumption
ALT-1	✓ The transition of Coal, Wood, Charcoal and Petcoke to Natural Gas is assumed to reach 25%, 50% and 100% in industries by 2030, 2040 and 2047, respectively.
ALT-2	✓ Implementation of community boilers and fuel consumption is expected to decrease by 30% for the years 2030, 2040 and 2047.
ALT-3	✓ The introduction of Green Hydrogen is assumed to reach 5% and 8% in industries by 2040 and 2047, respectively.
ALT-4	✓ Reduction in ash content and sulphur content by 40% and 30% respectively, by using washed coal. This is assumed to reach 25%, 50% and 70% by 2030, 2040 and 2047, respectively.

Table 6: Descriptions of the Alternative Scenarios Assessed in the Mining Sector

Scenarios	Assumption
ALT-1	✓ The sprinkling of water at every stage including loading and unloading of overburden and coal reduces the emission by 75%, and transport of coal and overburden reduces the emission by 70%. These assumptions are based on TERI's past experience and discussions with different stakeholders.
ALT-2	✓ Reducing the drop height during loading and unloading can reduce the emissions by 70%. These assumptions are based on TERI's experience and discussions with different stakeholders.
ALT-3	✓ Paving of roads can reduce the emissions by 80%. These assumptions are based on TERI's experience and discussions with different stakeholders.
ALT-4	✓ Best management practices reduce the emissions by 60%. These assumptions are based on TERI's experience and discussions with different stakeholders.

Results and Inference:

Table 7: Change in Industry Emissions Under Alternate Scenarios, Compared to 2047

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: Transition to cleaner fuel	-92%	-89%	-85%	-21%	-29%	-29%	-22%
ALT 2: Community Boilers	-11%	-11%	-10%	-3%	-3%	-3%	-3%
ALT 3: Impact of Green Hydrogen	-8%	-8%	-8%	-8%	-8%	-8%	-8%
ALT 4: Coal beneficiation	-25%	-21%	-21%	0%	-7%	-7%	-2%

Table 8: Change in Mining Emissions Under Alternate Scenarios, Compared to 2047

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: Water sprinkling	-74%	-	-	-	-	-	-
ALT 2: Reducing the drop	-25%	-	-	-	-	-	-
ALT 3: Paved Roads	-19%	-	-	-	-	-	-
ALT 4: Process Optimisation	-60%	-	-	-	-	-	-

The four alternative scenarios (ALT1–ALT4) propose a transformative pathway for reducing industrial emissions in Madhya Pradesh.

- ALT1 assumes a progressive transition from solid fuels (coal, wood, petcoke, charcoal) to natural gas, reaching 100% by 2047. This shift is expected to significantly reduce PM, SO_2, and BC emissions, particularly in districts like Indore, Dewas, and Dhar.
- ALT2, which focuses on the implementation of community boilers, aims to reduce coal consumption by 30% across the timeline, targeting smaller units with dispersed operations—this is particularly relevant for Indore, Dewas, and Sagar.
- ALT3 introduces green hydrogen as an industrial fuel, reaching 5% penetration by 2040 and 8% by 2047, offering promising climate co-benefits by reducing CH_4 emissions. This will especially benefit methane-heavy districts such as Raisen and Dhar.
- Lastly, ALT4 targets a reduction in ash and sulfur content using washed coal, phased in to reach 70% coverage by 2047. This measure is expected to substantially reduce PM and SO_2 emissions in coal-reliant districts like Indore, Dewas, and Sagar. Together, these targeted interventions underscore the need for decentralised and sector-specific emission control strategies.

Power Sector

As of 2023, 62.5% of the state's power was sourced from coal-based TPPs, down from 81.7% in 2019. The power sector is the largest emitter of SO_2 (358 kt/yr) and NO_x (297 kt/yr) in the state. SO_2 emissions particularly contribute to the formation of secondary particulate matter, worsening $PM_{2.5}$ pollution across the region. At an asset level, Gadarwara STPP (58.48 kt) and M.B. Power Ltd (50.29 kt) were identified as the highest SO_2 contributors in the state.

BAU and ALT Scenario:

Under the BAU scenario by 2030, emissions are expected to rise significantly relative to baseline levels. PM_{10} and $PM_{2.5}$ are projected to increase by 63% and 64%, respectively. NO_x emissions will increase by 43%, while CO emissions may rise by 76%. NMVOCs, CH_4, and BC emissions are also anticipated to grow by 57%, 49%, and 71%, respectively. By 2040, the emissions trajectory shows a more severe increase across all pollutants. PM_{10} and $PM_{2.5}$ levels are projected to rise by 188% and 189%, while NO_x and CO emissions will escalate to 152% and 211%, respectively. NMVOCs and CH_4 emissions will increase by 177% and 162%, and BC emissions are expected to reach 201% of baseline levels.

Table 9: Descriptions of the Alternative Scenarios Assessed in the Power Sector

Scenario	Renewable Energy Share	Biomass Co-firing	Gas-Based Power	SO_2 Control	NO_x Control
ALT-1	60% (2030), 70% (2040), 75% (2047)	10% in TPP boilers	-	100% FGD in TPPs by 2030	100% SCR in TPPs by 2030
ALT-2	Constant at 50%	10% in TPP boilers	10% (2030), 20% (2040), 30% (2047)	100% FGD in TPPs by 2030	100% SCR in TPPs by 2030
ALT-3	55% (2030), 60% (2040), 65% (2047)	10% in TPP boilers	5% (2030), 10% (2040), 15% (2047)	100% FGD in TPPs by 2030	100% SCR in TPPs & gas plants by 2030

Results and Inference:

Table 10: Change in Power Sector Emissions Under Alternate Scenarios, Compared to 2047

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: High Renewables with Biomass Co-firing	-50%	-87%	-93%	-50%	-50%	-50%	-50%
ALT 2: Balanced Renewables with Gas Expansion	-30%	-82%	-88%	-18%	-27%	-30%	43%
ALT 3: Moderate Renewables with Solar and Gas Integration	-40%	-84%	-91%	-34%	-39%	-41%	-4%

ALT1 and ALT3 came out as the most effective strategies for reducing SO_2 and NO_x emission load from the sector. The ALT1 scenario assumes a rapid transition toward renewable energy with aggressive end-of-pipe pollution control measures, including 100% coverage of FGD and SCR technologies by 2030 and 10% biomass co-firing by mass in coal-fired boilers. The ALT3 scenario combines the scaling up of renewable energy with a phased substitution of coal-based generation capacity by natural gas, maintaining the same levels of pollution control deployment and biomass co-firing as in ALT1. CH_4 emissions exhibit marginal increases in gas-based systems but remain lower than BAU projections due to the combined effect of renewables and reduced fossil fuel usage. Overall, the findings reinforce the necessity of an integrated strategy combining renewable energy expansion, targeted retrofits of pollution control technologies, and demand-side interventions. Enabling policy frameworks, concessional finance, regulatory compliance mechanisms, and capacity-building initiatives will be essential to accelerate the transition.

Waste Sector

The state has consistently been a frontrunner for setting good practice examples on waste management in the country. Consistent with this, the waste sector contributed 61 kt/year of methane emissions in 2019, accounting for 5% of total CH_4 emissions in the state. Solid waste processing and landfill emissions are the primary sources with urban centres like Indore, Bhopal, Jabalpur and Gwalior identified as significant CH_4 emission hotspots.

BAU and ALT Scenario:

The BAU scenario represents a scenario where, of the total waste generated, 7,213 tons per day (TPD) (with a 90% collection efficiency) is being collected, with about 90% of waste being processed. In this baseline scenario, the state focuses majorly on composting, recycling, waste combustion and anaerobic digestion (AD) for treatment of waste. Of the approximately 90% of waste being processed, the majority (66%) is composted followed by recycling (21%), waste combustion (12%), and anaerobic digestion (1%) with 764 TPD being disposed off. The BAU scenario estimates project a significant fall in methane emissions by 2047 (over 80%), compared to the baseline year (2019), in line with the state's continued policy push for mitigation of waste sector emissions.

Table 11: Brief description of alternative scenarios for the waste sector

Scenarios	Description
ALT-1	✓ 99% of collected waste is diverted to composting, anaerobic digestion, waste combustion, and recycling. ✓ Waste processing includes: 52% composting (3877 TPD), 8% anaerobic digestion (597 TPD), 14% waste combustion (1050 TPD), and 26% material recovery facilities (MRFs) (1907 TPD). ✓ Open burning rate assumes 2% of uncollected waste burned by residents and 2% at landfills. ✓ Increased collection and treatment efficiency from BAU (90%) to ALT scenarios (99%) reduces open burning levels.
ALT-2	✓ 99% of collected waste is diverted, prioritizing waste combustion and recycling. ✓ Composting and anaerobic digestion capacities remain the same as BAU. ✓ Waste processing includes: 58% composting (4310 TPD), 1% anaerobic digestion (59.7 TPD), 14% waste combustion (1050 TPD), and 27% recycling (2011 TPD). ✓ Open burning rate assumptions remain the same as in ALT-1.

Results and Inference:

Table 12: Change in Waste sector Emissions under Alternate Scenarios, Compared to BAU in 2047

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: Energy Recovery Scenario	-77%	-78%	-	-	-	-61%	-16%
ALT 2: Resource Recovery	-14%	-14%	-	-	-	-45%	-19%

The waste sector alternate scenarios underscore the importance of a systems-level approach to integrated solid waste management (ISWM), supported by technological innovation and decentralized solutions. A district-specific approach is critical for optimizing waste sector interventions across the state. Cities like Jabalpur, Gwalior, and Ujjain require strengthening of MRF infrastructure and promotion of anaerobic digestion and composting to reduce landfill dependency and manage high organic waste volumes. Industrial-adjacent districts such as Rewa, Satna, Dewas, and Dhar are ideal for RDF aggregation and industrial co-processing, especially in cement plants, fostering industrial symbiosis. In agricultural districts like Sehore, Raisen, Chhindwara, and Seoni, decentralized bio-methanation leveraging cattle dung and crop residue should be prioritized. In tribal and forested districts such as Shahdol, Umaria, Balaghat, and Mandla, the focus should be on achieving full door-to-door collection, promoting segregation at source, and introducing low-cost, decentralized composting.

Agriculture and Livestock Sector

Open burning of agricultural residue remains a major concern, contributing to PM_{10}, $PM_{2.5}$, BC, SO_2, NO_x, and NMVOCs. Hoshangabad, Chhindwara, Seoni, Narsinghpur, and Raisen emerged as the top contributors, together accounting for about 25% of total agriculture residue burning-based BC emitted from the state. Districts like Balaghat, Rewa, Raisen, Mandla, Satna, and Jhabua recorded the highest methane emissions from rice cultivation. However, methane emissions from livestock estimated at 843 kt/year remains the single largest source of CH_4. The leading districts include Sagar, Morena, Rewa, Khargone, Chhindwara, and Satna.

BAU and ALT Scenario for the Agriculture Sector:

The rice cropland in the state was estimated to emit 257 kt of CH_4 in 2019–20. The annual rice production in the state in 2019–20 was ~7.3 Mt, which is 4% of the total annual rice production in the country. Considering the contribution of the state to the total annual rice production of the country remains constant, it was estimated that the rice production in Madhya Pradesh will reach roughly 9.1 Mt/year during 2050-51. The state's rice growing area must be expanded from 3.1 Mha in 2019–20 to 4.9 Mha by 2050–51 under the current crop yield scenario. The emissions in the BAU scenario will rise from 257 kt/yr in 2019 to about 471 kt/yr in 2047.

Table 13: Descriptions of the Alternative Scenarios Assessed in the Agriculture Sector

Scenarios	Assumption
ALT-1	✓ Promotes DSR to reduce water use, labor costs, and methane emissions. ✓ 30,000 ha adopted DSR in drought-prone districts (2022-23). ✓ 5% annual DSR adoption (2030-40), increasing to 8% (2040-50). ✓ A complete ban on agricultural residue burning is assumed from 2030 onward, resulting in a 100% reduction in associated emissions.
ALT-2	✓ Biochar from crop residue (40-60 million tonnes annually) as an alternative to burning is promoted. ✓ Combining biochar with intermittent flooding can reduce methane emissions by up to 60%. ✓ A complete ban on agricultural residue burning is assumed from 2030 onward, resulting in a 100% reduction in associated emissions.
ALT-3	✓ Madhya Pradesh leads with 1.731 million ha under natural farming (~45% of India's total). ✓ Expansion under Madhya Pradesh Natural Agriculture Development Board (2022) and NMNF. ✓ 20% annual adoption (2030-40), rising to 30% (2040-50). ✓ A complete ban on agricultural residue burning is assumed from 2030 onward, resulting in a 100% reduction in associated emissions.

Results and Inference for the Agriculture Sector:

Table 14: Change in Agricultural Emissions Under Alternate Scenarios, Compared to 2047

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: DSR with water management	-100%	-100%	-100%	-100%	-100%	-100%	-3%
ALT 2: Biochar application to cropland	-100%	-100%	-100%	-100%	-100%	-100%	-6%
ALT 3: Natural farming	-100%	-100%	-100%	-100%	-100%	-100%	-20%

Among the three alternative mitigation scenarios described in the study, ALT3 emerges as the most effective long-term strategy for reducing methane emissions, with potential reductions of up to 65% from rice ecosystems. ALT3 should be prioritized in districts where natural farming is already being promoted, such as Jabalpur, Sagar, Chhindwara, and Hoshangabad, leveraging momentum and existing capacity. ALT1 provides a technically viable and scalable option, especially in drought-prone and water-stressed districts like Tikamgarh, Chhatarpur, and Datia. ALT2 be targeted in rice-dominant districts with high residue generation, such as Balaghat, Mandla, Seoni, and Shahdol, where the risk of residue burning is higher and land availability for decentralized units is feasible.

BAU and ALT Scenario for the Livestock Sector:

Madhya Pradesh produced (17.8 Mt (Million Ton)) about 8.6% of the total annual milk production (198.4 MMT) in the country during 2019-20. Accordingly, the projected milk production in the state was estimated as 30.6 Mt in 2030-31, 54.8 Mt in 2040-41 and 98.2 Mt in 2050-51 following a 6% annual increase in milk production to meet the rising demand of the country, keeping the same share of milk production of the state in the country. Under the BAU scenario, CH_4 emissions from cattle populations in the state were estimated as 1509 kt/yr, 2703 kt/yr and 4841 kt/yr kt/yr during 2030-31, 2040-41 and 2050-51, respectively.

Table 15: Descriptions of the Alternative Scenarios Assessed in the Livestock Sector

Scenarios	Assumption
ALT-1	✓ Inspired by National Dairy Development Board (NDDB) initiatives. ✓ Encourages balanced feeding to optimize energy, protein, and minerals.
ALT-2	✓ Financial incentives to farmers for adopting indigenous breeds under natural farming schemes. ✓ The crossbreed and buffalo population decreases by 5% annually. ✓ To sustain milk production, the indigenous cattle population increases: ✓ +500 cattle (2020-30), +900 cattle (2030-40), +1,600 cattle (2040-50).
ALT-3	✓ Combines fodder management with indigenous cattle promotion (ALT1 + ALT2). ✓ Balanced feeding will be more effective in reducing emissions compared to Scenario 2 alone.

Results and Inference for the Livestock Sector:

Table 16: Change in Livestock Emissions Under Alternate Scenarios, Compared to 2047

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: Fodder management	-	-	-	-	-	-	-10%
ALT 2: Promotion of indigenous cattle population	-	-	-	-	-	-	14%
ALT 3: Promotion of indigenous cattle vis-à-vis nutritional enrichment	-	-	-	-	-	-	3%

Among the three scenarios, ALT3 (Integrated approach: Indigenous cattle + Balanced feeding) offers the most balanced and sustainable pathway. It offsets the increased methane emissions from a larger indigenous cattle population (as in ALT2) through nutritional interventions that enhance feed efficiency. ALT3 also ensures that milk productivity and methane mitigation can progress hand-in-hand. This scenario should be prioritized in regions with mixed dairy systems and access to fodder enrichment services, such as Indore, Sehore, Dewas, and Ujjain, where cooperative networks and extension systems can support both breed and feed transitions. ALT1 (Fodder management) is the most technically feasible and cost-effective short-term intervention, offering 10–15% reduction in methane emissions without altering livestock composition. This scenario can be rapidly scaled in intensive dairy districts like Bhopal, Gwalior, and Jabalpur, which already have access to feed distribution infrastructure, veterinary support, and cooperative milk networks.

Residential Sector

The residential sector in MP is the largest contributor to NMVOCs, primarily from biomass-based cooking and heating. Fuelwood is the dominant source of emissions in most districts, with areas like Dindori, Mandla, Katni, and Balaghat relying on it almost exclusively. Crop residue use is significant in districts such as Alirajpur and Anuppur, while charcoal-derived carbon plays a notable role in West Nimar and Jhabua. Some districts, including Bhind, Dhar, Morena, and Rajgarh, exhibit a mixed fuel-use pattern, whereas others, such as Mandla and Umaria, rely mainly on biomass.

BAU and ALT Scenario:

Under the BAU scenario, household LPG usage was estimated to grow at 10.68% annually in urban and rural areas of Madhya Pradesh during 2030, 2040 and 2047. The increased rate of LPG usage would reduce the number of biomass-using households in Madhya Pradesh, but still, 18% of rural households by 2047 would continue to depend on biomass fuels for cooking activity based on the present trend. The emission load of various pollutants from residential cooking activity in the state

Table 17: Brief description of alternative scenarios for the residential sector

Scenarios	Description
ALT-1	✓ Population growth at **1.39% (rural)** and **1.97% (urban)** per year. ✓ **LPG consumption grows annually by 10.68%**, based on government data. ✓ Households using biomass in **2030, 2040, and 2047** transition to **improved solid fuel cookstoves** with higher combustion efficiency.
ALT-2	✓ Population growth and LPG expansion as in ALT1. ✓ By **2030**, **20% of non-LPG users adopt improved cookstoves**, **20% adopt solar cookstoves (Surya Nutan)**, and **60% switch to biogas**. ✓ By **2040**, **80% of non-LPG users transition to biogas**, while the remaining **20% use solar cookstoves** and **10% use improved cookstoves**. ✓ By **2047**, all non-LPG users in rural areas switch to **biogas-based cooking**.
ALT-3	✓ Population growth and LPG expansion as in ALT1. ✓ By **2030**, **20% of non-LPG users adopt improved cookstoves**, **20% switch to biogas**, and **60% use solar cookstoves**. ✓ By **2040**, **80% of non-LPG users transition to solar cookstoves**, while **20% use biogas** and **10% continue with improved cookstoves**. ✓ By **2047**, all non-LPG users shift entirely to **solar cookstoves**.

Results and Inference:

Table 18: Change in Residential Emissions Under Alternate Scenarios, compared to 2047 Emissions

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: Improved Biomass Transition	-27%	-21%	-13%	-28%	-16%	-28%	-27%
ALT 2: Biogas-Dominant Shift	-94%	-53%	-41%	-98%	-58%	-100%	-89%
ALT 3: Emphasis on Solar cooking	-96%	-76%	-48%	-98%	-58%	-100%	-97%

The ALT2 and ALT3 scenarios in the residential sector provide maximum benefits in reducing $PM_{2.5}$, BC, and VOC_S emissions. An effective approach would be to supplement LPG penetration with other clean energy solutions, such as biogas adoption. Additionally, another high-impact strategy is the transition from traditional cookstoves to solar-powered cookstoves. It would be particularly beneficial for Madhya Pradesh to prioritise these alternate strategies in districts with low LPG penetration, such as Dindori, Mandla, Balaghat, Alirajpur, Anuppur, West Nimar (Khargone), Jhabua, Bhind, Dhar, Morena, and Rajgarh. Meanwhile, in urban centres, where LPG uptake is steadily increasing due to rising per capita incomes, it may be more effective to continue expanding LPG access rather than introducing additional alternative technologies. Achieving widespread adoption would require not only financial incentives but also behavioral shifts among communities.

Recommended Pathways and Recommendations

Madhya Pradesh has emerged as a frontrunner in sub-national climate action, with strong institutional foundations such as the SAPCC and nationally recognized leadership in urban waste management. To effectively mitigate non-CO_2 pollutants in Madhya Pradesh, a cohesive and strategic approach is essential—one that moves beyond siloed sectoral interventions and embraces integrated, cross-cutting solutions. Mainstreaming SLCP mitigation into the broader state climate and air quality planning ecosystem is also a critical lever. This includes aligning future actions with existing frameworks such as the State Action Plan on Climate Change (SAPCC), the National Clean Air Programme (NCAP), and key flagship schemes like Swachh Bharat Mission (Urban) 2.0, AMRUT, and SATAT.

Targeted technical and financial levers across sectors offer immediate opportunities for acceleration. In the transport sector, for example, Madhya Pradesh can link real-time emissions monitoring with enforcement and vehicle scrappage, while pooling NCAP funds, 15th and upcoming 16th Finance Commission grants, and PPPs to scale low-emission zones, charging infrastructure, and clean freight corridors. In industry and mining, reallocating industrial subsidies, leveraging mining royalties and CSR funds, and introducing performance-linked incentives tied to verified reductions in $PM_{2.5}$, methane, and black carbon – alongside equipment-as-a-service models – can overcome capital and maintenance barriers. Methane mitigation in waste and agriculture can be scaled through landfill gas capture, clustered waste-to-energy projects (building on the Rewa model), SATAT-linked CBG plants, and farmer-focused financing models such as pay-for-performance, FPO aggregation, and equipment leasing for crop residue management. Across sectors, innovative financing – green bonds, cess-based air quality funds, international climate finance (GCF/GEF), and PPP-led waste and bioenergy projects can unlock scale, while capacity building for ULBs, district departments, and enforcement agencies ensures long-term effectiveness. The main body of the report details the recommended sector-specific pathways and implementation frameworks through which Madhya Pradesh can translate its strong planning architecture into measurable reductions in non-CO_2 emissions and sustained co-benefits.

Introduction

Our atmosphere has been changing rapidly as a consequence of continuous emissions due to human activities. This has resulted in critical changes to our climate including environmental issues like air pollution. Atmospheric concentrations of pollutants are found to be much above their natural background concentrations across the world, which has resulted in undesirable effects on humans and the environment in the last few decades.

In India, air pollution has now become an issue of serious concern, with more than 70% of cities violating the prescribed standards of PM_{10} concentrations[1]. At the same time, the country is experiencing signs of a warming climate with potentially devastating effects in the long term. Air pollution and climate change are often considered two sides of the same coin, with their interdependence mediated through complex atmospheric mechanisms[2]. Historically, most countries, including India, have tackled these issues in isolation, without recognising their overlapping areas and interdependence.

Consumption of fossil fuels, increasing transportation needs, urban congestion, and seasonal agricultural crop residue burning are the primary sources of air pollution. Sharp increase in population coupled with rapid growth of industries and urbanization have acted as the primary drivers aggravating the issue. The levels of $PM_{2.5}$ and PM_{10} are found to be extremely higher than the WHO guidelines in most cities in India.[3]

Recognizing the severe burden of air pollution, the Indian Government has introduced several interventions, including the Swachh Bharat Mission (SBM) for solid waste management, the Pradhan Mantri Ujjwala Yojana (PMUY), and Unnat Chulha Abhiyan (UCA) for promoting improved cookstoves and clean fuel, the Saubhagya scheme for electrification, the National Electric Mobility Mission Plan (NEMMP) to increase zero-emission vehicle adoption, and the accelerated introduction of Bharat Stage VI (BS-VI) fuel.[4,5,6] More recently, the National Clean Air Programme (NCAP) was introduced in 2018 to reduce ambient particulate concentrations, aiming for a 40% reduction of $PM_{2.5}$ and PM_{10} in 132 non-attainment cities by 2026, based on 2017 levels.[7] In 2020, following the 15th Finance Commission's recommendations, the Government of India allocated about $1.7 billion over five years to fight air pollution in 42 Indian cities with million-plus populations, provided they reduce their air pollution levels by 15% annually. This is the world's first performance-based fiscal transfer funding program for urban air quality management.[8]

Further, research on co-benefits has shown that climate policies can generate additional environmental, health, social, and economic benefits.[9] The 21st session of the United Nations Conference of the Parties (COP21) in Paris in December 2015 marked a milestone in pursuing integrated mitigation efforts for climate change and air pollution without hindering economic growth in low-and-middle-income countries.[10] As the third-largest emitter of greenhouse gases globally, after China and the United States, India plays a key role in international negotiations; and has implemented various policies to improve energy efficiency and mitigate climate change at national and local levels.[11]

To achieve the national goals, states in India play a crucial role in implementing national policies and programs locally. The success of initiatives like the NCAP relies heavily on state-level execution and monitoring. States can innovate and adopt best practices tailored to their unique environmental challenges, contributing to national goals of reducing pollution and mitigating climate change. Further, India's federal structure allows states like Madhya Pradesh to develop specific strategies based on their emission inventories and sectoral analyses. This localized approach ensures more effective and sustainable interventions, addressing the root causes of pollution and climate change within the state.

On these lines, Madhya Pradesh has undertaken a broad set of targeted initiatives to tackle air pollution and climate change, aligning with national priorities across key sectors. In agriculture, the state promotes Direct Seeded Rice (DSR), organic farming, and natural farming through the Madhya Pradesh Natural Agriculture Development Board. The Madhya Pradesh Renewable Energy Policy 2025 and Solar Power Policy (2012) are driving a clean energy transition, while biomass blending mandates and solar pump deployment under PM-KUSUM support rural energy access. Industrial emissions are being addressed through the Madhya Pradesh Industrial Promotion Policy 2025 and adopting Flue Gas Desulfurization systems, with sustainable mining practices guided by the state's Mineral Policy. Clean mobility is advancing under the Madhya Pradesh EV Policy 2025 and Smart Cities Mission, with diesel vehicle phase-outs and CNG/LPG transitions. Residential sector efforts include LPG access via PMUY, improved biomass stoves, and promotion of solar cooking. In waste management, the state has scaled up treatment infrastructure and pioneered carbon credit trading through the Indore Municipal Corporation. These coordinated actions reflect Madhya Pradesh's strong push toward emission reduction and sustainable development.

While Madhya Pradesh has made significant strides, fragmented air quality and climate efforts highlight the need for integrated governance. This report emphasizes the dual approach of long-term decarbonization and rapid reduction of Short-Lived Climate Pollutants (SLCPs) in the immediate term, identifying key sectoral mitigation opportunities. These insights not only guide policy and investment in the state but also serve as a model for sub-national climate action across India and beyond.

From Air Quality to Climate Action: Leveraging non-CO_2 Pollutant Mitigation - A Path Beyond Decarbonisation

Beyond CO_2, a range of non-CO_2 pollutants play a crucial role in both air pollution and climate change. The scientific community now acknowledges the significant role of air pollutants such as BC, O_3, CH_4, and HFCs in climate change. These pollutants, known as short-lived climate-forcing pollutants (SLCPs), contribute to the warming of the climate, while others, like sulfates from sulfur dioxide, have a cooling effect on the climate. Growing scientific evidence highlights the co-benefits of managing air pollution and climate change simultaneously.[12] Effective air pollution management through remediation measures, policy interventions, and abatement strategies can contribute to long-term plans aimed at curbing climate change, forming a winning combination[13] Some critical SLCPs, which are major contributors to warming and air quality, generally include:

1. **Black Carbon (BC):** Black carbon is a powerful climate-forcing aerosol with a short atmospheric lifetime of just a few days to weeks.[14] It is a key driver of global warming and is the light-absorbing component of particulate matter (PM). Primarily emitted from the incomplete combustion of fossil fuels and biomass-based fuels, its climate impact depends on its location in the atmosphere. At ground level, BC directly warms the air by absorbing solar radiation and emitting heat. It also impacts cloud microphysics, altering precipitation patterns and posing as a hazardous air pollutant with severe health consequences.
2. **Hydrofluorocarbons (HFCs):** HFCs are synthetic greenhouse gases primarily used as refrigerants, solvents, and in foam production. Some HFCs have global warming potentials (GWP) hundreds to thousands of times greater than CO_2 over a 20-year period. HFC emissions mainly result from leakage during the use and disposal of products containing these gases.
3. **Tropospheric ozone (O_3) and Its Precursors:** Tropospheric ozone is the third most important greenhouse gas after CO_2 and CH_4.[15] It absorbs infrared radiation (heat) from the Earth's surface, reducing the amount of radiation that escapes to space. It is not emitted directly but forms through reactions between precursor gases—such as CO, NO_x, and VOCS (including methane)—which result from both natural and human activities. Ozone interacts with both shortwave and longwave radiation, contributing to climate warming.[16]

4. **Methane (CH_4):** Methane is a highly potent greenhouse gas. Over 20 years, one kilogram of methane has more than 80 times the warming impact of the same amount of CO_2.[17] Approximately 45% of today's net global warming is driven by methane emissions from human activities.[18] Sources of methane include both natural processes, such as wetlands, and human activities, including agriculture (e.g., rice paddies, livestock digestion), landfills, and fossil fuel extraction. Human activities account for about 60% of global methane emissions.[19] Methane also acts as a precursor to O_3. It reacts with hydroxyl radicals (OH) in the atmosphere, forming methyl radicals (CH_3), which subsequently oxidize to produce O_3 in the presence of NO_x.

Addressing SLCPs offers a critical opportunity to complement decarbonization efforts and achieve rapid reductions in warming. This approach provides significant co-benefits, including improved air quality, reduced health impacts, and enhanced food security.

Table 19: SLCPs and their Global Warming Potential (GWP)

SLCP	Global Warming Potential (GWP)
Methane	More than 80 times that of CO_2 over a 20-year horizon
Black Carbon	Thousands of times greater than CO_2 on a per-mass basis (remains in the atmosphere for only a few days to weeks)
Hydrofluorocarbons	GWPs of HFCs vary widely but some HFCs can have GWPs ranging from hundreds to thousands of times that of CO_2 over 20 years
Tropospheric Ozone	Indirect GWP since it is not emitted directly but contributes to warming through its formation

Note: Global Warming Potential (GWP) is an index to measure the potency of greenhouse gases to absorb infrared thermal radiation over a given time frame after their addition to the atmosphere. Essentially, the higher the GWP of a gas, the more that given gas warms the planet when compared to CO_2 over that period. This time for GWP is typically 100 years.[21]

The UNEP/WMO report, published in 2011, paid attention to SLCPs, pointing out that reducing their concentration in the atmosphere through implementing 16 available measures by 2030 offers an opportunity to reduce the rate of global warming by about half over the coming decades. This will lead to a global temperature about 0.5°C lower than the baseline trajectory in 2050.[22] These measures would also provide large air quality benefits, leading to over 2 million fewer deaths per year globally after 2030, as well as avoiding crop yield losses of tens of millions of tonnes of only four staple crops. Thus, the early action on reducing SLCPs along with GHG emission reductions can help achieve the 'well below' 2°C targets of the Paris Agreement. The IPCC report (2018) on limiting the increase in warming to 1.5°C emphasized that despite drastic reduction in CO_2 emissions, the 1.5°C goal would not be achieved without significant methane, black carbon, and HFC emission reductions.[23] SLCP mitigation is therefore a major focus of policy development to reduce climate change and achieve air quality goals. Research and policymaking organizations should simultaneously focus on reducing air pollutants and climate forcers (GHGs and SLCPs).[24,25,26]

Policy Responses to SLCP Emissions

Due to the intricate scientific linkage between air quality and climate change, clear policy guidance embedding the interaction between the two can result in enhanced co-benefits for climate, human health, and ecosystems. Even from the point of view of Sustainable Development Goals (SDG), there is a great opportunity to contribute by including the air quality and climate change linkages in designing policies to address them. Several multilateral agreements and individual countries across the world have already undertaken this linkage in their policies, which are detailed in the section below. These may be useful for India in rolling out collective climate action policies.

Multilateral Agreements and Processes

International organizations have emphasized the critical need to address SLCPs, underscoring both their direct mitigation benefits and the broader co-benefits associated with their reduction. These organizations have also established comprehensive regulatory frameworks and policy recommendations to facilitate the mitigation of SLCP emissions. Notably, international agreements such as the Montreal Protocol (1987) have provided a robust legal and regulatory foundation for addressing specific SLCPs. Universally ratified, the Montreal Protocol established differentiated timelines for developed and developing countries to phase out the production and consumption of ozone-depleting substances[27].

Building upon this framework, the Kigali Amendment (2016) introduced regulations to curtail HFCs, which, while not ozone-depleting, are potent climate-warming agents. The amendment mandates a phased reduction in HFC usage in refrigeration and air-conditioning by over 80%[28], with its effective implementation and complementary national and regional regulations projected to mitigate global warming by 0.05°C–0.07°C by 2050[29]. Furthermore, the United Nations Framework Convention on Climate Change (UNFCCC) acknowledges SLCPs as significant contributors to overall GHG emissions, reinforcing the necessity for targeted mitigation measures.

Underpinned by these international agreements, global calls to action for addressing SLCP emissions have been prominently advanced by institutions such as the United Nations Environment Programme (UNEP) and the Intergovernmental Panel on Climate Change (IPCC). The Climate & Clean Air Coalition to reduce Short-Lived Climate Pollutants (CCAC), convened under UNEP and comprising approximately 60 participating countries alongside a Scientific Advisory Panel, seeks to accelerate mitigation efforts through initiatives such as the Global Methane Initiative. The coalition is actively engaged in capacity building and awareness generation, particularly within developing nations, to mobilize both public and private sector efforts against key climate pollutants[30]. Additionally, it fosters regional and international collaboration to strengthen mitigation strategies and advance scientific understanding of SLCPs.

Further mitigation efforts are being pursued through initiatives such as the Global Alliance for Clean Cookstoves and the Global Methane Initiative, which aim to reduce emissions of black carbon and methane from major anthropogenic sources. In the realm of regulatory interventions, the International Maritime Organization (IMO) introduced the International Shipping Emissions Regulation (2020), which mandated a reduction in the sulfur content of marine fuels from 3.5% to 0.5%.[31] This regulation is designed to limit the formation of sulfate aerosols and fine particulate matter ($PM_{2.5}$), thereby mitigating adverse health impacts, particularly in coastal regions of South Asia and Africa.

Global Response

Several nations have incorporated SLCP mitigation into their national climate policies and strategies (See Figure 3). The United States has adopted multiple regulatory measures, including the U.S. Methane Emissions Reduction Action Plan (2021), which targets methane emissions from key sectors such as landfills, agriculture, and oil and gas operations. The American Innovation and Manufacturing (AIM) Act (2020) mandates the phasedown of HFCs through regulatory controls on production and imports, while the Ozone Transport Commission (OTC) and Regional Haze Rule seek to mitigate inter-state ozone pollution and enhance air quality in national parks and open spaces. Similarly, Chile has incorporated SLCPs into its Nationally Determined Contributions (NDCs) under the Paris Agreement (2015) and introduced a Green Tax on industrial and transportation sectors to regulate GHGs and SLCPs.

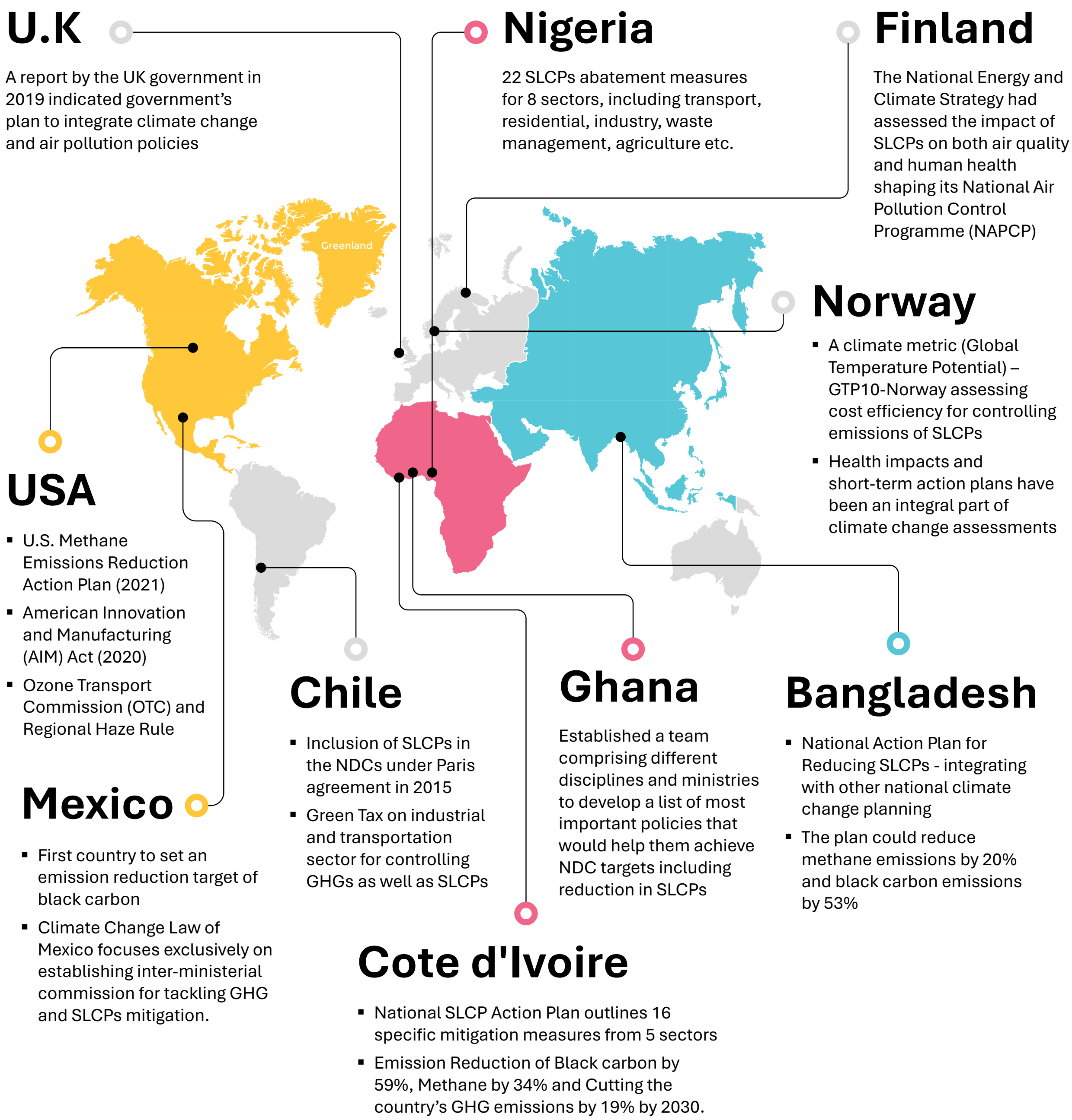

Figure 3: Global Responses in addressing SLCPs

In Finland, the National Energy and Climate Strategy assessed the impact of SLCPs on air quality and public health, shaping the Finnish National Air Pollution Control Programme (NAPCP). Norway has employed a quantitative approach by developing the Global Temperature Potential (GTP10-Norway) metric, aimed at assessing the cost efficiency of SLCF control measures. The country has also incorporated health impact assessments and short-term action plans into its broader climate policies. In the United Kingdom, a 2019 government report outlined plans to integrate climate change and air pollution policies to ensure a more cohesive mitigation strategy. Ghana has established a multi-sectoral team to identify key policies for meeting NDC targets, including strategies for SLCP reduction.

Mexico was the first country to establish a BC emission reduction target as part of its NDCs. It has further introduced the Climate Change Law, which mandates the creation of an Inter-Ministerial Commission to promote cooperation and knowledge exchange for the mitigation of GHGs and

SLCPs. Côte d'Ivoire has adopted a National SLCP Action Plan, which outlines sixteen mitigation measures across five major source sectors. Full implementation of these measures is projected to reduce BC emissions by 59%, CH_4 emissions by 34%, and overall GHG emissions by 19% by 2030, thereby fulfilling over half of the country's climate mitigation commitments[32]. Nigeria has established 22 SLCP abatement measures spanning eight sectors, including transport, residential, industrial, waste management, and agriculture. Bangladesh's National Action Plan for Reducing Short-Lived Climate Pollutants aligns SLCP mitigation with its broader national climate policies and revised NDCs, targeting a 17-24% by 2030 reduction in CH_4 emissions and a 53% reduction in BC emissions, in accordance with its commitments under the Paris Agreement[33].

At the sub-national level, several regions have implemented targeted SLCP reduction strategies. In the United States, California's SLCP Reduction Strategy (2017) aims to reduce CH_4 and HFCs by 40% and anthropogenic BC by 50% relative to 2013 levels by 2030. Similarly, the New York State Methane Reduction Plan (2017) aligns with the state's objective of reducing GHG emissions by 40% by 2030, focusing on CH_4 mitigation in the oil and gas, waste (landfills), and agricultural sectors. Stockholm, Sweden, has undertaken initiatives under the International Energy Agency (IEA) to convert organic waste into biogas, which is subsequently utilized for public transportation and heating. Additionally, Stockholm has introduced Low Emission Zones (LEZs) to restrict the use of high-emission vehicles in designated areas, thereby reducing BC emissions.

In Nigeria, the Lagos Integrated Waste Management Program has been implemented to mitigate CH_4 emissions through enhanced waste collection and landfill management. Similarly, Spain's Basque Country has incorporated SLCP reduction measures into its Climate Change Strategy (2050), with a particular focus on mitigating methane emissions from the waste and agricultural sectors. These initiatives underscore the significance of integrating SLCP mitigation strategies at both the national and sub-national levels, demonstrating the potential for enhanced climate action and improved air quality management. These experiences provide valuable insights for India, aiding in the formulation of policies that effectively integrate SLCP mitigation strategies at both national and sub-national levels.

India's Perspectives on Addressing SLCPs

India is a member and signatory to several global initiatives addressing SLCPs, including the Montreal Protocol, the Kyoto Protocol, and the Paris Agreement. In alignment with these international commitments, India has increasingly acknowledged air pollution as a pressing social and environmental issue. Concurrently, the country is experiencing the impacts of climate change, which pose long-term disruptive risks. While air pollution and climate change are governed by distinct policies, they are intrinsically linked through their sources, impacts, and mitigation strategies.

1987
Montreal Protocol
India became a signatory aimed at phasing out ozone-depleting substances, including hydrofluorocarbons (HFCs).

2005
Kyoto Protocol
India became a signatory to reducing greenhouse gas emissions, including SLCPs like methane and black carbon.

2010
National Solar Mission
To establish India as a global leader in solar energy, and achieve energy security through large-scale deployment, R&D, and cost reduction to reach grid parity by 2022.

2015
Paris Agreement
India submitted first Nationally Determined Contributions (NDC) – reducing emission intensity of economy by 33–35% from 2005 levels.

2022
India Cooling Action Plan (NCAP)
To promote energy efficient cooling and climate-friendly refrigerant.

2022
Update to NCAP & NDC
NCAP target updated to 46% reduction in atmospheric particulate matter concentration by 2026. NDC target updated to reduce the emissions intensity of its economy by 45% and achieving 50% non-fossil fuel capacity by 2030.

2019
National Clean Air Program (NCAP)
By 2024, reduce atmospheric particulate matter concentration by 20–30% compared to 2017.

2016
Kigali Amendment
India agreed to a phase down of HFCs, reinforcing its commitment to limiting high global warming refrigerants.

Figure 4: India's Actions in addressing SLCPs

The Indian government has undertaken numerous measures to combat air pollution and mitigate climate change. These include initiatives such as the Swachh Bharat Mission for improved waste management, the Pradhan Mantri Ujjwala Yojana and Unnat Chulha Abhiyan to promote cleaner cooking fuels, the Saubhagya scheme for expanding electricity access, and the National Electric Mobility Mission Plan to encourage the adoption of zero-emission vehicles. Additionally, the accelerated rollout of Bharat Stage VI fuel standards has played a crucial role in curbing vehicular emissions. In 2019, India introduced the National Clean Air Programme (NCAP), which aims to reduce particulate matter (PM_{10}) concentrations by upto 40% or achievement of National Ambient Air Quality Standards for PM_{10} concentrations by 2025-26. The India Cooling Action Plan (ICAP), launched in 2019, provides a strategic framework to enhance energy efficiency and promote climate-friendly refrigerants in line with the Kigali Amendment. Furthermore, India's Nationally Determined Contributions (NDCs) commit to achieving 50% of electric power from non-fossil fuel sources by 2030 and establishing an additional carbon sink of 2.5–3 GT through afforestation efforts.

Why we need sub-national action: Case for Madhya Pradesh

A one-size-fits-all approach to air pollution and climate change mitigation is ineffective in India due to the country's diverse geography, socio-economic conditions, and pollution sources. Implementing only a national plan overlooks the unique challenges faced by different states and cities. The sub-national plans are crucial because:

- **Diverse Sources of SLCPs Across States:**

  India's SLCP emissions arise from varied sources across states, making a uniform national policy ineffective. BC emissions in the Indo-Gangetic Plain (IGP) largely come from conventional cooking and crop residue burning, while coal-based industries in Jharkhand and Odisha contribute significantly to the east. CH_4 emissions also vary—while paddy cultivation in Punjab, Haryana, Uttar Pradesh and Bihar is a dominant source, landfill emissions are more concerning in urbanized states like Maharashtra and Tamil Nadu. Similarly, HFC emissions are higher in commercial hubs like Mumbai and Bengaluru due to high air-conditioning demand, whereas rural areas have minimal contribution. Tropospheric ozone precursors, including NO_X and NMVOCs, stem from different sectors—urban vehicle emissions in Delhi, power plants in West Bengal, and fertiliser use in agricultural belts. Given these regional differences, SLCP mitigation strategies must be tailored to specific emission profiles rather than relying on a single national plan.

- **Geographic and Climatic Factors Affect SLCP Persistence:**

  India's diverse climate and geography significantly influence how SLCPs behave in the atmosphere. In the IGP, wintertime temperature inversions trap pollutants, worsening BC's climate and health effects. In contrast, coastal states like Kerala and Tamil Nadu experience stronger winds and humidity, which aid pollutant dispersion, though they face greater risks from sea level rise. Mountainous regions such as Uttarakhand and Himachal Pradesh suffer from BC deposition on glaciers, accelerating glacial melt, an issue less relevant to central Indian states. These geographic variations mean that air pollution and climate change mitigation policies must be customised to account for region-specific atmospheric conditions, instead of applying a uniform strategy nationwide.

- **Socio-Economic and Developmental Constraints:**

  The feasibility of SLCP reduction measures varies based on state-level economic conditions and policy priorities. Wealthier states like Maharashtra and Karnataka can invest in advanced solutions like landfill gas recovery and electric vehicle infrastructure, while economically weaker states like Bihar and Jharkhand require lower-cost interventions, such as improved biomass cookstoves. Similarly, energy access disparities mean that LPG promotion may be a viable clean cooking solution in urban areas, but rural regions may need alternative options like improved cookstoves, biogas, and electric cooking. Additionally, industrialised states like Gujarat and Tamil Nadu prioritise emission reductions in manufacturing, while agrarian states like Punjab and Rajasthan focus more on methane reduction in farming. A rigid, centralised policy would not accommodate these economic and sectoral differences, reinforcing the need for state-driven strategies.

- **Governance, Implementation, and Enforcement Challenges:**

  Air pollution and SLCP mitigation require strong enforcement, but governance capacity differs across states. Some states, such as Delhi and Maharashtra, have proactive pollution control boards and well-established monitoring systems, enabling them to implement strict vehicular and industrial emission controls. In contrast, other states face institutional challenges in enforcing regulations due to a lack of infrastructure and financial resources. Decentralised governance mechanisms, such as city-specific action plans under the NCAP, have already shown better results than top-down mandates. A similar approach for SLCP mitigation—where states and cities design customised strategies—can improve enforcement, monitoring, and overall policy effectiveness.

- **Enhancing Co-Benefits Through Localised Policies:**

  Targeted SLCP mitigation strategies can simultaneously improve air quality and support state-specific development goals. For instance, reducing diesel transport emissions in Delhi cuts both NO_X and BC, while CH_4 capture from landfills in Mumbai and Chennai contributes to both pollution control and renewable energy generation. Crop residue management policies in Punjab and Haryana not only reduce winter air pollution but also limit CH_4 emissions from decaying biomass. Aligning SLCP reduction strategies with existing state development priorities, such as integrating CH_4 mitigation with sustainable agriculture or linking black carbon reduction with clean energy transition, can ensure that air pollution and climate goals reinforce each other, making interventions more effective and sustainable.

While a national SLCP mitigation framework is necessary for overall policy direction, funding, and international alignment, state-specific action plans are essential to account for India's regional diversity. Variations in emission sources, climatic conditions, economic constraints, governance capacity, and sectoral priorities require localised solutions that go beyond a one-size-fits-all approach. Strengthening state-level planning will not only accelerate SLCP mitigation but also maximise co-benefits for air quality, public health, and climate resilience.

Building on this understanding, Madhya Pradesh serves as an important case study for state-level SLCP mitigation. The state experiences a mix of urban and rural pollution sources, with BC from biomass burning, CH_4 from agriculture and waste, and industrial emissions contributing to air quality and climate challenges.

In Madhya Pradesh, particularly in urban areas of the state, exposure to SLCPs and other harmful air pollutants—including PM_{10}, $PM_{2.5}$, SO_2, CO, and ozone precursors—is particularly high due to dense populations and proximity to major emission sources such as transport, industry, agriculture, and household combustion. This pollution burden is further compounded by rising temperatures and increased heat stress, which disproportionately affect vulnerable groups, including the elderly, children, pregnant women, individuals with chronic illnesses, and socially disadvantaged communities. Together, these conditions elevate the risk of heat-related illnesses and mortality.

Adding to the complexity is the Urban Heat Island (UHI) effect, a phenomenon where urban environments experience higher temperatures than their rural surroundings due to the heat-retaining properties of concrete, asphalt, and built infrastructure. SLCPs such as BC and ground-level O3 exacerbate this effect by absorbing heat and reducing the Earth's natural reflectivity. However, mitigating SLCPs can offer a valuable co-benefit by reducing the intensity of the UHI effect. For example, cutting BC emissions can decrease atmospheric heat absorption, while phasing out HFCs and promoting energy-efficient cooling systems can lower waste heat emissions and reduce urban temperatures[34].

Madhya Pradesh is experiencing significant increases in heat stress and rising temperatures, with both observed and projected trends underscoring the urgency for climate adaptation[35]. Currently, summer temperatures in the state fluctuate between 22°C and 48°C, with extreme heat already posing risks to health, agriculture, and water resources. Climate projections indicate that average annual maximum temperature in Madhya Pradesh is projected to rise by 1.3°C-1.6°C by mid-century and 2.0°C-4.3°C by end-century compared to 1981-2010 baseline levels. Minimum temperature is projected to rise by about 1.4°C-1.8°C by mid-century and 2.6°C-5.3°C by end-century compared to 1981-2010 baseline levels.[36] These changes align with trends in extreme heat events, such as longer warm spells and more frequent warm days/nights, as highlighted in climate exposure indicators. The rising temperatures exacerbate vulnerabilities, especially in districts like Dindori, Bhind, and Sidhi, where adaptive capacities are low, compounding risks to livelihoods, public health, and ecosystems. Such trends underscore the critical need for targeted strategies to mitigate heat stress and enhance resilience across Madhya Pradesh.

Higher urban temperatures drive up the demand for air conditioning and cooling, especially in commercial and residential buildings. This leads to a spike in electricity consumption, increasing operational costs for businesses and energy bills for households, placing pressure on already strained urban power infrastructure. Elevated temperatures, especially during extended heat waves, can reduce outdoor and manual labour productivity in sectors like construction, transport, and informal street-level work. This directly impacts income levels and economic output in urban areas. Additionally, the rising heat-related illnesses due to UHI, such as heatstroke, dehydration, and cardiovascular stress, will burden urban healthcare systems, leading to increased public health spending and economic losses from absenteeism and reduced workforce efficiency.

Thus, targeted SLCP mitigation efforts not only serve to improve air quality and protect public health but also contribute meaningfully to urban climate resilience by cooling cities and reducing heat stress impacts on vulnerable populations. Madhya Pradesh, recognising these interlinked challenges, has implemented various policies to mitigate the impact of air pollution and climate change — these are discussed in the following section.

Subnational-Level Actions: Madhya Pradesh's Initiatives

Madhya Pradesh has proactively implemented measures to tackle air pollution and climate change while aligning with national policies and initiatives. The state has introduced various policies to promote sustainable development, enhance air quality, and mitigate climate impacts. Figure 5 below shows the summary of the actions taken by the state at the sub-national level:

Agriculture and Livestock

Madhya Pradesh has aligned its agricultural policies with national initiatives to reduce emissions and promote sustainable farming. The state has integrated the Direct Seeded Rice (DSR) implementation policy into its agricultural strategies, significantly reducing methane emissions by lowering water usage in rice cultivation. To support natural farming, the state established the Madhya Pradesh Natural Agriculture Development Board and presently leads in organic farming, with 0.76 million hectares, accounting for 27% of India's total organic cultivation area[37]. Over the last four years, the area under rice and wheat production increased by 50% and 53%, respectively, contributing to an increase in agricultural emissions. In response, the state has promoted crop diversification, encouraging the cultivation of horticultural and other cash crops through financial and policy incentives, with the objective of reducing the environmental impacts associated with conventional cereal production[38]. Further, the Mukhya Mantri Krishak Unnati Yojana provides the financial incentives (in 2025-26, Rs 850 crore has been allocated under this scheme) for crop diversification[39].

To mitigate emissions from the livestock sector, Madhya Pradesh has adopted improved fodder management and balanced cattle feeding practices, drawing on guidance from the National Dairy Development Board (NDDB). These practices aim to reduce methane emissions from enteric fermentation. Furthermore, under the Gobar Dhan Scheme, the state is supporting the development of community-level biogas systems that utilize cattle dung and agricultural residues to produce clean cooking fuel.

Complementing these efforts, the state has also implemented several breed improvement and livestock development schemes, including the Nandishala Scheme, Sammunat Pashu Prajanan Yojana, and the Gau-Bhains Vansh Prajnan Viniyaman Adhiniyam. These programmes aim to enhance the productivity and genetic quality of cattle, which indirectly contributes to emission reductions by improving feed efficiency and reducing the herd size required for the same level of output. Collectively, these integrated interventions support emissions reductions across the agriculture and livestock sectors.

SECTORS	POLICY ACTION AND ACHIEVEMENTS

AGRICULTURE & LIVESTOCK	- Direct-Seeded Rice (DSR)
	  – Methane Reduction with less usage of water
	- Natural/Organic Farming
	  – Madhya Pradesh Natural Agriculture Board/Prakritik Krishi Vikas Board established in 2022
	  – 0.76 million hectares, accounting for 27% of India's total organic cultivation area
	- Balanced Cattle Feeding (NDDB Model)
	  – Methane reduction from animal
	- Improved Fodder Management
	  – Contributing to lowering methane emissions
	- Crop Diversification Scheme

POWER	- Madhya Pradesh Renewable Energy Policy 2025
	  – 30% of State energy mix by 2027 and 50% of State energy mix by 2030.
	  – 10,000 MW Renewable energy technology-based park.
	  – Total Renewatble Energy Generation Capacity is 6124.51 MW as of 2023.
	- Solar Power Policy, 2012
	- Installed Capacity 3170.05 MW.
	- Biomass Policy, 2011
	- Installed capacity 134.94 MW.
	- Installed Flue Gas Desulfurization (FGD) systems to curb sulfur dioxide emissions.
	- PM-KUSUM Yojana
	- Reduction dependency of DG Sets and fossil-fuel-based energy.
	- Selective Catalytic Reduction technology

INDUSTRY AND MINING	- Madhya Pradesh Industrial Promotion Policy 2025
	  – Encouraging industries to adopt cleaner production technologies.
	- Perform, Achieve, and Trade (PAT) Mechanism
	  – Enhance energy efficiency and lower emissions in energy-intensive industries, 74% DCs achieved their SEC targets.
	- Retrofitting Emission Control Devices in DG Sets
	- Mineral Policy of Madhya Pradesh
	- Continuous Ambient Air Quality Monitoring Stations (CAAQMS) in mining areas.
	- Mine Closure Guidelines issued by the Ministry of Coal.
	- Forest (Conservation) Transformation Programme
	- Offset the environmental impact of deforestation.
	- NCAP Industrial Emissions Guidelines by MoEFCC
	- CPCB Guidelines on Community Boilers
	- Coal Ash Standards

SECTORS	POLICY ACTION AND ACHIEVEMENTS
RESIDENTIAL	Pradhan Mantri Ujjwala Yojana (PMUY) Bhopal (2018) (TIME TARGET FOR IMPLEMENTATION: 12 Months) : Under PMUY 74925 LPG Gas connections provided to weaker sections by OICL and BPCL. Dewas (2018) (TIME TARGET FOR IMPLEMENTATION: 12 Months) : Gas Authority of India Limited has laid PNG pipeline. Surya Nutan, a solar cooking technology. Gobar Dhan Scheme, community-level biogas systems. National Biomass Cook Stove Programme
TRANSPORT	SMART Cities Mission Developing intelligent transport systems, expanding Bus Rapid Transit Systems (BRTS). Dewas (2018) (TIME TARGET FOR IMPLEMENTATION: 12 Months) : Diesel-based public transport like Tempo 89 were phased out before year 2015. Sagar (2018) (TIME TARGET FOR IMPLEMENTATION: 12 Months) : 5-year-old diesel autos banned since 09.03.15. Also, 943 diesel vehicles replaced with LPG. Madhya Pradesh EV Policy 2025 Aiming to transform urban mobility by ensuring that 40% of new two-wheeler registrations and 70% of three-wheeler registrations are electric. Inter-City Electric Bus Deployment Established to introduce the state's first inter-city electric bus fleet. Vehicle Scrappage Policy 2022 National Policy on Biofuels, 2018 and Scheme for implementation of Biofuel Projects in Madhya Pradesh, 2025
WASTE	Swachh Bharat Mission – 6,773 tonnes of waste generated daily, of which 79.17% is still sent to landfills. – 600 TPD compost plant, a 35 TPD biomethanation plant at Chothiram and Kabitkhedi. Carbon Credit Trading – Indore Municipal Corporation (IMC) – earning ₹50 lakh from the sale of 1.70 lakh tonnes of CO_2 under the Verified Carbon Standard (VCS). MP State Environmental Plan, 2024 Solid Waste Management Rules, 2016

Figure 5: Comprehensive mapping of policies and actions for emission reduction in Madhya Pradesh

Source: TERI's analysis with reference to Draft SAPCC, City Action Plan for Control of Air Pollution In The Non-Attainment Cities Of Madhya Pradesh and State Sectoral Policies

Power

Madhya Pradesh has implemented several initiatives to reduce emissions and transition toward cleaner energy sources. The Madhya Pradesh Renewable Energy Policy 2025 targets 30% by 2027 and 50% by 2030 of the state energy mix, and a 10,000 MW renewable energy technology-based park by 2027[40]. Earlier, the state had implemented the Solar Power Policy (2012), promoting solar park development and encouraging small-scale developers to expand solar energy generation. As of 2023, the state has a capacity of 3022 MW of energy generation from solar plants[41]. Similarly, the Biomass-based Electricity (Power) Project Implementation Policy (2011, amended in 2013 and 2015) supports biomass-based power generation through regulatory incentives, reducing dependence on fossil fuels. The state has mandated biomass blending in coal-based power generation, introducing a 5% blending requirement in 2024, with plans to increase it to

7% by 2025[42]. To address industrial emissions, two major power plants have installed Flue Gas Desulfurization (FGD) systems to curb sulfur dioxide (SO_2) emissions, aligning with national norms set by the Ministry of Environment, Forest and Climate Change (MoEF&CC). In the agricultural sector, the Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) Yojana (2019) promotes solar-powered agricultural pumps, offering a 60% subsidy on pump costs and a 50% subsidy on supporting structures, reducing reliance on fossil-fuel-based energy. Additionally, the state has implemented the Madhya Pradesh Pump Hydro Storage Scheme[43], 2025 and MP Small Hydro Power Policy which reduces dependency on fossil fuels.

Industry and Mining

Madhya Pradesh has undertaken several initiatives in the industry and mining sector to reduce emissions and promote sustainable development. The Madhya Pradesh Industrial Promotion Policy 2025 includes provisions for Green Industrialisation Assistance, encouraging industries to adopt cleaner production technologies. The state also implemented the Perform, Achieve, and Trade (PAT) Mechanism which made a significant enhancement in energy efficiency (by PAT cycle I, 74% DCs achieved their SEC targets) and lowered emissions in energy-intensive industries . Additionally, retrofitting Emission Control Devices in Diesel Generator (DG) Sets is crucial to curb particulate and gaseous pollutants from industrial power backup systems.

In the Mining sector, the Mineral Policy of Madhya Pradesh emphasises the need for sustainable mining practices by balancing economic development with environmental conservation . In alignment with national and international environmental standards, the state has implemented Continuous Ambient Air Quality Monitoring Stations (CAAQMS) in mining areas to ensure real-time tracking of air pollutants such as PM_{10}, $PM_{2.5}$, SO_2, and NO_x, which are commonly associated with mining operations. Additionally, in compliance with the Mine Closure Guidelines issued by the Ministry of Coal, approved Mine Closure Plans incorporate scientific methodologies to rehabilitate mined-out areas, reducing fugitive dust emissions and restoring ecological balance. Public Sector Undertakings (PSUs) engaged in mining have also adopted proactive afforestation initiatives, contributing to carbon sequestration and improving air quality . The Compensatory Afforestation Programme, which mandates the identification and timely plantation of trees on degraded or non-forest land, further enhances the mitigation of emissions by offsetting the environmental impact of deforestation. Moreover, the adoption of eco-friendly mining technologies, such as dust suppression systems, water sprinklers, and enclosed material transportation, has played a crucial role in curbing airborne emissions .

Residential

Madhya Pradesh is actively promoting clean cooking solutions to reduce emissions in the residential sector. The Pradhan Mantri Ujjwala Yojana (PMUY) (2016) provides free LPG connections to women from BPL families, replacing traditional biomass-based cooking methods with cleaner alternatives. To further reduce emissions, the state has promoted improved biomass cookstoves in rural areas, which enhance fuel efficiency and lower harmful emissions. In addition to these measures, the government is encouraging the adoption of Surya Nutan, a solar cooking technology, targeting rural and semi-urban households to decrease reliance on biomass fuels. To support a broader transition to clean fuels, the state has also launched the Madhya Pradesh City Gas Distribution Network Development and Expansion Policy (2025). This policy aims to expand the piped natural gas infrastructure for residential use and promote cleaner transportation fuels across urban areas. Over the next 6 to 8 years, the state targets the establishment of approximately 60 lakh domestic PNG connections and the development of 1,207 compressed natural gas (CNG) stations, contributing to reduced household air pollution and improved energy sustainability .

Transport

Madhya Pradesh has undertaken several initiatives in the transport sector to reduce emissions and enhance sustainable urban mobility. Under the SMART Cities Mission, cities like Bhopal, Indore, Ujjain, Gwalior, Jabalpur, Satna, and Sagar are developing intelligent transport systems, expanding Bus Rapid Transit Systems (BRTS), and introducing metro rail networks to improve urban mobility and air quality.

To curb vehicular emissions, the state has phased out older commercial diesel vehicles, with Dewas transitioning away from diesel-based public transport within a year and Sagar banning five-year-old diesel auto-rickshaws, replacing 943 diesel vehicles with LPG models . Indore converted its bus fleet to CNG, replaced diesel tempos with LPG vehicles, and expanded CNG refuelling stations in cities like Gwalior. Furthermore, the state has released the Scheme for Promotion of Ethanol and Bio-fuel Production in 2021, within the National Biofuels Policy 2018. This promotes the adoption of cleaner fuels in vehicles, adhering to the national Target of 10% blending of fuel-grade ethanol with petrol by 2022 and 20% by 2025.

The Madhya Pradesh EV Policy 2025 aims to transform urban transport by ensuring that 40% of new two-wheeler registrations and 70% of three-wheeler registrations are electric by the end of the policy period . The state has partnered with private entities like YoloBus and Easy Green Mobility to introduce Madhya Pradesh's first inter-city electric bus fleet, marking a significant shift toward low-

emission public transport. Additionally, the MP Vehicle Scrappage Policy can contribute to SLCPs emission reduction by phasing out old, high-emission vehicles, significantly cutting black carbon, ozone precursors, and refrigerant leakage. Scheme for implementation of Biofuel Projects aims to increase the biofuel production within the state to reduce import dependency and provide a cleaner alternative to fossil fuels, particularly for transport sector .

Efforts to ease traffic congestion and emissions include infrastructure upgrades under the Bhopal Smart City Project, such as an integrated traffic management system and the construction of flyovers and bypass roads in cities like Dewas and Ujjain within a year. These initiatives collectively contribute to making urban transport more efficient and environmentally sustainable.

Waste Management

Madhya Pradesh has implemented various schemes in the waste sector to reduce emissions and improve waste management. Under the Swachh Bharat Mission, the state has enhanced waste collection and processing, though challenges remain, with 6,773 tonnes of waste generated daily, of which 79.17% is still sent to landfills . To address this, the state is focusing on increasing waste treatment and energy conversion.

Madhya Pradesh has also pioneered climate finance initiatives in waste management. The Indore Municipal Corporation (IMC) became the first civic body in India to generate revenue through carbon credit trading, earning ₹50 lakh from the sale of 1.70 lakh tonnes of CO_2 under the Verified Carbon Standard (VCS) programme of the UNFCCC.

Key projects supporting emission reduction include a 600 TPD compost plant, a 35 TPD bio methanation plant at Choithram and Kabitkhedi, and a 1.5 MW solar plant. These initiatives contribute to methane reduction from organic waste, promote renewable energy generation, and align with sustainable waste management practices .

Furthermore, under the National Biogas Programme, the Madhya Pradesh State Agro Industries Development Corporation (MPSAIDC) has established a target of deploying approximately 3,600 biogas plants by 2023-24, with capacities ranging from 1 to 25 cubic meters . The state-designated agency is responsible for setting up the yearly targets in the state. These plants are intended to provide a decentralised source of clean cooking fuel while contributing to emission reduction objectives in the residential energy sector.

Despite these efforts, air quality management and climate policies in India often function in isolation, highlighting the need for an integrated governance framework. Strengthening collaboration among central and state governments, non-governmental organisations, and the private sector is essential to ensuring a cohesive and effective response to air pollution and climate challenges. Aligning air quality initiatives with broader climate action will enable Madhya Pradesh to advance a sustainable, low-carbon development trajectory, improving public health, environmental resilience, and long-term climate mitigation efforts.

Against the above backdrop, it becomes evident that the most effective strategy overall is to combine the marathon of decarbonising the energy system with the sprint to rapidly reduce non-CO2 SLCP emissions. This report provides a crucial analysis of SLCPs in MP, a state grappling with significant air quality and climate challenges. By meticulously examining SLCP emissions across various sectors, this study illuminates key mitigation opportunities that can pave the way for cleaner air, improved public health, and a more sustainable future. The findings and recommendations presented herein are poised to inform policy decisions, guide strategic investments, and empower stakeholders to take decisive action. Moreover, this report serves as a valuable model for other states in India and beyond, underscoring the pivotal role of sub-national action in addressing SLCPs and achieving a more sustainable future for all.

Spatial Footprint of SLCP in Madhya Pradesh: A Satellite-Based Sectoral Assessment

The preceding chapter provides an overview of the context for developing a state-specific SLCP mitigation strategy for Madhya Pradesh, highlighting key aspects related to emission sources, climatic conditions, socio-economic factors, and the existing policy landscape. Before presenting the quantitative emission inventory and scenario framework that constitute the analytical foundation of this report, this chapter provides an independent top-down assessment of the state's pollution burden using satellite remote sensing observations. This assessment serves two key objectives: first, to identify and demonstrate the spatial distribution of atmospheric column burdens of SLCPs and air pollutants across districts in the state; and second, to examine, on a sector-by-sector basis, the limitations of satellite-derived evidence, thereby underscoring the necessity of a bottom-up, activity-based emission inventory for the policy analysis and scenario development presented in subsequent chapters.

This section presents a satellite-derived spatial analysis of SLCP and air quality hotspots across Madhya Pradesh using the 2019 baseline year, consistent with the baseline adopted throughout this report and aligned with the NCAP mandate. The analysis draws on multi-sensor composites[i] from Sentinel-5P/TROPOMI (atmospheric column retrievals[ii] of NO_2, SO_2, CO, HCHO, and CH_4), MODIS MAIAC (aerosol optical depth[iii]), VIIRS Day/Night Band (night-time radiance as an activity proxy), FIRMS (active fire detections), and SEDAC (population and settlement grids). All datasets were accessed through Google Earth Engine and composited to a common spatial reference grid. Technical specifications, dataset details, and statistical methods are provided in the Annexure.

It is important to note at the outset that all satellite products used here measure atmospheric column quantities, not surface emission rates. Column densities integrate the signal over the full vertical atmospheric column and are sensitive to transport, dilution, and background concentrations in addition to local emissions. They are used in this chapter as spatial indicators of where pollution burdens are elevated and which broad source categories are likely responsible, not as quantitative measures of sectoral emission rates, which are the subject of the inventory in Chapter 5.

A Spatially Differentiated Pollution Landscape: Four Distinct Regions

Reading the individual pollutant column composites together reveals that Madhya Pradesh is not a spatially homogeneous pollution landscape. Four geographically distinct regions emerge when the NO_2, SO_2, CH_4, and AOD layers are examined alongside each other, each characterised by a dominant atmospheric signature that reflects underlying differences in land use, economic activity, and population distribution. This spatial heterogeneity is the observational basis for the argument made in the preceding chapter: that district-level targeting, not uniform state-level policy, is required for effective SLCP mitigation.

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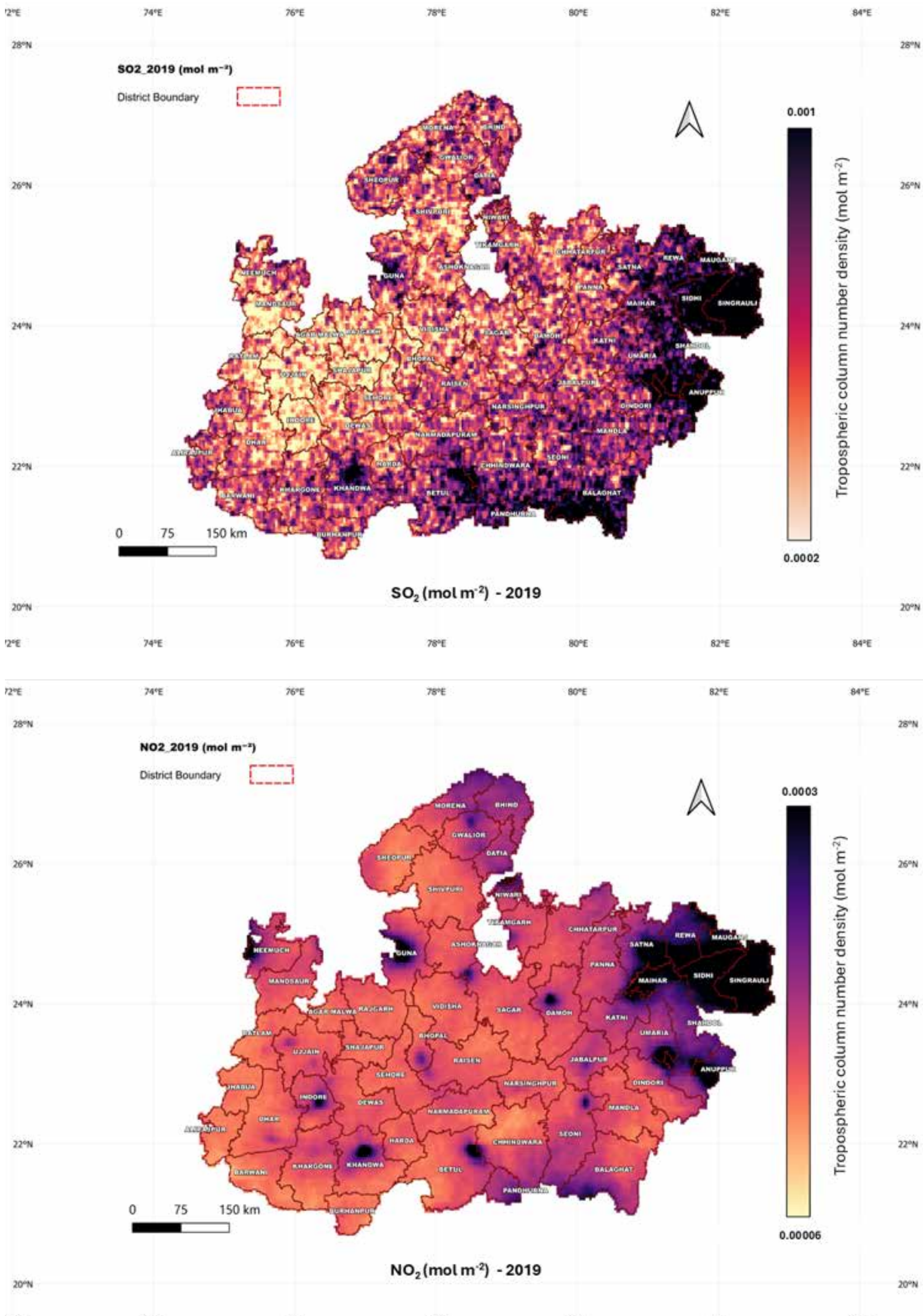
i Composites refer to single summary maps created by combining and averaging multiple satellite observations collected over a period of time, to produce a clean, consistent dataset.

ii Atmospheric column retrievals simply mean using satellites or ground instruments to measure the total amount of a specific substance (NO_2, SO_2, CO, HCHO, and CH_4 in this report) reaching from the ground up to space.

iii Aerosol

Figure 6 presents the four principal pollutant composites as a panel of individual maps: SO_2 and NO_2 tropospheric column number densities, CH_4 column-averaged dry-air mole fraction[iv], and aerosol optical depth from MODIS MAIAC. Each map is presented on its own scale and unit, preserving the physical meaning of the respective satellite retrievals. The spatial patterns across these four layers, read together, define the four pollution regions described in Table [19]. No normalisation or merging of layers across different measurement units is applied in this figure, the regional characterisation is based on the consistent spatial co-occurrence of signals across the individual composites.



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iv Dry-air mole fraction refers to the number of molecules of a gas out of every molecule in a sample of air, after all water vapour has been removed.

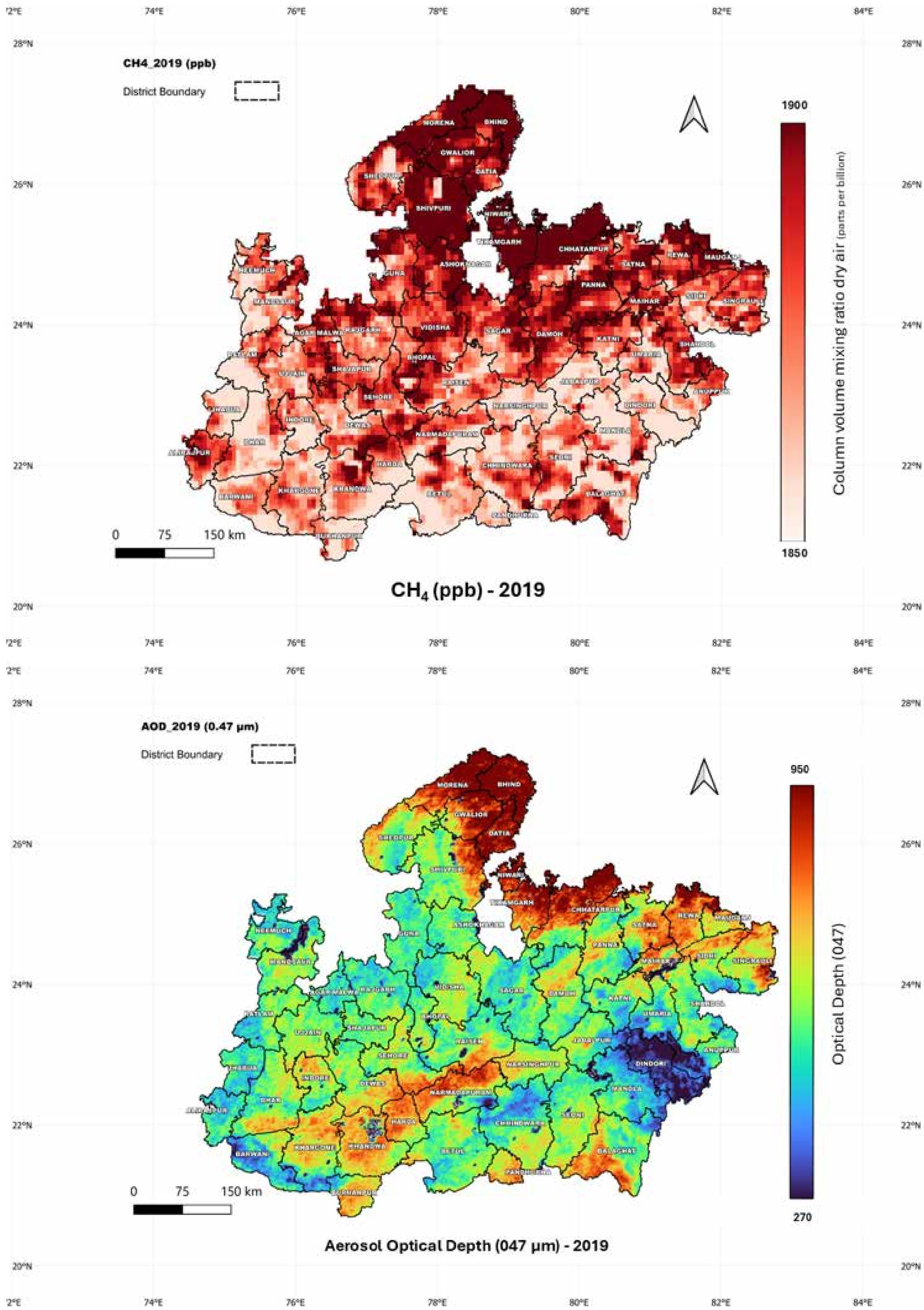


Figure 6: Individual Pollutant Column Composites, Madhya Pradesh 2019

((a) Sentinel-5P/TROPOMI annual mean composites for SO_2 and (b) NO_2, (c) column-averaged CH_4, and (d) MODIS MAIAC aerosol optical depth, for 2019. Each panel is displayed on its own physical scale and unit; layers have not been normalised or combined across different measurement units. Madhya Pradesh district boundaries overlaid.)

Table 20: Regional Pollution Landscape of Madhya Pradesh — Satellite-Derived Classification, 2019

Region	Core Districts	Dominant Satellite Signal	Principal Pollutants / SLCPs of Concern
Eastern Industrial-Power Core	Singrauli, Sidhi, Mauganj, Rewa, Anuppur, Shahdol, Balaghat	SO_2 + NO_2 peak column values dominating the state-level spatial pattern; VIIRS confirms persistent point-source nodes co-located with TPP assets	SO_2, NO_x (coal combustion); CO, HCHO (incomplete combustion and co-located biomass burning)
Northern Agro-Residential Belt	Morena, Bhind, Gwalior, Datia, Shivpuri, Tikamgarh, Chhatarpur, Sheopur	CH_4 column enhancement above background; elevated AOD and UVAI; high population-weighted exposure across individual pollutant layers	CH_4 from agriculture, livestock, and residential combustion (spatially co-located; not separable by satellite); PM aerosol from dust and combustion
Central-Western Urban Corridor	Indore, Bhopal, Ujjain, Dewas, Jabalpur, Gwalior	Moderate NO_2 and CO column enhancement; high VIIRS night radiance; CH_4 co-located with urban landfill points	NO_x, NMVOCs (transport and industry); CH_4 (urban waste); PM (industry and transport)
South-Eastern Forest Belt	Mandla, Dindori, Anuppur, Alirajpur, Jhabua, Barwani	Lowest column values across all individual pollutant composites; cold spot on NO_2, SO_2, CH_4, and AOD layers; highest NDVI values in the state	Low atmospheric column burden reflecting low source intensity and low population density; forest-dominant land cover

Source: Satellite analysis for this study based on Sentinel-5P/TROPOMI, MODIS MAIAC, VIIRS, FIRMS, SEDAC composites (2019). Regional classification is based on the consistent spatial co-occurrence of signals across individual pollutant composites; it does not imply equivalence or additivity of the constituent species. Sectoral attribution is indicative. Quantitative emission estimates are presented in Chapter 5.

The eastern belt is overwhelmingly characterised by the highest SO_2 and NO_2 column values in the state, consistent with coal combustion from thermal power generation. The northern belt shows elevated CH_4 and AOD across a large rural footprint, consistent with the combined presence of agriculture, livestock, and residential combustion. The central-western corridor registers moderate NO_2 and CO column enhancement co-located with high VIIRS night radiance, reflecting urban transport, industrial, and waste sources. The south-eastern forest belt registers the lowest values across all four individual pollutant composites, providing an important internal spatial reference for interpreting the relative intensity of the other three regions.

Sectoral Atmospheric Signatures: Evidence and Analytical Limits

For each sector covered in this report, the satellite composites provide spatial evidence of varying strength and specificity. The following sub-sections describe what the satellite signal confirms for each sector, alongside the precise analytical limitation that makes a bottom-up emission inventory necessary. These limitations are not peripheral caveats — they reflect structural constraints of atmospheric column remote sensing that define what satellite data can and cannot establish for policy-oriented emission analysis.

Power and Energy Generation

The power sector produces the most unambiguous sectoral signal in the 2019 composites. The SO_2 and NO_2 annual composites show their strongest column enhancement over the eastern belt, with peak values over the Singrauli-Anuppur corridor significantly higher than any other region in the state, dominating the state-level spatial pattern of both pollutants. Three converging satellite observations support the attribution to coal-fired thermal power generation. First, SO_2 has an atmospheric lifetime of 1–2 days in the troposphere, sufficient to resolve persistent point-source plumes, the eastern enhancement is present consistently across the annual composite, consistent with year-round operation of large combustion facilities. Second, the scale of both SO_2 and NO_2 column values over the eastern districts is consistent with the known capacity of major coal-fired thermal power plants (TPPs) in this corridor. Third, VIIRS night-radiance composites independently confirm the spatial co-location of bright point-source nodes with the known locations of NTPC Vindhyachal, Sasan, Mahan, MB Power (Anuppur), and the Gadarwara TPP, providing activity-based corroboration of the combustion attribution. Secondary NO_2 enhancements are visible over Khandwa (industrial and biomass combustion) and Balaghat (industrial, biofuel, and rice-mill cluster), though these are substantially weaker than the eastern power core.

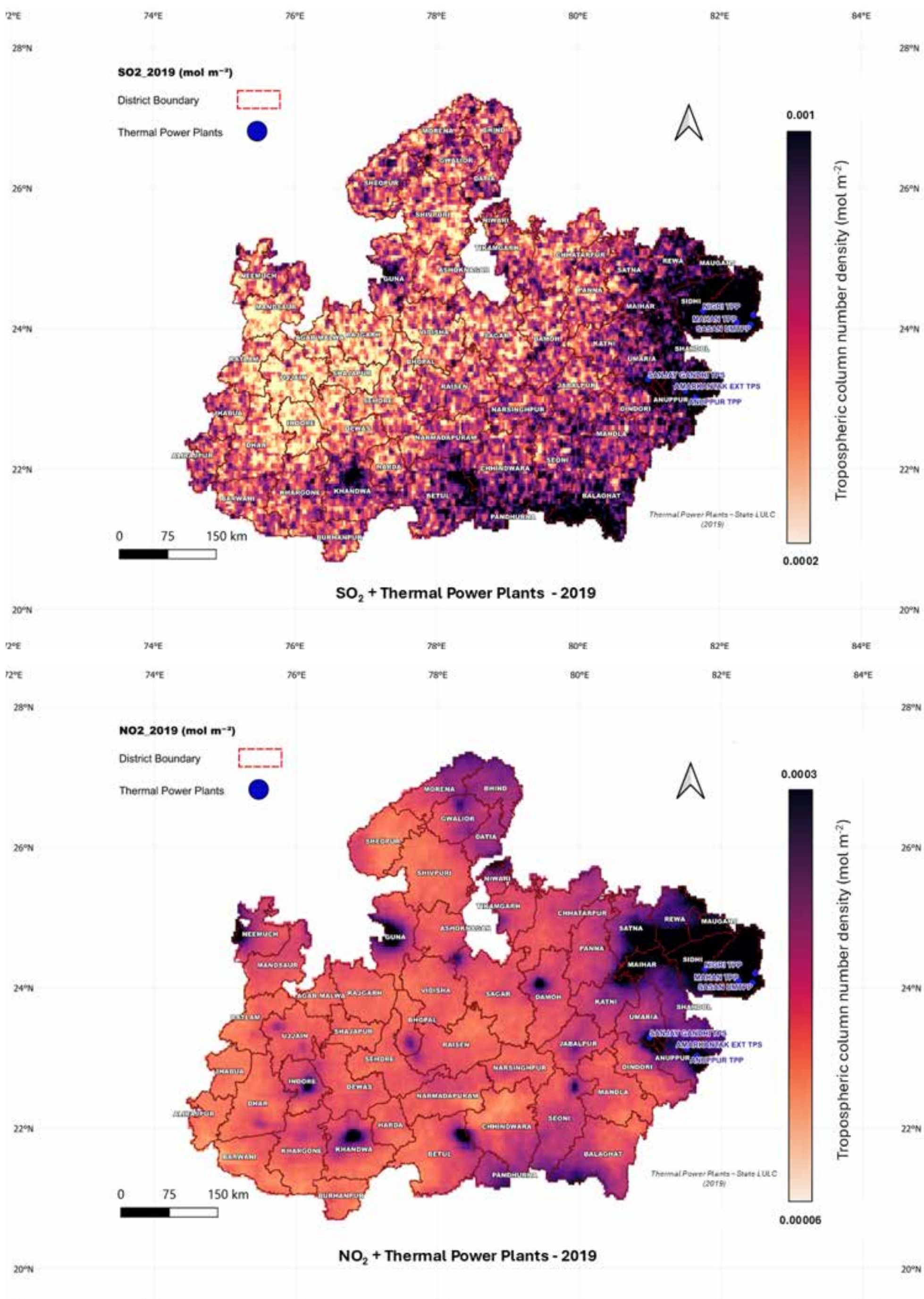


Figure 7: SO_2 and NO_2 column composites with thermal power plants overlaid.

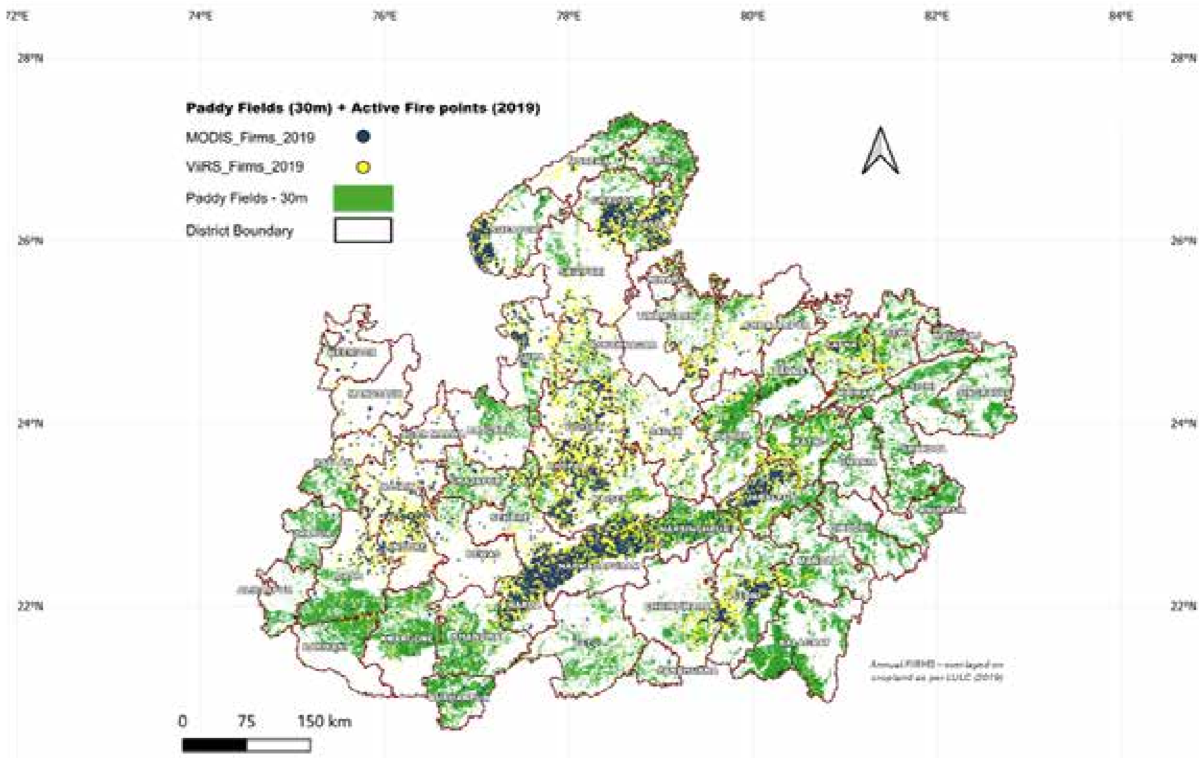
While the satellite composites clearly identify the eastern belt as the dominant zone of SO_2 and NO_2 enhancement, the column-integrated signal cannot be disaggregated to attribute specific fractions to individual power plant assets. Designing targeted end-of-pipe emission control interventions, such as prioritising which plants require FGD or SCR installation first requires asset-level emission estimates derived from plant-specific fuel consumption data and emission factors, which only a bottom-up inventory approach can provide.

Agriculture and Biomass Burning

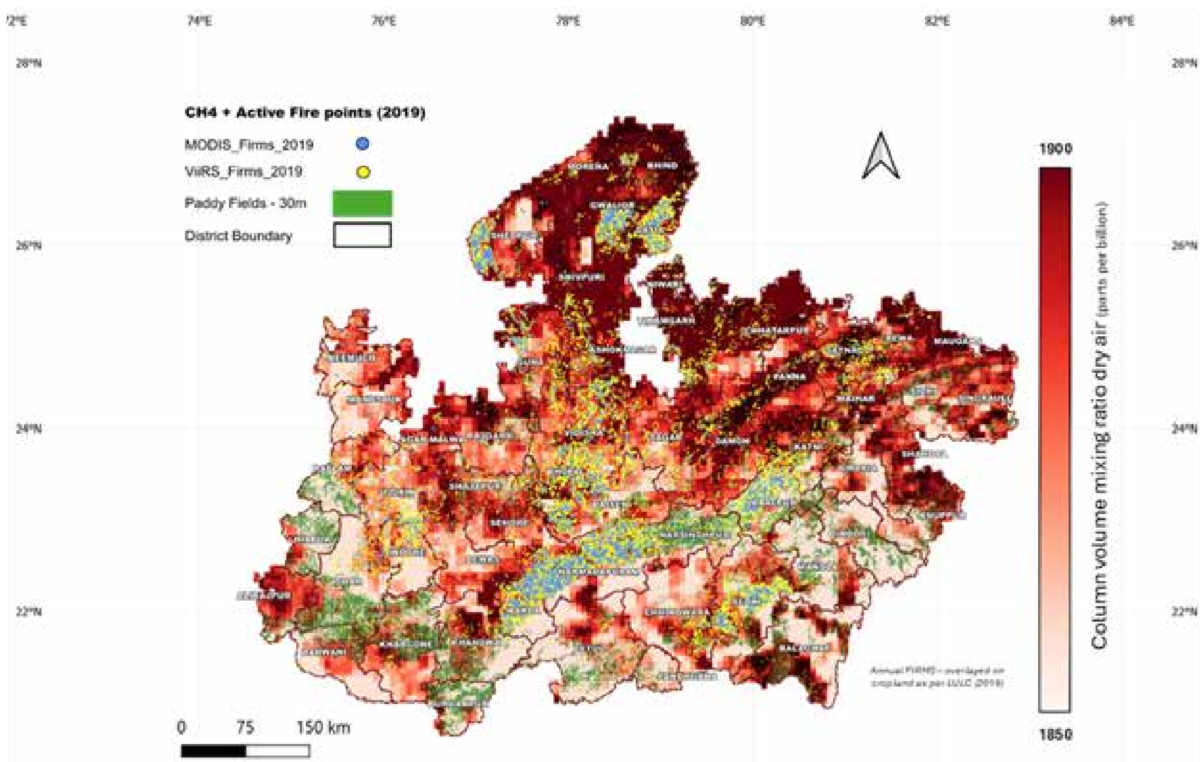
The agricultural signal is distributed across a substantially larger spatial footprint than the power sector, reflecting the dispersed nature of its sources. CH_4 column enhancement above background is concentrated in the northern belt (Morena, Bhind, Gwalior, Sheopur, Shivpuri, Datia, Niwari, Tikamgarh, Chhatarpur), consistent with the prevalence of rice cultivation and livestock in these districts. A secondary CH_4 enhancement is detectable over the Balaghat-Mandla-Anuppur eastern belt, where rice cultivation is prevalent. However, the CH_4 signal in this zone also reflects contributions from coal mining fugitive emissions, making agricultural attribution in this corridor uncertain and not independently confirmable from column data alone. It should be noted that TROPOMI CH_4 is sensitive to surface albedo and aerosol loading, and signals are interpreted as column-integrated enhancements above background rather than surface-level emission rates.

The seasonal residue burning signal is captured through FIRMS active fire detections for the October–November 2019 kharif harvest window. Active fire pixels, with fire radiative power[v] (FRP) overlayed, consistent with agricultural residue burning rather than the higher FRP values typically associated with forest fires, cluster across Narmadapuram, Chhindwara, Seoni, Narsinghpur, Raisen, Sheopur, and Jabalpur on the Sentinel-2 kharif paddy cropland mask. The spatial overlay of FIRMS detections with CO and HCHO column enhancements is consistent with incomplete combustion from open field burning. However, along the eastern fringe (Singrauli-Sidhi-Mauganj-Rewa), CO and HCHO signals are spatially co-located with thermal power and mining combustion, precluding clean single-source attribution in that zone

[v] Fire Radiative Power (FRP) refers to a satellite-derived value indicating the intensity or heat output of a fire at the moment of detection, expressed in megawatts (MW). Higher FRP values indicate more intense, hotter fires (such as forest fires), while lower FRP values indicate cooler, smouldering fires, consistent with agricultural stubble burning.



Paddy fields (30m) + Annual active fire points - 2019



CH_4 (ppb) + Annual active fire points - 2019

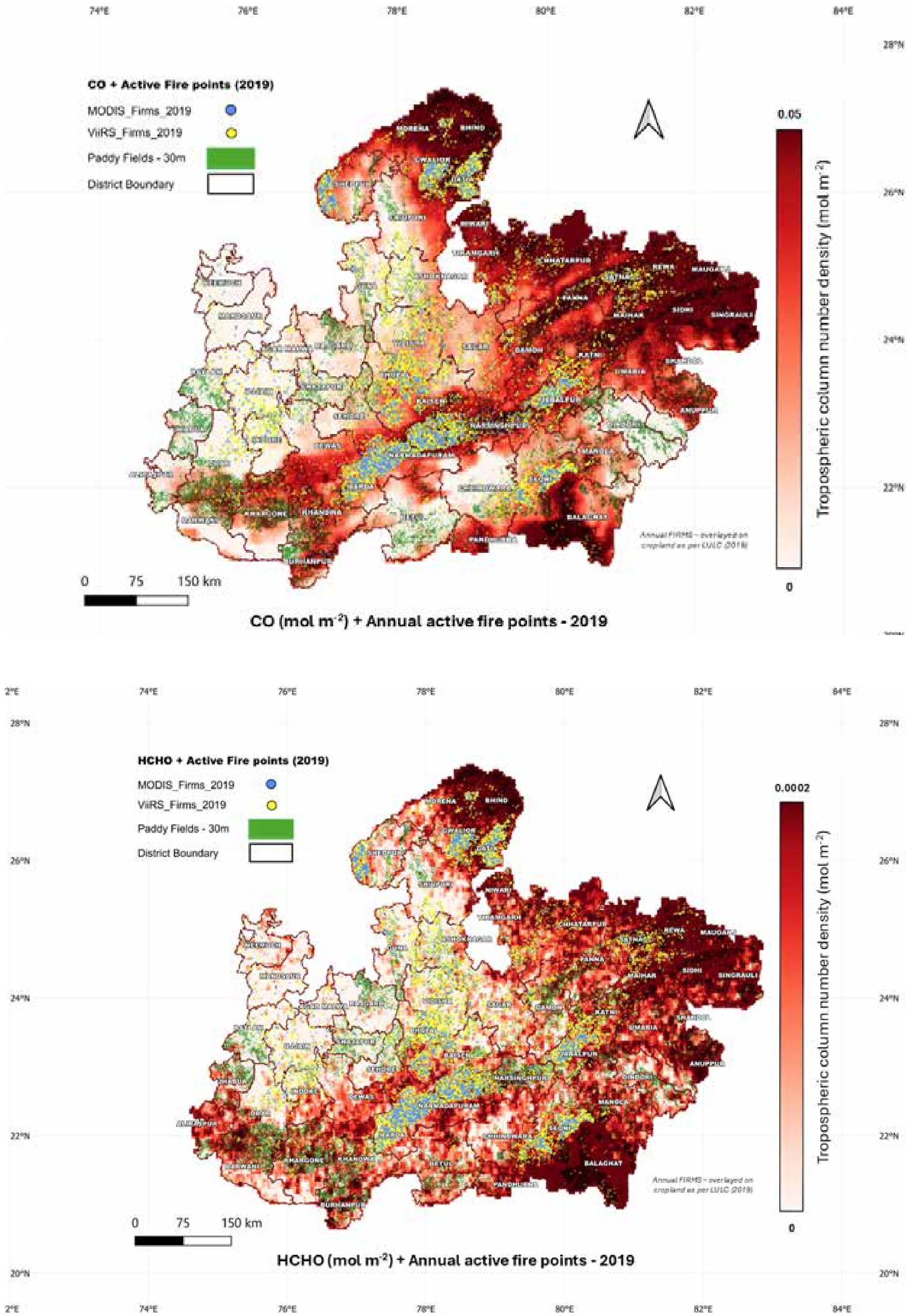


Figure 8: (a) FIRMS active fire detections (MODIS Terra + Aqua and Suomi NPP/VIIRS, ~1 km resolution) for the 2019 residue burning across the year on the Sentinel-2 kharif paddy cropland mask (30 m), (b) The CH_4 layer, (c) CO layer (d) HCHO layer.

The CH_4 column enhancement in the northern belt is a composite atmospheric signal from rice cultivation, livestock enteric fermentation, residential biomass combustion, and waste, all spatially co-located in the same districts. Satellite column retrievals cannot assign fractional contributions to individual source types within the same grid cell. This separation is analytically critical because rice cultivation and livestock are treated as distinct sectors in the scenario analysis, each with different mitigation interventions and emission trajectories. Bottom-up activity-based estimation, drawing on crop area statistics and livestock population data with sector-specific emission factors, is the only method capable of producing this disaggregation.

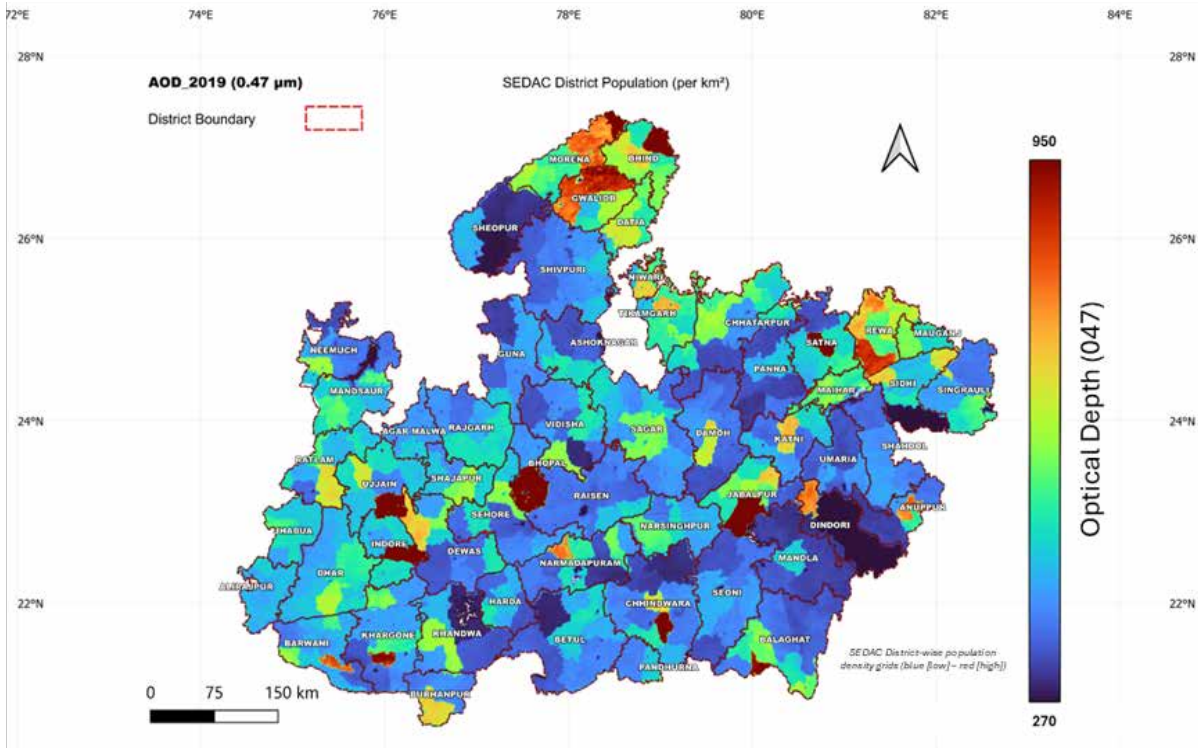
Livestock

Livestock specifically enteric fermentation from cattle and buffalo populations, represents the single largest source of CH_4 in Madhya Pradesh. Despite its sectoral significance, livestock has no independent atmospheric signature detectable from satellite data. The CH_4 enhancement observed over the northern belt is a spatially inseparable composite signal from multiple co-located sources including agriculture, residential combustion, and livestock. No spectral, spatial, or temporal feature in the satellite composite can be used to isolate the livestock contribution. The districts with the highest livestock CH_4 potential, including Sagar, Morena, Rewa, Khargone, Chhindwara, and Satna, identified in the inventory (Chapter 5) show elevated CH_4 columns, but this enhancement reflects the combined signal of all co-located sources and cannot be attributed to livestock alone.

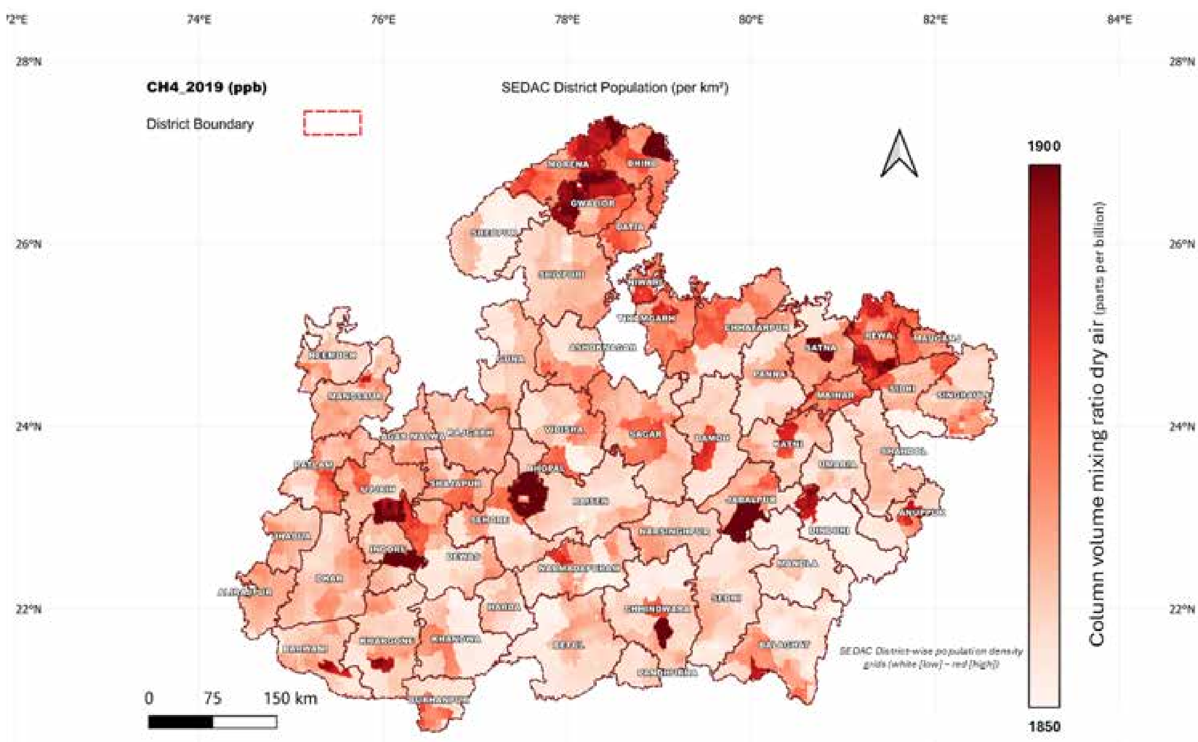
Residential Combustion

The residential sector's spatial burden is characterised by examining where individual pollutant column layers, particularly NO_2, CO, HCHO, and CH_4, overlap with high population density from the SEDAC GPWv4 grid. Each pollutant layer is assessed individually against the population grid while no cross-unit normalisation or merging of layers is applied. This approach does not measure residential emission rates, it indicates where elevated atmospheric column burdens coincide with high population density, which is the relevant spatial dimension for assessing aggregate exposure and prioritising district-level intervention.

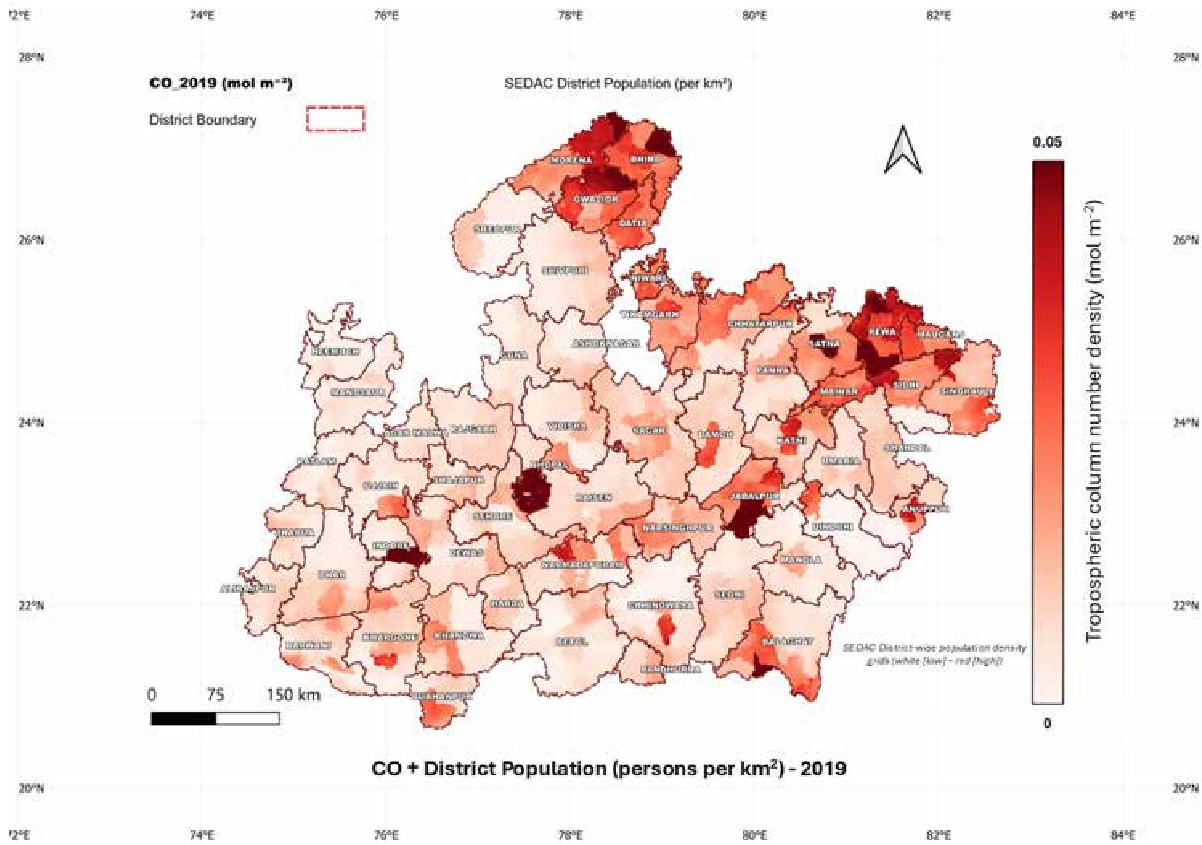
Across the individual column layers weighted against population density, the highest overlap is found across the northern belt (Sheopur, Morena, Bhind, Gwalior, Datia, Shivpuri, Tikamgarh, Niwari, Chhatarpur, Panna, Satna, Sidhi, Singrauli), with secondary peaks in the Narmadapuram-Chhindwara belt and at the urban cores of Indore, Bhopal, Jabalpur, and Gwalior. The south-eastern forest belt (Mandla-Dindori) appears relatively low on this spatial assessment, which reflects low population density rather than low per-capita atmospheric burden. The inventory, presented in Chapter 5, confirms that these districts have among the highest per-household emission intensities in the state due to near-total reliance on biomass fuel, a pattern that population-weighted column assessments systematically underestimate in sparsely populated areas.

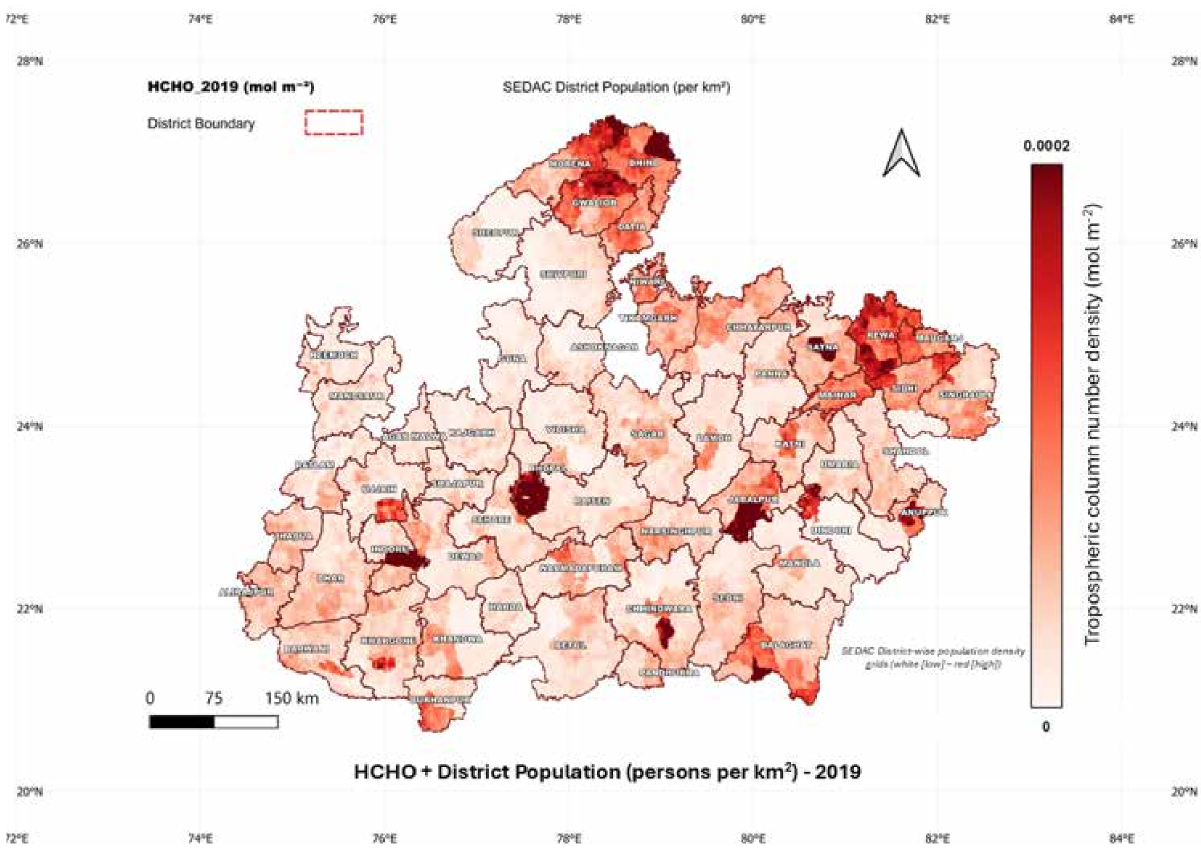


Aerosol Optical Depth (047 µm) + District Population (persons per km²) - 2019



CH_4 + District Population (persons per km²) - 2019


CO_2019 (mol m⁻²)
District Boundary
SEDAC District Population (per km²)
0.05
0
Tropospheric column number density (mol m⁻²)
SEDAC District-wise population density grids (white [low] – red [high])
0 75 150 km
CO + District Population (persons per km²) - 2019


HCHO_2019 (mol m⁻²)
District Boundary
SEDAC District Population (per km²)
0.0002
0
Tropospheric column number density (mol m⁻²)
SEDAC District-wise population density grids (white [low] – red [high])
0 75 150 km
HCHO + District Population (persons per km²) - 2019

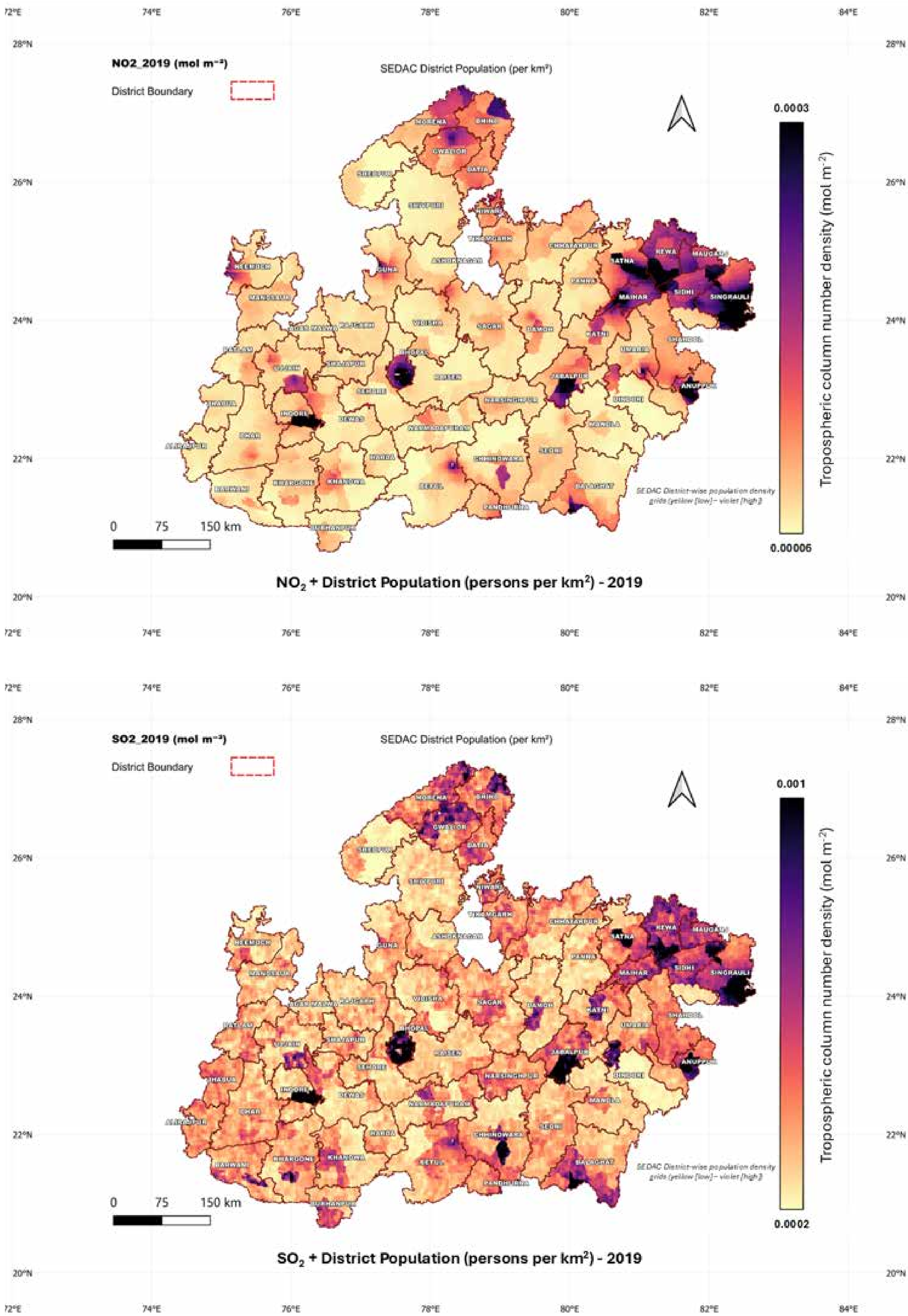


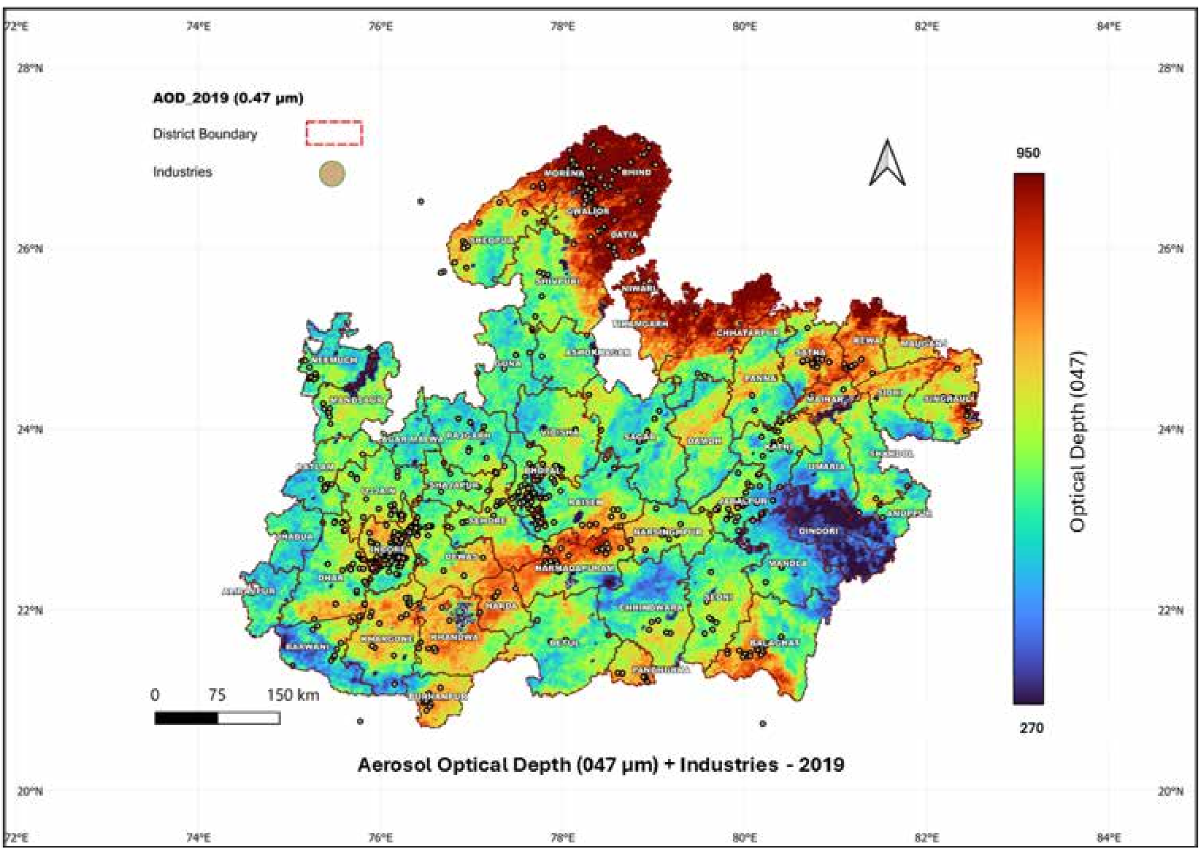
Figure 9: Per-pollutant population-weighted column layers for 2019

(a) AOD, (b) CH_4, (c) CO, (d) HCHO, (e) NO_2, (f) SO_2; each independently weighted by SEDAC GPWv4 gridded population density, 2019. Each panel is presented in its original physical unit weighted by population. The maps indicate districts where high atmospheric column burdens coincide with high population density and do not represent surface emission rates.

Population-weighted column layers cannot distinguish a household using LPG from one using fuelwood, crop residue, or charcoal, as all contribute to the same atmospheric column signal. The residential ALT scenarios are structured entirely around fuel type: the proportion of households still dependent on biomass fuels is the key activity variable, and its reduction through clean cooking transitions is the mechanism of emission reduction. Identifying and projecting these households by district and fuel type requires household energy survey data and fuel-specific emission factors from the bottom-up inventory and is a major limitation of satellite-based assessments.

Industry

The industrial aerosol signal is assessed through MODIS MAIAC AOD at 0.47 µm and the Sentinel-5P UVAI, both of which are sensitive to absorbing and scattering aerosols associated with industrial combustion and dust. Presented as separate layers, they reveal a more spatially diffuse pattern than the power sector's sharp point-source signal, consistent with the distributed character of industrial activity across multiple clusters and fuel types. Three zones are identifiable. The Satna-Maihar-Katni limestone and cement belt shows a continuous elevated AOD and UVAI signal in a region without large coal-fired TPPs, supporting attribution to industrial mineral dust and high-emission fuel combustion. The Indore-Ujjain-Dewas corridor is identifiable as a small and medium enterprise (SME) cluster, with elevated AOD consistent with the use of high-emission fuels in dispersed industrial units. The northern Chambal-Gwalior belt (Morena, Bhind, Gwalior, Datia, Sheopur) shows elevated AOD and UVAI consistent with a mixed signal from mineral dust, road transport, and industrial sources. The south-eastern forest belt (Mandla-Dindori) registers the lowest aerosol values, consistent with minimal industrial activity and dense vegetation cover



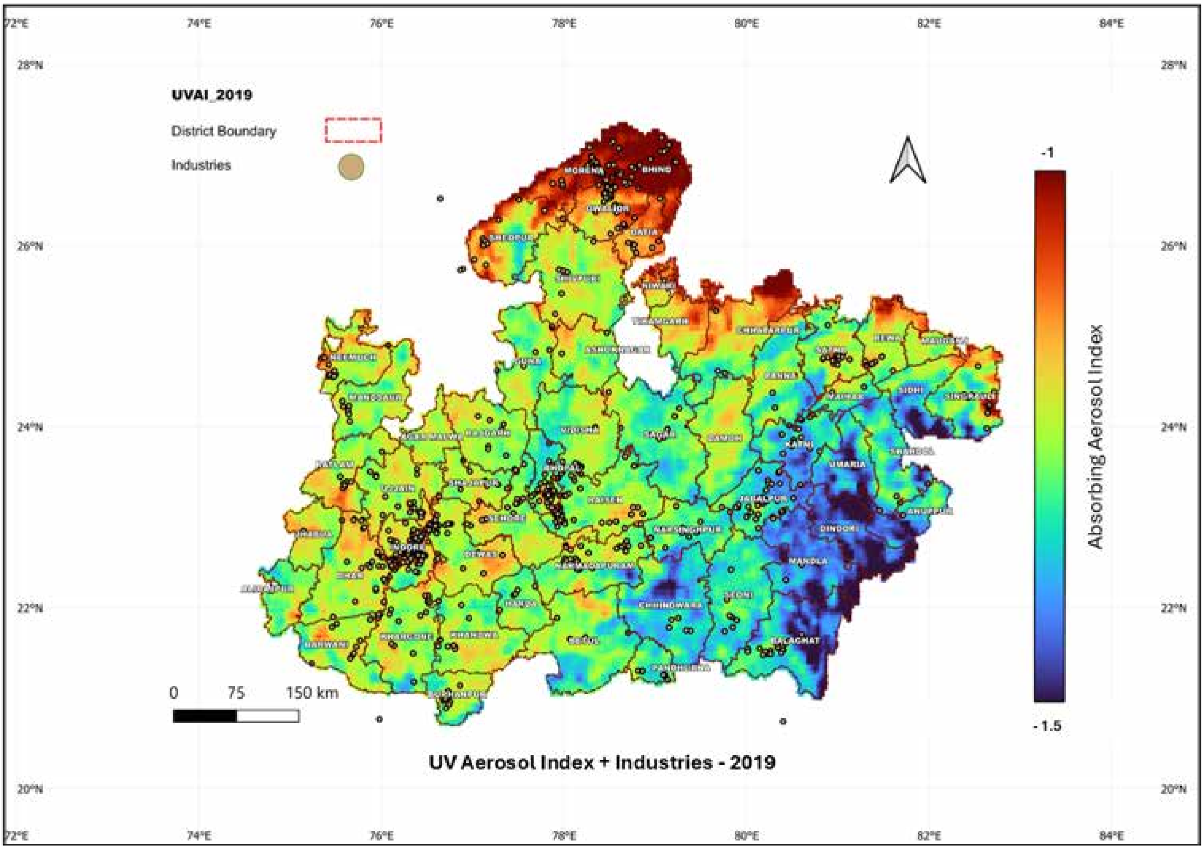
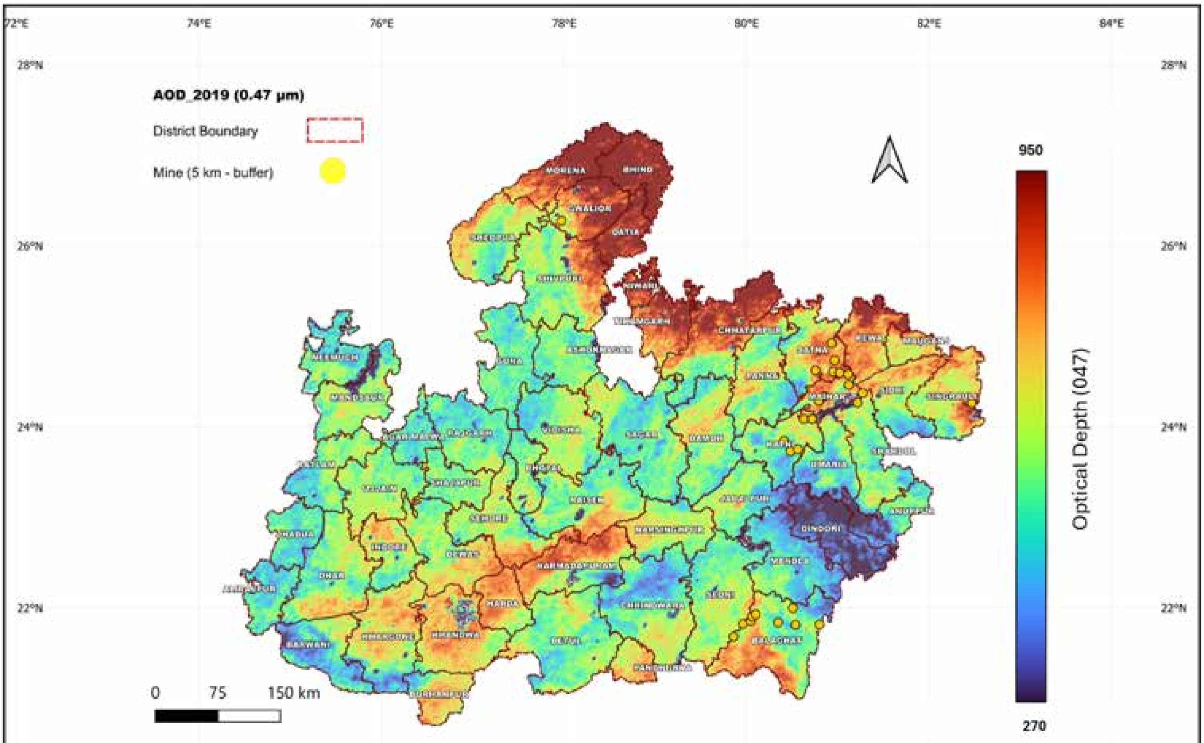


Figure 10: AOD and (b) UVAI industrial aerosol composites with industry point overlay for 2019

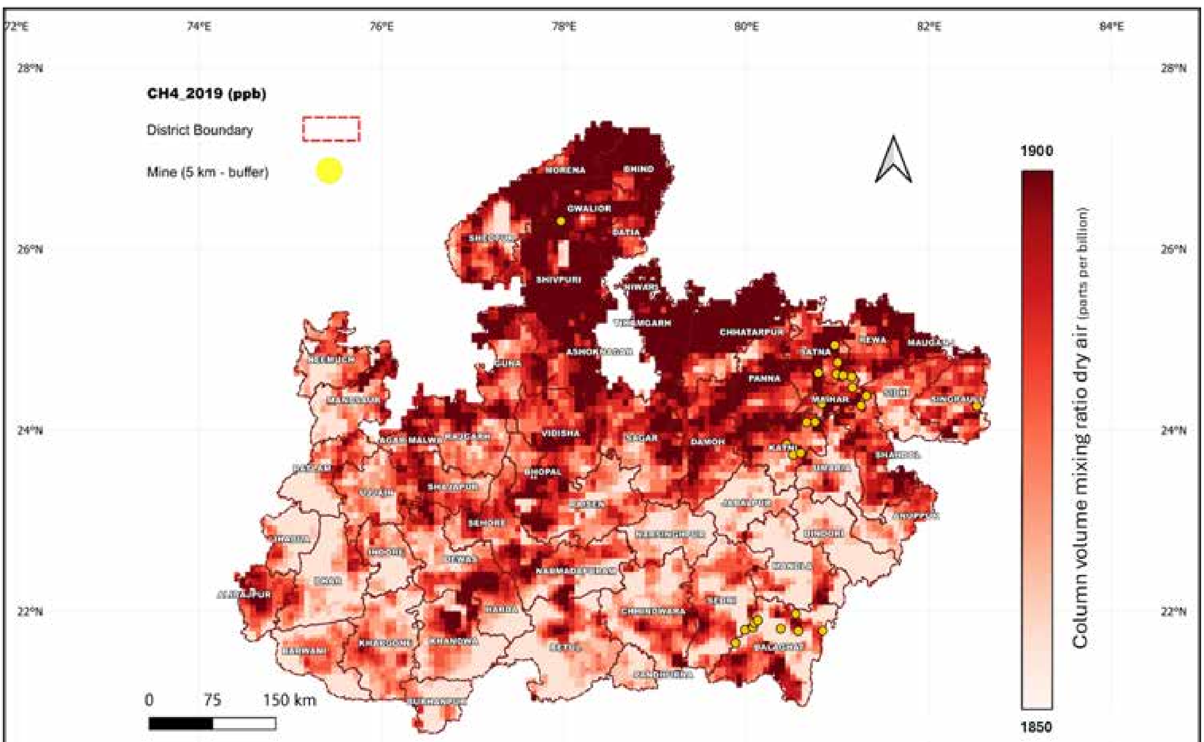
AOD is a column-integrated optical quantity sensitive to dust, smoke, and industrial aerosols simultaneously; it cannot separate these components without additional chemical transport modelling. In the northern Chambal belt particularly, the industrial aerosol signal cannot be distinguished from mineral dust and road resuspension. More critically, the industrial ALT scenarios like transition from solid fuels to natural gas, or community boilers, or green hydrogen introduction, and coal beneficiation, operate at the level of fuel type and combustion technology per unit of industrial output. These require fuel consumption statistics and technology-specific emission factors from the inventory, which aerosol column proxies cannot provide.

Mining

The mining sector's atmospheric signature is assessed through two separate satellite layers overlaid on major mine locations with a 5 km buffer derived from the state LULC classification: an AOD and UVAI aerosol composite capturing dust and combustion emissions, and the CH_4 composite for methane from coal seam fugitive emissions. Two principal spatial signatures are identifiable. The Singrauli-Anuppur coal mining belt and Balaghat manganese mining belt show localised AOD, UVAI, and CH_4 enhancements on the mine buffer overlay. However, the Singrauli mining signal might be masked in the AOD layer by the TPP plume from adjacent thermal power plants (TPP) and is more clearly distinguishable on the CH_4 and UVAI layers. The Satna-Maihar limestone mining belt generates a continuous AOD enhancement which can be associated with industrial quarrying and dust generation. The northern Chambal belt (Morena, Bhind, Gwalior, Sheopur, Datia) shows elevated AOD and UVAI consistent with a mixed signal of mineral dust and road transport emissions, this signal cannot be attributed to mining specifically without additional source-apportionment analysis.



Aerosol Optical Depth (047 µm) + Mine (5 km buffer) - 2019



CH_4 (ppb) + Mine (5 km buffer) - 2019

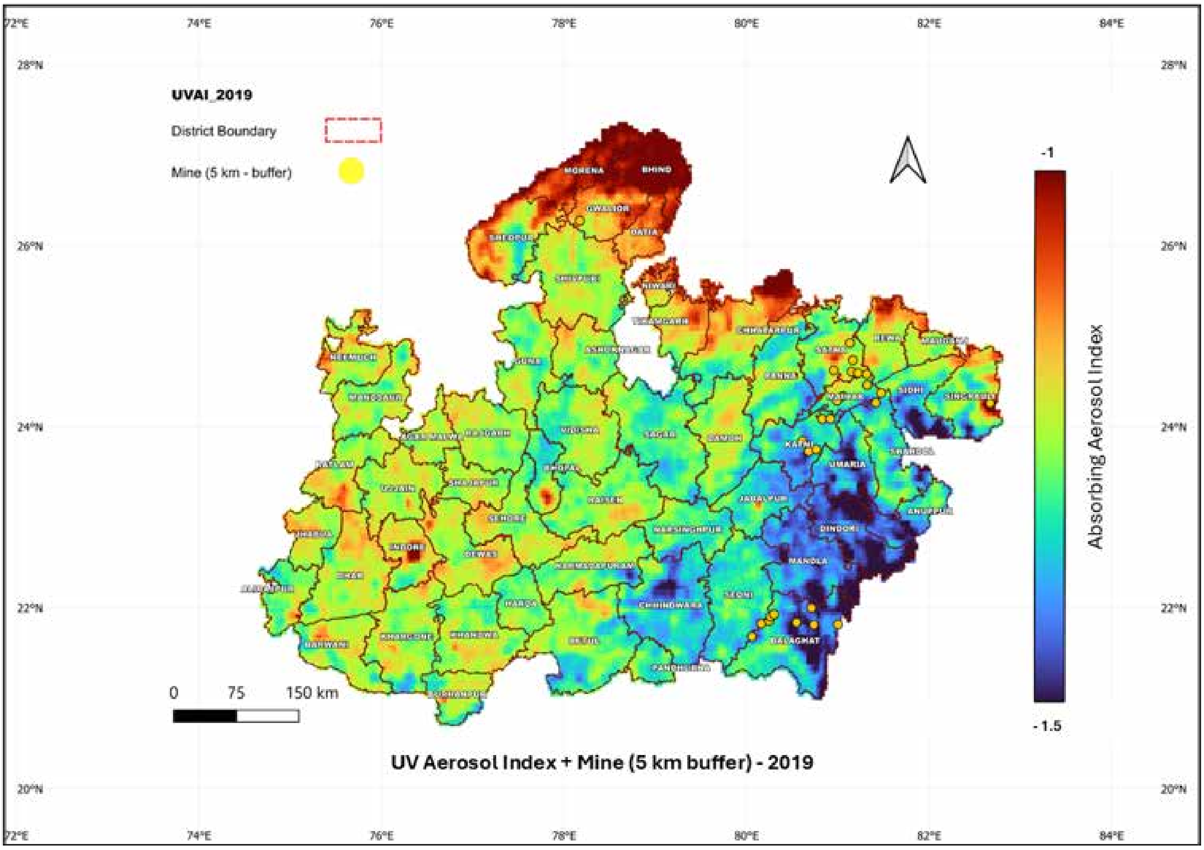


Figure 11: Mining aerosol and methane composites with 5 km mine buffer overlay, two-panel display

Coal seam CH_4 from Singrauli mines is spatially inseparable from the adjacent TPP atmospheric plume on the satellite raster, making independent quantification from column data impossible. The mining dust ALT scenarios, water sprinkling at loading and unloading points, reduction of material drop height, paving of haul roads, and process optimisation, are formulated in terms of activity-level parameters including overburden removal volumes, transport distances, and road surface type. These require a bottom-up dust emission inventory using activity data and site-specific emission factors, not satellite aerosol proxies.

Waste

The waste sector produces a spatially specific and analytically distinguishable atmospheric signal relative to other CH_4 sources in the state. Persistent CH_4 column enhancement at Indore, Bhopal, Jabalpur, and Gwalior is co-located with VIIRS maximum-radiance peaks[vi] and an ancillary municipal landfill point layer. This signal is spatially distinguishable from the broad agricultural CH_4 background of the northern belt on the basis of two converging observations: it is confined to high-density SEDAC population grid cells corresponding to urban nodes, whereas the agricultural CH_4 background occupies diffuse low-radiance rural areas. Also, the absence of co-occurring FIRMS active fire detections, combined with co-location with VIIRS hightlights landfill point data, supports attribution to landfill outgassing rather than open biomass burning. Secondary urban CH_4 hotspots are identifiable at Ujjain and Rewa. In peri-urban districts such as Gwalior and Morena, the urban waste signal partially overlaps the broader agricultural CH_4 background and cannot be cleanly separated without additional source-apportionment analysis.

[vi] Maximum radiance peaks refer to the brightest points of night-time light detected by the VIIRS satellite sensor, indicating locations with the highest concentration of artificial light. Here it is used as a proxy to identify major urban centres where large municipal landfills are typically located.

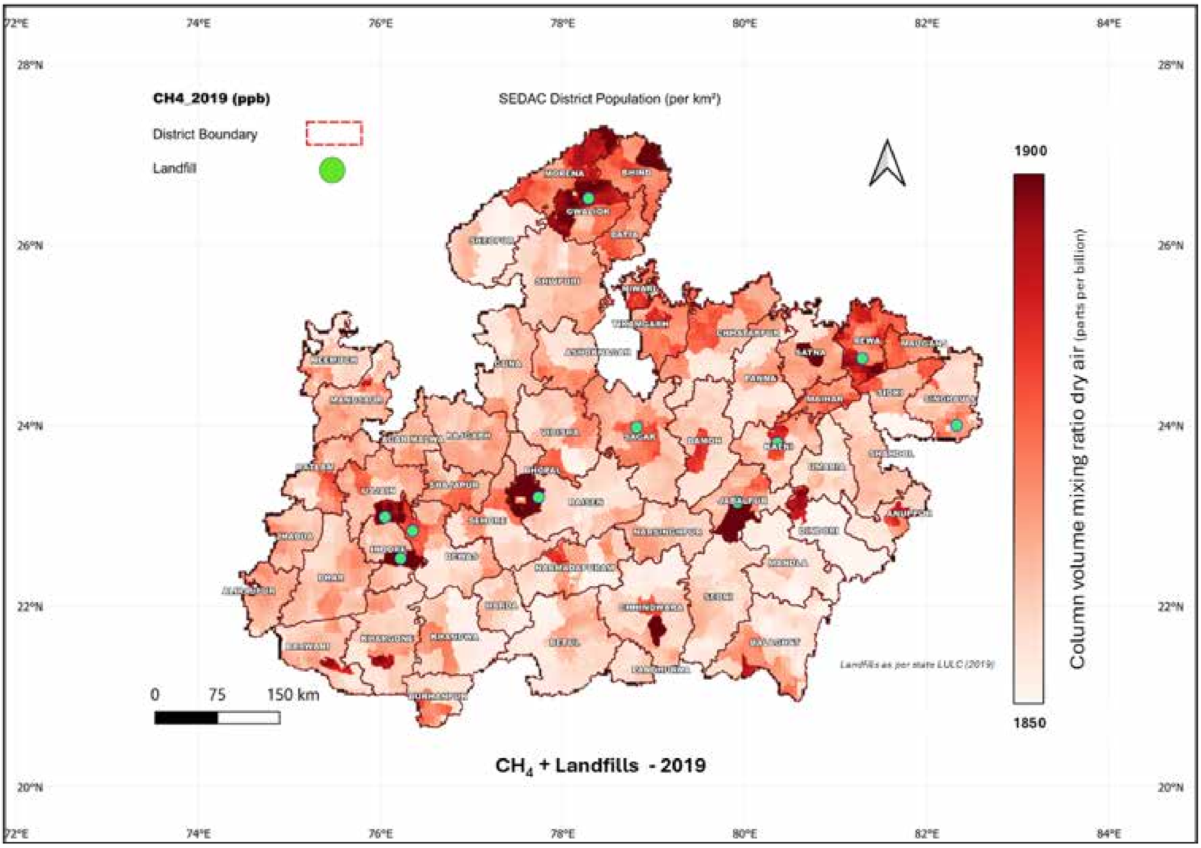


Figure 12: CH_4 composite with urban landfill points and sedac population density overlay, 2019

While the satellite supports attribution of CH_4 enhancements to urban waste sources at the four major cities, it cannot differentiate methane from open landfills, composting, anaerobic digestion, or waste combustion, the distinct treatment pathways around which the waste sector ALT scenarios are structured. The trajectory of waste sector emissions through 2047 depends on changes in waste generation volumes, collection efficiency, and treatment-mix proportions, all of which require activity-based modelling from waste management statistics.

Transport

Transport-related combustion is characterised through the spatial overlay of the NO_2 column composite with the VIIRS Day/Night Band maximum-radiance composite and the primary road network (NH-44, NH-46, NH-30 corridors and major OSM roads). Through this overlay, the urban centres of Indore, Bhopal, Gwalior, and Jabalpur are identifiable as elevated NO_2 nodes co-located with high night-time radiance, and a continuous radiance signature is visible along the national highway corridors connecting these centres. It is important to note that the transport NO_2 signal is not independently detectable on the raw state-level NO_2 composite, the absolute scale of NO_2 column values is dominated by the eastern power sector, and the transport contribution is only resolved when cross-referenced spatially with road network and VIIRS radiance data. This characteristic of the data underscores the limited standalone utility of NO_2 column retrievals for transport attribution in states where point-source power sector emissions are the dominant column signal.

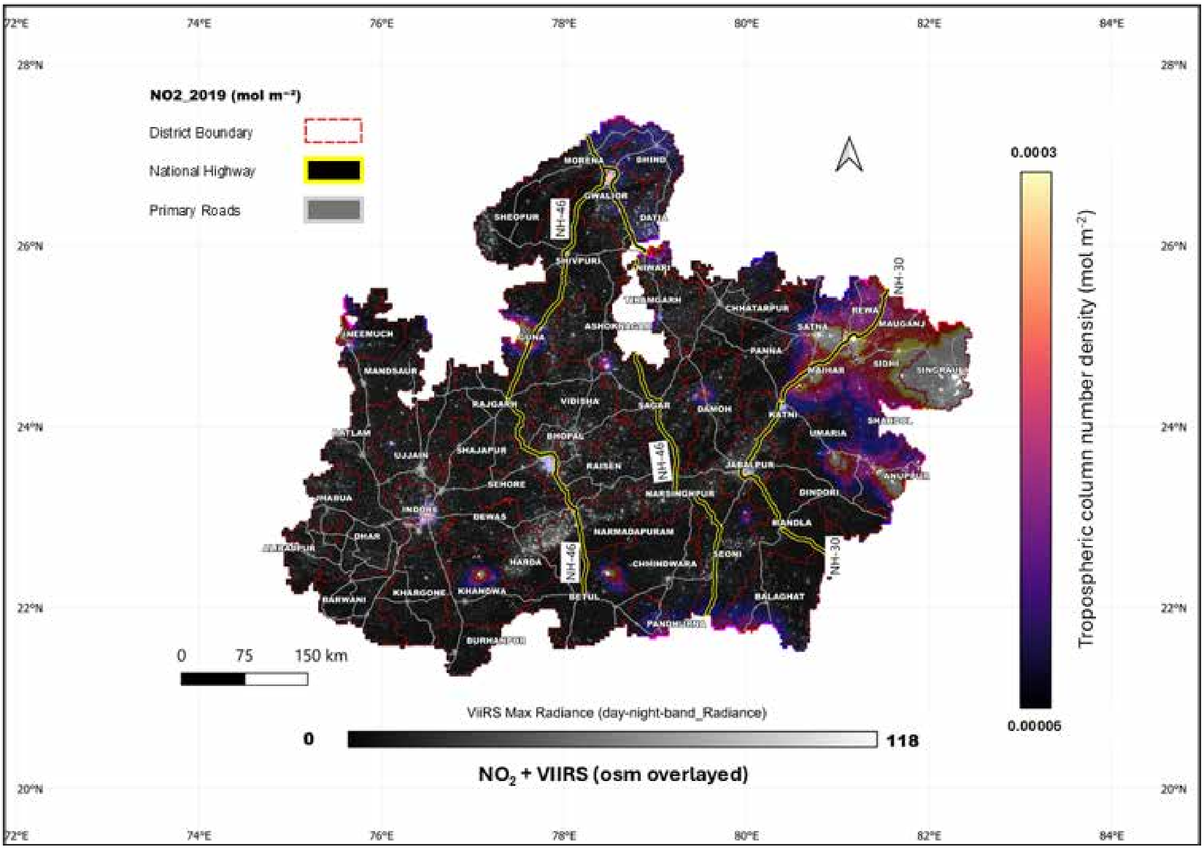


Figure 13: VIIRS night radiance, primary road network and NO_2 column overlay

Even with road-network overlay, the transport NO_2 signal cannot be separated from adjacent industrial and power sector contributions in the same urban districts. More fundamentally, the three transport ALT scenarios, EV adoption, vehicle scrappage, and biodiesel blending, operate at the level of vehicle fleet composition, vehicle age profile, and fuel type. Quantifying the emission reduction potential of these interventions requires vehicle registration data, fuel consumption statistics, and vehicle-km travelled estimates from transport demand modelling. These are activity-level parameters that satellite NO_2 column retrievals cannot provide.

The satellite analysis establishes that Madhya Pradesh's SLCP burden is real, geographically concentrated, and sectorally differentiated, but the limitation of satellite datasets is that it cannot, quantify the magnitude of sectoral contributions or model the emission reduction potential of specific policy interventions. To bridge this gap, the study develops a bottom-up activity-based emissions inventory for 2019, disaggregated by sector and pollutant, which serves as the foundation for the scenario analysis and mitigation roadmap presented in subsequent chapters.

Integrated Sectoral Assessment: Satellite Evidence and Inventory Requirements

Table 21 below consolidates the satellite-derived atmospheric findings and the specific inventory requirement for each sector. The pattern that emerges is consistent across all sectors, satellite data provides spatially informative evidence of where atmospheric column burdens are elevated and which broad source categories are likely contributing, but is structurally unable to deliver the sectoral quantification, source disaggregation, and policy counterfactual analysis required for the mitigation roadmap developed in this report.

Table 21: Sectoral Satellite Atmospheric Evidence and Emission Inventory Requirements, Madhya Pradesh 2019

Sector	What Satellite Detects	Key Hotspot Districts (Satellite-Derived)	Specific Limitation: Why Emission Inventory Is Required
Power	SO_2 + NO_2 dominance in eastern belt; VIIRS confirms TPP asset locations as bright point-source nodes	Singrauli, Sidhi, Mauganj, Anuppur, Rewa, Gadarwara corridor	Satellite confirms the eastern belt as the dominant combustion zone but cannot disaggregate asset-level contributions (e.g., individual TPP plants) needed to prioritise end-of-pipe controls such as FGD and SCR installation.
Agriculture & Biomass Burning	CH_4 column in northern belt; FIRMS active fire detections (FRP 5–10 MW) on kharif cropland mask (Oct–Nov)	Morena, Bhind, Gwalior, Tikamgarh, Chhatarpur; Narmadapuram, Chhindwara, Narsinghpur (fires)	Satellite cannot separate CH_4 from rice cultivation from that of co-located livestock and residential sources in the same northern belt. Inventory is required to model distinct interventions such as DSR adoption and residue-burning bans.
Livestock	No independent satellite signal detectable; CH_4 in northern belt is a composite of multiple co-located sources	Spatially co-located with agriculture belt; not independently attributable	Livestock — the state's single largest CH_4 source — is entirely invisible as an independent signal in satellite column retrievals. Quantification and scenario modelling (fodder management, breed composition) depend entirely on the activity-based inventory.
Residential	Per-pollutant population-weighted exposure layers (NO_2, CH_4, CO, HCHO) highest across northern belt; urban nodes identifiable on NO_2 and CO layers	Entire northern belt (Sheopur to Singrauli); Indore, Bhopal, Jabalpur, Gwalior urban cores	Population-weighted column layers cannot distinguish a household using LPG from one using fuelwood. They cannot identify biomass-dependent households targeted by clean cooking ALT scenarios. Fuel-use disaggregation requires household survey data and fuel-specific emission factors.
Industry	Diffuse AOD + UVAI aerosol signal; Satna-Maihar-Katni belt and Indore-Ujjain-Dewas corridor identifiable	Satna, Maihar, Katni; Indore, Ujjain, Dewas, Bhopal, Sagar, Dhar	AOD cannot separate industrial PM from road dust or construction emissions. Fuel-switching and process-change ALT scenarios require fuel consumption data and technology-specific emission factors.
Mining	AOD + UVAI composite on 5 km mine buffers; CH_4 composite separately; Singrauli signal partly masked by adjacent TPP plume	Singrauli-Anuppur (coal), Balaghat (manganese), Satna-Maihar (limestone)	Coal seam CH_4 is inseparable from the TPP plume in the satellite raster. Dust abatement ALT scenarios are formulated in activity-level terms — overburden removal volumes, transport distances, road surface type — that satellite aerosol proxies cannot provide.
Waste	Persistent CH_4 co-located with VIIRS urban nightlights and landfill point layer at four major cities	Indore, Bhopal, Jabalpur, Gwalior (primary); Ujjain, Rewa (secondary)	Satellite supports waste attribution at urban nodes but cannot differentiate CH_4 from open landfills, composting, anaerobic digestion, or waste combustion — the distinct treatment pathways around which ALT scenarios are structured.
Transport	NO_2 + VIIRS radiance aligned with NH corridors; urban nodes visible only via spatial overlay with road network	Indore, Bhopal, Gwalior, Jabalpur; NH-44, NH-46, NH-30 corridors	Transport NO_2 is not independently detectable at the state level — it is dominated by the eastern power sector and only visible through overlay with road network and VIIRS data. EV adoption and scrappage scenarios require vehicle fleet composition, fuel type, and vehicle-km data from transport demand modelling.

Source: Satellite analysis for this study (Sentinel-5P/TROPOMI, MODIS MAIAC, VIIRS, FIRMS, SEDAC, 2019). All satellite signals reflect atmospheric column burdens, not surface emission rates. Individual pollutant composites are presented on their own physical scales; no cross-species normalisation or combination is applied. Sectoral attribution is based on spatial co-location with known source types and is indicative. Quantitative emission estimates are presented in Chapter 5.

From Spatial Evidence to Emission Quantification: The Case for a Bottom-Up Inventory

The sector-by-sector analysis above reveals a consistent and structurally defined gap between what satellite atmospheric observation can establish and what evidence-based SLCP policy design requires. This gap arises directly from the nature of what satellite column retrievals measure, and it manifests in three specific and recurring ways across every sector examined in this chapter.

Source co-location prevents sectoral disaggregation. In the northern agro-residential belt, the CH_4 column enhancement is a composite signal from rice cultivation, livestock enteric fermentation, and residential biomass combustion, sources that are spatially indistinguishable at the scale of TROPOMI's retrieval resolution. In the eastern belt, SO_2 and CH_4 from coal mines cannot be separated from the adjacent TPP atmospheric plume. In urban centres, waste sector CH_4 partially overlaps with the peri-urban agricultural background. Each of these source pairs requires entirely different policy interventions, and their quantitative separation can only be achieved through an activity-based emission inventory that draws on sector-specific activity data and emission factors.

Policy scenario analysis requires activity-level data, not atmospheric column densities. Every alternative scenario assessed in this report is formulated in activity-level terms, the fraction of the vehicle fleet transitioning to EVs, the proportion of industrial units switching from coal to natural gas, the area under Direct Seeded Rice, the number of households adopting clean cooking technologies. These are not quantities that can be derived from atmospheric column retrievals. Translating a policy intervention into an emission change requires activity data, fuel consumption, vehicle-km, crop area, livestock population, multiplied by technology- and fuel-specific emission factors, which is precisely the approach of the bottom-up inventory.

Forward projection requires a structural emission model, not a historical snapshot. The 2019 satellite composites are single-year observations of atmospheric state. They cannot project what emissions will be in 2030, 2040, or 2047 under a Business-as-Usual trajectory, nor can they simulate the emission trajectory under any alternative policy scenario. The mitigation roadmap developed in this report, its BAU projections, its sectoral scenario comparisons, and its recommended pathways, requires a structural emission model with explicit sectoral growth rates, technology penetration assumptions, and emission factors projected forward in time.

Together, these constraints define the precise and complementary role of the satellite analysis in this report: it provides independent spatial validation that Madhya Pradesh's SLCP burden is real, geographically concentrated, and sectorally differentiated, it confirms the broad spatial pattern of which zones of the state carry the highest atmospheric burdens, and it establishes the observable 2019 baseline against which the state's emission trajectory begins. The task of quantifying that baseline at the sectoral level, and projecting what it could become under different policy choices, is what the emission inventory and scenario framework developed in the following chapter addresses.

Approach to develop SLCP reduction roadmap (Methodology)

Estimating Base Year Emissions

The base year emissions for various pollutants—PM_{10}, $PM_{2.5}$, CO, SO_2, NO_x, BC, NMVOCs, and CH_4—were estimated by developing an emissions inventory for the year 2019. Since the key pollutants assessed are integral to India's air pollution strategy and many of them fall under the NCAP mandate, which requires states to evaluate emission reductions relative to 2019, this year was selected as the baseline for the assessment.

The base year analysis encompasses key sectors such as transportation (tailpipe emissions), industry (industrial combustion and mining), diesel generator sets, thermal power plants, residential (household cooking), agriculture (covering open burning of agricultural residue and emissions related to cultivation), livestock (including emissions from enteric fermentation and manure management), and waste (open burning of municipal solid waste, and landfills). Additionally, to ensure a comprehensive assessment of the base year, smaller sectors such as crematoria, construction, and road dust were also included to assess an emission profile of the state in 2019. Emission estimates are based on activity types, emission factors, pollution abatement technologies employed, and control efficiency.

The basic equation followed by the study is,

$$Ep = \sum_R \sum_S \sum_F A_{R,S,F} \times EF_{R,S,F} \times (1 - \alpha_{R,S,F}) \times X_{p,R,S,F}$$

where, Ep is the annual emission of a pollutant (p) (Kt); R is the region/district; S is the sector; F is the type of fuel; A is the activity data (fuel consumption or other emission related data); EF is the emission factor (Kt per unit of fuel use) of the pollutant (p); α is the removal efficiency (%) of pollutant (p) with the installed pollution control technology and X is the actual application rate of the control technology[58]. The activity data and control technology datasets for 2019 across various sectors were primarily compiled from publicly available national and state government reports. Additionally, the Environmental Planning & Coordination Organisation (EPCO) of Madhya Pradesh facilitated the collection of sector-specific datasets unavailable in the public domain by coordinating with relevant line departments. However, some data gaps were addressed using information from published peer-reviewed literature. Figure 14 illustrates the overall framework for emission estimation used in this study. Detailed sector-specific methodologies for developing emission inventories, along with comprehensive emission inventories for each sector, are provided in Annexure. It is important to note that the emission inventory provides a macro-level estimate and does not represent a fully detailed bottom-up assessment, primarily due to the statewide scale of the analysis and limited availability of disaggregated primary data. However, it represents the most up-to-date and spatially refined emission inventory available for the state of Madhya Pradesh to date.

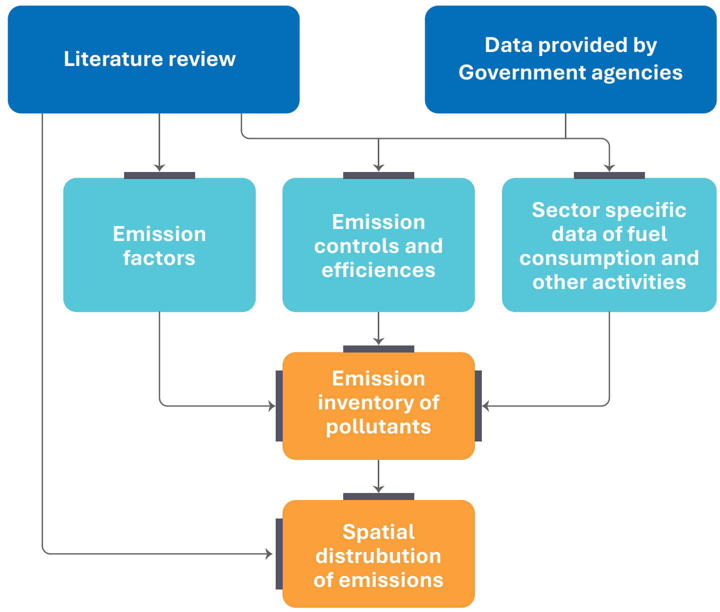


Figure 14: Emission Estimation Framework followed by the Study

Building Scenarios for the Study

To evaluate the potential of existing policies to reduce SLCP emissions, examine their ambition levels, identify gaps and additional strategies, and determine the emission reduction potential of various interventions, the study analysed the emission growth trajectories of different SLCPs and air pollutants in MP. Emissions scenarios—Baseline and Alternate—were considered, with each scenario representing distinct combinations of policy ambitions and strategies, calculating emission trajectories for milestone years (2030, 2040, and 2047). These scenarios align with the state's sector-specific policies. In the absence of such policies, national policies have been applied, or relevant sectoral policies and reports from other states have been referenced. The scenarios are as follows:

Baseline Scenario (BAU)

This scenario reflects the sectoral growth projections for Madhya Pradesh under current conditions. It takes into account certain interventions that have already been implemented and addresses non-CO_2 emissions.

1

Alternate Scenarios (ALT)

These scenarios assume the successful implementation of additional interventions aimed at reducing non-CO_2 emissions. These scenarios evaluate the impact of proposed measures on short-term (2030), mid-term (2040), and long-term (2047) policy targets. The year 2047 has been chosen as the long-term target as it aligns with the Government of India's 'Viksit Bharat by 2047' initiative, which envisions transforming India into a developed nation by its 100th year of independence. The interventions include specific sectoral policies planned by the state or similar measures being implemented in other parts of the country.

2

Baseline Scenario

The Baseline Scenario represents a Business-as-Usual (BAU) approach. It assumes that starting from the 2019 emission levels, sectoral activities grow according to the specified growth rates (as outlined in Table 22) and no additional policy measures are implemented by the state government to specifically address emissions of SLCPs and other non-CO_2 pollutants in these sectors. Essentially, the BAU scenario serves as the reference point against which we compare the effectiveness of mitigation interventions in the alternate scenarios. By contrasting the BAU emissions with those in the alternate scenarios, we can assess the efficacy of various mitigation strategies.

Table 22: Reference Points for Sector-Wise Growth Projections

Sector	Growth Rate (y-o-y)	Rationale	Reference
Residential	- Population Growth: 1.39% (Rural), 1.97% (Urban) - LPG Consumption Growth: 10.68%	- Population growth rate has been taken from the Population projections report for India and states 2011-2036 (MoHFW). - District-level LPG consumption data (2019–2023) provided by the Food, Civil Supplies and Consumer Affairs Department, Government of Madhya Pradesh, used to project LPG-using households.	MoHFW 2020
Transport	9.79%	Derived from the average annual growth of the transport sector between 2012–13 and 2020–21. Growth in vehicle registrations estimated from VAHAN and MoRTH data.	VAHAN Dashboard, MoRTH
Industry	5.22%	Calculated using the long-term growth trend (2010–11 to 2022–23) of state-level industrial GSDP. Incorporates assumptions on Air Pollution Control Devices (APCDs) from NCAP city action plans.	RBI Handbook (2022-2023)
Mining	6.6%	Calculated based on the trend in annual growth rate for the past 13 years starting from 2010-11. The annual growth rate for different years was estimated based on the yearly coal production for each year.	Coal Directory (2010-2023)
Power	8.14% (2021–2030) 5.83% (2030–2047)	The Power Demand growth rate was estimated using the MARKAL energy systems modelling framework, reflecting existing policy targets and past trends in electricity demand growth.	Low Carbon Pathways for Madhya Pradesh, TERI
Agriculture	~1%	MP's rice production is projected in proportion to its 4% contribution to national output. National demand is expected to grow from 162 Mt (2030–31) to 227 Mt (2050–51). A complete ban on the open burning of agricultural residues has been assumed from 2030.	National Rice Research Institute (2020); Department of Agriculture & Farmers Welfare (DoA&FW), MoEFCC, National Clean Air Programme. (2019)(ban on burning of agriculture waste and crop residues)
Livestock	6%	MP's milk production growth projected using its 8.6% share of national output. Aligned with India's projected milk demand of over 300 million metric tons by 2030.	National Dairy Development Board
Waste	Population Growth: 1.39% (Rural), 1.97% (Urban)	Population growth rate has been taken from the Population projections report for India and states 2011-2036 (MoHFW). Waste generation growth derived from historical trends in waste collection (2014–2021) as per CPCB reports.	MoHFW 2020 Central Pollution Control Board Solid Waste Management Rules Reports;

Alternative Scenarios

The Alternate Scenarios represent a combination of the state's existing and planned sectoral interventions and the expected emission reduction outcomes from their implementation. Further, the scenarios also analyse policies which are either in the pilot stage or in discussions in other parts of the country, and implementation of these hypothetical scenarios will result in achieving higher standards of SLCP and other non-CO_2 pollutants reduction. These scenarios evaluate the aggregate quantitative impact on activity levels in each sector for the years 2030, 2040, and 2047. In these scenarios, various sectoral policy documents were referred to evaluate the impact.

The selection of specific policy interventions for quantification was guided by two main criteria: the direct impact of the policy on SLCP and other non-CO_2 pollutant emission sources in the state, and the feasibility of quantifying its impact based on defined targets that enable measurement of emission reduction benefits. Since many policies are indicative or directional in nature and lack clearly defined activity-level targets, quantitative estimates for sectoral activities have been assumed, as detailed in Table 22. Wherever the relevant state policies specify quantitative targets, these have been included and extrapolated to address gaps. Table 23 outlines the specific policies that form the foundation of the various alternative scenarios assessed in this analysis.

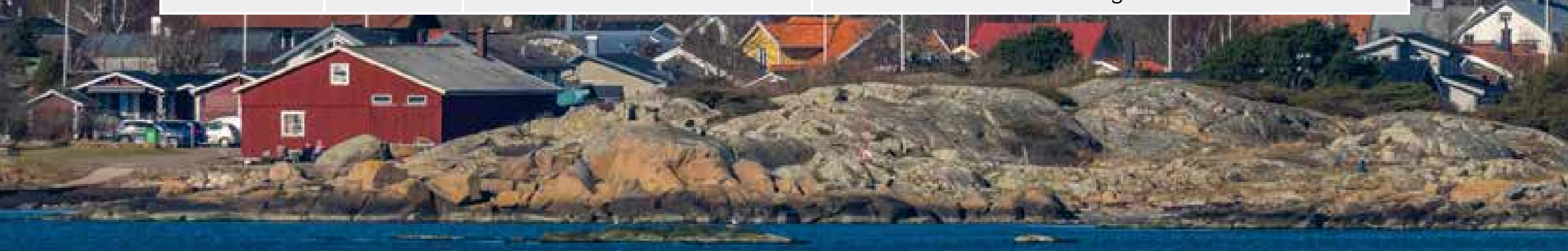
The sectoral target assumptions are based on observed trends from 2020 to 2024, under the premise that these trends represent the effective implementation of sectoral policies for the 2020–2030 period—such as the expansion of LPG use, the introduction of BS-VI standards, a complete ban on open burning of agricultural residue, and increased milk production in line with national targets. Further assumptions are informed by the strategic directions outlined in Madhya Pradesh's sector-specific policies and regulations, supplemented by national policy targets wherever applicable.

Emissions under each scenario were estimated using activity data projected under the BAU scenario, with adjustments made to account for intervention-specific reductions resulting from fuel substitution with cleaner alternatives and the adoption of low-emission technologies and practices.

Table 23: Reference Policies for Quantifying SLCP Mitigation in Alternative Pathways

Sector	Scenario	Policy Basis / Strategy	Description
Residential	ALT-1	National Biomass Cookstove Programme (NBCP), MNRE	Promotes improved biomass cookstoves to reduce indoor air pollution and SLCP emissions.
	ALT-2	MP Rural Livelihoods Project (MPRLP), MP-DAY-SRLM	Encourages adoption of biogas plants and smokeless stoves, particularly in tribal districts.
	ALT-3	"Surya Nutan" Solar Cooking Initiative (EKI & IOCL)	Supports clean indoor solar cooking in underserved communities through distribution of "Surya Nutan" devices.
Transport	ALT-1	Madhya Pradesh Electric Vehicle (EV) Policy, 2025	Assesses SLCP reduction through enhanced EV adoption across the state.
	ALT-2	National Vehicle Scrappage Policy, 2022	Evaluates emission reduction from phasing out older vehicles as per policy targets.
	ALT-3	National Policy on Biofuels, 2018	Incorporates biodiesel blending: 5% by 2030, and an aspirational 20% similar to ethanol blending targets.

Sector	Scenario	Policy Basis / Strategy	Description
Industry	ALT-1	NCAP Industrial Emission Guidelines (MoEFCC)	Advocates gaseous fuels and stringent PM, SO_2, and NO_x standards for industries using solid fuels.
	ALT-2	CPCB Guidelines on Community Boilers, 2024	Promotes shared energy-efficient boilers for MSME clusters to reduce emissions.
	ALT-3	MP Renewable Energy Policy, 2022	Explore the use of green hydrogen in industrial applications as an alternative fuel.
	ALT-4	MoEFCC Coal Ash Standards	Restricts coal with ash content >34% in plants >500 km from pithead; extended to industries in MP.
Mining	ALT-1	These assumptions are based on TERI's experience and discussions with different stakeholders like Kaniha, MCL (Mahanadi Coal-field Limited).	The sprinkling of water at every stage, including the loading and unloading of overburden and coal, reduces the emission by 75%, and the transport of coal and overburden reduces the emission by 70%.
	ALT-2		Reducing the drop height during loading and unloading can reduce the emissions by 70%.
	ALT-3		Paving of roads can reduce the emissions by 80%.
	ALT-4		Best management practices reduce the emissions by 60%.
Power	ALT-1	MP Renewable Energy, Wind, and Solar Policies	Builds on state targets: 20% RE by 2024, 30% by 2027, and 50% by 2030; assumes higher RE penetration.
	ALT-2	Gas-Based Generation (State Planning)	Incorporates gas-based power plants to offset coal dependency while supporting RE targets.
	ALT-3	Hybrid Approach	Mix of ALT-1 and ALT-2, combining RE scale-up with partial gas-based substitution.
Agriculture	ALT-1	DSR Guidelines (MP & DoAFW)	Promotes Direct Seeded Rice to reduce methane emissions; no quantified targets available.
	ALT-2	DoFW&AD, KVK, Research	Promote the application of biochar in soil to enhance C sequestration and the availability of nutrients.
	ALT-3	National Mission on Natural Farming (NMNF) & MP Natural Farming Board	Supports natural, low-input agriculture to reduce synthetic inputs and improve soil health.
Livestock	ALT-1	National Dairy Development Board (NDDB) Guidelines	Encourages balanced cattle feeding to reduce enteric methane emissions.
	ALT-2	MP Natural Farming Initiatives	Promotes indigenous cattle breeds under natural farming for sustainable livestock practices.
	ALT-3	Combined Strategy	Integrates ALT-1 and ALT-2 to maximize livestock-related SLCP reductions.
Waste	ALT-1	MP State Environment Plan, 2024	Considers current and proposed waste treatment capacities, especially waste-to-energy plants.
	ALT-2	MPPCB ISWM Cluster Model	Envisions enhanced waste recovery via MRFs and decentralized waste management across ULBs.



Data limitations and Resolution

- Owing to the lack of region-specific emission factors (EFs), EFs from similar regions have been utilized.
- Due to a lack of state-specific targets and fuel transition forces, the assessment relied on central government goals, which may not align with the local context.
- Certain small sectors were not included in the emission inventories. However, their overall impact at the state level is negligible, particularly for those sectors whose data are not compiled at the state level and rely on primary surveys, such as roadside eateries.
- Household fuel consumption data for cooking and heating in the residential sector is collected every ten years. Changes in consumption patterns have been estimated using the 76th NSSO report by the Ministry of Statistics and Programme Implementation.
- Limited information on vehicle de-registration in different districts, the central government directive has been employed as being implemented uniformly across the state.
- The specific implementation of policies across different areas or industries is not fully known. Thus, uniform assumptions have been made based on government directives, such as control efficiency, for similar industries.
- Owing to limited knowledge on location-specific strategy implementation in future years, it has been assumed that the interventions are uniformly implemented across the state.

State's SLCP Emissions and Mitigation Pathways

Base Year Emissions

In 2019, the total emissions of key air pollutants in Madhya Pradesh were estimated as part of this study, highlighting the scale of air quality and climate challenges in the state. The emissions of PM were significant, with PM_{10} at 631 kt/year and $PM_{2.5}$ at 308 kt/year, contributing to severe air pollution and health concerns. BC emissions stood at 38 kt/year, further exacerbating atmospheric warming. Among gaseous pollutants, SO_2 emissions were 424 kt/year, primarily from industrial and power sector activities, while NO_X emissions reached 620 kt/year, mainly from vehicular and diesel combustion sources. $NMVOC_S$ were estimated at 470 kt/year, contributing to secondary pollutant formation and ozone generation. Additionally, CH_4 emissions were the highest at 1,196 kt/year, reflecting contributions from agriculture, waste, and mining activities. The detailed sector-wise emissions have been provided in Table 24.

The sectoral emissions data for Madhya Pradesh in 2019 offers valuable insights into the primary contributors to pollution in the state. Based on the estimates, the transport, power, industries, residential, agriculture, and livestock sectors emerge as the dominant sources of different pollutants.

Table 24: Sector-wise emissions (kt/year) of different pollutants in Madhya Pradesh

	PM_{10}	$PM_{2.5}$	BC	SO_2	NO_X	$NMVOC_S$	CH_4
Transport Sector	19.2	18.6	13	3	281	174	5
Residential Sector	92	60	5	10	23	223	4
Industry and Mining Sector	102	35	0.4	14	7	1	163
Power (Thermal + DG)	24	10	1	358	297	16	18
Agriculture Sector	188	132	18	38	12	46	257
Livestock Sector	-	-	-	-	-	-	843
Waste Sector	4	4	0.1	0.4	-	-	61
Road dust re-suspension	181	43	-	-	-	-	-
Construction	18	3	-	-	-	-	-
Crematoria	3	2	0.1	0.1	0.4	9	1
Total	**631**	**308**	**38**	**424**	**620**	**470**	**1352**

Transport Sector: A Growing Concern

The transport sector is a significant emitter of BC, NO_X, and NMVOCS, contributing approximately 13 kt/year, 281 kt/year, and 174 kt/year, respectively. These emissions are expected to increase due to rapid urbanization and growing vehicular activity across Madhya Pradesh. Notably, NO_x emissions from transport account for 45% of total NO_x emissions, making it a critical contributor to ozone formation and secondary particulate matter, both of which significantly impact air quality and human health.

Power Sector: The Largest Contributor to SO_2 and NO_x

The power sector, primarily comprising coal-fired thermal power plants, is the largest emitter of SO_2 and NO_x in the state, with emissions of 358 kt/year and 297 kt/year, respectively. These emissions contribute to the formation of secondary particulate matter, worsening $PM_{2.5}$ pollution across the region. Despite accounting for only 4% of PM_{10} and 3% of $PM_{2.5}$ emissions, the sector's role in generating gaseous pollutants with secondary particulate formation potential underscores the need for emission control technologies such as flue gas desulfurisation (FGD) systems and selective catalytic reduction (SCR) for NO_x mitigation.

Industrial Emissions: Air Pollution Control Devices Making an Impact

Industrial activities in Madhya Pradesh emitted 102 kt/year of PM_{10}, 35 kt/year of $PM_{2.5}$, and 163 kt/year of CH_4 in 2019. Although industries remain a significant source of PM emissions, their contribution to SO_2 and NO_x emissions (3% and 1%, respectively) is relatively lower, assuming compliance with air pollution control devices (APCDs). However, CH_4 emissions from coal mining, estimated at 162 kt/year, remain a significant concern, highlighting the urgent need for stringent mitigation measures and effective emission control strategies.

Residential Sector: A Major Source of NMVOCs and Particulate Matter

The residential sector is the largest contributor to NMVOCs, estimated at 223 kt/year, primarily from biomass-based cooking and heating. In addition, this sector emits PM_{10} (92 kt/year), $PM_{2.5}$ (60 kt/year), BC (5 kt/year), and NO_x (23 kt/year), underscoring the urgent need for cleaner cooking alternatives such as LPG, electric cooking, or improved biomass stoves. The sector's high NMVOCs emissions (47% of total NMVOCs emissions) highlight the significant role of household air pollution in outdoor air quality degradation.

Agricultural Burning: A Growing Challenge

Open burning of agricultural residue remains a major concern, contributing to PM_{10} (188 kt/year), $PM_{2.5}$ (132 kt/year), BC (18 kt/year), SO_2 (38 kt/year), NO_x (12 kt/year), and NMVOCs (46 kt/year). These emissions not only deteriorate air quality but also contribute to regional haze and visibility reduction. The need for alternative residue management strategies, such as bio-decomposers, mechanized residue incorporation, and bioenergy applications, is crucial to reducing emissions from this sector to comply with city action plans submitted under NCAP.

Livestock and Agriculture: The Largest Source of Methane Emissions

Methane emissions from livestock alone were estimated at 843 kt/year, making it the single largest source of CH_4 in Madhya Pradesh, followed by agriculture (257 kt/year). Additional CH_4 emissions from industry and mining (163 kt/yr) and the waste sector (61 kt/year) further contribute to greenhouse gas accumulation. Given methane's high global warming potential, targeted mitigation strategies such as improved livestock feed management, biogas adoption, and controlled manure management are necessary.

Waste Sector: A Manageable but Persistent Source

The waste sector contributed 61 kt/year of methane emissions, accounting for 5% of total CH_4 emissions in the state. Solid waste processing and landfill emissions are the primary sources, emphasizing the need for better waste segregation, landfill gas recovery, and enhanced waste-to-energy initiatives to control methane emissions from this sector.

Road Dust: A Key Contributor to Particulate Matter

Re-suspension of road dust was responsible for 181 kt/year of PM_{10} and 43 kt/year of $PM_{2.5}$ emissions, contributing 29% and 14% of total PM_{10} and $PM_{2.5}$ emissions, respectively. As one of the largest contributors to coarse particulate matter, road dust emissions highlight the need for paved roads, dust control measures, and improved street cleaning practices to mitigate airborne dust pollution.

Construction and Crematoria: Minor but Notable Sources

The construction sector contributed 18 kt/year of PM_{10} emissions, accounting for 3% of total PM_{10} emissions, while crematoria emissions were relatively minor, contributing 3 kt/year of PM_{10} and 9 kt/year of NMVOCs. The impact of these sources can be reduced through construction dust control regulations and improved cremation technologies such as electric or LPG-based crematoria.

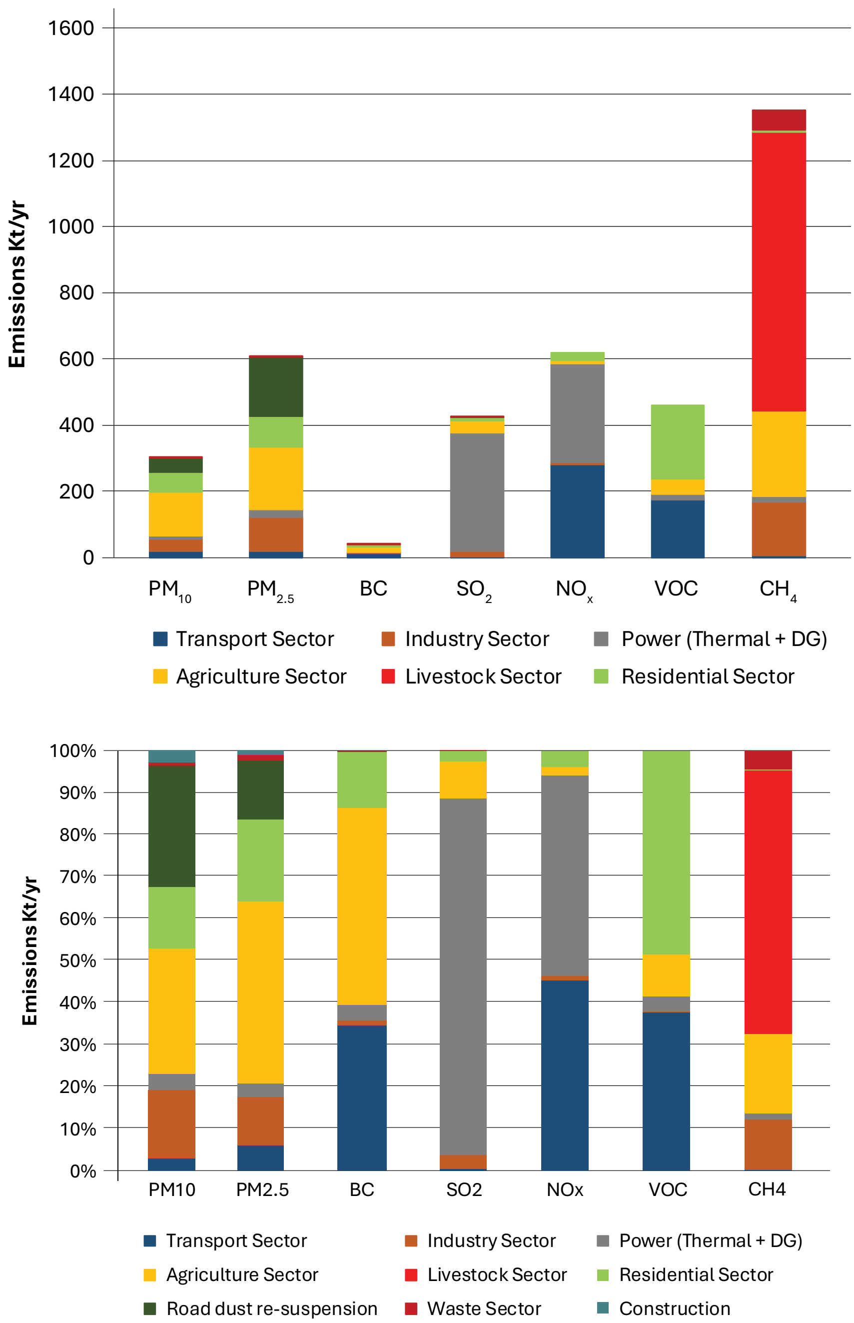


Figure 15: Sectoral contribution in 2019 for different pollutants in Madhya Pradesh (A: In absolute numbers, B: In Percentage)

In conclusion, the analysis identifies the transport, industry, and agriculture sectors as key priority areas for reducing emissions of black carbon, particulate matter, sulphur dioxide, nitrogen oxides, volatile organic compounds, and methane in Madhya Pradesh. Targeted mitigation efforts in these sectors offer substantial potential for curbing SLCPs. In the transport sector, reducing NO_x and NMVOCs emissions will be crucial in limiting the formation of secondary pollutants such as ozone and nitrates, which significantly impact air quality. Additionally, emissions from the livestock, agriculture, residential, mining and waste sectors, particularly NMVOCs and methane, require focused interventions to minimise their contribution to air pollution and climate change. Addressing these challenges demands a comprehensive, multi-sectoral approach, integrating technological advancements, regulatory enforcement, and behavioural shifts to achieve long-term improvements in air quality and emission reductions across Madhya Pradesh.

In the next section, we conduct a deeper analysis to assess how emissions from these sectors are expected to evolve in future years and evaluate the potential impacts of various mitigation strategies. This assessment will provide critical insights into the effectiveness of different policy measures and help identify the most efficient pathways for reducing emissions and improving air quality in the state.

Sectoral Emissions

Pollution in Madhya Pradesh stems from multiple sources, each contributing distinct pollutants with varying environmental and health implications. While overall emission estimates provide a broad understanding of pollution levels, a sector-wise analysis is essential for devising effective and targeted mitigation strategies.

Different sectors—such as transport, industry, power generation, residential cooking, agriculture, and waste—have unique emission profiles, necessitating sector-specific interventions rather than a one-size-fits-all approach. For instance, while transport emissions primarily consist of NO_X and BC, power plants are the dominant source of SO_2. Without identifying these sectoral contributions, policy measures risk being ineffective or misdirected.

Assessing sector-wise emissions also enables policymakers to prioritise actions based on impact and feasibility. Sectors with high emissions and significant public health consequences, such as residential biomass burning and vehicular pollution, may require urgent interventions. Conversely, sectors with emerging or future growth in emissions, like transport outside the present urban areas and industrial expansion, demand proactive measures to prevent worsening air quality trends.

Furthermore, this assessment plays a crucial role in aligning air quality improvement efforts with broader climate and sustainability goals. Many pollutants, such as CH_4 and black carbon, are also potent climate forcers. By addressing emissions at the sectoral level, the state can achieve co-benefits for both air quality and climate mitigation, ensuring a more sustainable and health-conscious development pathway.

While the study estimates a comprehensive set of pollutants—including PM_{10}, $PM_{2.5}$, BC, SO_2, NO_X, NMVOCs, CO and CH_4—spatial distribution maps are presented for $PM_{2.5}$, BC, CH_4, NO_X, and NMVOCs. These pollutants were selected based on their significance for air quality and climate co-benefits, regulatory relevance, and ability to act as proxies for broader pollutant categories. For example, $PM_{2.5}$ captures the most health-damaging fraction of particulates and reflects proxy hotspots of PM_{10} and SO_2. Similarly, NO_2 and NMVOCs are effective indicators of NO_x and VOCS emissions, which drive ozone formation. This focused representation avoids redundancy and supports a clearer understanding of emission hotspots and sectoral impacts.

The following sections provide a detailed deep dive into emissions from each sector, highlighting key pollutants, underlying causes, and potential avenues for mitigation.

Residential

Household air pollution is considered one of the world's major environmental risk factors. It is mainly caused by the use of unprocessed solid fuels for cooking activity, which includes biomass (e.g. wood, crop residues, dung cake), coal and kerosene. There is an increasing number of health issues, such as acute respiratory infections (ARI), chronic pulmonary diseases (COPD), asthma, heart diseases, cataract, pneumonia, low birth weight, and tuberculosis, associated with indoor air pollution. In India, the residential sector is the second largest consumer of energy, following the industry sector. People from a low socio-economic background of rural India and urban slums are forced to rely on solid biomass fuels due to their ease of availability and low cost. Large quantities of particulate matter, CO, SO_2, NO_X, CH_4 and NMVOCs are released into the ambient atmosphere and indoor environment due to the burning of traditional fuels.

As per the Census (2011), about 95% of rural households and 34% of urban households in Madhya Pradesh were dependent on traditional biomass fuel for cooking activity. Whereas, only 3.5% of rural households and 60% of urban households had access to a clean cooking facility.[59] However, there is significant growth in household LPG connections after 2011, which affects the biomass and kerosene usage pattern in the residential sector for cooking activity[60]. Therefore, biomass and kerosene consumption in the residential sector in Madhya Pradesh during 2019 were re-estimated by incorporating the state-level growth rate of LPG consumers provided by the Food, Civil Supplies and Consumer Affairs department, Government of Madhya Pradesh.

Accordingly, an annual LPG consumption growth of 9.2% has been considered for Madhya Pradesh which was provided by Food, Civil Supplies and Consumer Affairs department, Government of Madhya Pradesh. The increase in the number of households using LPG is then uniformly distributed to adjust the number of households using fuelwood, crop residue, dung cake and kerosene during 2019. The growth of LPG coverage and consumption showed significant improvements in urban areas, where 92% of households were dependent on LPG for cooking. However, considering similar LPG consumption growth (9.2%) in rural areas, less than 10% of households are estimated to have access to a clean cooking facility, and the majority of the population was still relying on traditional biomass fuel (mainly fuelwood) as a primary energy source to meet their cooking needs (details of fuel consumption have been provided in anexxure of the report). Traditional cooking practices, characterised by inefficient biomass stoves, release substantial amounts of PM, BC and CO along with a range of NMVOCs that contribute to ozone formation. These emissions not only contribute to climate warming but also have severe health implications.

Further, the spatial distribution of emissions as shown in Figure 16 presents a picture where residential sector in Madhya Pradesh has varying levels of emissions in different districts due to the varying use of LPG and traditional fuels like fuelwood, crop residue, and charcoal-derived carbon. Fuelwood is the dominant source of emissions in most districts, with areas like Dindori, Mandla, Katni, and Balaghat relying on it almost exclusively. Crop residue use is significant in districts such as Alirajpur and Anuppur, while charcoal-derived carbon plays a notable role in West Nimar and Jhabua. Meanwhile, LPG adoption has increased in the major urban centres of the state like Indore, Bhopal, and Gwalior. Some districts, including Bhind, Dhar, Morena, and Rajgarh, exhibit a mixed fuel-use pattern, whereas others, such as Mandla and Umaria, rely mainly on biomass. These variations highlight the diverse energy use patterns across Madhya Pradesh, emphasising the need for localised approaches to reduce emissions from the residential sector.

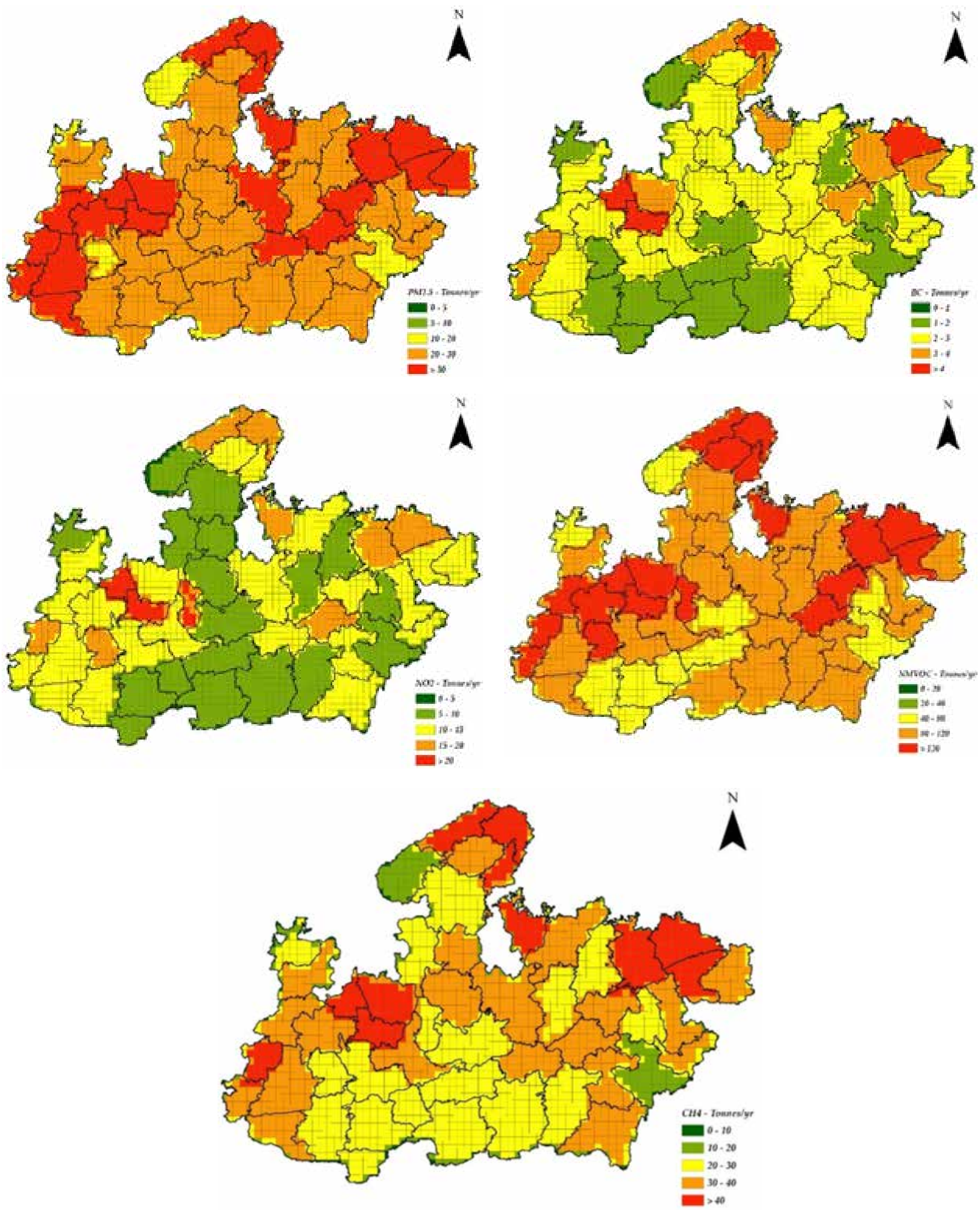


Figure 16: Spatial distribution of residential emissions for different pollutants in MP at 12×12 km^2 grid scale

The sections below provide an in-depth analysis of emission projections from residential cooking activity in Madhya Pradesh under different scenarios. It highlights the potential emission reductions achievable through varying levels of intervention and technology adoption, offering insights into the most effective strategies for mitigating air pollution and achieving climate co-benefits in the state.

BAU scenario of the residential sector

Under the BAU scenario, emissions have been projected considering the growth pattern of LPG consumption in residential households of Madhya Pradesh. District level domestic LPG consumption

(2019 to 2023) information provided by the Food, Civil Supplies and Consumer Affairs department, Government of Madhya Pradesh, were used to project the growth trend of LPG usage in the state during future years. Accordingly, household LPG usage was estimated to grow at 10.68% annually in urban and rural areas of Madhya Pradesh during 2030, 2040 and 2047.

Growing population at 1.97% annually and domestic LPG usage at 10.68% annually, urban households are achieving 100% LPG connection by 2030. However, a growing population at 1.39% annually and domestic LPG usage at 10.68% annually, rural households are achieving 82% LPG connection by 2047. Under the BAU scenario, the emission load of various pollutants is anticipated to reduce due to an increased rate of LPG consumption in residential households in future years. The increased rate of LPG usage would reduce the number of biomass-using households in Madhya Pradesh, but still, 18% of rural households by 2047 would continue to depend on biomass fuels for cooking activity based on the present trend. The emission load of various pollutants from residential cooking activity in the state of Madhya Pradesh is expected to reduce between 2% and 3% during 2030, 11% and 24% during 2040 and 42% and 69% during 2047 with respect to the baseline emission (2019).

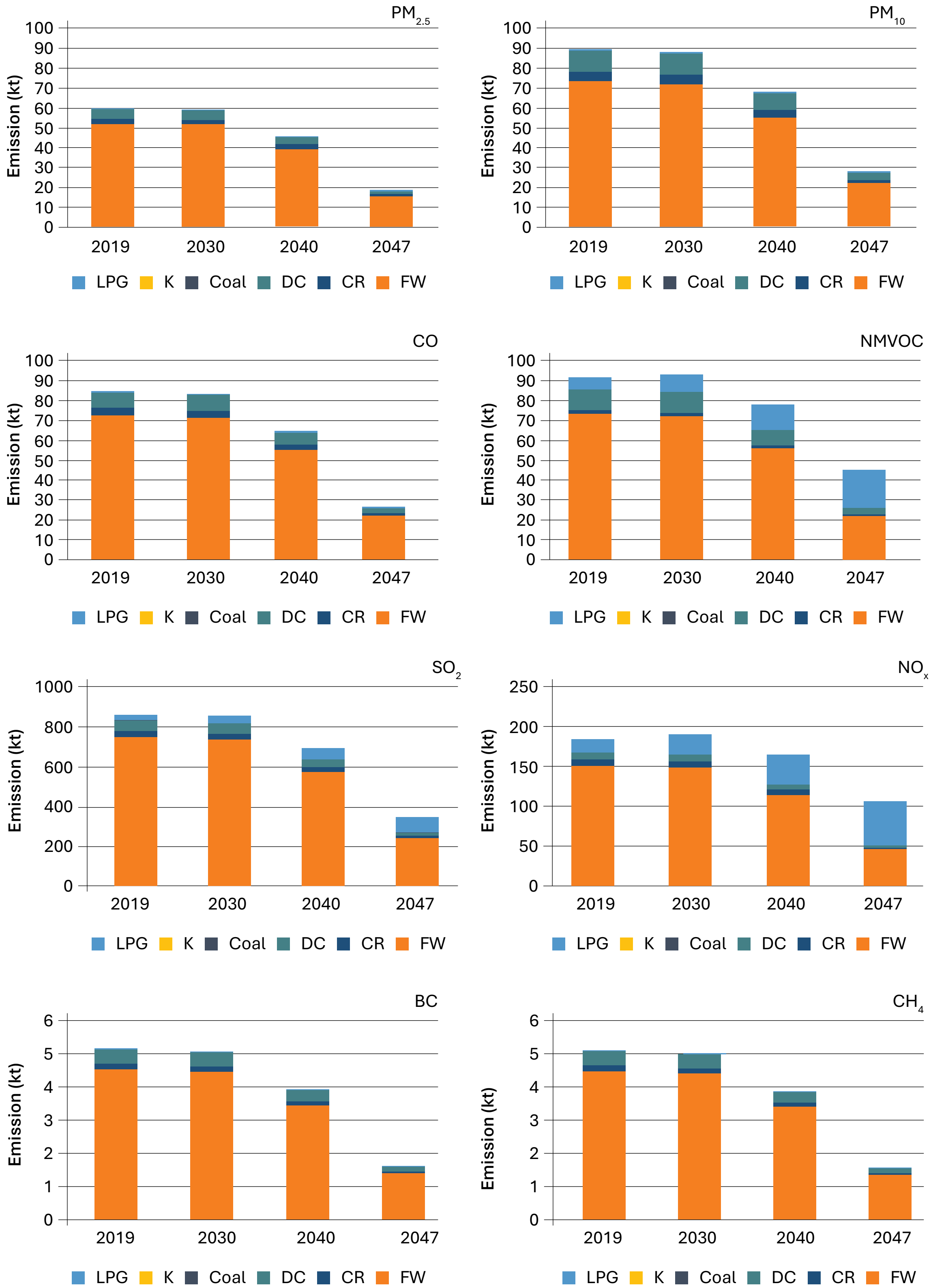


Figure 17: Fuel wise emission (kt) of different pollutants from residential cooking activity in Madhya Pradesh during 2019, 2030, 2040 and 2047 under BAU scenario

FW: Fuelwood; CR: Crop Residue; DC: Dung Cake; K: Kerosene; LPG: Liquified Petroleum Gas

Table 25: Brief description of alternative scenarios for the residential sector

Scenarios	Description
ALT-1	▪ Population growth at **1.39% (rural)** and **1.97% (urban)** per year. ▪ **LPG consumption grows annually by 10.68%**, based on government data. ▪ Households using biomass in **2030, 2040, and 2047** transition to **improved solid fuel cookstoves** with higher combustion efficiency.
ALT-2	▪ Population growth and LPG expansion as in ALT1. ▪ By **2030**, **20% of non-LPG users adopt improved cookstoves**, **20% adopt solar cookstoves (Surya Nutan)**, and **60% switch to biogas**. ▪ By **2040**, **80% of non-LPG users transition to biogas**, while the remaining **20% use solar cookstoves** and **10% use improved cookstoves**. ▪ By **2047**, all non-LPG users in rural areas switch to **biogas-based cooking**.
ALT-3	▪ Population growth and LPG expansion as in ALT1. ▪ By **2030**, **20% of non-LPG users adopt improved cookstoves**, **20% switch to biogas**, and **60% use solar cookstoves**. ▪ By **2040**, **80% of non-LPG users transition to solar cookstoves**, while **20% use biogas** and **10% continue with improved cookstoves**. ▪ By **2047**, all non-LPG users shift entirely to **solar cookstoves**.

Alternative scenario 1 (ALT1): Improved Biomass Transition

(Based on National Biomass Cookstove Programme (NBCP), MNRE)

Under the ALT1 scenario, the emission load from the residential sector is projected based on the assumption that LPG consumption will grow at 10.68% annually as considered under the BAU scenario. However, growing LPG usage at 10.68% annually, about 20%, 47% and 82% of rural households is achieving LPG penetration during 2030, 2040 and 2047 while; remaining 80%, 53% and 18% would still depend on traditional biomass fuel as primary energy source during 2030, 2040 and 2047 respectively. Therefore, it is assumed that biomass-dependent households during 2030, 2040 and 2047 would gradually shift from traditional cookstoves to improved, less-smoky solid fuel cookstoves with better combustion efficiency. According to the test report approved by Biomass Cookstove Test Centre under the Ministry of New and Renewable Energy (MNRE), an improved biomass cookstove with thermal efficiency of 28% can achieve significant emission reduction[61]. Unless there is a sustainable supply of LPG for cooking activity in residential households, particularly in rural areas, the implementation of improved solid fuel cookstoves would emit less smoke compared to traditional cookstoves. Accordingly, assuming co-implementation of LPG fuel and improved solid fuel cookstove, the emission load of different pollutants is expected to reduce between 12% and 14% during 2030, 18% and 21% during 2040 and 14% and 28% during 2047 with respect to corresponding emissions under the BAU scenario.

Alternative scenario 2 (ALT2): Biogas-Dominant Shift

(Based on MP Rural Livelihoods Project (MPRLP) and MP-DAY-SRLM)

As per the baseline situation, about 82% of rural households are achieving the LPG connection during 2047, while the remaining significant proportion of households (80% during 2030, 53% during 2040 and 18% during 2047) would continue to depend on traditional biomass fuel as a primary energy source. Therefore, under the ALT2 scenario, it is assumed that 20%, 20% and 60% of non-LPG using households in rural Madhya Pradesh would shift to improved cookstoves, Surya Nutan (solar) and biogas-based cooking, respectively, during 2030. Similarly, during 2040, 80% of non-LPG using households in rural Madhya Pradesh are assumed to shift to biogas-based cooking, whereas, remaining 20% and 10% of non-LPG households will use solar and improved cookstoves, respectively. Again, by 2047, remaining non-LPG-using households in rural Madhya Pradesh are assumed to shift to biogas-based cooking. Accordingly, the emission load of different pollutants is expected to decline between 61% and 77% by 2030, 63% and 91% by 2040 and 41% and 98% by 2047 with respect to corresponding emissions under the BAU scenario.

Alternative scenario 3 (ALT3): Emphasis on Solar Cooking

(Based on "Surya Nutan" Solar Cooking Initiative (EKI & IOCL))

Under the ALT3 scenario, the emission load from the residential sector is projected assuming that 20%, 20% and 60% of non-LPG-using households in rural Madhya Pradesh will shift to improved cookstoves, biogas and solar-based cooking, respectively, during 2030. Similarly, by 2040, 80% of non-LPG using households in rural Madhya Pradesh are assumed to shift to solar cookstoves, whereas, remaining 20% and 10% of non-LPG households will use biogas and improved cookstoves, respectively. Moreover, by 2047, remaining non-LPG-using households in rural Madhya Pradesh are assumed to shift to solar cookstoves. Accordingly, the emission load of different pollutants is expected to decline between 72% and 86% by 2030, 71% and 93% by 2040 and 48% and 99% by 2047 with respect to corresponding emissions under the BAU scenario.

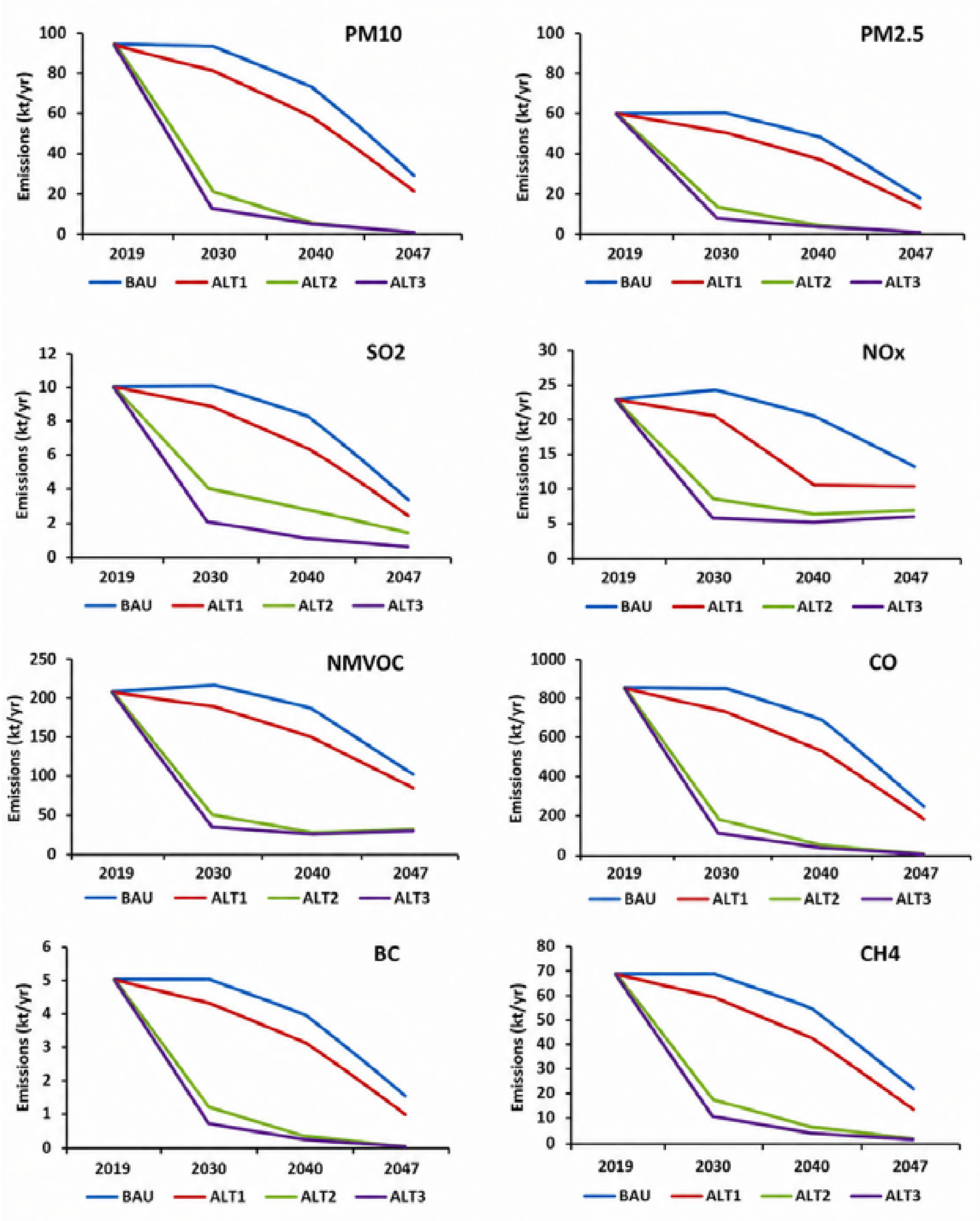


Figure 18: Emission (kt) of different pollutants from residential cooking activity in Madhya Pradesh during 2019, 2030, 2040 and 2047 under the BAU and alternate scenarios (ALT1, ALT2 and ALT3)

Table 26: Change in Residential Emissions Under Alternate Scenarios, compared to 2047 Emissions

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: Improved Biomass Transition	-27%	-21%	-13%	-28%	-16%	-28%	-27%
ALT 2: Biogas-Dominant Shift	-94%	-53%	-41%	-98%	-58%	-100%	-89%
ALT 3: Emphasis on Solar cooking	-96%	-76%	-48%	-98%	-58%	-100%	-97%

Key Insights from the Residential Sector Analysis

The residential sector is a significant contributor to air pollution and climate change, emitting about 19% $PM_{2.5}$, 13% of BC, and 47% of VOCS emissions in the state in 2019. While dependence on traditional biomass fuels has remained significant in rural kitchens, reducing their environmental impact is crucial. Following the current policy trends in the residential sector with an aim of ensuring a sustainable supply of LPG can significantly reduce reliance on biomass fuels, reducing emissions and improving air quality. The Ministry of Petroleum and Natural Gas launched the Pradhan Mantri Ujjwala Yojana (PMUY) to provide a cleaner cooking fuel alternative, LPG, for households relying on traditional fuels like firewood, coal, and cow-dung cakes, targeting both rural and low-income urban households. While the scheme has improved access to LPG as a cleaner cooking fuel but the high initial refill costs, limited subsidy accessibility, fuel stacking practices, and logistical challenges in rural areas contribute to the limited adoption of LPG, leading many rural households to continue relying on biomass and other traditional fuels. This ongoing dependence on biomass not only fulfils the immediate livelihood needs of communities that depend on forest resources but also exacerbates health risks and environmental impacts due to continued indoor pollution and carbon emissions from biomass burning. Moreover, this continued dependence on traditional biomass fuels requires the urgent need for targeted regulations, financial incentives, subsidies, and awareness programs to promote cleaner cooking alternatives.

The ALT1 strategy, which focuses on increasing LPG penetration alongside the adoption of improved cookstoves (ICS) for biomass, offers a culturally and economically viable solution for households struggling with LPG affordability, irregular supply, and limited availability. However, as seen in Figure 18, this approach results in the least reduction in $PM_{2.5}$, BC, and VOCS emissions compared to other alternatives.

In contrast, the ALT2 and ALT3 scenarios in the residential sector provide maximum benefits in reducing $PM_{2.5}$, BC, and VOCS emissions. A more effective approach would be to supplement LPG penetration with other clean energy solutions, such as biogas adoption. Biogas not only reduces methane and black carbon emissions but also serves as a clean fuel for cooking, lighting, and electricity generation. By replacing polluting wood, dung, and fossil fuels, biogas can contribute to slowing climate change, improving air quality, enhancing global health, reducing agricultural losses, and increasing energy access—ultimately improving the lives and livelihoods of rural communities.

Additionally, another high-impact strategy is the transition from traditional cookstoves to solar-powered cookstoves. This shift eliminates reliance on biomass fuels, significantly cutting SLCPs from household energy use. By fully replacing traditional stoves, solar cookstoves can lead to substantial improvements in air quality and a significant reduction in climate-altering emissions.

It would be particularly beneficial for Madhya Pradesh to prioritise these alternate strategies in districts with low LPG penetration, such as Dindori, Mandla, Balaghat, Alirajpur, Anuppur, West Nimar (Khargone), Jhabua, Bhind, Dhar, Morena, and Rajgarh. These areas face economic, infrastructural, and cultural barriers to widespread LPG adoption, making it essential to introduce alternative clean cooking solutions that align with local needs and resources. Meanwhile, in urban centres, where LPG uptake is steadily increasing due to rising per capita incomes, it may be more effective to continue expanding LPG access rather than introducing additional alternative technologies. As household incomes grow, LPG adoption is expected to naturally accelerate, reducing reliance on biomass and solid fuels over time.

While these measures may be more challenging to implement compared to simply distributing improved cookstoves, they offer long-term advantages in terms of affordability, accessibility, fuel availability, and energy security. Achieving widespread adoption would require not only financial incentives but also behavioral shifts among communities. However, in the long run, these solutions would deliver greater environmental benefits, enhance self-reliance in energy generation, and contribute to sustainable development in small villages and towns across Madhya Pradesh.

Transport

The transport sector in Madhya Pradesh is integral to the state's economic development, facilitating the movement of goods and people across its diverse regions. However, this sector faces significant environmental challenges due to its heavy reliance on road-based transportation and conventional fossil fuels, leading to increased air pollution and greenhouse gas emissions. Madhya Pradesh's transportation network predominantly depends on vehicles powered by diesel and petrol. This dependency has resulted in elevated levels of air pollutants, especially in urban centres like Bhopal and Indore.

According to this study's estimates, vehicular emissions emerge as a major source of NO_x, BC, SO_2, and VOCS in Madhya Pradesh. The emission estimates are based on the total number of registered vehicles in the state, categorised by fuel type, with a detailed methodology provided in the annexure.

Among transport emissions, diesel-powered vehicles contribute the highest share of PM_{10}, $PM_{2.5}$, BC, and SO_2 emissions, accounting for approximately 69% of these pollutants. In contrast, gasoline-powered vehicles are the primary contributors to NO_x (41%), CO (74%), CH_4 (74%), and VOCS (49%), emitting more of these pollutants than both diesel and CNG vehicles. While CNG vehicles produce comparatively lower emissions overall, they still make a notable contribution to NO_2 (25%), VOCS (29%), and SO_x (18%) of the total transport sector emissions.

The spatial distribution of these emissions has been allocated based on the total road length within each grid cell, considering both highways and arterial roads, as illustrated in Figure 19. The spatial distribution of transport sector emissions across Madhya Pradesh exhibits significant variation across districts, influenced by the density of road networks, vehicle population, and fuel usage patterns. Higher emissions are observed in urbanized and industrially developed districts such as Indore, Bhopal, Gwalior, and Jabalpur, which serve as major transportation hubs with dense traffic activity and extensive road networks. These districts show elevated levels of NO_X, $PM_{2.5}$, and VOCS emissions due to high vehicular density and congestion. In contrast, rural and less urbanized districts, particularly in the eastern and southern parts of the state, exhibit comparatively lower emission levels. Districts such as Sidhi, Singrauli, and Mandla, which have relatively lower vehicle densities and limited transport infrastructure, contribute less to the overall emissions. However, localized emission hotspots are still present along major highways and arterial roads, which facilitate intercity transport and goods movement from these districts.

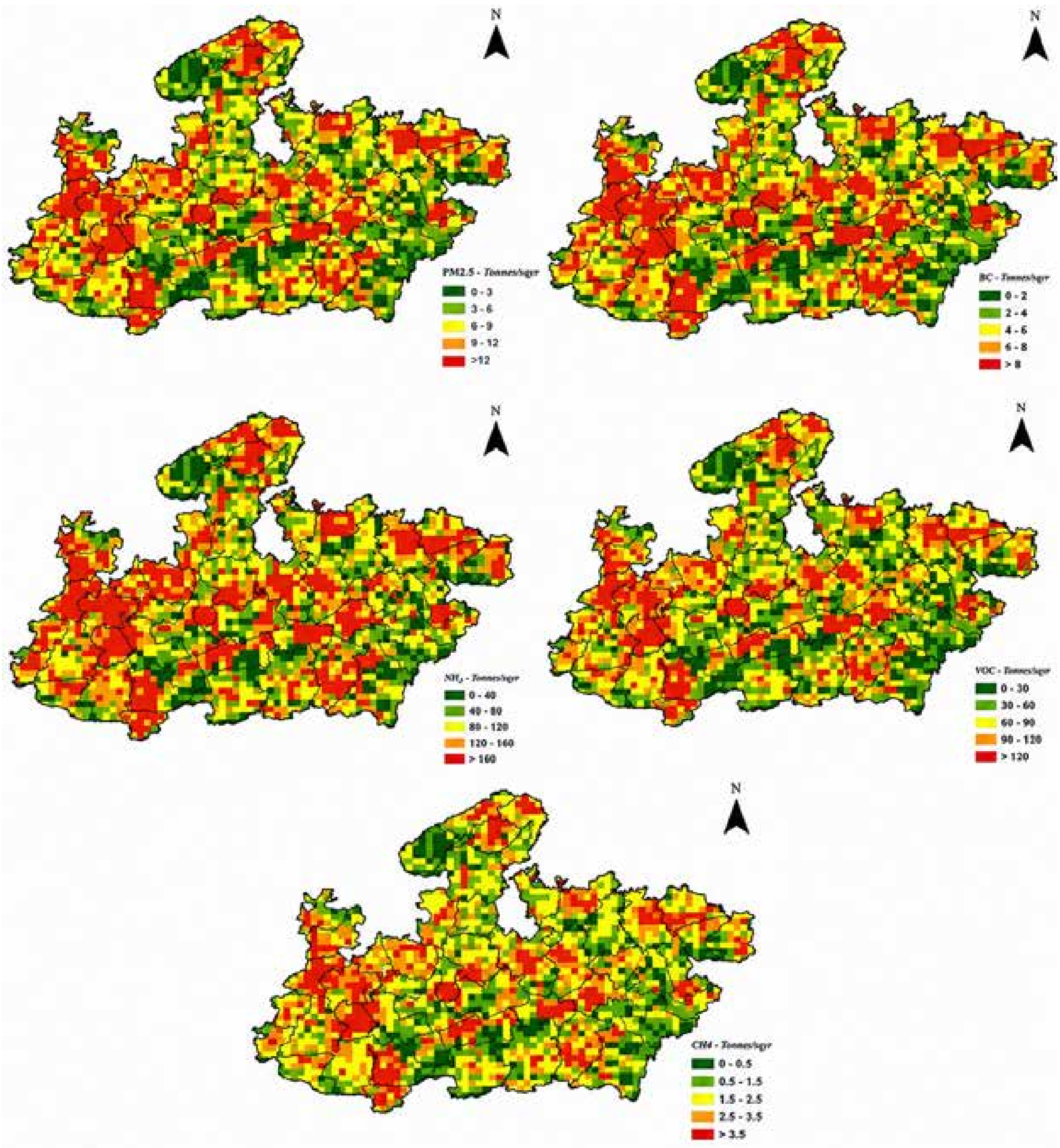


Figure 19: Spatial distribution of transport emissions for different pollutants in MP at 12×12 km grid scale

Additionally, the spatial maps indicate that diesel-powered vehicles contribute significantly to $PM_{2.5}$ and BC emissions, particularly in districts with a high share of commercial transport, including heavy-duty trucks and buses. Gasoline-powered vehicles dominate NO_X and VOC_S emissions, particularly in urban districts with a large number of two-wheelers and private cars. This district-wise analysis underscores the need for region-specific air quality mitigation strategies, with a focus on promoting cleaner fuels, improving public transport, and implementing emission control measures in high-impact zones. The detailed emission estimation methodology is provided in the annexure.

In response to these challenges, the Madhya Pradesh government has implemented several measures to promote sustainable and low-emission transportation. One of the key initiatives is the Madhya Pradesh EV Policy 2025, which aims to transform urban mobility by ensuring that 40% of new two-wheeler registrations and 70% of three-wheeler registrations are electric by the end of the policy period. To further support clean transportation state government has initiated "Inter-City Electric Bus Deployment", where the state has collaborated with private entities such as YoloBus and

Easy Green Mobility to introduce its first inter-city electric bus fleet. These buses are designed to operate with zero carbon emissions and minimal noise pollution, aligning with the state's vision for greener public transport. Additionally, significant efforts are being made to rehabilitate and upgrade major district roads, improving connectivity and reducing vehicular emissions through enhanced road conditions. These initiatives collectively contribute to the state's long-term strategy for sustainable and environmentally friendly transportation.

Madhya Pradesh's initiatives are in harmony with national efforts to enhance the environmental performance of the transport sector. The state's policies support the "Make in India" vision by encouraging local manufacturing of electric vehicles and related technologies. Additionally, the adoption of stringent vehicle emission norms and the promotion of cleaner fuels are key components of the state's strategy to mitigate transport-related pollution. Beyond policy measures, the Madhya Pradesh government is actively working to raise public awareness about the benefits of sustainable transport practices. Initiatives encourage walking, cycling, and the use of public transport, fostering an environmentally conscious society committed to reducing the carbon footprint of the transport sector.

Through these comprehensive measures, Madhya Pradesh is making significant progress toward developing a sustainable, efficient, and eco-friendly transportation system. This study provides a detailed assessment of emission projections under different scenarios, analyzing the impact of various policy interventions and technological advancements. It highlights the potential emission reductions achievable through different levels of intervention and the adoption of cleaner technologies. While these policies are well-intended and have the potential to drive significant improvements, a thorough impact assessment is essential to evaluate their effectiveness and ensure they achieve the desired outcomes. Additionally, presenting well-defined reduced-emission pathways will be crucial in guiding future strategies for mitigating air pollution and maximizing climate co-benefits in the state.

BAU Scenario of the Transport Sector in Madhya Pradesh

The transport sector plays a critical role in supporting this growth, but it also contributes significantly to air pollution and greenhouse gas emissions. The state's diverse topography, including urban centers, rural landscapes, and industrial zones, presents unique challenges in managing transport emissions. Understanding how these emissions might evolve under a BAU scenario is essential for planning sustainable transport interventions.

To project transport emissions under the BAU scenario (2019), vehicle registration growth rates from the VAHAN database and relevant data from the Ministry of Road Transport and Highways (MoRTH) have been utilized. The vehicle fleet in Madhya Pradesh is assumed to grow at an annual rate of approximately 9.79%, driven by population growth, rising incomes, and increasing urbanization. The introduction of BS-VI emission norms in 2020 is expected to reduce emissions per vehicle, but the overall increase in the number of vehicles, particularly in private and commercial sectors, will likely offset these benefits without further regulatory interventions.

Emission projections are provided for the years 2030, 2040, and 2047, considering the growth of the vehicle fleet and the adoption of BS-VI norms. These projections estimate emissions of key pollutants, which include $PM_{2.5}$, PM_{10}, NO_X, CO, CH_4, BC, SO_2, and VOCS. The BAU scenario offers insights into the future trajectory of transport emissions, serving as a baseline for developing policy measures to curb pollution and promote sustainable mobility. The projections are illustrated in Figure 20, offering a detailed look at the future emissions landscape under business-as-usual conditions.

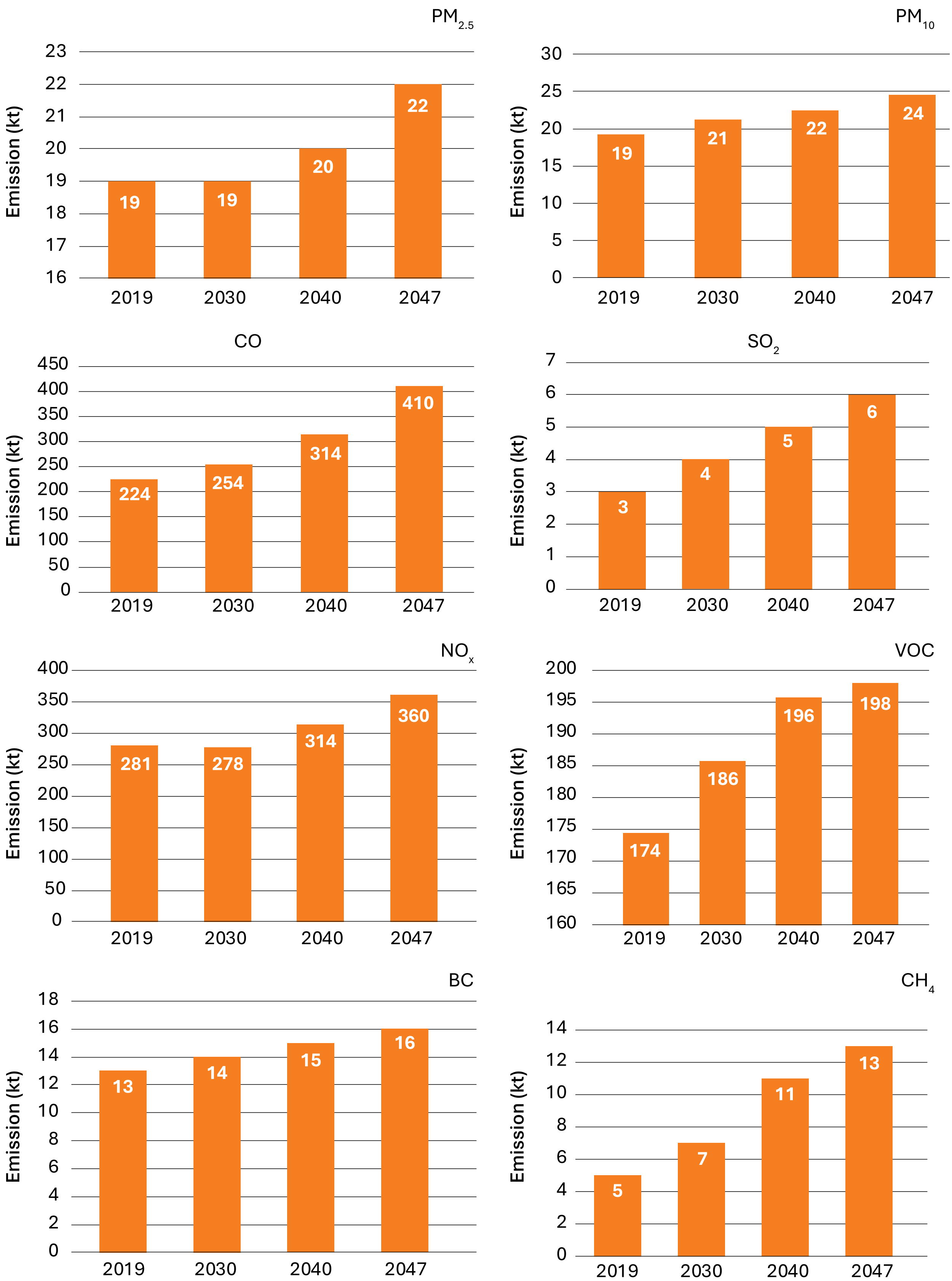


Figure 20: Emission (kt) of different pollutants from the transport sector in Madhya Pradesh during 2019, 2030, 2040 and 2047 under the BAU scenario

Under the BAU scenario, emissions from the transport sector in Madhya Pradesh are projected to rise significantly. PM_{10} emissions are expected to increase by 27%, reaching 24.4 kt in 2047, while $PM_{2.5}$ emissions are projected to grow by 19%, reaching 22.1 kt. NO_x emissions are estimated to rise by 28%, from 280.9 kt in 2019 to 359.6 kt in 2047. CO emissions are likely to witness the most significant increase of 83%, reaching 409.9 kt by 2047. CH_4 emissions are projected to surge by 165%, while BC emissions are expected to rise by 22%. SO_2 emissions are expected to more than double, increasing by 115%, and VOCS emissions are projected to rise by 14%.

Despite these increases, the implementation of BS-VI norms is expected to moderate the rate of emission growth. However, without additional policy interventions, emissions will continue to escalate. These projections underscore the need for comprehensive transport policies, including the promotion of public transport, adoption of electric vehicles, and implementation of stricter emission control measures, to mitigate the environmental impact of the transport sector in Madhya Pradesh.

Alternative Scenarios of the Transport Sector

To construct the alternative scenario, intervention analysis is performed to estimate the emissions reduction potential of different control strategies in the transport sector. Three alternate scenarios were assessed: faster adoption of electric vehicles (ALT-1), vehicle scrappage policy (ALT-2), and biodiesel blending (ALT-3). These interventions align with the existing policies of the Madhya Pradesh government and help quantify the impacts of different policy measures. A detailed description of the assumed control strategies in the sector, tested for their emission reduction potential, is provided in Table 27.

Table 27: Descriptions of the Alternative Scenarios Assessed in the Transport Sector

Scenarios	Description
ALT-1 (Faster EV Adoption)	▪ By 2030, 40% of all new two-wheeler registrations and 100% of new commercial two-wheeler fleet will be EVs. ▪ 70% of all new three-wheeler registrations (passenger and freight) will be EVs. ▪ 15% of all new four-wheeler registrations and 40% of all new bus registrations will be EVs. ▪ By 2040, 50% of all vehicle fleets will transition to EVs. ▪ By 2047, 70% of all vehicle fleets in all districts will be converted to EVs.
ALT-2 (Vehicle Scrappage Policy)	▪ By 2030, 30% of all 20-year-old petrol and 15-year-old diesel vehicles will be scrapped. ▪ By 2040, 60% of all 20-year-old petrol and 15-year-old diesel vehicles will be scrapped. ▪ By 2047, 80% of all 20-year-old petrol and 15-year-old diesel vehicles will be scrapped..
ALT-3 (Biodiesel Blending)	▪ By 2030, 5% biodiesel blending will be achieved. ▪ By 2040, biodiesel blending will be increased to 10%. ▪ By 2047, biodiesel blending will reach 20%.

The ALT-1 scenario assumes accelerated electrification across vehicle segments, including two-wheelers, three-wheelers, four-wheelers, and buses. The ALT-2 scenario involves phasing out older vehicles through a vehicle scrappage policy targeting petrol and diesel vehicles beyond their respective age limits. The ALT-3 scenario focuses on the blending of biodiesel at incremental rates, supporting the transition towards cleaner fuel alternatives.

These alternative scenarios offer significant emission reduction potential and align with national and state-level clean mobility goals. A higher penetration of electric vehicles, combined with a scrappage policy and biodiesel adoption, can accelerate the transition towards a low-emission transport sector in Madhya Pradesh.

Alternative scenario 1 (ALT1) Faster EV Adoption

(Based on Madhya Pradesh Electric Vehicle (EV) Policy, 2025)

In the ALT-1 scenario, the impact of accelerated electric vehicle adoption across Madhya Pradesh is evaluated to align with the state's commitment to sustainable transport and air pollution mitigation. The scenario envisions significant penetration of EVs across various vehicular segments, including two-wheelers, three-wheelers, four-wheelers, and buses, supported by robust policy frameworks, infrastructure development, and financial incentives.

By 2030, the scenario targets 40% of all new two-wheeler registrations as EVs, with 100% of new commercial two-wheelers as EVs. Additionally, 70% of all new three-wheeler registrations in both passenger and freight segments are expected to be electric, along with 15% of new four-wheeler registrations and 40% of new bus registrations. The transition intensifies by 2040, with 50% conversion of all types of fleets to EVs, culminating in 70% conversion of all types of fleets to EVs across all districts by 2047.

This accelerated EV adoption is projected to yield significant reductions in air pollutant emissions compared to the BAU scenario. By 2030, emissions of PM_{10} and $PM_{2.5}$ are expected to decline by 5% and 4%, respectively, while NO_X emissions are projected to reduce by 5%. CO emissions are expected to decrease by 7%, and BC emissions by 13%. Methane (CH_4) emissions are projected to reduce by 11%, with VOCS and SO_2 declining by 4% and 5%, respectively.

By 2040, the reductions are expected to become more pronounced, with PM_{10} emissions decreasing by 11%, $PM_{2.5}$ by 8%, and NO_X by 12%. CO emissions are projected to drop by 13%, CH_4 emissions by 21%, and BC emissions by 27%. VOCS emissions are estimated to decline by 7%, while SO_2 emissions will fall by 11%.

By 2047, the impact of widespread EV adoption will yield substantial emission reductions, with PM_{10} and $PM_{2.5}$ emissions projected to decline by 13% and 11%, respectively. NO_X emissions are expected to decrease by 15%, while CO emissions will drop by 16%. Methane emissions are projected to fall by 28%, BC emissions by 39%, and VOCS emissions by 9%. SO_2 emissions are expected to reduce by 15%, reflecting the significant contribution of EVs to improving air quality in Madhya Pradesh.

The ALT-1 scenario demonstrates the transformative potential of faster EV adoption in mitigating air pollution and enhancing environmental sustainability in Madhya Pradesh. The implementation of this scenario will require coordinated efforts across stakeholders, including policymakers, manufacturers, infrastructure developers, and the public.

Alternative scenario 2 (ALT-2): Vehicle Scrappage Policy

(Based on National Vehicle Scrappage Policy, 2022)

The ALT-2 scenario evaluates the impact of implementing a vehicle scrappage policy in Madhya Pradesh, which targets the removal of older, high-emission vehicles from the road. This policy aligns with the state's objectives to improve air quality and promote sustainable mobility. Under this policy, 30% of 20-year-old petrol and 15-year-old diesel vehicles are planned for scrappage by 2030, followed by 60% scrappage by 2040, and 80% scrappage by 2047.

This phased intervention is expected to yield substantial reductions in emissions compared to the BAU scenario. By 2030, the policy is projected to reduce PM_{10} emissions by 2%, $PM_{2.5}$ by 3%, NO_X by 10%, N_2O by 9%, CO by 19%, BC by 3%, SO_2 by 2%, and VOCS by 3%. The emission reduction is expected to intensify over time, with 2040 projections showing a 18% decrease in PM_{10}, 18% in $PM_{2.5}$, 9% in NO_X, 19% in N_2O, 19% in CO, 16% in CH_4, 10% in BC, 4% in SO_2, and 7% in VOCS. By 2047, the reductions are estimated to be even more pronounced, with a 25% decrease in PM_{10}, 18% in $PM_{2.5}$, 4% in NO_X, 5% in N_2O, 6% in CO, 11% in CH_4, 7% in BC, 3% in SO_2, and 9% in VOCS.

The scrappage policy not only addresses air quality improvement but also encourages the replacement of older vehicles with cleaner, more fuel-efficient alternatives, contributing to the state's long-term sustainability goals.

Alternative scenario 3 (ALT-3): Biodiesel Blending

(Based on National Policy on Biofuels, 2018)

The ALT-3 scenario evaluates the impact of biodiesel blending in the transport sector to promote cleaner fuel usage. Biodiesel, derived from renewable sources, offers a sustainable alternative to conventional diesel, aligning with environmental and air quality improvement goals. The intervention targets a gradual increase in biodiesel blending, with 5% blending by 2030, 10% by 2040, and 20% by 2047.

The introduction of biodiesel blending is expected to yield notable emission reductions. Compared to the BAU scenario, the intervention is projected to reduce PM_{10} emissions by 5% in 2030, 10% in 2040, and 20% in 2047. Similarly, $PM_{2.5}$ emissions are anticipated to decrease by 5% in 2030, 8% in 2040, and 20% in 2047. Reductions in NO_X emissions are projected to be 6% in 2030, 5% in 2040, and 9% in 2047. Additionally, N_2O emissions are expected to decrease by 6% in 2030, 7% in 2040, and 12% in 2047.

CO emissions are estimated to decline by 5% in 2030, 10% in 2040, and 12% in 2047, while CH_4 emissions are likely to reduce by 8% in 2030, 16% in 2040, and 21% in 2047. Significant reductions are also expected in BC emissions (7% in 2030, 20% in 2040, and 29% in 2047), SO_2 emissions (4% in 2030, 8% in 2040, and 11% in 2047), and VOCS emissions (3% in 2030, 5% in 2040, and 7% in 2047).

This intervention highlights the role of alternative fuels in achieving emission reduction goals and supporting sustainable transport practices.

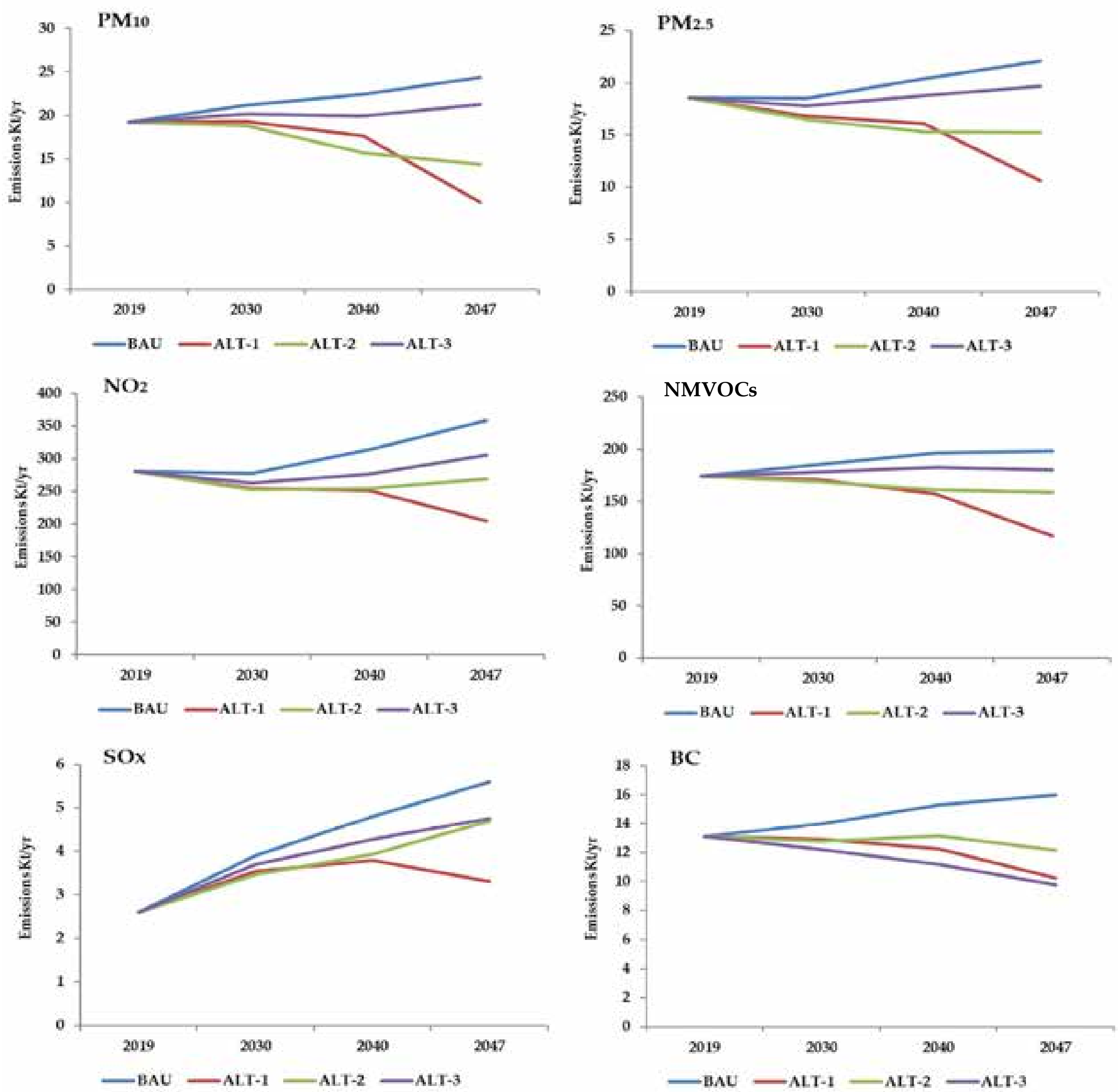


Figure 21: Emissions of $PM_{2.5}$, SO_2, NO_X, NMVOCs and BC during 2030, 2040 and 2047 from the Transport sector under BAU, ALT-1, ALT-2 and ALT-3 scenarios

Table 28: Change in Transport Emissions Under Alternate Scenarios, compared to 2047 Emissions

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: Faster EV Adoption	-52%	-41%	-43%	-76%	-41%	-36%	-80%
ALT 2: Vehicle Scrappage Policy	-31%	-16%	-25%	-44%	-20%	-24%	-58%
ALT 3: Biodiesel Blending	-11%	-15%	-15%	-16%	-9%	-39%	-28%

Key Insights from the Transport Sector Analysis

The transport sector in Madhya Pradesh is a major contributor to air pollution, accounting for approximately 35% of the state's BC emissions, 45% of NO_X, and 37% of NMVOCs as of 2019. These emissions vary based on the type of fuel used. Diesel-powered vehicles are the dominant source of BC, contributing around 69% of the transport sector's BC emissions. In contrast, NO_X emissions are largely from gasoline and CNG vehicles, contributing 41% and 25%, respectively. Similarly, 49% of NMVOCs emissions are from gasoline-powered vehicles, followed by 29% from

CNG-powered ones. Emissions from the transport sector are projected to rise considerably under the BAU scenario by 2047. NO_X emissions are expected to increase by 28%, continuing to make transport one of the largest sectoral contributors. CH_4 emissions are projected to increase by 165%, BC by 22%, NMVOCs by 14%, and SO_2 emissions could more than double, rising by 115%. While BS-VI vehicle standards will help mitigate some of this growth, their impact alone will be insufficient without additional targeted interventions.

To address this, three alternative policy scenarios were evaluated. The first, ALT1, promotes the adoption of EVs, in alignment with the national PM E-DRIVE policy. This scenario is particularly effective in reducing NO_X and NMVOCs emissions in urban areas, where gasoline and CNG vehicles are most prevalent. The second, ALT2, focuses on implementing a vehicle scrappage policy, accelerating the retirement of older, high-emitting vehicles and encouraging adoption of cleaner, fuel-efficient fleets. This policy supports broad-based emission reductions across all vehicle types. The third scenario, ALT3, targets diesel-related emissions through improvements in diesel fuel standards and quality. Given that diesel vehicles dominate freight movement across the state, particularly on national highways, this scenario addresses BC and PM emissions from both intra- and inter-state transport. Under ALT3, BC emissions could be reduced by nearly 29% by 2047 compared to the BAU scenario.

Given the emission trends and spatial patterns observed, it is recommended that the government pursue statewide implementation of all three mitigation strategies—electric vehicle (EV) adoption, vehicle scrappage, and cleaner diesel interventions. However, the deployment should be tailored to district-specific emission profiles and the institutional capacity to implement and sustain interventions. Effective implementation in Madhya Pradesh will require overcoming several critical challenges. For ALT1 (EV adoption), key constraints include the limited availability of public charging infrastructure, particularly in tier-2 and tier-3 cities, and the high upfront cost of EVs, which remains a barrier even with existing subsidies. To address these, the state must invest in the expansion of a reliable EV charging network, comprising fast-charging corridors along highways and strategically placed urban charging stations. Furthermore, targeted financial incentives and accessible financing schemes—especially commercial fleets—will be essential to drive market uptake. ALT2 (vehicle scrappage policy) may face resistance due to low public awareness, weak enforcement mechanisms, and the lack of formal scrappage infrastructure in many districts. The establishment of regionally distributed, authorized scrappage facilities, combined with streamlined incentive structures directly linked to the purchase of newer, cleaner vehicles, will be crucial. Incorporating scrappage verification into vehicle registration and periodic inspection systems will strengthen compliance and traceability.

District-level prioritization is essential. Urban centers such as Bhopal, Indore, Gwalior, and Jabalpur, where gasoline and CNG vehicle usage is high, should focus on EV deployment and scrappage policy implementation, supported by robust infrastructure and enforcement. Conversely, districts with high freight density and significant diesel consumption—such as Dewas, Dhar, Katni, and Rewa—should prioritize cleaner diesel strategies under ALT3, which addresses emissions from heavy-duty vehicles operating within and across state borders. ALT3 presents unique implementation challenges, particularly regarding the control of diesel fuel quality and enforcement. These efforts require close coordination with fuel suppliers, as well as mechanisms to monitor compliance among long-haul freight operators. The state can leverage its regulatory authority to encourage the adoption of cleaner diesel alternatives, such as high-cetane or B6/B7 biodiesel blends, and promote retrofitting of particulate filters in legacy fleets. Enhanced surveillance through real-time vehicle monitoring at toll plazas and logistics hubs can further improve enforcement efficiency.

Moreover, capacity constraints at the municipal level—especially in smaller urban areas—may limit the pace and scale of rollout. Strengthening institutional capacity through targeted training, integrating air quality and emission mitigation goals into state transport and urban planning frameworks, and leveraging public-private partnerships will be essential to ensure sustained and technically robust implementation across Madhya Pradesh.

Industry and Mining

Madhya Pradesh, one of India's most industrially diverse states, has a well-established manufacturing sector that significantly contributes to its economic growth. The industrial landscape of the state is characterized by a wide array of sectors, including textiles, chemicals, food processing, leather, engineering, automobiles, electronics and mining. However, while these industries drive economic progress, they are also major sources of greenhouse gas (GHG) and air pollutant emissions, presenting serious environmental and public health concerns.

The state hosts over 16.50 lakh registered micro, small, and medium enterprises (MSMEs), making it the seventh-largest hub for MSMEs in India. These enterprises constitute approximately 6.4% of the total MSMEs in the country and have been developed with a cumulative investment exceeding Rs 53,000 crore.[62] The MSME sector alone employs more than 86 lakh individuals, playing a critical role in Madhya Pradesh's economic landscape. In addition to MSMEs, large-scale industries such as pharmaceutical and medical device manufacturing, food processing, textiles, cement factories, ready-mix concrete plants, and an increasing number of automobile and electronics manufacturers further strengthen the industrial base of the state.

Despite its economic benefits, the rapid industrialization of Madhya Pradesh has led to significant environmental challenges, particularly in terms of air quality degradation. The heavy reliance on coal combustion for industrial energy needs has resulted in the emission of pollutants such as PM_{10}, $PM_{2.5}$, SO_2, NO_x, and SLCPs like CH_4 and BC. These emissions not only contribute to regional air pollution but also exacerbate climate change and pose severe health risks to the population.

One of the primary sources of industrial emissions in Madhya Pradesh is the combustion of fossil fuels in boilers and furnaces during manufacturing processes. These emissions, which include various air pollutants, are discharged into the atmosphere through industrial stacks after passing through Air Pollution Control Devices (APCDs). In recognition of the environmental impact of industrial pollution, the Central Pollution Control Board (CPCB) classifies industries into Red (highly polluting), Orange (moderately polluting), and Green (non-polluting) categories based on their emission levels. Furthermore, industries are categorized into small, medium, and large-scale enterprises according to their operational capacity. For emission estimation in this study, only industries classified under the red and orange categories have been considered.

According to data from the Madhya Pradesh Pollution Control Board (MPPCB), the state is home to 3,269 air-polluting industries. To accurately quantify emissions from these industries, a methodology based on fuel consumption activity data, fuel type, and the efficiency of APCDs installed has been adopted.

The manufacturing industries in Madhya Pradesh exhibit a distinct fuel consumption pattern, with coal being the predominant energy source, accounting for approximately 50% of the total fuel usage. This heavy reliance on coal significantly contributes to air pollution and greenhouse gas emissions. Biomass constitutes around 39%, reflecting some level of renewable energy adoption, though its share remains much lower than coal. Liquid fuels such as furnace oil, Light Diesel Oil (LDO), and diesel together account for 0.016%, primarily used in specific industrial operations. Petroleum coke (pet coke) contributes 7%, and while its usage is relatively lower, its high carbon intensity makes it a significant pollutant. Other fuels, including natural gas and alternative fuels (LPG, Charcoal), make up the remaining 3.49%. This distribution highlights the urgent need for cleaner energy alternatives and improved fuel efficiency in Madhya Pradesh's industrial sector to mitigate environmental and health impacts.

The spatial distribution of industrial emissions in Madhya Pradesh (Figure 22) highlights a hotspot of emission areas within the state in specific urban-industrial and mining districts. Indore emerges as the dominant emitter, contributing over 20% of PM, 12% of BC, and more than 10% of CH_4 and

NMVOCs of the total industrial emissions in the state due to the presence of numerous small- and medium-scale industries using high-emission fuels. Dewas follows, with around 14% of PM and 13% of SO_2 and NO_X emissions. Sagar, Dhar, Barwani, and Raisen are also key hotspots. Sagar contributes over 15% of PM and 13% of SO_2 and NO_X. Dhar and Barwani register 8–10% of PM and BC, while Raisen shows high SO_2 (15.2%) and NO_X (11.3%) of the total industrial emissions of the state, largely from coal and biomass-based units. CH_4 emissions are notably high in mining districts, with Singrauli alone accounting for 28.8%, followed by Dhar (10.7%) and Raisen (9.4%). Gwalior, Jabalpur, and Barwani also show elevated BC and NMVOCs emissions, reflecting reliance on coal, biomass, and petcoke in industrial processes. These spatial trends indicate the need for targeted interventions in high-emission districts through fuel substitution, improved emission controls, and technology upgrades.

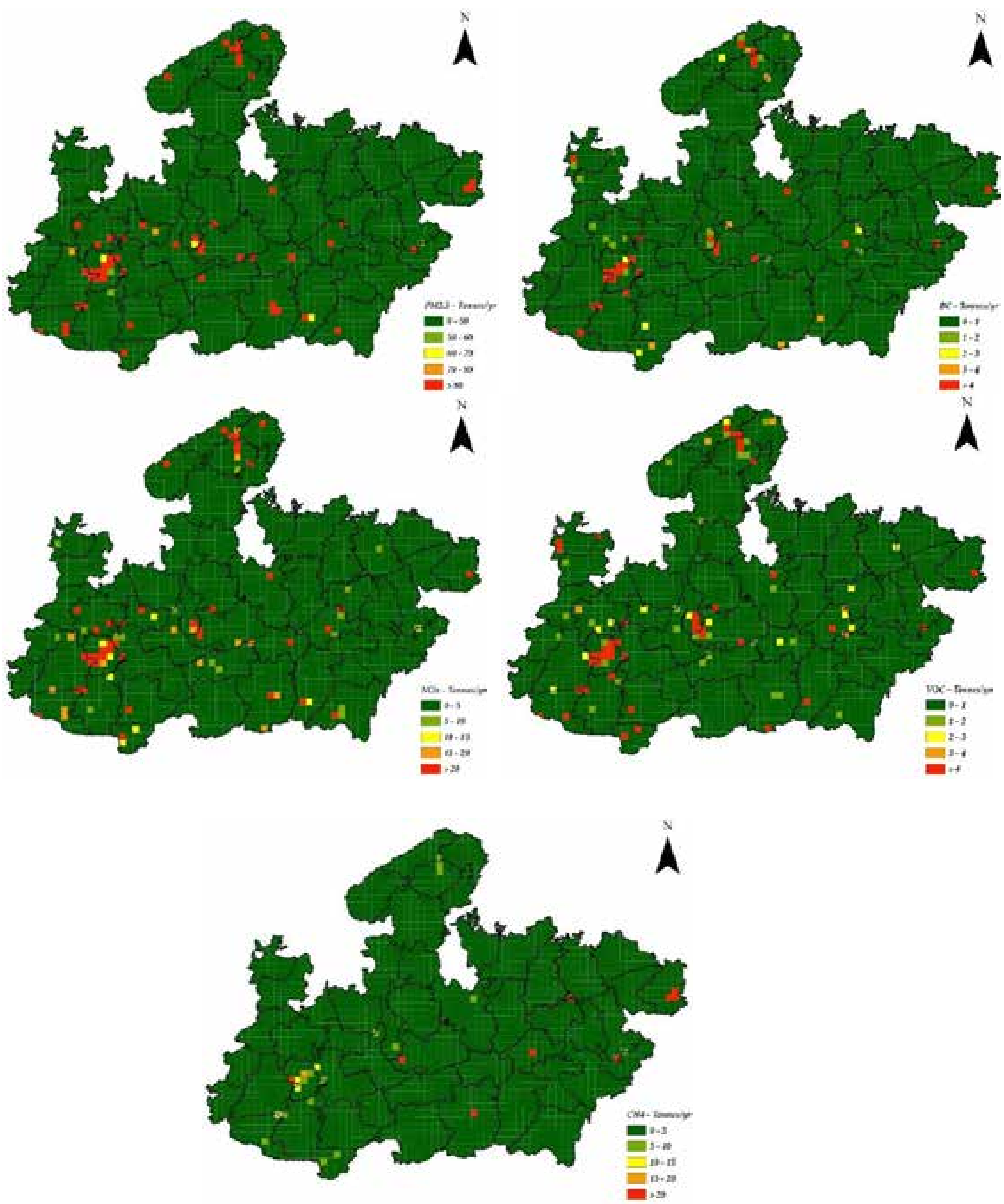


Figure 22: Spatial distribution of Industry sector emissions for different pollutants in MP at 12×12 km grid scale

By systematically assessing industrial emissions, this study aims to provide insights into the air pollution challenges in Madhya Pradesh and support the development of effective air quality mitigation strategies. In the following section, the BAU and ALT scenarios for industrial combustion and coal mining emissions have been estimated separately. This distinction is essential due to the fundamental differences in emission sources, mitigation strategies, regulatory frameworks, and environmental impacts associated with these two sectors. Industrial combustion emissions primarily originate from the burning of fossil fuels such as coal, oil, and gas in manufacturing processes, power generation, and other industrial activities. These processes release a mix of GHGs and air pollutants. In contrast, emissions from coal mining are dominated by CH_4 released during the extraction process, especially from underground mines, along with fugitive dust and minor amounts of other pollutants. By assessing these emission sources separately under the BAU and ALT scenarios, the analysis ensures a more targeted evaluation of mitigation strategies, helping to design sector-specific interventions that effectively reduce emissions and improve air quality while addressing climate commitments.

BAU Scenario of the Industry Sector in Madhya Pradesh

A Business-as-Usual (BAU) scenario for emissions from the industrial sector has been projected for the years 2030, 2040, and 2047, based on growth rates derived from literature reviews. The projected industrial sector growth rate of 5.22% is based on the Gross Domestic Product (GDP) growth of the industrial sector in 2019, as reported in the RBI Handbook for Madhya Pradesh (2022-2023). Additionally, an annual production growth rate of 6.6% was determined from historical coal production data spanning the past 13 years. The BAU scenario assumes that existing trends in industrial activity and emissions will persist until 2047 in the absence of significant policy interventions or technological advancements.

Using these growth rates, emission projections were developed for the years 2019, 2030, 2040, and 2047, as presented in Figure 23. Under the BAU scenario, emissions from the industrial sector and mining activities are expected to increase at a Compound Annual Growth Rate (CAGR) of 5% and 7%, respectively. By 2047, industrial emissions of PM_{10}, $PM_{2.5}$, SO_2, NO_x, NMVOCs, BC, and CH_4 are projected to be four times higher than their levels in 2019. Similarly, emissions from the mining sector, particularly PM_{10}, $PM_{2.5}$, and CH_4, are estimated to be six times higher than their 2019 levels. These projections underscore the need for stringent emission control strategies and cleaner technological interventions to mitigate future air quality impacts.

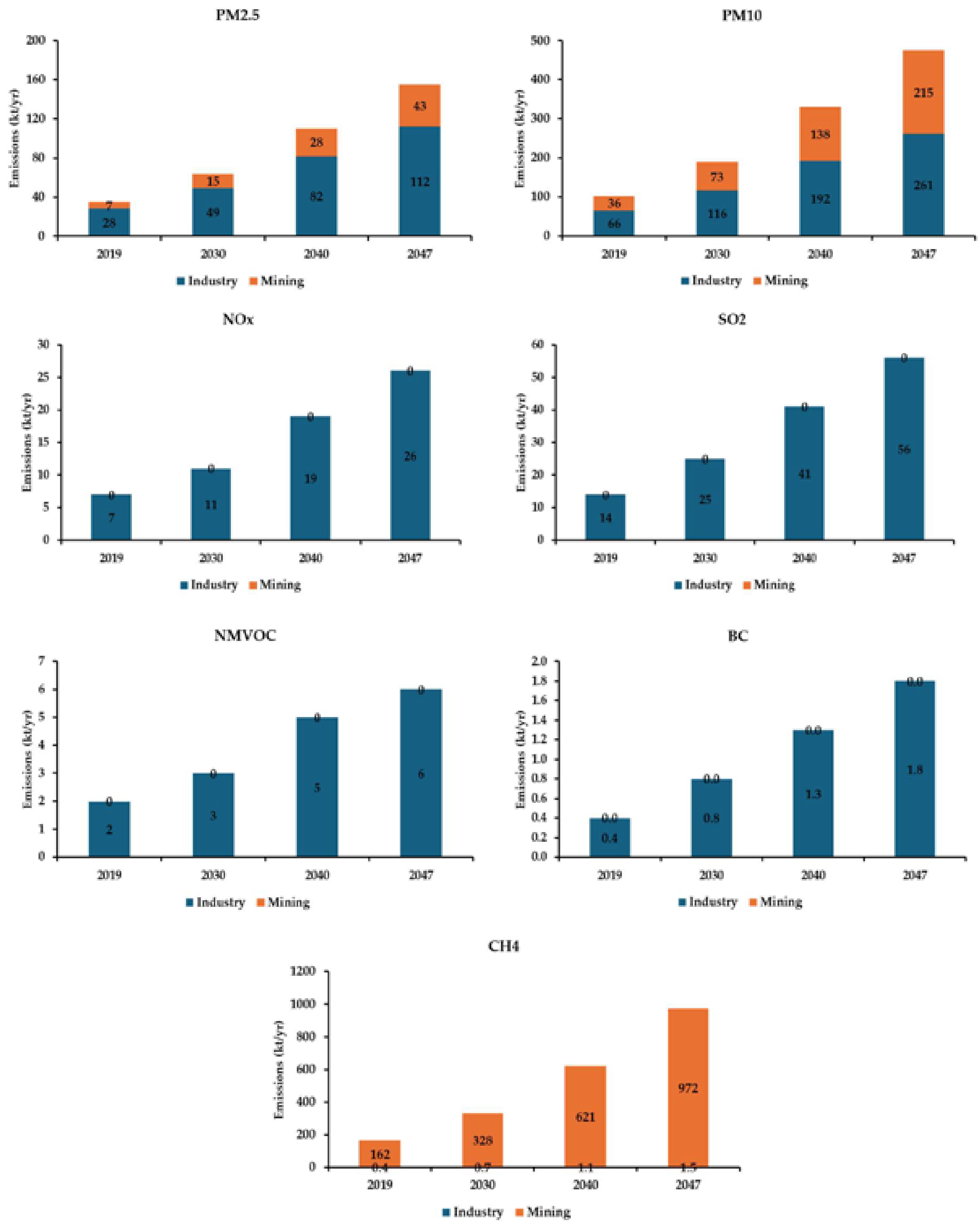


Figure 23: Emissions of PM_{10}, $PM_{2.5}$, SO_2, NO_X, NMVOCs, BC and CH_4 from the industrial combustion and mining sector during 2019, 2030, 2040, and 2047 under the BAU scenario

Alternative Scenarios of the Industrial Combustion Sector

This sector is a significant contributor to air pollution and greenhouse gas emissions, making targeted interventions critical for achieving cleaner and more sustainable operations. The analysis considers a range of strategies, including transitioning to cleaner fuels and enhancing technology adoption, particularly Air Pollution Control Devices (APCDs). In the industrial sector, four key measures are explored: the gradual transition from solid fuels like coal, charcoal, wood and pet coke to natural gas (ALT-1), the adoption of community boilers to optimise fuel use (ALT-2), introduction of green hydrogen as a fuel source by 2040 (ALT-3) and the introduction of coal washeries for coal beneficiation to reduce PM and BC emissions (ALT-4).

These interventions aim to significantly reduce emissions, enhance energy efficiency, and support Madhya Pradesh's transition to a low-carbon economy. A detailed description of the assumed control strategies in the sector, tested for their emission reduction potential, is provided in Table 29. The following section delves into the detailed analysis of emissions trends and the projected impact of these strategies under the ALT Scenario.

Table 29: Descriptions of the Alternative Scenarios Assessed in the Industry Sector

Scenarios	Assumption
ALT-1	▪ The transition of Coal, Wood, charcoal and petcoke to Natural Gas is assumed to reach 25%, 50% and 100% in industries by 2030, 2040 and 2047, respectively.
ALT-2	▪ Implementation of community boilers and fuel consumption is expected to decrease by 30% for the years 2030, 2040 and 2047.
ALT-3	▪ The introduction of Green Hydrogen is assumed to reach 5% and 8% in industries by 2040 and 2047, respectively.
ALT-4	▪ Reduction in ash content and sulphur content by 40% and 30% respectively, by using washed coal. This is assumed to reach 25%, 50% and 70% by 2030, 2040 and 2047, respectively.

Alternative scenario 1 (ALT-1): Transition to cleaner fuel

(Based on NCAP Industrial Emission Guidelines (MoEFCC))

In ALT1 Scenario, the transition from solid fuels (coal, wood, charcoal and pet coke) to natural gas as a fuel for combustion in industrial boilers is evaluated. This shift offers several significant benefits. Natural gas combustion leads to lower emissions of PM, SO_2, and NO_x, thereby improving air quality. However, it is important to note that natural gas, while generally cleaner than coal in terms of conventional pollutants, has a higher methane (CH_4) emission potential due to its composition. Methane is a potent short-lived climate pollutant, and leaks during extraction, transport, and combustion can offset some of the climate benefits typically associated with natural gas use (Howarth et al., 2011) .

The transition also enhances combustion efficiency due to the higher energy content of natural gas, leading to better heat generation and reduced maintenance requirements compared to coal. Furthermore, natural gas boilers require less water for cooling, which is particularly advantageous in water-scarce regions. This shift supports industries in meeting stringent environmental regulations while reducing the need for costly pollution control measures. Natural gas boilers offer greater operational flexibility with faster start-up times and more efficient emission control, enabling industries to adjust to changing demands quickly. Additionally, natural gas combustion produces minimal solid waste, reducing the environmental impact associated with ash disposal. By 2047, transitioning from solid fuels to natural gas is expected to result in substantial emission reductions compared to the BAU scenario for the same year. Specifically, emissions of PM_{10}, $PM_{2.5}$, SO_2, NO_2, NMVOCs, BC and CH_4 are projected to decrease by 95%, 92%, 89%, 85%, 29%, 29% and 22%, respectively.

Alternative scenario 2 (ALT-2): Community Boilers

(Based on CPCB Guidelines on Community Boilers, 2024)

In the ALT2 scenario, the adoption of community boilers is proposed as a centralized solution for supplying steam or heat to multiple industrial units within a designated cluster. This approach offers several advantages over individual boiler systems by optimizing fuel usage, reducing operational and maintenance costs, and minimizing system downtime. The centralization of boiler operations enhances fuel efficiency and facilitates more effective emission monitoring and control, leading to improved environmental outcomes. Additionally, the implementation of community boilers is expected to significantly reduce overall coal consumption within industrial clusters. The replacement of individual boilers with community boilers is projected to reduce fuel consumption by 30%. As a result, by 2047, emissions in the ALT2 scenario are estimated to decrease relative to the Business-as-Usual (BAU) scenario for the same year, with reductions of 11% for PM_{10}, $PM_{2.5}$, and SO_2, 10% for NO_x, and 3% for NMVOCs, BC, and CH_4. These reductions highlight the potential of community boilers as an effective mitigation strategy to enhance industrial energy efficiency and lower environmental impacts.

Alternative scenario 3 (ALT-3): Impact of Green Hydrogen

(Based on MP Renewable Energy Policy, 2022)

In the ALT3 scenario, the integration of green hydrogen as an industrial fuel is assessed. Produced via electrolysis using renewable energy sources such as wind, solar, and hydropower, green hydrogen offers a cleaner alternative to conventional fuels. This scenario projects that green hydrogen will replace 5% of existing industrial fuels by 2040 and 8% by 2047. By 2047, this transition is expected to result in an 8% reduction in PM_{10}, $PM_{2.5}$, SO_2, NO_2, NMVOCs, BC, and CH_4 emissions compared to the BAU scenario, highlighting its potential for industrial decarbonization and air quality improvement.

Alternative scenario 4 (ALT-4): Coal beneficiation

(Based on MoEFCC Coal Ash Standards)

In the ALT4 scenario, the implementation of coal beneficiation is assessed as a strategy to reduce emissions from industrial coal use. Coal beneficiation improves fuel quality by reducing impurities, leading to cleaner combustion and lower pollutant emissions. This scenario assumes a 25% adoption by 2030, 50% by 2040, and full implementation by 2047. As a result, by 2047, emissions are projected to decrease by 27% for PM_{10}, 25% for $PM_{2.5}$, 21% for SO_2, 21% for NO_2, 7% for NMVOCs, 7% for BC, and 2% for CH_4 compared to the BAU scenario, underscoring its effectiveness in mitigating industrial air pollution.

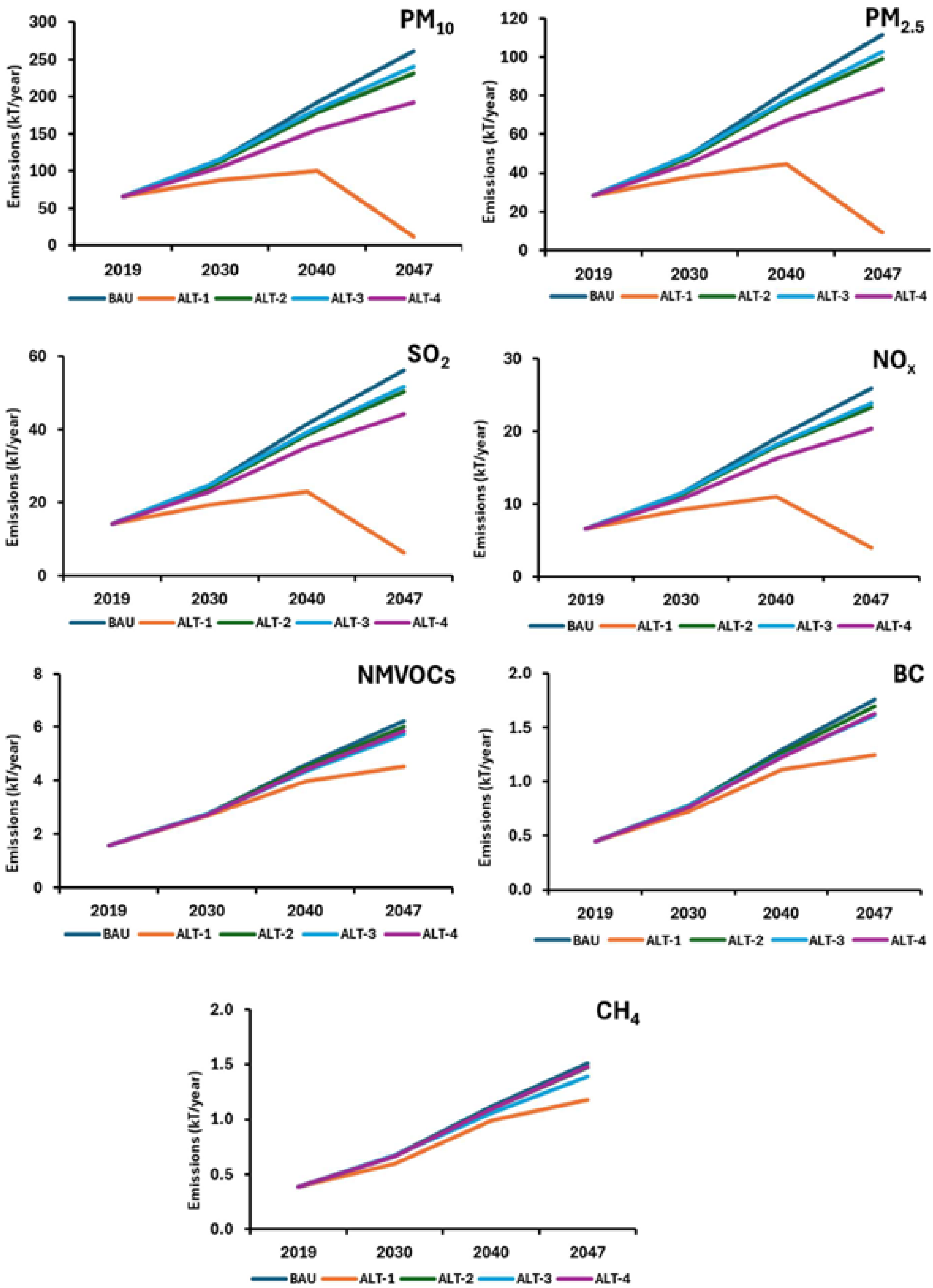


Figure 24: Emissions of PM_{10}, $PM_{2.5}$, SO_2, NO_X, NMVOCs, BC and CH_4 during 2019, 2030, 2040 and 2047 from the Industry Sector under ALT scenarios

Table 30: Change in Industry Emissions Under Alternate Scenarios, Compared to 2047

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: Transition to cleaner fuel	-92%	-89%	-85%	-21%	-29%	-29%	-22%
ALT 2: Community Boilers	-11%	-11%	-10%	-3%	-3%	-3%	-3%
ALT 3: Impact of Green Hydrogen	-8%	-8%	-8%	-8%	-8%	-8%	-8%
ALT 4: Coal beneficiation	-25%	-21%	-21%	0%	-7%	-7%	-2%

Alternative Scenarios of the Mining Sector

Several mitigation measures have been evaluated to reduce PM emissions from mining activities. These interventions aim to control dust generation at various stages of the mining process. The projected emission reductions strategies for PM_{10} and $PM_{2.5}$ under different ALT scenarios are outlined in Table 31.

Table 31: Descriptions of the Alternative Scenarios Assessed in the Mining Sector

Scenarios	Assumption
ALT-1	▪ The sprinkling of water at every stage including loading and unloading of overburden and coal reduces the emission by 75%, and transport of coal and overburden reduces the emission by 70%. These assumptions are based on TERI's past experience and discussions with different stakeholders.
ALT-2	▪ Reducing the drop height during loading and unloading can reduce the emissions by 70%. These assumptions are based on TERI's experience and discussions with different stakeholders.
ALT-3	▪ Paving of roads can reduce the emissions by 80%. These assumptions are based on TERI's experience and discussions with different stakeholders.
ALT-4	▪ Best management practices reduce the emissions by 60%. These assumptions are based on TERI's experience and discussions with different stakeholders.

Alternative scenario 1 (ALT-1): Water sprinkling

(Based on Stakeholder Consultation)

The implementation of water sprinkling at every stage of the mining process, including the loading and unloading of overburden and coal, is expected to reduce PM_{10} and $PM_{2.5}$ emissions by 74% by 2047 compared to the BAU scenario. This measure helps suppress airborne dust, significantly improving air quality in mining regions.

Alternative scenario 2 (ALT-2): Reducing the drop

(Based on Stakeholder Consultation)

Reducing the drop during loading and unloading operations minimizes dust dispersion. By 2047, this measure is projected to lower PM_{10} and $PM_{2.5}$ emissions by 25% compared to the BAU scenario, making it a cost-effective dust control strategy.

Alternative scenario 3 (ALT-3): Paved Roads

(Based on Stakeholder Consultation)

The paving of roads within mining sites helps in reducing dust resuspension caused by vehicular movement. This intervention is estimated to reduce PM_{10} and $PM_{2.5}$ emissions by 19% by 2047 compared to the BAU scenario, highlighting the importance of infrastructure improvements in dust control.

Alternative scenario 4 (ALT-4): Process Optimisation

(Based on Stakeholder Consultation)

The adoption of best management practices (BMPs) in mining operations aims to minimize dust emissions through a combination of process optimization and structural interventions. Key measures include:

01. Improving coal crushing and screening to reduce fine dust generation.
02. Encouraging covered coal transport to prevent fugitive dust emissions during transit.
03. Optimizing coal stockpile management to minimize wind erosion.
04. Implementing vegetative cover and erosion control on overburden dumps to stabilize loose material.
05. Installing wind barriers in active mining areas to reduce dust dispersion.

By 2047, the implementation of these BMPs is projected to reduce PM_{10} and $PM_{2.5}$ emissions by 60% compared to the BAU scenario, highlighting the effectiveness of integrated dust control strategies in mining operations.

These mitigation scenarios emphasize the potential for targeted interventions in the mining sector to significantly reduce dust emissions, contributing to improved air quality and reduced environmental impact.

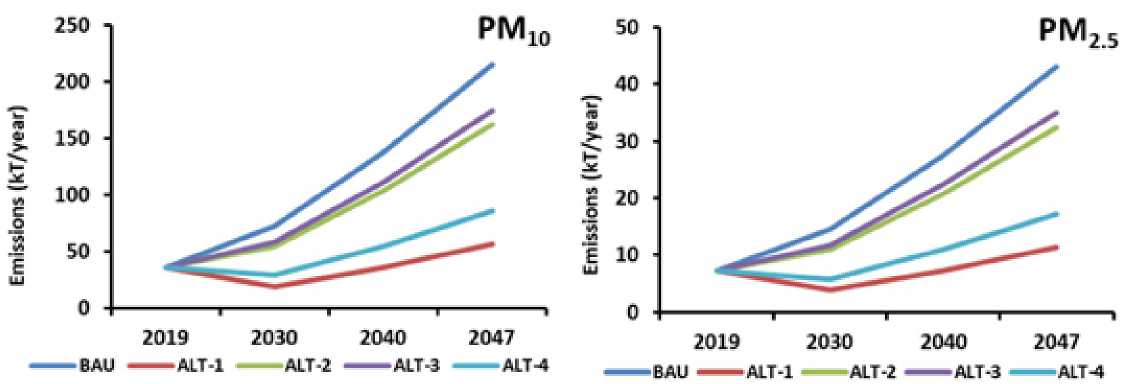


Figure 25: Emissions of PM_{10} and $PM_{2.5}$ during 2019, 2030, 2040 and 2047 from the Mining Sector under ALT scenarios

Table 32: Change in Mining Emissions Under Alternate Scenarios, Compared to 2047

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: Water sprinkling	-74%	-	-	-	-	-	-
ALT 2: Reducing the drop	-25%	-	-	-	-	-	-
ALT 3: Paved Roads	-19%	-	-	-	-	-	-
ALT 4: Process Optimisation	-60%	-	-	-	-	-	-

Key Insights from the Industry and Mining Sector Analysis

The industrial sector in Madhya Pradesh, encompassing manufacturing units and mining operations, was responsible for a moderate yet significant share of the state's emissions in 2019—contributing approximately 16% of PM_{10}, 11% of $PM_{2.5}$, 1% of BC, 3% of SO_2, 1% of NO_x, and 14% of CH_4. These estimates are based on fuel consumption patterns and coal production data, reflecting both combustion-related and fugitive emissions.

District-level analysis reveals a starkly localized nature of these emissions, with certain urban-industrial and mining-heavy districts contributing disproportionately. Indore emerged as the highest emitter across almost all pollutants, contributing over 20% and 12% of the industrial PM and BC emissions, and more than 10% of CH_4 and NMVOCs. Dewas closely follows, contributing approximately 14% of PM_{10} and $PM_{2.5}$ emissions and notable shares of SO_2 (13.2%) and NO_x (12.9%). Sagar also records high levels of PM and gaseous pollutants, with 16.4% of PM_{10}, 15.7% of $PM_{2.5}$, and over 13% of SO_2 and NO_x, driven by localized industrial activity.

Other prominent emission hotspots include Dhar, Barwani, and Raisen. Dhar contributes around 8.4% of particulate emissions and nearly 9% of SO_2 and NO_x, along with 10% of BC. Barwani registers a similar pattern, with over 8.9% of PM, approximately 7% of SO_2 and NO_x, and 10.3% of BC emissions. Raisen is a significant source of SO_2 and NO_x, contributing 15.2% and 11.3%, respectively, primarily due to coal and biomass-based industries.

Methane emissions are especially concentrated in mining regions. Singrauli alone accounts for 28.8% of methane emissions from the industrial sector, largely attributed to coal mining activities. High methane contributions are also observed in Dhar (10.7%) and Raisen (9.4%) due to the presence of natural gas and biomass-based industries.

Further, districts such as Gwalior, Jabalpur, Indore, and Barwani are key sources of black carbon and NMVOCs. Gwalior contributes 11.6% of black carbon and 5.6% of NMVOCs, while Jabalpur accounts for nearly 11% and 13.1%, respectively. These emissions are closely linked to the widespread use of biomass in small- and medium-scale manufacturing units, particularly those lacking emission abatement systems.

Looking forward, four alternative scenarios (ALT1–ALT4) propose a transformative pathway for reducing industrial emissions in Madhya Pradesh. ALT1 assumes a progressive transition from solid fuels (coal, wood, petcoke, charcoal) to natural gas, reaching 100% by 2047. This shift is expected to significantly reduce PM, SO_2, and BC emissions, particularly in districts like Indore, Dewas, and Dhar. ALT2, which focuses on the implementation of community boilers, aims to reduce coal consumption by 30% across the timeline, targeting smaller units with dispersed operations—this is particularly relevant for Indore, Dewas, and Sagar.

ALT3 introduces green hydrogen as an industrial fuel, reaching 5% penetration by 2040 and 8% by 2047, offering promising climate co-benefits by reducing CH_4 emissions. This will especially benefit methane-heavy districts such as Raisen and Dhar. Lastly, ALT4 targets a reduction in ash and sulfur content using washed coal, phased in to reach 70% coverage by 2047. This measure is expected to substantially reduce PM and SO_2 emissions in coal-reliant districts like Indore, Dewas, and Sagar.

Together, these targeted interventions underscore the need for decentralised and sector-specific emission control strategies. While the industrial sector may not be the largest emitter in Madhya Pradesh, its concentrated emission hotspots and proximity to urban populations make it a priority area for integrated air quality and climate mitigation planning.

Power

Similar to the rest of the nation, Madhya Pradesh is also witnessing a significant year-on-year increase in electricity demand, with projections indicating a Compound Annual Growth Rate (CAGR) of 8.14% from 2021 to 2030 and 5.83% from 2030 to 2047, according to TERI report, Low Carbon Pathways for Madhya Pradesh. This increasing demand highlights the critical role of conventional thermal power plants in ensuring a reliable and consistent energy supply across the state. Among the 21 thermal power plants operating in Madhya Pradesh, including captive units, coal-based TPPs remain the primary source of electricity generation. In 2019, 81.7% of the state's power generation came from coal-based TPPs, though this share decreased to 62.5% by 2023, as per CEA data, due to policy shifts and the growing emphasis on renewable energy.

Coal-based TPPs play a crucial role in managing the state's energy requirements, providing baseload power to meet the increasing consumption. However, these plants significantly contribute to environmental pollution and contribute to air pollution with a notable share. Emissions from coal combustion release large quantities of PM, SO_2, NO_x, and other pollutants, including black carbon and methane, which adversely affect air quality, climate and public health. The state's reliance on domestic coal has increased since 2022, following a policy decision to cease the use of imported coal to reduce external dependencies.

To mitigate the environmental impact of coal-based TPPs, Madhya Pradesh has implemented several policy measures and technological interventions. As part of it, the state mandates the blending of biomass with coal in thermal power generation. In 2024, a 5% biomass blending requirement was introduced, with plans to increase this proportion to 7% by 2025. This initiative aims to reduce carbon emissions, improve agriculture residue management, and enhance energy sustainability. Furthermore, two major power plants in Madhya Pradesh have installed Flue Gas Desulfurization (FGD) systems to curb sulfur dioxide emissions, aligning with national emission norms set by the Ministry of Environment, Forest and Climate Change (MoEF&CC).

Madhya Pradesh is also actively promoting renewable energy as a sustainable alternative to conventional coal-based power. The state aims to generate 50% of its electricity from renewable sources by 2030, reducing its reliance on fossil fuels and lowering emissions.

Emissions from coal-based thermal power plants are estimated based on the amount of coal consumed in the year 2019. Coal consumption serves as the activity data, while emission factors for coal combustion in thermal power plants (TPPs) are applied to calculate emissions. Coal consumption data for 2019 were obtained from the Central Electricity Authority (CEA) for each power plant. Additional information, including ash content, sulfur content, and details on air pollution control devices (APCDs), was obtained from the CEA database and reports from Madhya Pradesh Power Generating Co. Ltd. The detailed methodology followed for emissions estimation has been provided in Annexure.

Captive power plants have been considered part of the power sector because many are connected to the grid and supply a significant amount of power to the state. This integration makes their emissions a crucial component in estimating total emissions from the power sector. In this analysis, emissions are categorized from industrial captive thermal power plants (ICPPs) and utility-scale thermal power plants (USTPPs). In Madhya Pradesh, combined emissions from ICTPPs and USTPPs are 23.46 kt of PM_{10}, 357.73 kt of SO_2, and 1.13 kt of BC annually.

Among USTPPs, Vindhyachal STPP (3.85 kt) and Gadarwara STPP (3.07 kt) emitted the highest PM_{10}, while Gadarwara STPP (58.48 kt) and M.B. Power Ltd (50.29 kt) released the most SO_2. Although ICPPs emit lower amounts individually, their combined emission 0.11 kt of BC—are non-negligible, with Hindalco Industries (0.02 kt) as the largest contributor. Other pollutants, including NO_x, CO, NMVOCs, and CH_4, also contribute significantly to the state’s emissions from thermal power plants. The spatial allocation of emissions illustrated in Figure 26 has been done based on the exact latitude longitude of the power plant falling in the 12×12 km grid. Further, power plant wise emissions for 2019 have been provided in annexure.

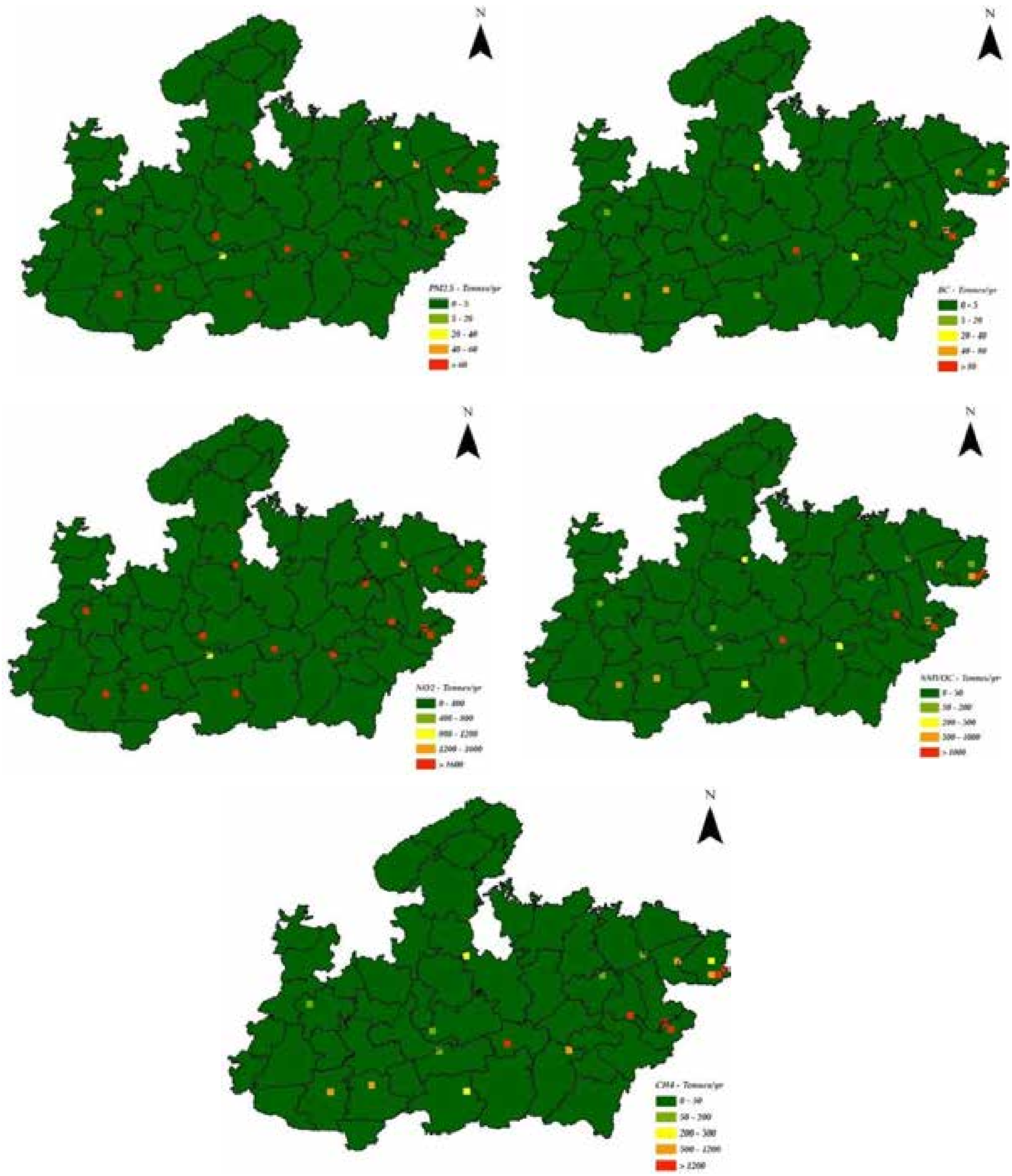


Figure 26: Spatial distribution of power sector emissions for different pollutants in MP at 12×12 km grid scale

BAU Scenario of the Power Sector in Madhya Pradesh

The BAU scenario analysis for Madhya Pradesh's power sector integrates key policies, government mandates, and projected energy trends to estimate future emissions. This analysis reflects the evolving energy scenario by accounting for policy interventions, technological advancements, and shifts in fuel usage across both thermal and renewable energy sources.

The power demand growth rate is derived from TERI's report (Low Carbon Pathways for Madhya Pradesh), which considers existing policies, historical trends, and advanced modelling using the MARKAL framework. According to these projections, the power demand is expected to grow at a rate of 8.14% annually between 2021 and 2030, followed by 5.83% from 2030 to 2040. In the absence of further projections beyond 2040, the growth rate for the period 2040 to 2047 is assumed to remain the same as between 2030 and 2040. This steady growth reflects the anticipated increase in electricity consumption driven by industrial, commercial, and residential needs over the coming decades.

In line with the Madhya Pradesh state government's decision to discontinue the use of imported coal, the BAU scenario assumes that 100% of the coal used in power plants will be supplied by domestic coal-producing entities from 2022 onward. The Revised Biomass Policy also plays a significant role in shaping sustainability. This policy mandates the co-firing of 7% biomass (by mass) in all thermal power plants, which is considered a permanent measure for the BAU years of 2030, 2040, and 2047.

Renewable energy policies have also been accounted for under the BAU analysis. According to the MP Renewable Energy Policy 2022, supported by other regulations such as the Wind Energy Policy and the Policy for Decentralized Renewable Energy Systems (2016), 50% of the total power demand will be met through renewable energy sources by 2030. The remaining 50% will be generated by existing and planned thermal power plants. In the absence of new official targets or policies beyond 2030, this distribution is assumed to remain unchanged for the years 2040 and 2047.

A crucial technological intervention considered in the analysis is the installation of FGD systems to reduce SO_2 emissions. As of 2024, Vindhyachal STPP and Khargone STPP have successfully implemented FGD systems with an 85% efficiency, and the associated reduction in SO_2 emissions is accounted for in the emission estimates. Given the high cost and phased approach of FGD installation, it is assumed that 30% of thermal power plants will adopt FGD technology by 2030, increasing to 60% by 2040 and 90% by 2047. Thermal power plants that already have FGD systems installed by 2024 are considered exceptions.

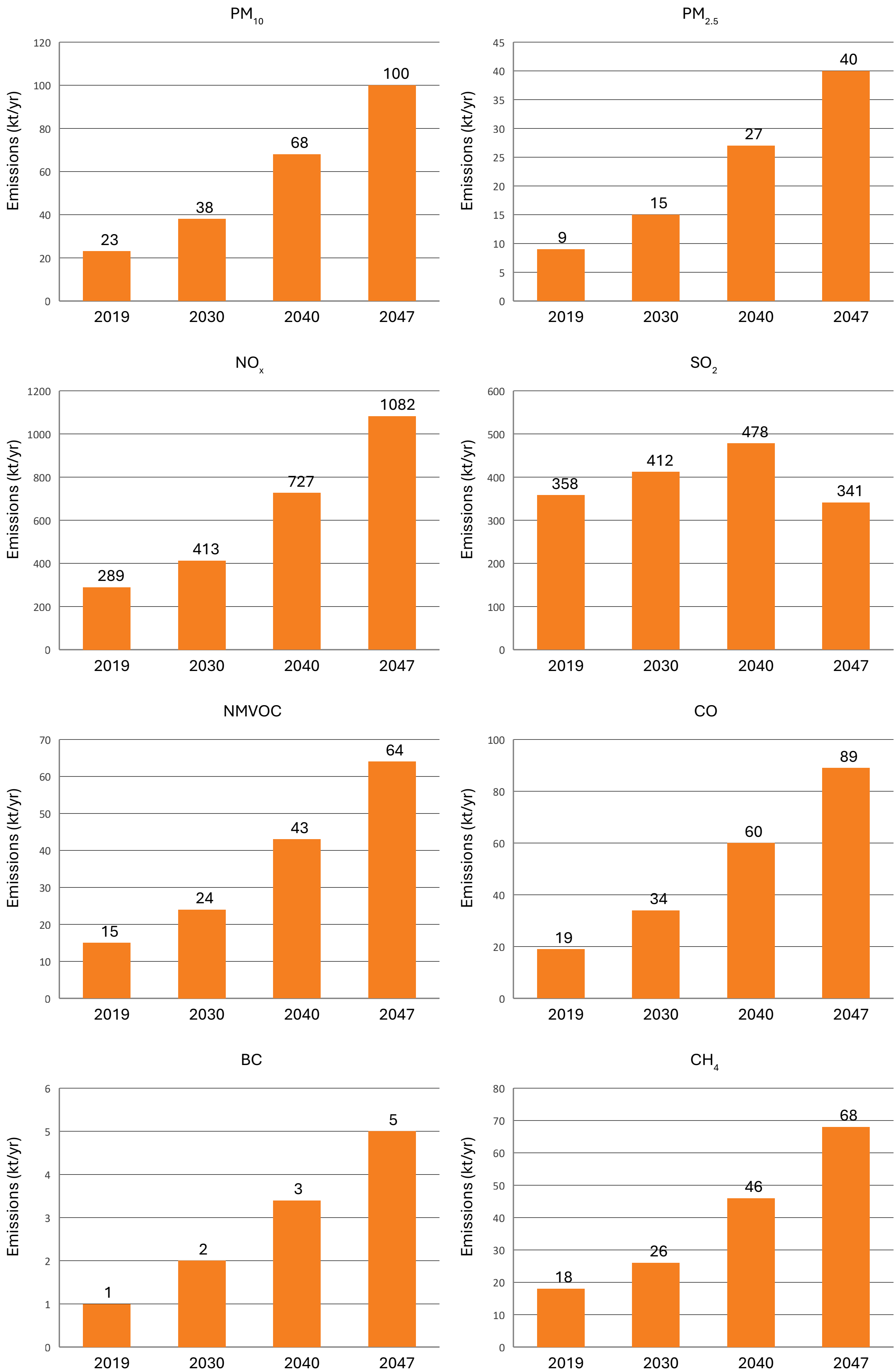


Figure 27: BAU scenario for 2030, 2040 and 2047 of different pollutants from thermal power plants

Under the BAU scenario, emissions from power plants in Madhya Pradesh are projected to increase substantially due to rising energy demands and the continued reliance on coal-based generation as illustrated in Figure 27. According to the projections, by 2030, emissions are expected to rise significantly relative to baseline levels. PM_{10} and $PM_{2.5}$ are projected to increase by 63% and 64%, respectively. NO_x emissions will increase by 43%, while CO emissions may rise by 76%. NMVOCs, CH_4, and BC emissions are also anticipated to grow by 57%, 49%, and 71%, respectively.

By 2040, the emissions trajectory shows a more severe increase across all pollutants. PM_{10} and $PM_{2.5}$ levels are projected to rise by 188% and 189%, while NO_x and CO emissions will escalate to 152% and 211%, respectively. NMVOCs and CH_4 emissions will increase by 177% and 162%, and BC emissions are expected to reach 201% of baseline levels.

Alternative Scenarios of the Power Sector in Madhya Pradesh

The study assesses three alternative scenarios to evaluate the impact of different energy transition pathways on emissions reduction in the power sector. These scenarios focus on renewable energy expansion, biomass co-firing, gas-based power generation, and pollution control measures in thermal power plants. The details of each ALT scenario has been provided in table 33 below.

Table 33: Descriptions of the Alternative Scenarios Assessed in the Power Sector

Scenario	Renewable Energy Share	Biomass Co-firing	Gas-Based Power	SO_2 Control	NO_x Control
ALT-1	60% (2030), 70% (2040), 75% (2047)	10% in TPP boilers	-	100% FGD in TPPs by 2030	100% SCR in TPPs by 2030
ALT-2	Constant at 50%	10% in TPP boilers	10% (2030), 20% (2040), 30% (2047)	100% FGD in TPPs by 2030	100% SCR in TPPs by 2030
ALT-3	55% (2030), 60% (2040), 65% (2047)	10% in TPP boilers	5% (2030), 10% (2040), 15% (2047)	100% FGD in TPPs by 2030	100% SCR in TPPs & gas plants by 2030

Alternate scenario 1 (ALT-1): High Renewables with Biomass Co-firing

(Based on MP Renewable Energy, Wind, and Solar Policies)

This scenario emphasizes a stronger shift towards renewable energy, driven by good governance, a commitment to achieving net-zero emissions, and collaborative efforts towards environmental protection. Under this scenario, Madhya Pradesh's proactive policies and actions will ensure that 50% of the state's energy demand is met through renewable sources by 2030. The share of renewable energy in the total energy supply is assumed to increase significantly, reaching 60% by 2030, 70% by 2040, and 75% by 2047. This scenario also considers stringent emission control measures for thermal power plants. With adequate financial support and regulatory actions, it is assumed that 100% of the thermal power capacity will be equipped with Flue Gas Desulfurization (FGD) systems by 2030 to control SO_2 emissions. Additionally, Selective Catalytic Reduction (SCR) technology will be installed on all thermal power plants to manage NO_x emissions. To lessen coal dependence and support effective crop residue management, 10% of the required coal (by mass) is assumed to be replaced with biomass.

By 2030, significant emission reductions are expected due to the implementation of advanced control technologies and an increased share of renewable energy. FGD systems will be installed on 100% of thermal power plants, leading to an 84% reduction in SO_2 emissions, while the adoption of Selective Catalytic Reduction (SCR) technology will reduce NO_x emissions by 88%. Other pollutants, including PM_{10}, $PM_{2.5}$, CO, NMVOCs, CH_4, and BC, are projected to decrease by 20% compared to Business-as-Usual (BAU) levels.

By 2040, further reductions will be achieved as 70% of the total energy supply is expected to come from renewable sources, reducing the reliance on coal-based power. NO_x emissions are projected to fall by 91%, while SO_2 emissions will decrease by 82% due to the full-scale operation of emission control systems. Emissions of PM_{10}, $PM_{2.5}$, CO, NMVOCs, CH_4, and BC are anticipated to decline by 40%, reflecting both increased renewable energy deployment and the continued operation of pollution control technologies. By 2047, renewable energy is expected to account for 75% of the total energy supply, leading to substantial reductions across all major pollutants. NO_x emissions will decrease by 93%, and SO_2 emissions will decline by 68%. Other pollutants, including PM_{10}, $PM_{2.5}$, CO, NMVOCs, CH_4, and BC, are projected to achieve a 50% reduction compared to BAU levels.

Alternate scenario 2 (ALT-2): Balanced Renewables with Gas Expansion

(Based on Gas-Based Generation (State Planning))

This Scenario focuses on maintaining the current renewable energy contribution while introducing gas-based power plants to replace a portion of coal-based thermal power generation. Under this scenario, the share of renewable energy in the state's electricity demand remains constant at 50% (as per BAU 20230) across all future years. To enhance environmental sustainability, 10% of coal-based thermal capacities will be replaced by gas-based power generation by 2030, increasing to 20% by 2040 and 30% by 2047. This transition is based on technical studies indicating that gas-based power plants produce significantly lower emissions of PM, SO_2, and short-lived climate pollutants (SLCPs) such as BC compared to traditional coal-based thermal plants. Similar to alternate scenario 1, this scenario assumes that 100% of coal-based power generation capacities have FGD systems installed and 10% biomass is used for co-firing in coal-based TPPs.

In this scenario, it is assumed that Selective Catalytic Reduction (SCR) systems are installed on all gas-based power plants to reduce NO_x emissions. This measure aligns with efforts to make natural gas a cleaner and more environmentally sustainable energy source. However, the successful implementation of this transition depends on the availability and consistent supply of natural gas, either through increased domestic production or imports.

By 2030, if 10% of coal-based thermal energy is replaced by gas-based power plants, SO_2 emissions are expected to reduce by 84% and NO_x emissions by 88%. This significant decrease will primarily result from the lower sulfur content in natural gas and the installation of Selective Catalytic Reduction (SCR) systems across all gas-based capacities. Emissions of PM_{10}, $PM_{2.5}$, and CO are projected to decrease by 20%, while NMVOCs are anticipated to decline by 9%. However, CH_4 emissions are likely to increase by 14% due to the combustion process in gas plants, which inherently emits more CH_4 compared to coal. BC emissions are expected to reduce by 10% owing to the cleaner combustion process.

By 2040, as the share of gas-based power increases to 20%, further improvements in air quality are projected. NO_x emissions are estimated to decrease by 91% and SO_2 emissions by 82%, reflecting the impact of enhanced emission control measures implemented during the BAU years. PM_{10}, $PM_{2.5}$, and CO emissions are expected to decline by 40%, while NMVOCs emissions are projected to reduce by 18%. However, CH_4 emissions are anticipated to increase by 29% due to the expanded use of natural gas. BC emissions are expected to reduce by 20%, reinforcing the cleaner profile of gas-based power plants. By 2047, with 30% of coal-based thermal energy replaced by gas, NO_x emissions are projected to achieve a maximum reduction of 93%, while SO_2 emissions are expected to decrease by 68%. PM_{10}, $PM_{2.5}$, and CO emissions are anticipated to reduce by 50%, reflecting the cumulative benefits of the gas transition and sustained emission controls. NMVOCs emissions are expected to decrease by 27%, while CH_4 emissions are projected to rise by 43%, posing a challenge in mitigating greenhouse gas outputs from gas-based plants. BC emissions are analyzed to decline by 30%, indicating a continuous improvement in reducing particulate emissions.

Alternate scenario 3 (ALT-3): Moderate Renewables with Solar and Gas Integration

(Based on Hybrid Approach ALT1 and ALT2)

This scenario integrates both renewable energy expansion and the introduction of gas-based power generation, combining the measures from the previous two scenarios. By 2030, renewable energy is assumed to contribute 55% of the total electricity demand, increasing to 60% by 2040 and 65% by 2047. Simultaneously, 5% of coal-based capacity will be replaced by gas-based power plants by 2030, with this share increasing to 10% by 2040 and 15% by 2047. All other assumptions regarding APCDs and the share of biomass co-firing are assumed to remain the same as in previous scenarios.

By 2030, this scenario is analyzed to achieve substantial reductions (with respect to BAU) in major pollutants due to a combined focus on renewable energy expansion and gas-based power generation. Notably, SO_2 emissions are expected to decrease by 84%, while NO_x emissions will see an 88% reduction. PM_{10}, $PM_{2.5}$, CO, and BC emissions will reduce by 20%, 20%, 20%, and 15%, respectively. NMVOCs will decrease by 14%, while CH_4 will show a modest reduction of 2% due to the partial replacement of coal-based power generation with renewable energy. By 2040, the reductions intensify as renewable energy is projected to meet 60% of the total energy demand, and 10% of coal-based generation is replaced by gas. NO_x emissions are expected to fall by 91%, while SO_2 emissions will decrease by 82%. PM_{10}, $PM_{2.5}$, CO, and BC emissions will see a 40%, 40%, 40%, and 28% reduction, respectively. NMVOCs emissions will decrease by 27%, while CH_4 emissions will continue to decline slightly by 4% due to increased reliance on cleaner gas-based generation.

By 2047, with 65% of energy demand sourced from renewables and 15% of coal-based energy replaced by gas, NO_x emissions are estimated to be reduced by 93%, and SO_2 emissions by 68%. Emissions of PM_{10}, $PM_{2.5}$, CO, and BC will further decrease by 50%, 50%, 50%, and 41%, respectively. NMVOCs emissions will fall by 39%, while CH_4 emissions will remain 4% lower than the BAU scenario, reflecting sustained improvements from the combined renewable energy transition.

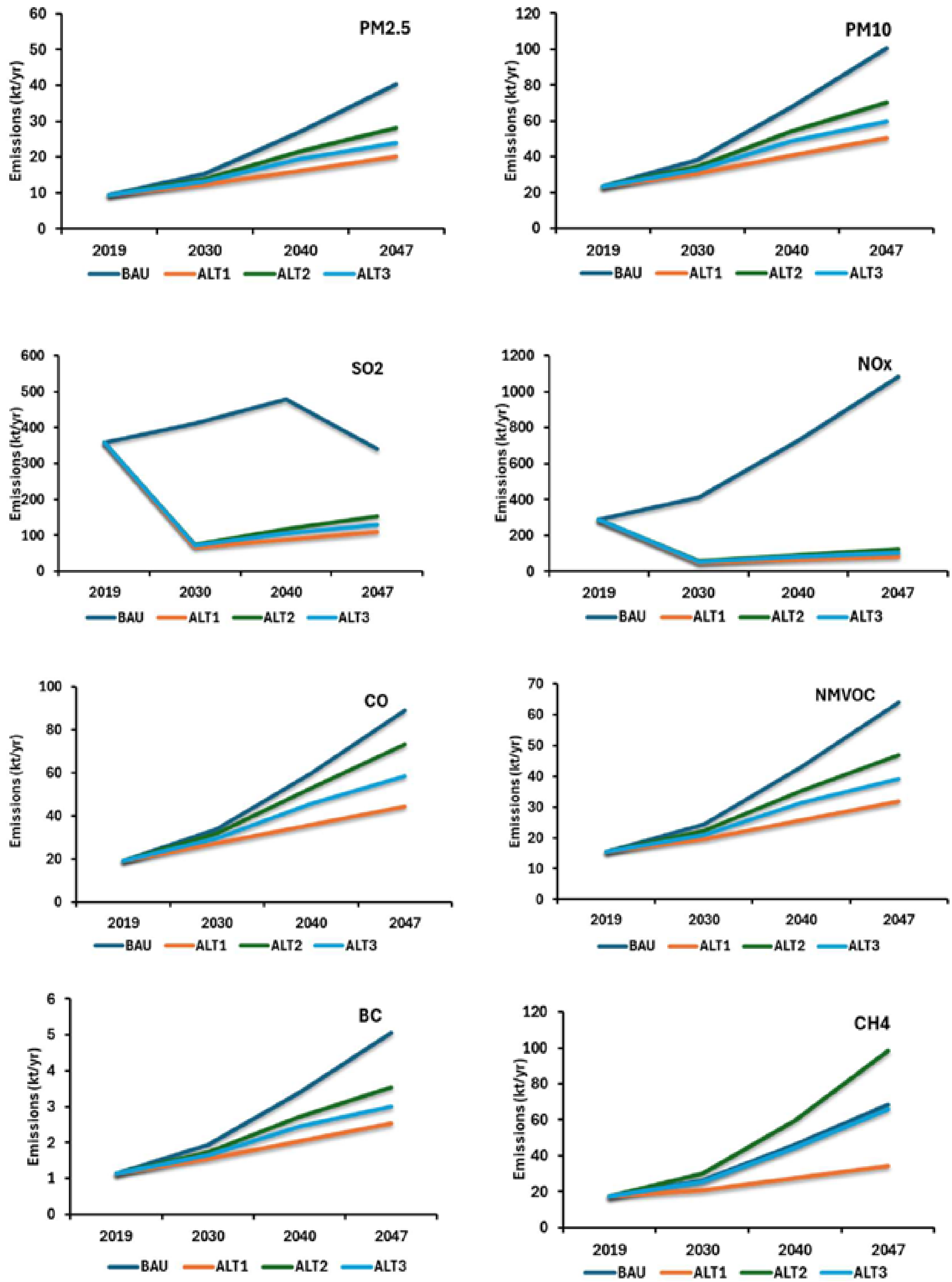


Figure 28: BAU scenario for 2030, 2040 and 2047 of different pollutants from thermal power plants

Table 34: Change in Power Sector Emissions Under Alternate Scenarios, Compared to 2047

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: High Renewables with Biomass Co-firing	-50%	-87%	-93%	-50%	-50%	-50%	-50%
ALT 2: Balanced Renewables with Gas Expansion	-30%	-82%	-88%	-18%	-27%	-30%	43%
ALT 3: Moderate Renewables with Solar and Gas Integration	-40%	-84%	-91%	-34%	-39%	-41%	-4%

Key Insights from the Power Sector Analysis

The power sector is the principal contributor to SO_2 and NO_x emissions in Madhya Pradesh, accounting for approximately 85% and 48% of the state's total emissions, respectively. This is primarily attributed to the high dependency on coal-fired thermal power plants (TPPs). While all operational TPPs are currently equipped with Electrostatic Precipitators (ESPs), effectively mitigating PM and BC emissions, control of SO_2 and NO_x remains limited due to the slow implementation of advanced pollution control technologies such as Flue Gas Desulfurization (FGD) units and Selective Catalytic Reduction (SCR) systems. The delay in deployment can be attributed to a combination of factors, including high capital and operating expenditures, technical integration constraints—particularly in older plants with space and design limitations—supply chain bottlenecks, and limited availability of skilled workforce and maintenance infrastructure.

To evaluate emission reduction potential, three alternative policy and technology scenarios were assessed, based on which ALT1 and ALT3 came out as the most effective strategies for reducing SO_2 and NO_X emission load from the sector. The ALT1 scenario assumes a rapid transition toward renewable energy with aggressive end-of-pipe pollution control measures, including 100% coverage of FGD and SCR technologies by 2030 and 10% biomass co-firing by mass in coal-fired boilers. The ALT3 scenario combines the scaling up of renewable energy with a phased substitution of coal-based generation capacity by natural gas, maintaining the same levels of pollution control deployment and biomass co-firing as in ALT1. Under both scenarios, substantial emission reductions are achieved: by 2047, NO_x emissions are projected to decrease by 93%, and SO_2 emissions by 68%, relative to BAU levels. Additional co-benefits include up to 50% reductions in PM_{10}, $PM_{2.5}$, CO, NMVOCs, and BC. CH_4 emissions exhibit marginal increases in gas-based systems but remain lower than BAU projections due to the combined effect of renewables and reduced fossil fuel usage.

Furthermore, renewable energy deployment offers system-level benefits beyond emission reductions. The decentralisation of electricity generation through distributed renewable technologies, such as solar photovoltaic (PV) mini-grids and rooftop systems, has the potential to meet local energy demands in rural and peri-urban areas. Enhancing energy access in these regions will reduce dependency on centralised thermal generation, thus alleviating peak demand stress and enabling a gradual reduction in baseload coal capacity. This demand-side deflation, driven by localised self-sufficiency, is critical for decarbonising the power system while maintaining grid reliability and security.

Overall, the findings reinforce the necessity of an integrated strategy combining renewable energy expansion, targeted retrofits of pollution control technologies, and demand-side interventions. Enabling policy frameworks, concessional finance, regulatory compliance mechanisms, and capacity-building initiatives will be essential to accelerate the transition. Such coordinated action will not only mitigate SLCPs and criteria air pollutants from the power sector but also contribute significantly toward Madhya Pradesh's long-term air quality and climate objectives.

Waste Sector

Madhya Pradesh has been proactive in aligning its waste management strategies with national level regulations, particularly the Solid Waste Management Rules, 2016. The Urban Administration and Development Department (UADD) under the Government of Madhya Pradesh has been leading the state's efforts in formulating and implementing waste management strategies across its urban local bodies.

Solid waste management in the state is managed through a two-pronged strategy: Cluster-Based Integrated Solid Waste Management (ISWM) model and Decentralized Solid Waste Management approach to ensure both scalability and effectiveness. Under the Cluster-Based ISWM model approach, multiple ULBs are grouped together to manage waste through shared infrastructure and resources. This model adopts key treatment technologies such as waste to energy (WtE) and Waste to Compost (WtC) to process municipal solid waste. To expand this model, the state is currently developing 11 new waste management clusters to serve around 210 ULBs.[64]

Alongside the cluster model, the Decentralized Solid Waste Management (DSWM) approach empowers individual ULBs or neighborhoods to manage waste locally through standalone systems. This model is particularly effective in promoting source segregation, community-level composting, and reducing the need for long-distance transportation of waste. Many ULBs have adopted various treatment and processing techniques such as material recovery facilities (MRFs) for recyclable waste, composting units for organic waste, and biomethanation plants for generating biogas.

Furthermore, Madhya Pradesh is also advancing in zero waste landfill policy by implementing strategies like waste segregation at source, promoting recycling and reuse and exploring waste to energy solutions with cities like Jabalpur and Indore leading the way.[65],[66]

By integrating ISWM clusters with localized waste management solutions, the state is creating a sustainable and scalable model to improve operational efficiency, reduce environmental impacts and move towards a more circular economy model of waste management.

The waste sector emissions in Madhya Pradesh have been estimated using the SWEET tool and spatially distributed over a 12×12 km resolution grid. This distribution is based on a hybrid methodology combining population density and area ratios, recognizing that waste generation is closely linked to population concentration. As such, more densely populated areas are associated with higher emissions from waste-related activities due to higher amount of waste generation in those areas.

The pollutants assessed include BC, CH_4, SO_2, and $PM_{2.5}$. CH_4 emissions are particularly prominent in urban districts such as Indore, Bhopal, Jabalpur, and Gwalior, where large volumes of biodegradable waste are deposited in landfills. These urban centres emerge as significant CH_4 hotspots due to continuous organic waste decomposition under anaerobic conditions. Emissions of BC, SO_2 and PM2.5 follow a similar spatial pattern, with elevated levels in urban and peri-urban districts. These pollutants are predominantly released from open burning of waste, a common practice in areas with inadequate waste management infrastructure.

Overall, the spatial variability of waste sector emissions across districts is marked by higher concentrations in urban regions and relatively lower levels in rural districts. However, the current distribution approach can be further improved by integrating precise geolocation data of landfill sites and dumpsites. This would enhance the accuracy of emissions allocation, especially for methane and other pollutants associated with site-specific waste degradation processes. Incorporating such spatial detail would also strengthen the relevance of the inventory for district-level planning and targeted mitigation under clean air and climate strategies.

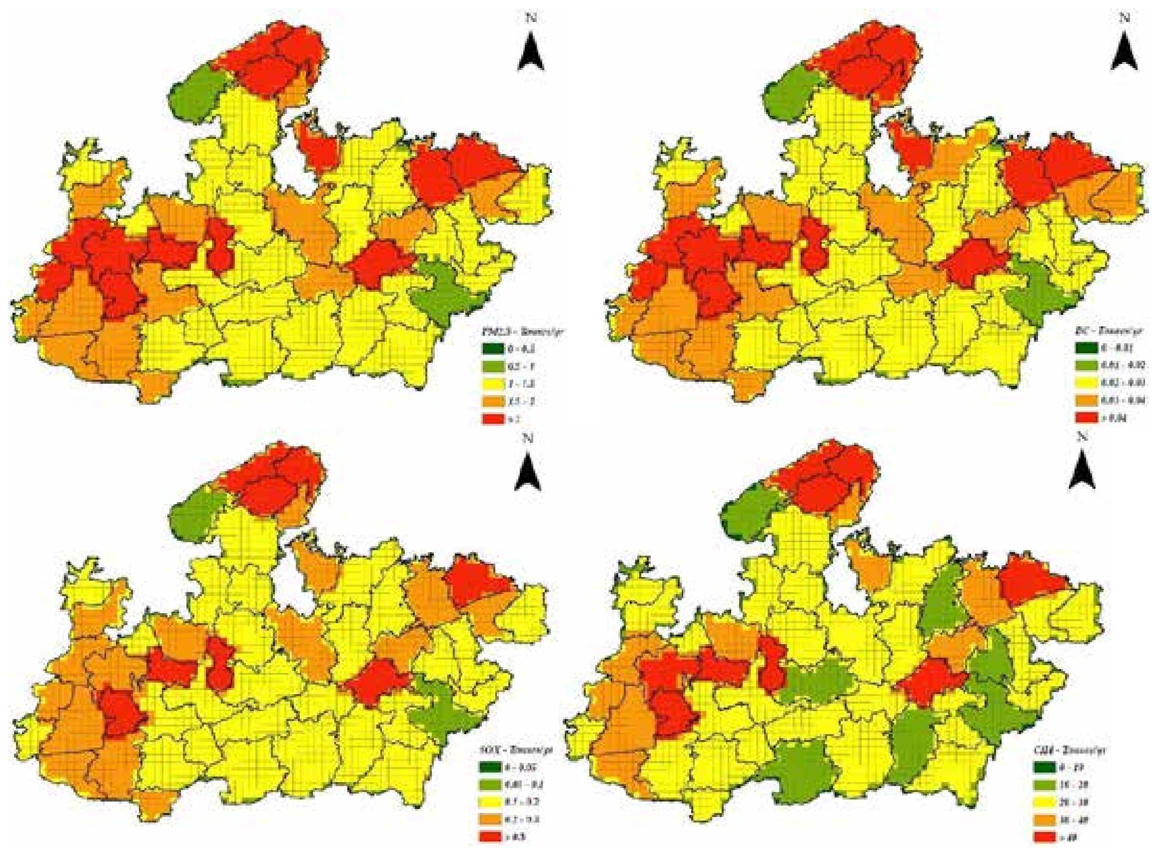


Figure 29: Spatial distribution of Waste sector emissions for different pollutants in MP at 12×12 km grid scale

To enable informed policy planning and evaluate the potential impact of different waste management strategies, it is essential to not only understand the current spatial distribution of emissions but also to assess how these emissions may evolve in the future. Building on the current emission estimates and spatial patterns, the following section presents a forward-looking analysis. It outlines both BAU and ALT scenarios projected for Madhya Pradesh's waste sector, providing a comprehensive emission forecast through 2047, as analysed using the SWEET. The emission factors utilized in SWEET form the basis for this scenario analysis, allowing for an assessment of the long-term implications of various waste management interventions.

BAU Scenario of the Waste Sector in Madhya Pradesh

A BAU scenario for waste sector emissions has been developed which projected the emissions till 2047 in the SWEET.[67] The BAU scenario represents a scenario where, of the total waste generated, 7,213 tons per day (TPD)[68] (with a 90% collection efficiency) is being collected, with about 90% of waste being processed. In this baseline scenario, the state focuses majorly on composting, recycling, waste combustion and anaerobic digestion (AD) for treatment of waste. Of the approximately 90% of waste being processed, the majority (66%) is composted followed by recycling (21%), waste combustion (12%), and anaerobic digestion (1%) with 764 TPD being disposed off. Currently, the state is facing several challenges in waste management:

- There is an inadequate presence of Material Recovery Facilities (MRFs) in Urban Local Bodies (ULBs), with only 360 out of 406 ULBs having established MRFs.[69]
- Existing waste management plants are not being utilized to their full capacity.[70]
- There is a shortage of training programs and capacity-building initiatives.[71]
- ULBs are struggling to achieve 100% door-to-door waste collection.[72]
- Many existing landfills lack proper capping, leading to environmental concerns.[73]

Regarding the assumptions considered for open waste burning, although it is banned in India, municipal solid waste (MSW) is still burned due to gaps in the waste management system. Based on findings from previous study, this study includes open waste burning rate in the baseline scenario as 5% of uncollected waste being burnt by residents and 2% being burnt at landfill.[74] Only municipal solid waste is considered in this analysis, excluding agricultural, construction, and demolition waste and other types of waste.

Based on the projected annual growth rates (0.3%) for waste collection in this sector, the BAU scenario has been developed, and emission loads have been estimated. The estimates for the years 2020, 2030, 2040, and 2047 are shown in Figure 30.

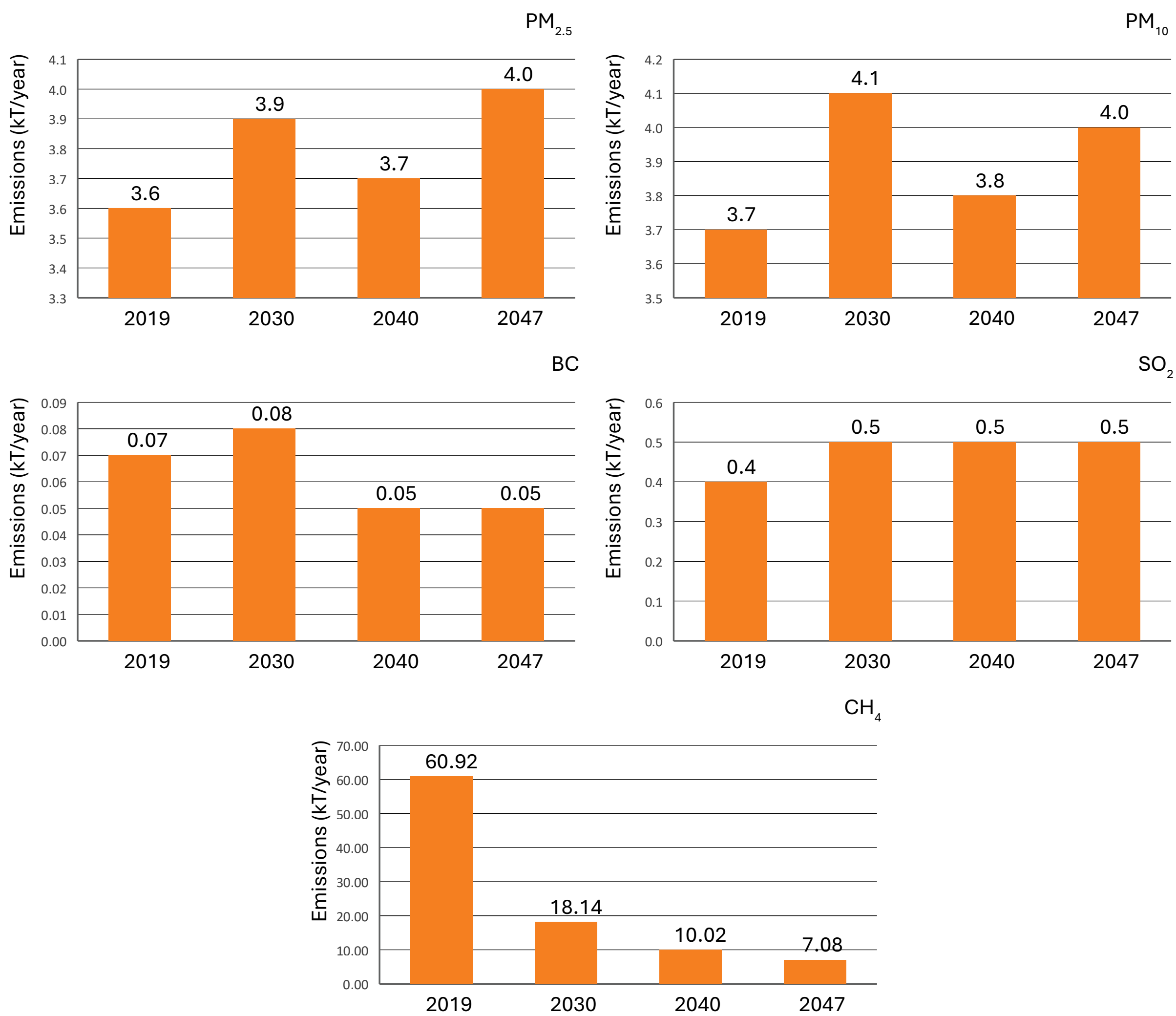


Figure 30: 2019, BAU scenario for 2030, 2040 and 2047 of different pollutants from the Waste sector

Alternative Scenarios of the Waste Sector in Madhya Pradesh

The ALT scenarios for Madhya Pradesh's waste sector aim to align waste management practices with the state's planned policy measures, as mentioned in Table 35. These scenarios provide ALT-1 based on the proposed plants to be established by the state government. Whereas ALT-2 scenario focuses on increasing waste diversion to waste combustion and recycling rather than anaerobic digestion and composting. This scenario is closely aligned with the state's Integrated Solid Waste Management (ISWM) cluster strategy, which prioritizes Waste-to-Compost, Waste-to-Energy and strengthening of MRFs as key treatment solutions as primary treatment solutions.[75]

Table 35: Brief description of alternative scenarios for the waste sector

Scenarios	Description
ALT-1	▪ 99% of collected waste is diverted to composting, anaerobic digestion, waste combustion, and recycling. ▪ Waste processing includes: 52% composting (3877 TPD), 8% anaerobic digestion (597 TPD), 14% waste combustion (1050 TPD), and 26% material recovery facilities (MRFs) (1907 TPD). ▪ Open burning rate assumes 2% of uncollected waste burned by residents and 2% at landfills. ▪ Increased collection and treatment efficiency from BAU (90%) to ALT scenarios (99%) reduces open burning levels.
ALT-2	▪ 99% of collected waste is diverted, prioritizing waste combustion and recycling. ▪ Composting and anaerobic digestion capacities remain the same as BAU. ▪ Waste processing includes: 58% composting (4310 TPD), 1% anaerobic digestion (59.7 TPD), 14% waste combustion (1050 TPD), and 27% recycling (2011 TPD). ▪ Open burning rate assumptions remain the same as in ALT-1.

Alternative scenario 1 (ALT-1): Energy Recovery Scenario

(Based on MP State Environment Plan, 2024)

The ALT-1 scenario outlines 99% of the diversion of collected waste (total collected waste is 7506.18TPD of which 7431.11 TPD (99%) is diverted) to the proposed processing facilities to be developed by state which includes composting of 3877 TPD (52%), anaerobic digestion of 597TPD (8%), waste combustion plant of 1050 TPD (14%), and MRFs of 1907 TPD (26%). For open burning, the rate of open waste burning considered is that 2% of uncollected waste is burned by residents and 2% is burned at the landfill. Since collection and treatment efficiency increased from BAU (90% each) to ALT-1 scenarios (99% each) certain improvement in the reduction of open burning rates is assumed from the BAU levels. These interventions will result in more diversion of waste from solid waste disposal sites and reduction of the burning of waste, which will in turn, control air pollution emissions attributable to this scenario. For instance, in the ALT-1 scenario, $PM_{2.5}$ emissions are projected to decrease by 13.05%, 60%, and 60% in each of the studied years: 2030, 2040, and 2047, respectively, in comparison to BAU.

Alternative scenario 2 (ALT-2): Resource Recovery-Oriented Scenario

(Based on MPPCB ISWM Cluster Model)

The ALT-2 scenario takes a different strategic approach. While it also seeks to improve waste diversion, it focuses more heavily on enhancing resource recovery through recycling and energy generation. This scenario prioritizes the expansion of waste-to-energy technologies and the strengthening of MRFs to maximize the production and use of Refuse-Derived Fuel (RDF). RDF is generated by processing dry, high-calorific-value fractions of MSW and is used as a renewable fuel source, especially in cement kilns and thermal power plants. Within this scenario, out of the total of 7506.18 TPD waste collected, 99% (7431.11 TPD) of the waste is diverted to different diversion facilities. The scenario prioritizes waste combustion and recycling and composting and AD facilities remain the same as BAU. Of the 7431.11 TPD sent for diversion, 4310 TPD (58%) is set for composting, 59.7 TPD (1%) is set for anaerobic digestion, 1050 TPD (14%) is set for waste combustion, and 2011 TPD (27%) is set for recycling. For open burning, rate assumptions remain the same as in ALT1.

In summary, while both alternate scenarios aim to enhance waste processing and reduce environmental impacts, ALT-1 leans heavily on state policy implementation and biological treatment methods, whereas ALT-2 emphasizes on technological interventions and market-driven solutions like RDF production and material recovery. A hybrid approach between these pathways could ensure long-term sustainability for the state.

The shift towards ALT 1 and ALT 2 from BAU has more waste being diverted from SWDS, leading to varying increases or decreases in CH_4, PM_{10}, $PM_{2.5}$, SO_2, and BC emissions.

In all the alternative scenarios, the PM_{10}, $PM_{2.5}$, and SO_2 emissions primarily originate from waste combustion. In case of SO_2 emissions, ALT1 shows a significant reduction compared to ALT2. This is likely because ALT1 prioritizes more organic waste diversion (composting and anaerobic digestion), lowering waste combustion volume and reducing the amount of sulfur-containing waste entering combustion. In contrast, ALT2 retains more waste for combustion due to less diversion, leading to relatively higher SO_2 emissions. In the case of PM, a significant contributor to PM_{10} and $PM_{2.5}$ emissions in ALT scenarios is waste combustion and open burning of waste. In both ALT1 and ALT2, waste combustion and open burning rates remain the same. However, ALT2 shows significantly higher PM_{10} and $PM_{2.5}$ emissions from combustion. This is because, in ALT2, a larger share of dry waste is retained in combustion, while in ALT1, more materials are shifted to alternative processing methods, reducing the combustion-based PM emissions. All the aforementioned emissions in 2030, ALT1 show a drastic drop in emissions, corresponding to SWDS closures and reduced open burning. In 2040 and 2047, emissions remain lower in ALT1 but increase slightly compared to 2030 due to continued waste transport and handling. In ALT2, emissions levels do not drop as much because waste diversion to combustion still produces some emissions.

CH_4 emissions decrease significantly in both alternative scenarios compared to BAU, particularly after 2030. Under BAU, waste continues to be disposed off in landfills, leading to prolonged CH_4 generation from anaerobic decomposition. ALT2 shows a slightly greater reduction in CH_4 emissions than ALT1 as a shift towards waste combustion and recycling, and higher composting reduces waste disposal in landfills, thereby lowering CH_4 emissions. By 2031, landfill operations are expected to cease, reducing spontaneous waste decomposition and CH_4 release.

BC emissions decline in ALT1 compared to BAU. ALT2 shows only a moderate decrease in BC emissions compared to ALT1. Here, BC is a major byproduct of open burning, followed by waste collection and transportation, and waste combustion. In ALT2, due to increased waste combustion, leading to a slower decline in BC emissions. In 2030, BC emissions decline sharply in both the ALT scenarios due to the cessation of spontaneous landfill fires. In 2040 and 2047, emissions increase slightly due to continued transportation and waste handling.

Overall ALT1 is the more environmentally beneficial scenario, as it significantly reduces CH_4, PM_{10}, $PM_{2.5}$, and BC emissions, mainly due to landfill closures, enhanced dry and organic waste processing. ALT2 still reduces emissions compared to BAU but does not achieve the same level of reductions as ALT1. This is primarily due to its heavier reliance on dry waste, specifically waste combustion rather than composting and anaerobic digestion. The most notable reductions in emissions occur post-2030, when landfill closures and cessation in spontaneous burning at SWDS with continuous waste processing take effect. However, some emissions rise again in later years due to continued waste transportation and processing activities.

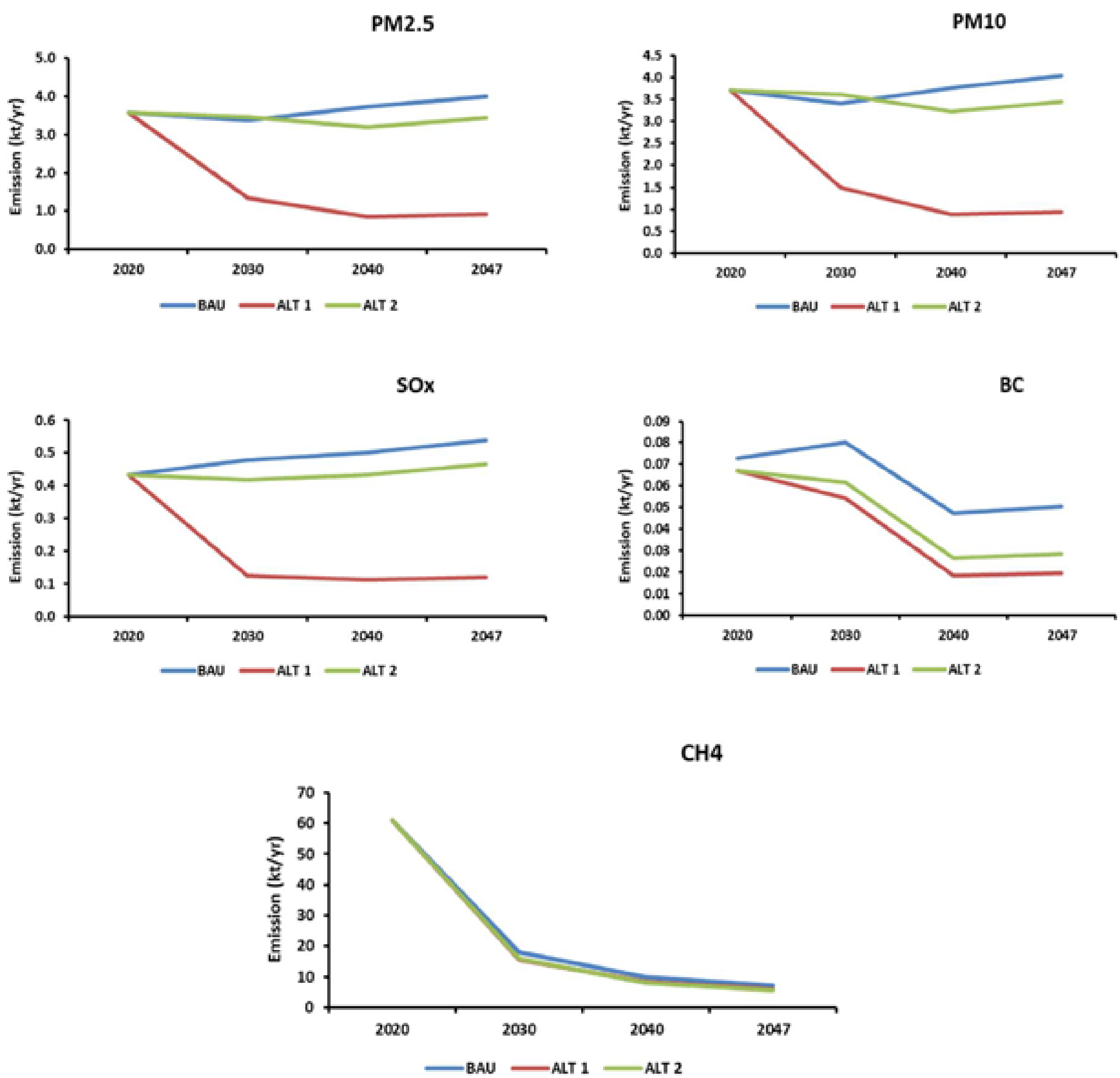


Figure 31: Emission pathways of BAU and ALT scenarios of waste sector till 2047

Table 36: Change in Waste sector Emissions under Alternate Scenarios, Compared to BAU in 2047

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: Energy Recovery Scenario	-77%	-78%	-	-	-	-61%	-16%
ALT 2: Resource Recovery	-14%	-14%	-	-	-	-45%	-19%

Key Insights from the Waste Sector Analysis

The waste sector is the third-largest source of methane (CH_4) emissions in Madhya Pradesh, following agriculture and energy. While the state has made commendable progress in implementing waste management reforms, further systemic improvements are essential to minimize emissions and align with long-term environmental and climate goals. Emissions in the sector primarily arise from landfill operations, open burning, waste collection and transportation, and the use of diesel-powered waste-handling equipment. The analysis presented in this study highlights the critical need to prioritise low-emission waste diversion strategies, such as composting, anaerobic digestion (AD), and advanced material recovery, over emission-intensive approaches like waste combustion.

Scenario-based assessment shows that transitioning from a BAU trajectory to proactive pathways—namely ALT-1 and ALT-2—offers substantial benefits. ALT-1, which emphasizes composting, bio-methanation, and decentralized treatment infrastructure, results in the most significant reduction in CH_4, BC, SO_x, and $PM_{2.5}/PM_{10}$ emissions. This scenario also supports improved air quality, reduced leachate-related soil and groundwater contamination, and minimized risks of landfill fires. The promotion of decentralized biogas plants using municipal solid waste, agricultural residue, and cattle dung presents a scalable and low-carbon alternative to fossil fuels. This aligns with national schemes such as SATAT and GOBARdhan and offers rural economic co-benefits by generating employment and revenue for farmers and local entrepreneurs.

ALT-2, which focuses on increased recycling and Refuse-Derived Fuel (RDF) generation, facilitates industrial symbiosis, particularly with cement kilns and waste-to-energy (WTE) applications. While it yields slightly higher emissions than ALT-1 due to its combustion-based components, it enhances resource recovery and energy generation potential. Both ALT scenarios underscore the importance of a systems-level approach to integrated solid waste management (ISWM), supported by technological innovation and decentralized solutions.

However, several implementation barriers persist. Infrastructure gaps, such as the limited presence and underutilization of Material Recovery Facilities (MRFs)—only 360 out of 406 Urban Local Bodies (ULBs) have operational MRFs—impede optimal material segregation and processing. Incomplete door-to-door waste collection, inadequate source segregation, and a shortage of trained personnel further constrain system efficiency. Many existing landfills remain uncapped, contributing to uncontrolled emissions and environmental hazards. Moreover, awareness and technical understanding of advanced waste processing methods like RDF production and WTE technologies are limited across local administrative bodies.

Additionally, emissions from the sector are compounded by the widespread use of diesel-powered waste transport vehicles and equipment, contributing significantly to CO_2, BC, and particulate emissions. A phased transition to low- or zero-emission fleets—such as those powered by electricity, natural gas, or hydrogen—combined with smart route optimization systems, can drastically reduce fuel use and operational costs.

Strengthening Madhya Pradesh's waste management system will require robust implementation of decentralized models, effective enforcement of the cluster-based ISWM framework, and a strong push for behavioral change at the household level to enable 100% source segregation and door-to-door collection. Investment in capacity building, awareness programs, and institutional training is essential to operationalize advanced technologies and ensure long-term sustainability.

Further, a district-specific approach is critical for optimizing waste sector interventions across Madhya Pradesh, given the diverse urban, industrial, and rural profiles. In leading urban centers such as Indore and Bhopal, sustained efforts in waste management have positioned them among the best-performing cities nationally, with Indore consistently ranking first in Swachh Survekshan. Cities like Jabalpur, Gwalior, and Ujjain require strengthening of MRF infrastructure and promotion of anaerobic digestion and composting to reduce landfill dependency and manage high organic waste volumes. Industrial-adjacent districts such as Rewa, Satna, Dewas, and Dhar are ideal for RDF aggregation and industrial co-processing, especially in cement plants, fostering industrial symbiosis.

In agricultural districts like Sehore, Raisen, Chhindwara, and Seoni, decentralized bio-methanation leveraging cattle dung and crop residue should be prioritized. These areas can align with national schemes such as GOBARdhan and SATAT to support clean energy generation and rural entrepreneurship. Sagar and Damoh present opportunities for piloting integrated solid waste management clusters and scientific landfill closures. In tribal and forested districts such as Shahdol, Umaria, Balaghat, and Mandla, the focus should be on achieving full door-to-door collection, promoting segregation at source, and introducing low-cost, decentralized composting. This prioritization will not only address emission reduction but will also support broader co-benefits in agriculture, rural development, and industry, reinforcing the state's integrated and decentralized waste management goals.

Notably, the benefits of improved waste management will extend beyond emission reductions—supporting cleaner energy systems, enhancing agricultural value chains through residue utilization, and creating industrial linkages—thus contributing to broader environmental, economic, and public health outcomes across the state.

Agriculture and Livestock

Agriculture and livestock play a crucial role in Madhya Pradesh's economy, with over 70% of the population residing in rural areas and depending on these sectors for their livelihoods. However, less than half of the state's total land area is cultivable, and its distribution varies due to differences in topography, rainfall, and soil composition. The primary agricultural regions include the Chambal Valley, Malwa Plateau, and Rewa Plateau, while the fertile Narmada Valley, covered with alluvial deposits, supports high-yield cultivation.

Rice, wheat, sorghum (jowar), corn (maize), pulses (peas, beans, lentils), and peanuts (groundnuts) are the dominant crops in the state. Rice, a tropical crop and a staple in the local diet, is primarily grown during the Kharif season, with the highest production in the Wainganga Basin, Maikal Plateau, Baghelkhand Plateau, Katni-Jabalpur Region, and Rewa Plateau. In 2020-21, rice was cultivated on 3,441 thousand hectares, producing 12,502 thousand metric tons, marking a 13.04% increase from the previous year. Balaghat, Katni, and Seoni are the top rice-producing districts. Despite its agricultural significance, rice cultivation is a major source of methane (CH_4) emissions due to anaerobic decomposition in flooded paddy fields. Further, there has been an increasing trend of open burning of agricultural residue in the state. The data from the Consortium for Research on Agroecosystem Monitoring and Modeling from Space (CREAMS), an interdisciplinary research initiative of Indian Agricultural Research Institute, New Delhi shows that between 2020 and 2025, Madhya Pradesh has emerged as a consistent hotspot for agricultural fires, particularly during the Rabi harvesting season in April–May. The state recorded its highest activity in 2022 with 27,759 fire counts and 221,928 MW of fire radiative power (FRP), maintaining a leading position nationally. Although there has been a gradual decline in fire counts over the years—falling to 18,833 in 2023 and stabilizing at 13,665 in both 2024 and 2025—MP continues to rank among the top burning states during this period. In the Kharif harvesting season (October–November), MP showed a rising trend, starting from 8,160 fires in 2021 and increasing to 12,500 by 2023. Notably, in 2024, MP surpassed the traditionally dominant state of Punjab to become the highest fire-contributing state in this season, with 6,496 fires and 39,707 MW FRP.

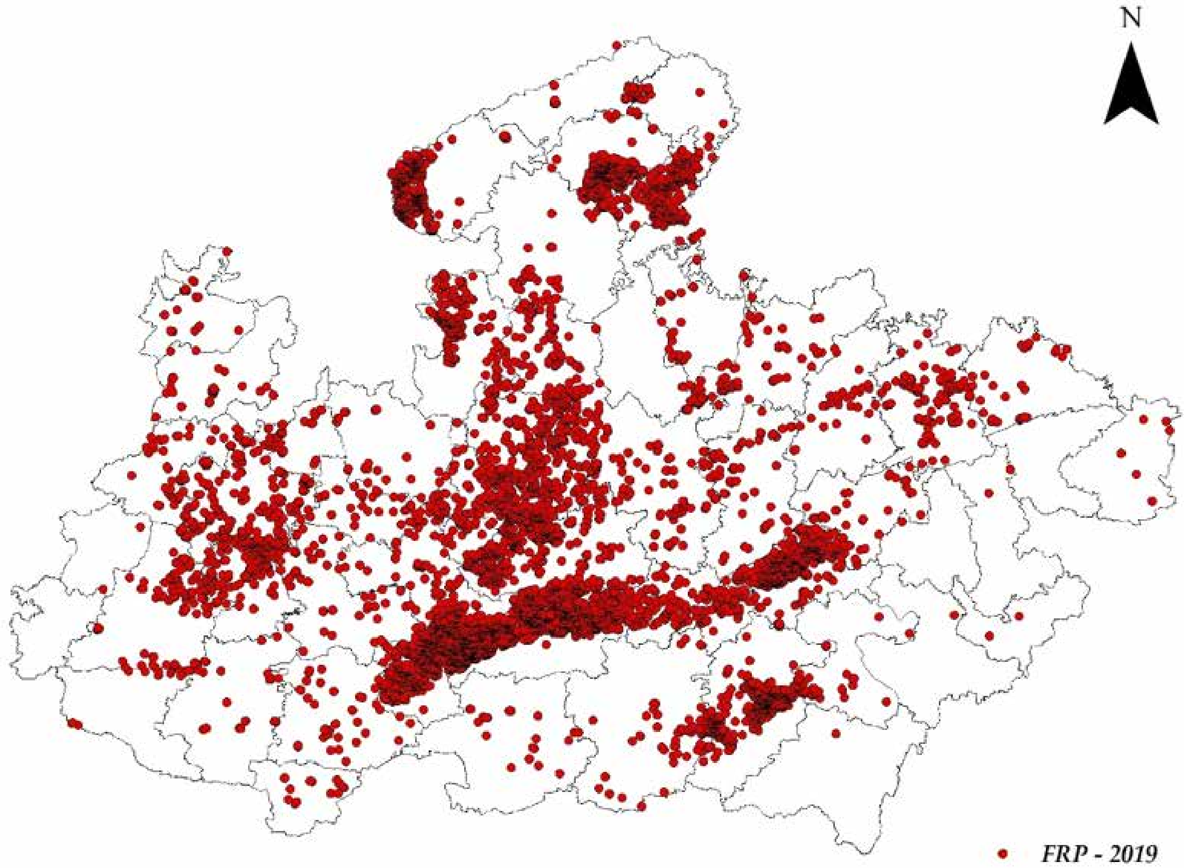


Figure 32: Biomass fires detected over agricultural land in 2019 across Madhya Pradesh

The analysis conducted under this study for 2019, using satellite-based detection using VIIRS sensors, identified a significant number of biomass burning incidents across agricultural lands in Madhya Pradesh shown in figure 32, highlighting seasonal peaks associated with residue burning practices. Spatial analysis revealed that districts in the northern and central parts of the state experienced the highest intensity of agricultural fires. These regions are characterized by intensive cultivation of wheat and other cereal crops, leading to considerable post-harvest biomass generation.

Further as per the emission estimates for 2019, several districts in Madhya Pradesh recorded notably high emissions from agricultural residue burning (Figure 32). Chhindwara, Seoni, Hoshangabad, Narsinghpur, and Raisen emerged as the top contributors, releasing substantial amounts of $PM_{2.5}$, PM_{10}, and Black Carbon. For instance, these five districts together accounted for about 25% of total agriculture residue burning BC emitted from the state with maximum emitted from Hoshangabad, while closely followed by Seoni and Raisen. These emissions indicate concentrated agricultural burning activities, particularly in the central, northern and southeastern regions of the state. Other significantly impacted districts include Ujjain, Satna, Sehore, and Rewa, which also demonstrated elevated levels of both particulate matter and gaseous pollutants, underscoring the need for region-specific residue management interventions and enforcement strategies.

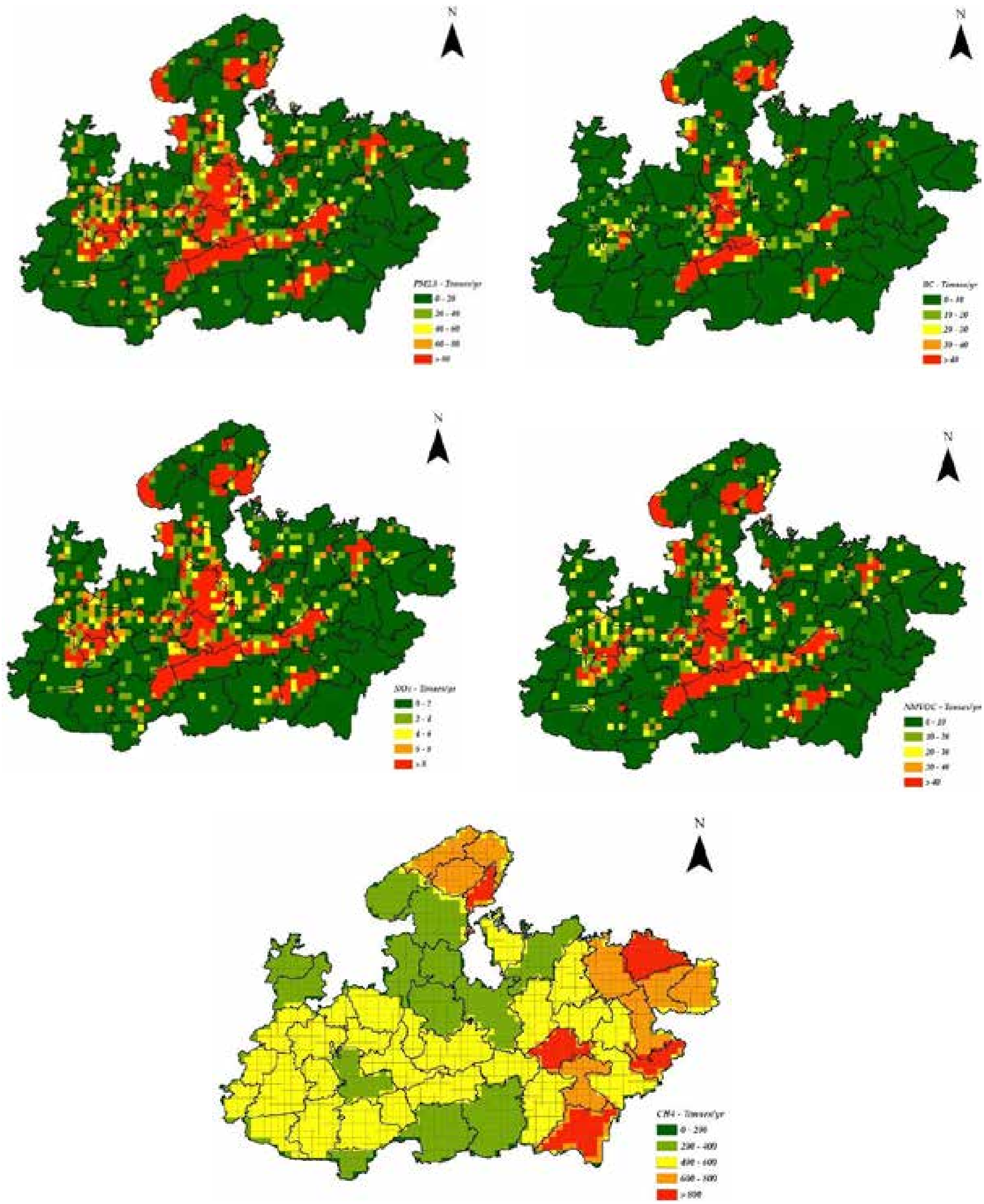


Figure 33: Spatial distribution of Agriculture and livestock sector emissions for different pollutants in MP at 12×12 km grid scale

Livestock farming is another critical component of the state's rural economy and a significant contributor to methane emissions, primarily from enteric fermentation and manure management. Madhya Pradesh has an animal density of 110 per square kilometer, with Sidhi district having the highest livestock population and Burhanpur district the lowest. Tikamgarh has the highest animal density, while Hoshangabad has the lowest. The state ranks third in the country for milk production, with a total output of 171 thousand metric tonnes, and Morena and Sheopur are the leading milk-producing districts. To further enhance milk production, the Cooperative Dairy Development Program, modelled after Anand's dairy initiative, was introduced in 1970. The emission of CH_4 from the enteric fermentation of cattle was estimated as 843 kt during 2019-20.

Given the extensive agricultural and livestock activities, emissions from these sectors—particularly methane from rice cultivation and livestock, as well as nitrous oxide from fertiliser use—significantly contribute to air pollution and greenhouse gas emissions in Madhya Pradesh.

The following analysis, done under this study for 2019, illustrated in Figure 33 shows district-level emissions for both sources, highlighting spatial variation and relative contributions. Emissions from rice cultivation show a high degree of variability across districts, largely influenced by the extent of irrigated paddy fields. Districts like Balaghat (28.8 kt), Rewa (20.8 kt), Raisen (16.4 kt), Mandla (15.1 kt), Satna (15.0 kt), and Jhabua (14.5 kt) recorded the highest methane emissions from rice cultivation, due to significant paddy-growing areas in these districts. For the livestock sector, emissions from the total bovine population were considerably higher in magnitude compared to rice cultivation. The leading districts include Sagar (26.23 kt), Morena (24.59 kt), Rewa (24.98 kt), Khargone (24.14 kt), Chhindwara (23.21 kt), and Satna (22.35 kt). These districts have large cattle and buffalo populations, contributing significantly to enteric methane emissions due to the ruminant digestive process.

A few districts, such as Balaghat, Betul, Chhatarpur, and Chhindwara, show high emissions from both rice cultivation and livestock, making them dual hotspots for methane emissions within the agricultural domain. Conversely, urbanized districts like Bhopal exhibited relatively low total emissions from both sources, consistent with their reduced agricultural land use and smaller livestock holdings.

The data clearly demonstrate that while livestock-related emissions dominate in terms of absolute values across all districts, the spatial pattern of rice cultivation emissions adds further granularity and helps identify priority areas for targeted mitigation. Addressing these emissions through improved livestock management, sustainable rice cultivation practices, and targeted mitigation strategies is essential for reducing environmental impacts while ensuring food security and economic stability in the state. The section below provides the BAU and ALT scenarios from the agriculture and livestock sectors, as both sectors have different mitigation strategies and due to the importance of these sectors in overall emission of CH_4, the intervention analysis has been done in a separate section.

BAU Scenario of the Agriculture Sector in Madhya Pradesh

In Madhya Pradesh, rice is grown on about 3 lakh 7 thousand hectares of land during the kharif season under rainfed conditions, and on roughly 4,000 hectares during the summer (Rabi) season using irrigation water. The rice cropland in the state was estimated to emit 257 kt of CH_4 in 2019–20. The annual rice production in the state in 2019–20 was ~7.3 Mt, which is 4% of the total annual rice production in the country

The domestic demand for rice in India is projected to be 197 Mt/annum during 2050-51 (NRRI, 2020). Furthermore, it is anticipated that rice exports will rise in order to support the anticipated economic expansion of India by 2050–51. It was estimated that, taking into account the rice exports, the nation will need roughly 227 million tons of rice during 2050-51. Considering the contribution of the state to the total annual rice production of the country remains constant, it was estimated that the rice production in Madhya Pradesh will reach roughly 9.1 Mt/year during 2050-51. The state's rice growing area must be expanded from 3.1 Mha in 2019–20 to 4.9 Mha by 2050–51 under the current crop yield scenario. The emissions in the BAU scenario will rise from 257 kt/yr in 2019 to about 471 kt/yr in 2047. The overall emission pathway for the BAU scenario has been illustrated in Figure 34.

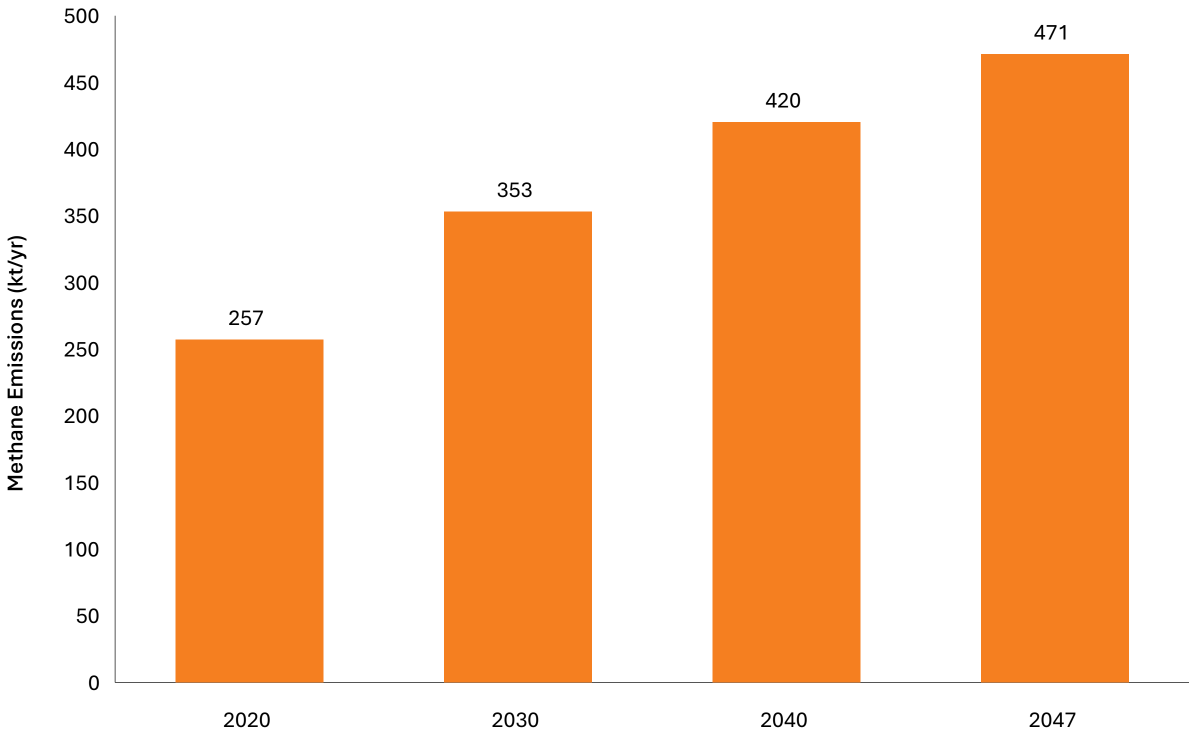


Figure 34:BAU scenario of methane emissions for different years from agriculture sector

Alternative Scenarios of the Agriculture Sector in Madhya Pradesh

To mitigate methane emissions from rice cultivation and livestock, Madhya Pradesh is exploring sustainable agricultural practices. Key strategies include Direct Seeded Rice (DSR) with improved water management, biochar application, and natural farming, each contributing to reduced emissions and improved soil health. DSR adoption aims to conserve water and cut methane emissions from flooded rice fields, while biochar offers an alternative to crop residue burning, significantly lowering emissions. Natural farming, already widespread in the state, enhances soil resilience and reduces methane emissions from rice ecosystems. In addition to these measures, a complete ban on open burning of crop residues is assumed to be effectively implemented by 2030 across the state. This intervention is expected to result in a 100% reduction in all pollutant emissions from agricultural burning in all scenarios and across the three target years (2030, 2040, and 2047). Table 37 summarises the key assumptions for each scenario.

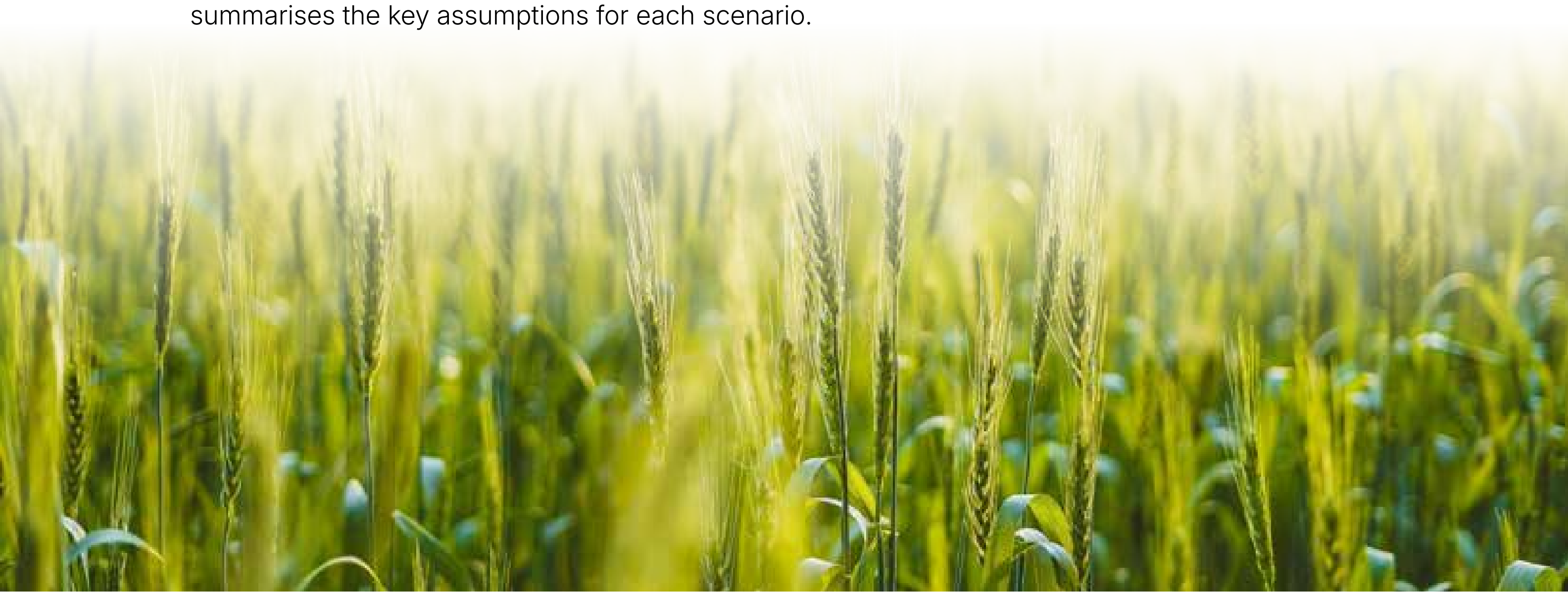


Table 37: Descriptions of the Alternative Scenarios Assessed in the Agriculture Sector

Scenarios	Assumption
ALT-1	▪ Promotes DSR to reduce water use, labor costs, and methane emissions. ▪ 30,000 ha adopted DSR in drought-prone districts (2022-23). ▪ 5% annual DSR adoption (2030-40), increasing to 8% (2040-50). ▪ A complete ban on agricultural residue burning is assumed from 2030 onward, resulting in a 100% reduction in associated emissions.
ALT-2	▪ Biochar from crop residue (40-60 million tonnes annually) as an alternative to burning is promoted. ▪ Combining biochar with intermittent flooding can reduce methane emissions by up to 60%. ▪ A complete ban on agricultural residue burning is assumed from 2030 onward, resulting in a 100% reduction in associated emissions.
ALT-3	▪ Madhya Pradesh leads with 1.731 million ha under natural farming (~45% of India's total). ▪ Expansion under Madhya Pradesh Natural Agriculture Development Board (2022) and NMNF. ▪ 20% annual adoption (2030-40), rising to 30% (2040-50). ▪ A complete ban on agricultural residue burning is assumed from 2030 onward, resulting in a 100% reduction in associated emissions.

Alternative scenario 1 (ALT-1): DSR with water management

(Based on DSR Guidelines (MP & DoAFW)

The Direct Seeded Rice (DSR) implementation policy in Madhya Pradesh, India, is part of a broader effort to promote sustainable rice cultivation, conserve water, reduce labour costs, and address environmental concerns like methane emissions rising from paddy cultivation. While there isn't a single, standalone "DSR Implementation Policy" document exclusively for Madhya Pradesh, the state has integrated DSR promotion into its agricultural strategies, aligning with national and regional goals for climate-resilient farming.

In Madhya Pradesh, DSR adoption has been limited compared to northern states. For instance, in 2022-23, anecdotal evidence from agricultural department reports and news suggests that DSR was implemented on a few thousand hectares as part of pilot projects and awareness campaigns. It was estimated by the state Agriculture department that about 30,000 ha of rice growing area have been adopted to DSR in drought-prone districts of the state. Given the state's policy push—through subsidies on seed drills, training via Krishi Vigyan Kendras (KVKs), and private sector involvement, DSR coverage is likely to increase by 2030. It was assumed that about 5% rice growing area will be adopted to DSR annually between 2030-31 and 2040-41, while this rate will increase to 8% between 2040-41 and 2050-51.

Alternative scenario 2 (ALT-2): Biochar application to cropland

(Based on DoFW&AD, KVK, Research)

Biochar application is implicitly supported and encouraged within the broader framework of the state's agricultural and environmental policies, which align with national initiatives promoting sustainable farming, soil health, and climate change mitigation. Madhya Pradesh generates significant crop residue, including rice straw, with estimates of 40-60 million tonnes annually across all crops. The state discourages residue burning—a widespread practice that contributes to air pollution—and encourages alternatives like biochar production. While not a formal policy, pilot projects and extension programs in the state have explored converting rice straw into biochar. Combining biochar with intermittent flooding can reduce methane emissions upto 60% .

Alternative scenario 3 (ALT-3): Natural farming

(Based on National Mission on Natural Farming (NMNF) & MP Natural Farming Board)

Madhya Pradesh has promoted natural farming through the Madhya Pradesh Natural Agriculture Development Board (established in April 2022) and aligns with national initiatives like the National Mission on Natural Farming (NMNF). The state has historically led in organic farming acreage, with 0.76 million hectares under organic cultivation by 2020.

In May 2022, Madhya Pradesh's Farmer Welfare and Agriculture Minister reported that 17.31 lakh hectares (1.731 million hectares) out of India's 38 lakh hectares (3.8 million hectares) of natural farming were in Madhya Pradesh. This suggests that ~45% of India's natural farming area was in the state at that time. It was assumed that initially there will be similar adoption rate of NF as that of DSR; however, following the adoption rate of natural farming in the state it was assumed that the annual rate of adoption to natural farming will increase to 20% of cropping area for 10 years after 2030-31 and 30% for 10 years after 2040-41. Evidently, different methods of natural farming can reduce methane emissions from rice ecosystems by about 65%.

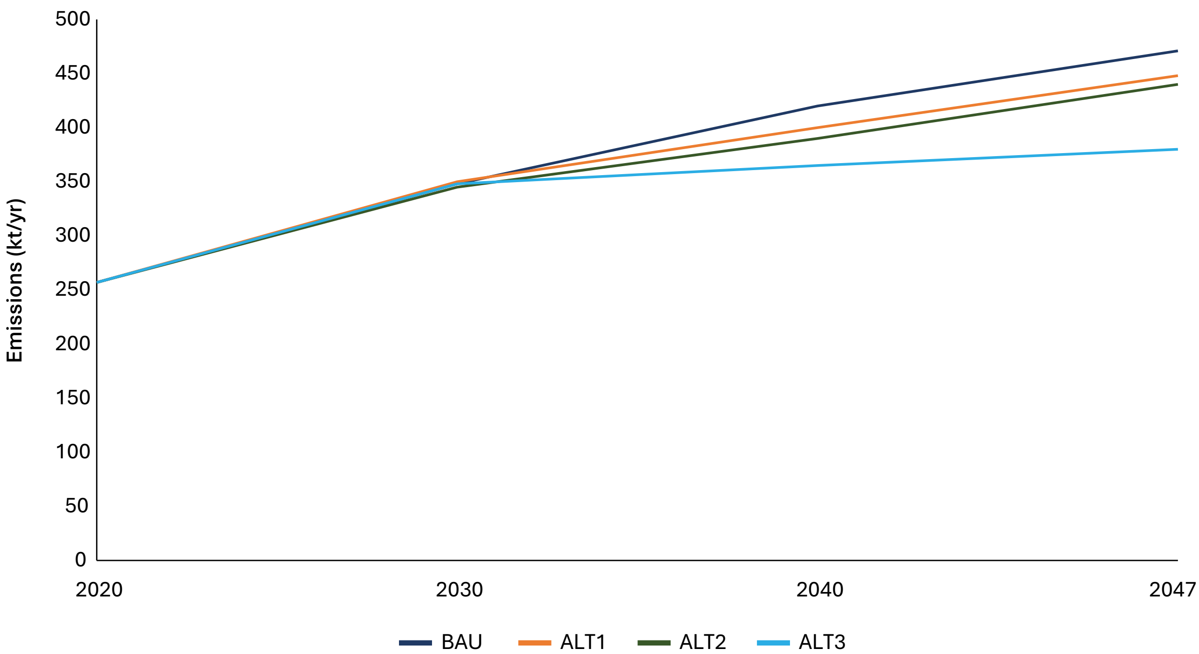


Figure 35: Agricultural CH_4 emission pathways under different ALT scenarios of Madhya Pradesh compared to BAU

Table 38: Change in Agricultural Emissions Under Alternate Scenarios, Compared to 2047

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: DSR with water management	-100%	-100%	-100%	-100%	-100%	-100%	-3%
ALT 2: Biochar application to cropland	-100%	-100%	-100%	-100%	-100%	-100%	-6%
ALT 3: Natural farming	-100%	-100%	-100%	-100%	-100%	-100%	-20%

BAU Scenario of the Livestock Sector in Madhya Pradesh

Milk demand in India is projected to grow significantly, driven by population growth, rising incomes, and shifting dietary preferences. By 2030, the milk demand will reach around 300 million tons, as estimated by the National Dairy Development Board (NDDB) of India. This suggests an annual growth of ~6% in milk production. This demand surge is attributed not only to population growth but also to increasing urbanisation and a higher focus on protein-rich diets, which include dairy products. Meeting this demand will require continued improvements in productivity, number of cattle and animal health, apart from rural milk infrastructure development.

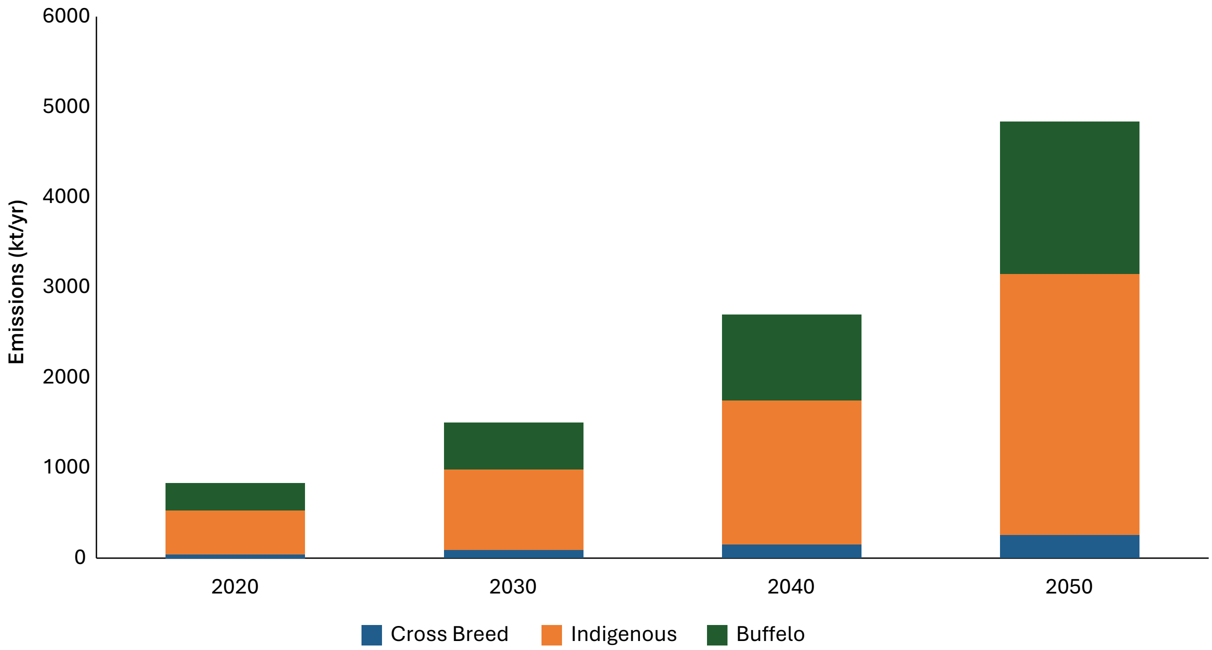


Figure 36: BAU scenario CH_4 emissions from different livestock

Madhya Pradesh produced (17.8 Mt (Million Ton)) about 8.6% of the total annual milk production (198.4 MMT) in the country during 2019-20. Accordingly, the projected milk production in the state was estimated as 30.6 Mt in 2030-31, 54.8 Mt in 2040-41 and 98.2 Mt in 2050-51 following a 6% annual increase in milk production to meet the rising demand of the country, keeping the same share of milk production of the state in the country.

The milk production was converted to the total cattle population following the distribution of the total cattle population in the state during 2019-20. This suggested a significant increase in methane emission due to enteric fermentation of the cattle population during 2050-51 compared to that in 2019-20. Under the BAU scenario, CH_4 emissions from cattle populations in the state were estimated as 1509 kt/yr, 2703 kt/yr and 4841 kt/yr kt/yr during 2030-31, 2040-41 and 2050-51, respectively as illustrated in figure 36.

Alternative Scenarios of the Livestock Sector in Madhya Pradesh

The study assessed the impact of major livestock policies being implemented in the state of Madhya Pradesh, such as fodder management and promotion of indigenous cattle. But the policies individually are not sufficient to combat the issue of milk requirement and methane reduction. Optimizing fodder quality enhances digestion efficiency, reducing methane emissions per unit of milk produced. Encouraging indigenous cattle breeds aligns with natural farming initiatives but requires balancing milk demand while managing emissions. Integrating both approaches—nutritional enrichment and cattle population shifts—offers a more effective pathway for emission reduction. Table 39 summarizes the key assumptions for each scenario.

Table 39: Descriptions of the Alternative Scenarios Assessed in the Livestock Sector

Scenarios	Assumption
ALT-1	▪ Inspired by National Dairy Development Board (NDDB) initiatives. ▪ Encourages balanced feeding to optimize energy, protein, and minerals.
ALT-2	▪ Financial incentives to farmers for adopting indigenous breeds under natural farming schemes. ▪ The crossbreed and buffalo population decreases by 5% annually. ▪ To sustain milk production, the indigenous cattle population increases: ▪ +500 cattle (2020-30), +900 cattle (2030-40), +1,600 cattle (2040-50).
ALT-3	▪ Combines fodder management with indigenous cattle promotion (ALT1 + ALT2). ▪ Balanced feeding will be more effective in reducing emissions compared to Scenario 2 alone.

Alternative scenario 1 (ALT1): Fodder management

(Based on National Dairy Development Board (NDDB) Guidelines)

Inspired by national efforts like those of the National Dairy Development Board (NDDB), Madhya Pradesh encourages balanced feeding practices for cattle. These programs optimize nutrient intake (energy, protein, and minerals) to improve milk productivity. The change in fodder quality is reportedly reducing the CH_4 emissions from enteric fermentation by 10-15%

Alternative scenario 1 (ALT2): Promotion of indigenous cattle population

(Based on MP Natural Farming Initiatives)

The Madhya Pradesh government is promoting the indigenous cattle population in the state as part of natural farming scheme through financial support to the farmers adopting to indigenous cattle breed. It was assumed that the cross breed and buffalo population in the state will decrease by 5% annually and accordingly the population of indigenous cattle will increase to support the estimated future milk production in the state. It is important to meet the demand of milk while decreasing the population of cross breed cattle. It was estimated that additional about 500 dairy indigenous cattle population will be required between 2020 and 2030, about 900 dairy indigenous cattle population between 2030 and 2040 and ~1600 indigenous cattle between 2040 and 2050. However, this increase overall methane emission from enteric fermentation.

Alternative scenario 1 (ALT3): Promotion of indigenous cattle vis-à-vis nutritional enrichment (Based on the combination of ALT1 and ALT2)

The decrease in crossbreed and buffalo population under scenario 2 reduces the CH_4 emission from the enteric fermentation of daily cattle; however, when fodder management also included with the cattle population management, these together further reduce the emission of CH_4 from the enteric fermentation of the cattle. The changes in methane emissions from enteric fermentation of cattle livestock in Madhya Pradesh under different policy scenarios have been illustrated in Figure 37.

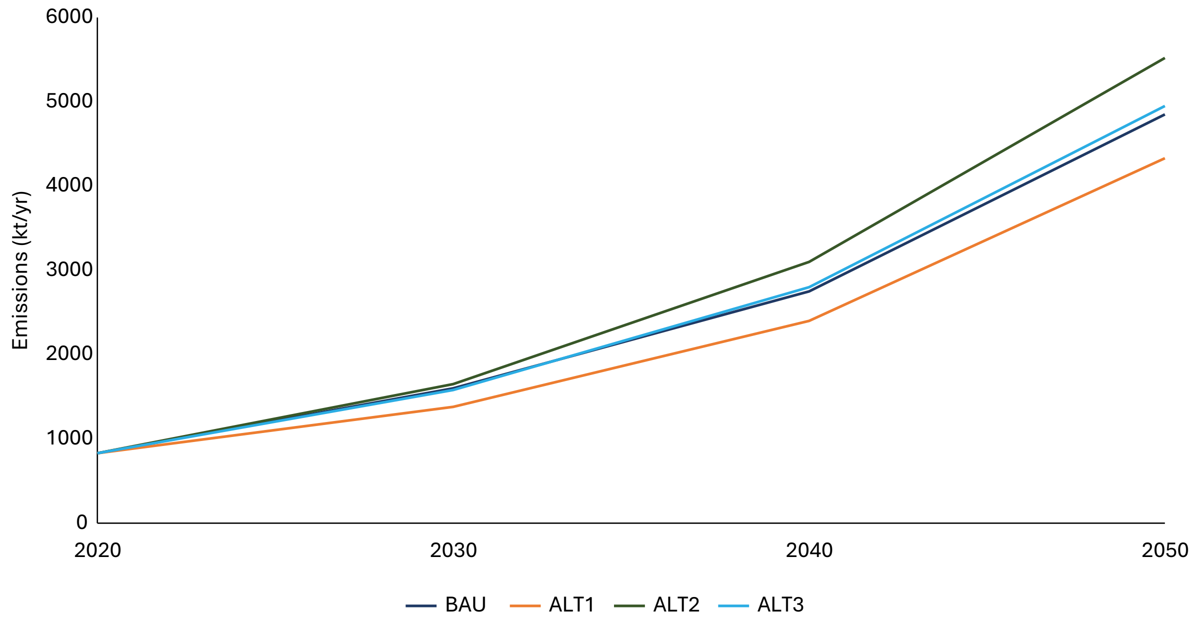


Figure 37: Livestock sector's CH_4 emission pathways under different ALT scenarios of Madhya Pradesh compared to BAU

Figure 37 below presents the projected methane emissions from enteric fermentation in Madhya Pradesh's livestock sector, disaggregated by animal category—crossbreeds, indigenous cattle, and buffaloes—under BAU and three alternative scenarios (ALT1, ALT2, ALT3) from 2020 to 2050. Across all scenarios, indigenous cattle emerge as the dominant source of methane emissions, reflecting their larger population share and the shift in livestock composition. Under BAU, emissions from indigenous cattle increase consistently, from approximately 497 kt in 2020 to 2857 kt in 2050, accounting for nearly 60% of total methane emissions by the end of the period. Emissions from crossbreeds and buffaloes also rise, but to a lesser extent, reflecting proportional herd growth.

Under ALT1, ALT2, and ALT3, emissions trends vary based on the mix of herd management and nutritional interventions. ALT1, focused on improved feeding, achieves lower emissions across all categories despite growth in indigenous cattle, due to better nutrient efficiency. ALT2, which prioritises indigenous breed promotion while phasing out crossbreeds and buffaloes, results in the highest methane emissions by 2050, driven by a significant rise in indigenous cattle. ALT3, which combines both strategies, moderates this increase—indigenous cattle remain the main source, but better feed quality helps curb emissions, keeping overall levels lower than ALT2.

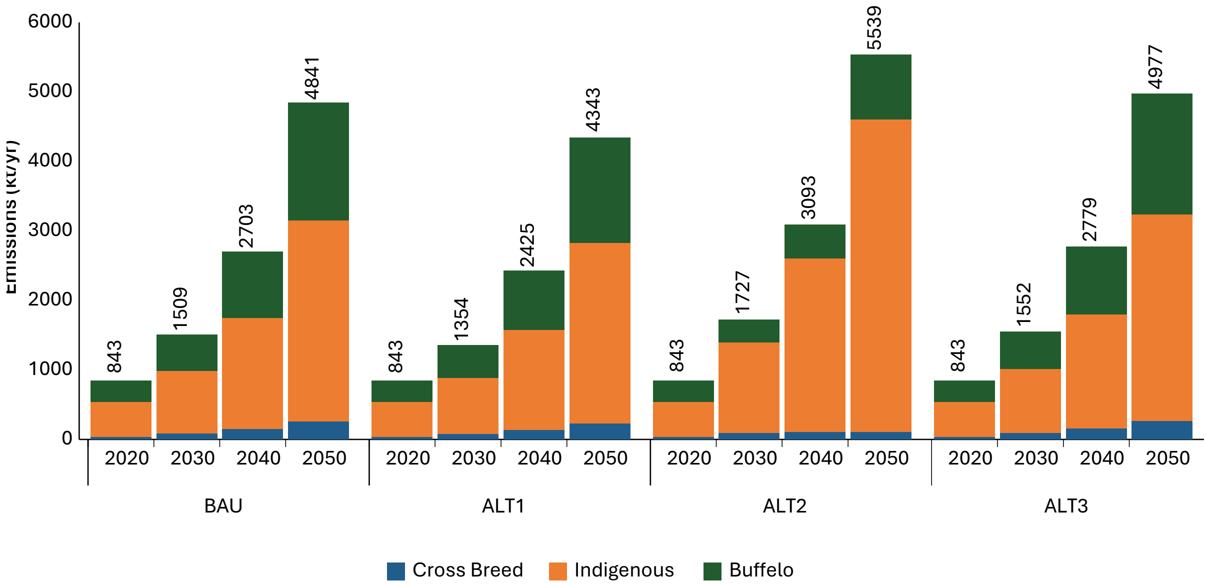


Figure 38: Changes in methane emissions from enteric fermentation of cattle livestock in Madhya Pradesh under different policy scenarios

Overall, the analysis highlights that while indigenous cattle are central to maintaining dairy production, their increasing numbers could significantly raise methane emissions unless complemented by nutritional interventions and herd optimization strategies, as reflected in ALT1 and ALT3.

Table 40: Change in Livestock Emissions Under Alternate Scenarios, Compared to 2047

Scenarios	$PM_{2.5}$	SO_x	NO_2	CO	VOCs	BC	CH_4
ALT 1: Fodder management	-	-	-	-	-	-	-10%
ALT 2: Promotion of indigenous cattle population	-	-	-	-	-	-	14%
ALT 3: Promotion of indigenous cattle vis-à-vis nutritional enrichment	-	-	-	-	-	-	3%

Key Insights from the Agriculture and Livestock Sector Analysis

The agriculture and livestock sector in Madhya Pradesh is a major source of SLCP emissions, contributing around 47% of the state's BC, 80% of CH_4, and 2% of NO_x emissions as of 2019—primarily from enteric fermentation, rice cultivation, and crop residue burning. Enteric fermentation alone accounts for over 79% of the state's methane emissions, with hotspots in Bundelkhand and Chambal. While particulate emissions are lower overall, they spike during the harvesting season due to widespread burning. Under a BAU scenario, emissions are projected to rise significantly by 2047, driven by intensified farming and growing demand for livestock products. To address this, six alternative mitigation scenarios—three each for agriculture and livestock—were evaluated under this study.

Addressing CH_4 emissions from rice cultivation and BC emissions from crop residue burning are key challenges in Madhya Pradesh's agriculture sector. Three alternative mitigation scenarios assessed under the study—ALT1 (Direct Seeded Rice), ALT2 (Biochar Application), and ALT3 (Natural Farming)—offer varied co-benefits and feasibility considerations. Among the three, ALT3 emerges as the most effective long-term strategy for reducing methane emissions, with potential reductions of up to 65% from rice ecosystems. The state already leads in the practice of natural farming, offering a strong institutional foundation for expansion. However, its broader adoption faces challenges including the need for behavioral change among farmers, reduced initial yields in some cases, and the requirement for sustained extension support. ALT3 should be prioritized in districts where natural farming is already being promoted, such as Jabalpur, Sagar, Chhindwara, and Hoshangabad, leveraging momentum and existing capacity. ALT1 provides a technically viable and scalable option, especially in drought-prone and water-stressed districts like Tikamgarh, Chhatarpur, and Datia. CH_4 reductions are significant due to decreased waterlogged conditions, and the method aligns with ongoing state incentives and mechanization schemes. The key barriers include limited awareness, lack of suitable machinery (like seeders and zero-tillage equipment), and the need for reliable irrigation control. Extension efforts through KVKs and bundling DSR with groundwater conservation schemes can help accelerate uptake. ALT2 offers strong potential for simultaneously reducing PM and BC emissions from residue burning and lowering methane when used with intermittent irrigation. However, its success depends on the development of localized biochar production infrastructure, training for application techniques, and market linkages for surplus biomass. It should be targeted in rice-dominant districts with high residue generation, such as Balaghat, Mandla, Seoni, and Shahdol, where the risk of residue burning is higher and land availability for decentralized units is feasible.

In the livestock sector, CH_4 emissions from enteric fermentation are a growing concern, especially with the expanding dairy demand. The state's policy directions—centered on balanced fodder nutrition and promotion of indigenous cattle breeds—offer potential mitigation pathways. However, each intervention has trade-offs between emission reductions, milk productivity, and implementation feasibility. Among the three scenarios, ALT3 (Integrated approach: Indigenous cattle + Balanced feeding) offers the most balanced and sustainable pathway. It offsets the increased methane emissions from a larger indigenous cattle population (as in ALT2) through nutritional interventions that enhance feed efficiency. ALT3 also ensures that milk productivity and methane mitigation can progress hand-in-hand. This scenario should be prioritized in regions with mixed dairy systems and access to fodder enrichment services, such as Indore, Sehore, Dewas, and Ujjain, where cooperative networks and extension systems can support both breed and feed transitions. ALT1 (Fodder management) is the most technically feasible and cost-effective short-term intervention, offering 10–15% reduction in methane emissions without altering livestock composition. It improves digestibility and energy intake, thus enhancing milk yield per animal and reducing emissions per liter of milk. This scenario can be rapidly scaled in intensive dairy districts like Bhopal, Gwalior, and Jabalpur, which already have access to feed distribution infrastructure, veterinary support, and cooperative milk networks. However, its success depends on sustained supply chains for balanced feed ingredients and farmer training.

ALT2 (Indigenous cattle promotion) supports alignment with natural farming efforts and local breed conservation but poses significant challenges. While indigenous breeds require less intensive input and are more resilient to local conditions, their lower milk yields mean that to meet dairy demand, herd sizes must increase, leading to higher absolute methane emissions. Unless paired with nutritional improvements, ALT2 may counteract its own mitigation goals. This approach can be considered in tribal or rainfed regions such as Mandla, Dindori, Betul, and Chhindwara, where indigenous breeds are already prevalent and less dependence on commercial feed exists.

So, in summary, in Madhya Pradesh, a mix of targeted interventions is key to reducing methane emissions while supporting livelihoods. In agriculture, natural farming (ALT3) offers the highest mitigation potential but needs strong institutional support, DSR (ALT1) is easier to scale in drought-prone areas, and biochar (ALT2) provides air quality co-benefits where residue burning is common. In livestock, the combined strategy (ALT3) balances emission reduction with milk demand but requires coordination. Fodder management (ALT1) delivers quick gains in dairy belts, while breed promotion alone (ALT2) may raise emissions if not paired with feed strategies. A district-wise approach will be critical for effective implementation.

Roadmap for Madhya Pradesh: Integrating Sectoral Interventions into a Statewide Strategy

This study presented a comprehensive assessment of alternative strategies to mitigate emissions of SLCPs and some other non-CO_2 pollutants across key sectors in Madhya Pradesh, including residential energy use, transport, industrial combustion, mining, power generation, agriculture and livestock, and municipal solid waste. Each sector was analysed with multiple alternative scenarios to identify the most effective mitigation measures, based on sector-specific emission inventories, future activity projections, and the feasibility of implementation within the state's socio-economic context.

The assessment found that significant emission reductions are technically feasible across all sectors by 2047, as illustrated in Table 41. For instance, in the residential sector, the transition from solid fuels to clean energy alternatives such as LPG, biogas, and solar cookstoves could reduce black carbon and methane emissions by up to 100% and 97%, respectively. Similarly, in the transport sector, a combination of electric vehicle adoption, vehicle scrappage policies, and biofuel blending could reduce $PM_{2.5}$, NO_2, CO, and BC emissions by 52%, 43%, 76%, and 36%, respectively. Industrial combustion emissions could also be drastically reduced by adopting cleaner fuels, energy-efficient boilers, and renewable energy-based processes. Other sectors such as mining, waste, power, and agriculture-livestock also demonstrated meaningful reduction potential under the respective alternative strategies evaluated.

Table 41: Summary of emission reduction under different alternative scenarios compared to BAU in 2047

Sector	Strategies	$PM_{2.5}$	SO_2	NO_x	CO	NMVOCs	BC	CH_4
Residential	ALT 1	-27%	-21%	-13%	-28%	-16%	-28%	-27%
	ALT 2	-94%	-53%	-41%	-98%	-58%	-100%	-89%
	ALT 3	-96%	-76%	-48%	-98%	-58%	-100%	-97%
Transport	ALT 1	-52%	-41%	-43%	-76%	-41%	-36%	-80%
	ALT 2	-31%	-16%	-25%	-44%	-20%	-24%	-58%
	ALT 3	-11%	-15%	-15%	-16%	-9%	-39%	-28%
Industrial combustion	ALT 1	-92%	-89%	-85%	-21%	-29%	-29%	-22%
	ALT 2	-11%	-11%	-10%	-3%	-3%	-3%	-3%
	ALT 3	-8%	-8%	-8%	-8%	-8%	-8%	-8%
	ALT 4	-25%	-21%	-21%	0%	-7%	-7%	-2%
Mining	ALT 1	-74%	-	-	-	-	-	-
	ALT 2	-25%	-	-	-	-	-	-
	ALT 3	-19%	-	-	-	-	-	-
	ALT 4	-60%	-	-	-	-	-	-

Sector	Strategies	$PM_{2.5}$	SO_2	NO_x	CO	NMVOCs	BC	CH_4
Power	ALT 1	-50%	-87%	-93%	-50%	-50%	-50%	-50%
	ALT 2	-30%	-82%	-88%	-18%	-27%	-30%	43%
	ALT 3	-40%	-84%	-91%	-34%	-39%	-41%	-4%
Waste	ALT 1	-77%	-78%	-	-	-	-61%	-16%
	ALT 2	-14%	-14%	-	-	-	-45%	-19%
Agriculture	ALT 1	-100%	-100%	-100%	-100%	-100%	-100%	-3%
	ALT 2	-100%	-100%	-100%	-100%	-100%	-100%	-6%
	ALT 3	-100%	-100%	-100%	-100%	-100%	-100%	-20%
Livestock	ALT 1	-	-	-	-	-	-	-10%
	ALT 2	-	-	-	-	-	-	14%
	ALT 3	-	-	-	-	-	-	3%

While the sector-wise analysis provided a strong understanding of the emission reduction potential under various alternatives, a more integrative approach is necessary to define a feasible yet ambitious emission reduction trajectory for the state. Hence, based on the mitigation performance of each intervention and its alignment with ongoing state and national policies, we selected one preferred strategy from each sector. For sectors where synergies among multiple alternatives could yield greater impact, a combined strategy was adopted. For example, the recommended pathway for transport merges electric vehicle adoption, vehicle scrappage, and biofuel blending policies to leverage both technological and policy-driven reductions. Similarly, the industry pathway combines the adoption of community boilers, green hydrogen usage, and improved coal standards.

These selected interventions have been assembled into a single "recommended pathway" that represents the most effective, regionally adapted strategy for SLCP and co-pollutant mitigation in Madhya Pradesh. The recommended pathway is rooted in science, informed by data, and aligned with existing initiatives such as the National Clean Air Programme (NCAP), State Action Plan on Climate Change (SAPCC), PM Ujjwala Yojana, Swachh Bharat Mission, and others. Importantly, this pathway is designed to not only achieve emission reductions but also to deliver co-benefits for public health, energy access, economic development, and climate resilience.

While the study estimates a comprehensive suite of pollutants—including PM_{10}, $PM_{2.5}$, BC, SO_2, NO_x, NMVOCs, CO, and CH_4—the pathways are presented in detail for five key pollutants: $PM_{2.5}$, BC, CH_4, NO_x, and NMVOCs. These pollutants were selected based on their combined relevance for air quality management and climate change mitigation, as well as their utility as proxies for broader pollutant groups. $PM_{2.5}$, for instance, is the most health-damaging fraction of particulate matter and also serves as a spatial and policy-relevant proxy for PM_{10} and SO_2 emissions. Similarly, NO_2 and NMVOCs are effective indicators of total NO_x and VOC emissions, which are precursors to ground-level ozone—a major pollutant impacting both human health and agriculture. This focused representation ensures analytical clarity, avoids redundancy, and highlights sector-specific hotspots and priorities in a way that is actionable for policymakers and planners.

The subsequent sections of the report present the detailed results from this recommended pathway, outlining the projected reductions in pollutant emissions across different timeframes (2030, 2040, and 2047), while also highlighting the expected air quality and climate benefits for Madhya Pradesh.

Recommended Pathway for Madhya Pradesh

Based on the analysis conducted in this study, Madhya Pradesh demonstrates substantial potential for reducing emissions of SLCPs and other non-CO_2 pollutants across multiple sectors. Achieving these reductions would support India's national climate commitments and enhance the long-term sustainability of the state's economy. However, effective mitigation requires the establishment of well-defined policy targets, which must be informed by a comprehensive understanding of sector-specific emission profiles. Table 42 summarises key policy measures that, while ambitious, can be implemented by the state through appropriate incentives and prioritisation to support the mitigation of SLCPs and non-CO_2 pollutants across relevant sectors. These interventions have been identified based on the assessment carried out in this study to evaluate their emission reduction potential. Building on this, we assessed the projected reductions in emission loads of SLCPs and other non-CO_2 pollutants across various sectors in Madhya Pradesh that could be achieved through the implementation of these selected interventions. Figures 39–43 illustrate the results of this analysis, which compares emissions from all major sectors under the baseline scenario with those under the intervention scenarios, highlighting the potential impact of alternative sectoral strategies.

Table 42: Selected policies with maximum possibility of implementation and reduction (Recommended Pathway)

Sector	Scenario	Policy Basis / Strategy	Description
Residential	ALT-3	Focus on "Surya Nutan" Solar Cooking Initiative (EKI & IOCL)	Population growth at 1.39% (rural) and 1.97% (urban) per year. LPG consumption grows annually by 10.68%, based on government data. By 2030, 20% of non-LPG users adopt improved cookstoves, 20% switch to biogas, and 60% use solar cookstoves. By 2040, 80% of non-LPG users will transition to solar cookstoves, while 20% use biogas and 10% continue with improved cookstoves. By 2047, all non-LPG users will shift entirely to solar cookstoves.
Transport	Combined Strategy of ALT-1, ALT-2 and ALT-3	Madhya Pradesh Electric Vehicle (EV) Policy, 2025 National Vehicle Scrappage Policy, 2022 National Policy on Biofuels, 2018	By 2030, 40% of all new 2w and 100% of new commercial two-wheelers will be EVs. Additionally, 70% of new 3w, 15% of new 4w, and 40% of new buses will also be EVs. Biodiesel blending will be set at 5%, and 30% of 20-year-old petrol and 15-year-old diesel vehicles will be scrapped. By 2040, 50% of all vehicle fleets will be EVs, with biodiesel blending increasing to 10%. Scrapping will extend to 60% of 20-year-old petrol and 15-year-old diesel vehicles. By 2047, 70% of vehicle fleets across all districts will transition to EVs, with biodiesel blending reaching 20%. At this point, 80% of 20-year-old petrol and 15-year-old diesel vehicles will be scrapped, ensuring a cleaner, more sustainable transport sector.

Sector	Scenario	Policy Basis / Strategy	Description
Industry	Combined Strategy of ALT-2, ALT-3 and ALT-4	CPCB Guidelines on Community Boilers, 2024. MP Renewable Energy Policy, 2022. MoEFCC Coal Ash Standards.	30% reduction in fuel use via adoption of community boilers (ALT2) Transition to washed coal, achieving 40% lower ash and 30% lower sulphur content, with uptake of 25% by 2030, 50% by 2040, and 70% by 2047 (ALT4) Green hydrogen substitution for industrial energy demand, with 5% adoption by 2040 and 8% by 2047 (ALT3)
Mining	ALT-1	These assumptions are based on TERI's experience and discussions with different stakeholders like Kaniha, MCL (Mahanadi Coal-field Limited).	The sprinkling of water at every stage, including the loading and unloading of overburden and coal, reduces the emission by 75%, and the transport of coal and overburden reduces the emission by 70%.
Power	ALT-3	MP Renewable Energy, Wind, and Solar Policies Gas-Based Generation (State Planning)	Mix of ALT-1 and ALT-2, combining RE scale-up with partial gas-based substitution. By 2030, 55% of total energy demand will be met through cleaner sources, with 10% of biomass used for co-firing in boilers at thermal power plants. Additionally, 5% of coal-based thermal energy will be replaced by gas, and 100% of thermal power capacity will be equipped with FGD and SCR. By 2040, the share of cleaner energy will increase to 60%, with 10% of coal-based thermal energy replaced by gas. By 2047, cleaner energy will account for 65% of total demand, and 15% of coal-based thermal energy will be replaced by gas.
Agriculture	ALT-3	National Mission on Natural Farming (NMNF) & MP Natural Farming Board, MoEFCC, National Clean Air Programme. (2019) (ban on burning of agriculture waste and crop residues)	The adoption rate of natural farming (NF) in Madhya Pradesh was initially assumed to mirror that of Direct Seeded Rice (DSR). However, based on observed trends in the state, it is projected that the annual adoption rate of NF will accelerate to 20% of the cropping area for the decade following 2030-31, and further increase to 30% for the decade after 2040-41. In addition, a complete ban on agricultural residue burning is assumed from 2030 onward, resulting in a 100% reduction in associated emissions.
Livestock	ALT-3	National Dairy Development Board (NDDB) Guidelines	Combines balanced feeding (ALT-1) with the promotion of indigenous cattle (ALT-2). It focuses on optimising energy, protein, and minerals in cattle diets while increasing the indigenous cattle population by +500 (2020-30), +900 (2030-40), and +1,600 (2040-50).
Waste	ALT-2	MPPCB ISWM Cluster Model	Assumes 99% of collected waste is diverted, prioritising waste combustion and recycling, while composting and AD remain at BAU levels. Of the diverted waste, 66% goes to composting, 1% to anaerobic digestion, 14% to waste combustion, and 27% to recycling. With 99% collection and treatment efficiency, open burning is reduced, assuming 2% of uncollected waste is burned by residents and 2% at landfills.

$PM_{2.5}$ emission pathway of Madhya Pradesh

In 2019, the residential sector was the second-largest contributor to PM2.5 emissions in Madhya Pradesh, accounting for approximately 23% of the total. Under the Business-as-Usual (BAU) scenario, this share is projected to rise to 37% by 2030, before dropping sharply to just 8% by 2047. This trend reflects increased LPG penetration and a corresponding decline in biomass use, alongside a complete phase-out of open burning of agricultural residue—the state's largest source of $PM_{2.5}$—assumed to be eliminated by 2030 due to the effective enforcement of a total ban this causes in percent terms shares of other sectors to rise compared to 2019.

In 2019, the industry and mining sector and the transport sector were the third and fourth largest contributors, with estimated shares of 14% and 7%, respectively. Under the BAU scenario, the industry and mining sector's share is expected to rise substantially, reaching 40% by 2030 and 64% by 2047. In contrast, the transport sector's share remains relatively stable—11% in 2030 and 9% in 2047—though its absolute emissions continue to increase over time.

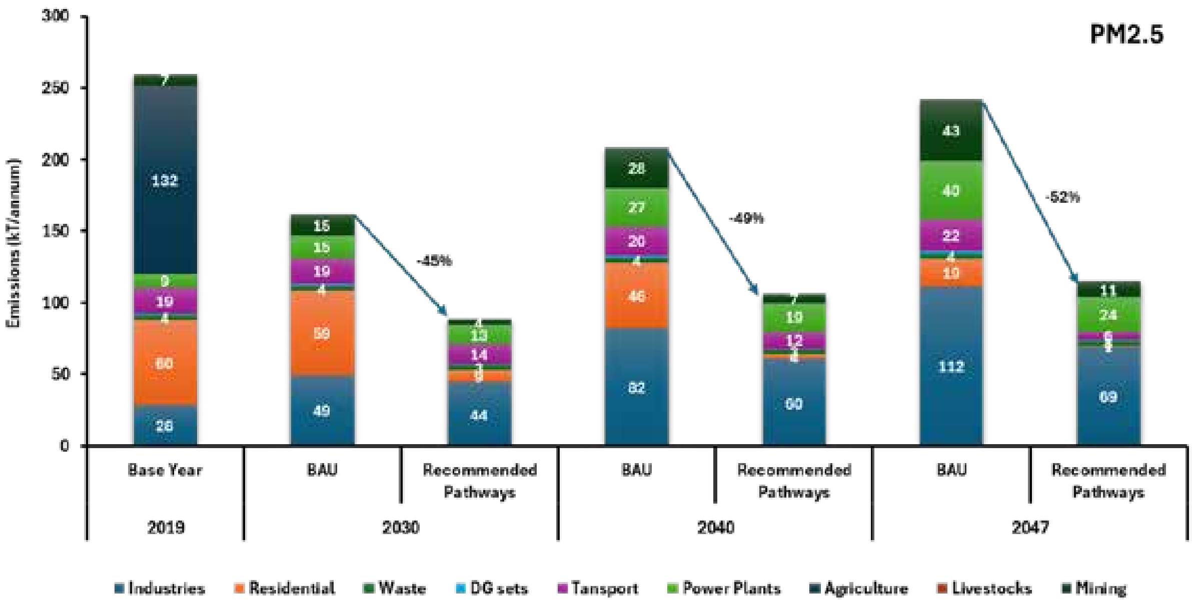


Figure 39: Annual changes in $PM_{2.5}$ emission under recommended pathways w.r.t BAU scenario

The recommended pathways for $PM_{2.5}$ emission reduction in Madhya Pradesh present a comprehensive strategy across various sectors. In the residential sector, the "Surya Nutan" Solar Cooking Initiative aims to transition non-LPG users to cleaner cooking technologies. By 2030, 60% of non-LPG users are expected to use solar cookstoves, with the remaining 40% split between improved cookstoves and biogas. By 2047, all non-LPG users are projected to shift entirely to solar cookstoves, reducing residential $PM_{2.5}$ emissions from 60 kt/yr in 2019 to just 1 kt/yr by 2047. The transport sector's recommended pathway integrates multiple strategies, including the Madhya Pradesh EV Policy, the National Vehicle Scrappage Policy, and the National Policy on Biofuels. This combined strategy aims to reduce $PM_{2.5}$ emissions through enhanced EV adoption, phasing out older vehicles, and incorporating biodiesel blending, resulting in a decrease from 19 kt/yr in 2019 to 6 kt/yr by 2047.

For the industry sector, the recommended pathway combines guidelines from the NCAP Industrial Emission Guidelines, CPCB Guidelines on Community Boilers, and the MP Renewable Energy Policy. This integrated approach promotes the use of gaseous fuels, energy-efficient boilers, and green hydrogen in industrial applications, leading to a reduction in industrial $PM_{2.5}$ emissions from 28 kt/yr in 2019 to 69 kt/yr by 2047, despite increased industrial activity. The power plants sector involves a hybrid approach that combines renewable energy scale-up with partial gas-based substitution, aiming to reduce reliance on coal and increase the use of cleaner energy sources. Consequently, $PM_{2.5}$ emissions from power plants are projected to decrease from 9 kt/yr in 2019 to 24 kt/yr by 2047.

The waste sector's recommended pathway envisions enhanced waste recovery through the MPPCB ISWM Cluster Model, promoting decentralised waste management and material recovery facilities, maintaining waste sector emissions at a low level, reducing from 4 kt/yr in 2019 to 3 kt/yr by 2047. In the mining sector, measures such as water sprinkling at various stages of coal handling are expected to significantly reduce $PM_{2.5}$ emissions, from 7 kt/yr in 2019 to 11 kt/yr by 2047. The agriculture sector is projected to have zero $PM_{2.5}$ emissions under the recommended pathways, transitioning to natural, low-input farming practices supported by the National Mission on Natural Farming. Similarly, the livestock sector's emissions are expected to remain negligible due to integrated strategies that maximise SLCP reductions. Overall, the recommended pathways aim to achieve substantial reductions in $PM_{2.5}$ emissions across all sectors, contributing to improved air quality and public health in Madhya Pradesh.

NO_x emission pathway of Madhya Pradesh

NO_x is a significant contributor to ground-level ozone and secondary $PM_{2.5}$ formation. In Madhya Pradesh, NO_x emissions in the base year 2019 were primarily driven by fossil fuel combustion in the power sector (289 kt, or 47%) and transport sector (281 kt, or 45%), together accounting for 92% of total NO_x emissions. Under the BAU scenario, emissions from these sectors are expected to grow sharply, particularly from power plants, which are projected to emit 1,082 kt of NO_x by 2047, nearly a fourfold increase from 2019 levels. This rise is attributed to the expanding coal-fired capacity to meet rising electricity demand. In contrast, NO_x emissions from the transport sector show a much more gradual increase under BAU, rising to 360 kt by 2047, due to the expected growth in vehicle population.

However, the recommended pathway scenario projects a very different trajectory, underpinned by a mix of cleaner technologies and policy interventions. In the power sector, the adoption of a hybrid strategy that includes a strong scale-up of renewable energy and partial substitution with gas-based power plants leads to a dramatic decline in NO_x emissions—from 289 kt in 2019 to just 102 kt by 2047. This is a 91% reduction compared to the BAU level for the same year, demonstrating the high mitigation potential of decarbonising the power sector. In the transport sector, the implementation of BS-VI emission norms and the promotion of EVs under the Madhya Pradesh EV Policy have a significant dampening effect on emissions growth. As a result, NO_x emissions from transport are projected to decline from 281 kt in 2019 to 176 kt in 2047 under the recommended pathway—almost half the BAU estimate of 360 kt, despite continued expansion in the vehicle fleet.

Other sectors also contribute to the overall emission reductions. In the residential sector, cleaner cooking solutions such as LPG, solar, and biogas stoves reduce NO_x emissions from 23 kt in 2019 to just 7 kt by 2047 under the recommended scenario. The industrial sector shows modest but important reductions, with emissions peaking at 26 kt in 2047 under BAU but limited to 18 kt under the recommended strategy, thanks to the adoption of energy-efficient boilers, green hydrogen use, and compliance with stricter emission standards. Notably, emissions from DG sets, a traditionally neglected source, are projected to increase even under the recommended pathway, rising from 8 kt in 2019 to 33 kt in 2047, indicating a need for further targeted action in this area.

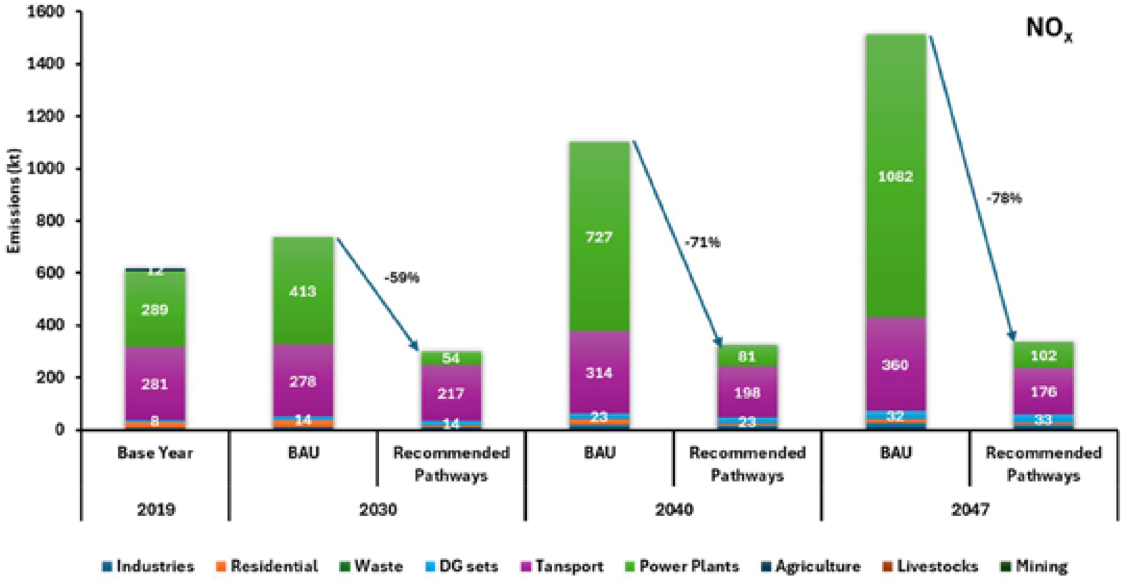


Figure 40: Annual changes in NO_x emission under recommended pathways w.r.t BAU scenario

Overall, the implementation of the recommended interventions across sectors results in substantial reductions in total NO_x emissions: by 59% in 2030, 71% in 2040, and 78% in 2047 compared to the BAU scenario, as illustrated in Figure 40. These findings highlight the importance of integrated action across sectors, particularly in power and transport, and demonstrate how climate-aligned policies can simultaneously deliver large-scale air quality and health benefits. The sustained reductions in NO_x emissions also help reduce ozone and secondary $PM_{2.5}$ concentrations, which are key to achieving both short- and long-term clean air targets in the state.

NMVOCs emission pathway of Madhya Pradesh

NMVOCs are also important precursors to ground-level ozone and secondary organic aerosols, contributing significantly to air pollution and public health risks. In 2019, NMVOC emissions in Madhya Pradesh were predominantly from the residential sector (223 kt, 49%) and the transport sector (169 kt, 37%), together accounting for over 86% of total emissions. The high emissions from the residential sector stem largely from the use of solid biomass fuels for cooking, which release unburnt hydrocarbons and other volatile compounds. In the transport sector, emissions arise from incomplete combustion in petrol- and diesel-powered vehicles, especially in urban centres.

Under the BAU scenario, NMVOC emissions from the residential sector are projected to decline gradually to 110 kt by 2047, reducing its share to 30% of the total, as clean cooking fuels like LPG and solar cookstoves become more widely adopted. Conversely, emissions from the transport sector continue to increase under BAU, reaching 185 kt by 2047, and becoming the largest source of NMVOCs (51%), due to rising vehicular demand, despite improvements in fuel quality and emission standards.

The recommended pathway, however, introduces targeted interventions across both of these sectors that significantly reduce total NMVOC emissions. In the residential sector, the adoption of solar cookstoves under the Surya Nutan initiative, biogas systems, and improved cookstoves results in a reduction from 223 kt in 2019 to just 46 kt by 2047—a nearly 80% cut relative to the base year. In the transport sector, a combination of BS-VI standards and accelerated EV uptake reduces NMVOC emissions from 169 kt in 2019 to just 54 kt by 2047, even as the number of vehicles on the road increases. These reductions demonstrate the effectiveness of clean combustion technologies and fuel-switching policies in curbing hydrocarbon emissions.

Other sectors contribute marginally but exhibit notable trends. Power plant emissions of NMVOCs increase under BAU, from 15 kt in 2019 to 64 kt in 2047, but are reduced to 39 kt under the recommended pathway due to higher renewable energy penetration and a shift toward cleaner fuels like natural gas. The industrial sector sees only a modest increase from 1 kt in 2019 to 5 kt in 2047 under BAU, mitigated to 4 kt under the recommended scenario through cleaner fuels and emission control technologies. NMVOC emissions from DG sets remain low but constant, increasing only slightly from 1 kt to 3 kt under BAU, and stabilizing at 1 kt under the recommended scenario.

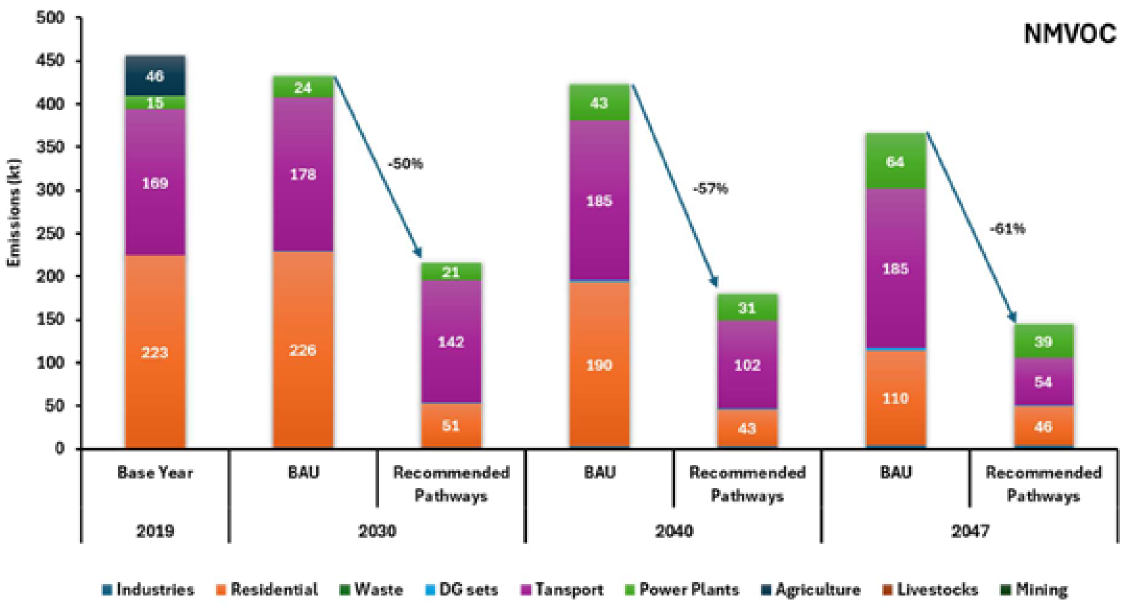


Figure 41: Annual changes in NMVOC emission under recommended pathways w.r.t BAU scenario

In total, implementation of the recommended interventions leads to a 50% reduction in NMVOC emissions by 2030, a 57% reduction by 2040, and a 61% reduction by 2047, relative to the BAU scenario. These reductions are driven primarily by structural transitions in the residential and transport sectors, with complementary improvements in power and industrial sectors. The co-benefits include lower ground-level ozone formation and reduced health risks, making the NMVOC mitigation pathway a critical component of Madhya Pradesh's broader air quality and climate strategy.

BC emission pathway of Madhya Pradesh

In 2019, black carbon, a significant component of $PM_{2.5}$ and a potent short-lived climate pollutant (SLCP), was predominantly emitted from agricultural burning (47%), the transport sector (35%), and the residential sector (13.41%) in Madhya Pradesh. Transport-related BC emissions stemmed primarily from diesel combustion in heavy-duty vehicles, while residential emissions were largely due to biomass burning for cooking and heating. Minor contributions arose from power and industrial sources. With the anticipated enforcement of a total ban on agricultural burning by 2030, this dominant BC source is expected to be eliminated, increasing the relative shares of transport and residential emissions compared to 2019. Consequently, mitigation efforts are prioritized on reducing BC emissions from these two sectors to address air quality and climate impacts effectively.

Under the BAU scenario, the sectoral pattern remains relatively unchanged, with the transport sector contributing 62–63% of total BC emissions through 2047, and the residential share declining to just 6%, as cleaner cooking fuels and technologies become more widespread. Total emissions from the transport sector are projected to increase from 13 kt in 2019 to 16 kt by 2047, while residential BC emissions decline from 5 kt to just 0.3 kt due to the implementation of improved cookstoves, LPG expansion, and the adoption of solar-based technologies.

The recommended pathway leads to a sharp decline in BC emissions across all major sectors. In the transport sector, electrification of vehicles and the phase-out of older diesel engines result in emissions declining to just 6 kt by 2047, a 63% reduction compared to BAU. The residential sector sees even greater reductions, falling to virtually zero (0.3 kt) by 2047, as clean cooking transitions become widespread. These two sectors alone account for the majority of the total reductions in BC.

While smaller in absolute terms, reductions also occur in other sectors. Power plant BC emissions are reduced from 2 kt to 1 kt through fuel substitution and renewable energy integration. Agricultural burning, which contributed significantly in the base year (18 kt), is eliminated entirely in both BAU and recommended scenarios by 2030, reflecting the strict enforcement of the ban on open burning of agricultural residues.

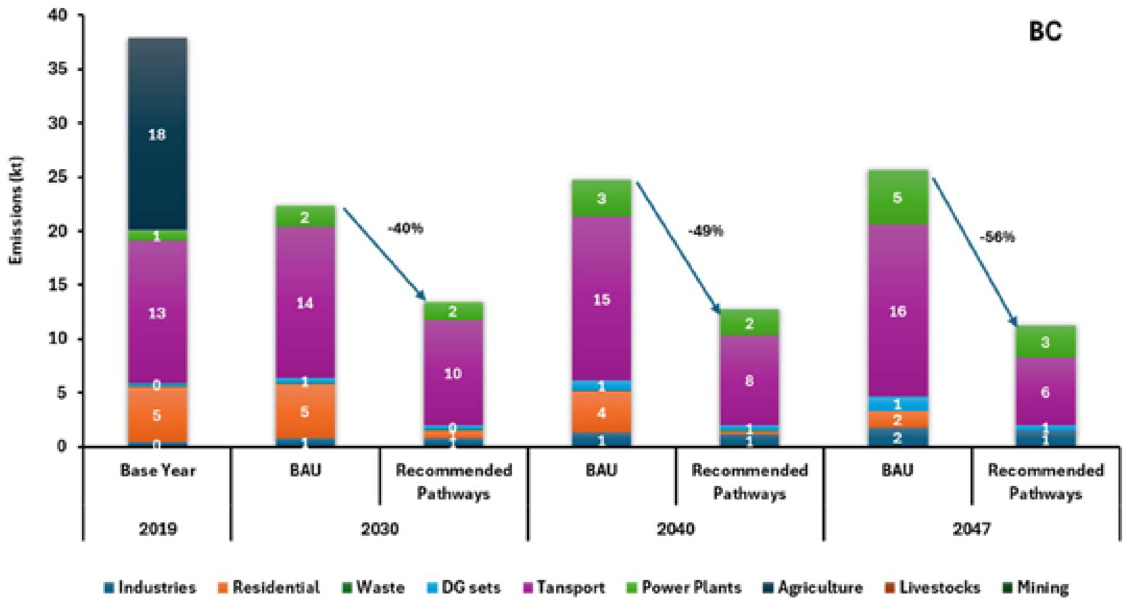


Figure 42: Annual changes in BC emission under recommended pathways w.r.t BAU scenario

In total, the recommended interventions lead to a 40% reduction in BC emissions by 2030, 49% by 2040, and 56% by 2047, relative to the BAU trajectory. These reductions contribute not only to improved air quality and health outcomes but also to immediate climate benefits due to the strong warming potential of black carbon. The dual advantage of these strategies makes BC mitigation a high-impact area within the state's clean air action agenda.

CH_4 emission pathway of Madhya Pradesh

In the base year 2019, CH_4 emissions in Madhya Pradesh were estimated at approximately 1,352 kt. The livestock sector was the dominant source, contributing around 60% (843 kt) of total emissions. This dominance continues under both the BAU and Recommended Pathways scenarios, with livestock emissions projected to increase to 4,841 kt (BAU) and 4,977 kt (Recommended Pathways) by 2047, solidifying its position as the most significant and steadily growing CH_4 source in the state.

The agriculture sector, which contributed 257 kt (18%) in 2019, ranks as the second-largest source in the base year. Emissions from this sector rise to 495 kt under BAU and 399 kt under the Recommended Pathways by 2047. This growth is attributed to the expansion of paddy cultivation and associated practices, particularly in the absence of widespread adoption of methane-reducing techniques such as improved water management or alternate wetting and drying. Under the recommended pathways, moderate reductions are achieved through the promotion of sustainable agriculture practices like Direct Seeded Rice and natural farming.

Methane emissions from coal mining, the third-largest source in 2019 at 162 kt (11%), are projected to grow substantially, reaching 972 kt by 2047 under both BAU and Recommended Pathways. This makes mining the second-largest CH_4 source by 2047. The increase is driven by the continued expansion of coal production and associated fugitive emissions, with no mitigation strategies currently assumed in either scenario. The persistence of high emissions from this sector highlights a critical gap in the state's methane mitigation efforts and underscores the urgent need for targeted measures such as coal mine methane recovery, flaring, or pre-mining degasification.

By contrast, the residential and waste sectors exhibit sharp declines in CH_4 emissions due to targeted interventions. Residential emissions drop from 68 kt in 2019 to 21 kt (BAU) and just 1 kt (Recommended Pathways) by 2047, largely due to the shift to cleaner cooking fuels like LPG and PNG. Similarly, waste sector emissions decline from 61 kt in 2019 to 7 kt (BAU) and 6 kt (Recommended Pathways) by 2047, reflecting improvements in solid waste collection, segregation, and processing, including composting and bio methanation.

Power sector emissions increase from 18 kt in 2019 to 68 kt (BAU) and 66 kt (Recommended Pathways) by 2047, driven by the continued use of fossil fuels. Transport emissions, while modest in scale, increase from 5 kt in 2019 to 13 kt under BAU and remain at 5 kt under the Recommended Pathways, in line with trends in fuel use and vehicle numbers.

Despite significant reductions in the residential and waste sectors, total methane emissions rise across all years, reaching 6,426 kt under the Recommended Pathways by 2047, slightly higher than the 6,419 kt projected under BAU. The relative difference is minimal in earlier years as well, with emissions being 1% lower in 2030 and 1% lower in 2040 under the Recommended Pathways compared to BAU.

This modest divergence highlights a structural limitation in the Recommended Pathways scenario: the lack of dedicated methane mitigation measures in the livestock and coal mining sectors, which together account for more than 90% of CH_4 emissions by 2047. Without targeted strategies for these high-impact sources, the potential for substantial CH_4 reductions remains limited. Addressing these sectors through measures such as enteric fermentation management, manure treatment, and coal mine methane capture will be essential for achieving deeper cuts in methane emissions and aligning with SLCP reduction and near-term climate goals.

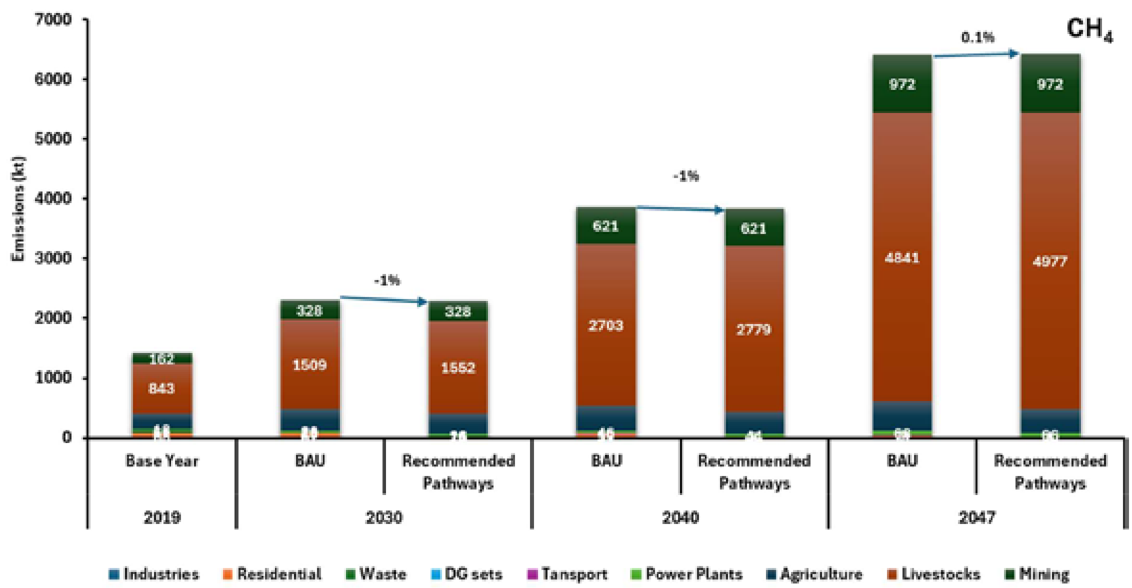


Figure 43: Annual changes in CH_4 emission under recommended pathways w.r.t BAU scenario

This scientific assessment presents a robust emission inventory and evaluates sector-specific alternatives to chart out an emission reduction pathway for Madhya Pradesh. Through an in-depth comparison of BAU and alternative scenarios, the study identifies a Recommended Pathway that integrates interventions from key polluting sectors—transport, industry, power, waste, and residential energy use.

The Recommended Pathway demonstrates the potential to substantially reduce harmful pollutants and deliver broad co-benefits for air quality, public health, and climate. Under this scenario, SO_2 and NO_x emissions are reduced by up to 80% and 78%, respectively, by 2047, mainly due to cleaner fuels in industries, decarbonisation of power, and electrification of transport. BC, a major air pollutant and SLCP, declines by 56%, primarily from reduced biomass burning and diesel use. NMVOC emissions fall by 61%, and CH_4 shows a modest increasing trend, mainly due to an increase in indigenous livestock along with mining activities and reduction in waste sector emissions negate each other.

However, this limited decline in methane points to one of the most critical gaps in Madhya Pradesh's current emission landscape: the absence of existing strategies to mitigate methane emissions from the coal mining sector. Methane emissions from mining are projected to rise steeply, accounting for nearly 16% of total CH_4 emissions by 2047 under BAU, yet no sectoral roadmap, mitigation policy, or institutional framework currently exists to address this. This represents a major missed opportunity, given methane's high global warming potential and the availability of established control technologies in other countries. Tackling this gap is essential to reduce the overall SLCP burden and secure near-term climate benefits.

The emissions analysis in this study includes a comprehensive suite of pollutants—PM_{10}, $PM_{2.5}$, SO_2, NO_x, CO, NMVOCs, BC, and CH_4—but focuses pathway results on five pollutants: $PM_{2.5}$, NO_x, NMVOCs, BC, and CH_4. These were selected based on their policy relevance, health and climate impacts, and utility as proxies for broader pollutant categories. For instance, $PM_{2.5}$ captures fine particulate risks while reflecting trends in PM_{10} and SO_2; NO_x and NMVOCs represent precursors to ozone, and BC and CH_4 offer dual climate and air quality co-benefits.

While the Recommended Pathway aligns with existing policy frameworks such as the NCAP, State EV Policy, PAT scheme, and Swachh Bharat Mission, effective implementation will require overcoming institutional, financial, and monitoring-related barriers. Coordination across departments, support for local capacity building, and access to finance remain key challenges.

To advance toward implementation, the following strategic actions are recommended:

- Establish a State Clean Air and Climate Action Cell to lead multi-sector coordination and align clean air and SLCP strategies with state climate goals.
- Develop sector-specific roadmaps, especially for mining, transport, and industries, with time-bound emission reduction targets.
- Introducing targeted methane mitigation strategies in high-impact sectors:
    - In mining, beyond current dust control measures, pilot methane capture, flaring, and pre-mining degasification projects.
    - In livestock, complement natural farming initiatives with manure management systems, community-scale biogas plants, and explore pilot use of enteric fermentation inhibitors such as 3-NOP or seaweed feed additives to reduce enteric methane.
    - In agriculture, strengthen interventions by promoting alternate wetting and drying (AWD) in rice fields, introducing low-methane rice varieties, and leveraging remote sensing to track irrigation and burning hotspots.
- Leverage national missions and central schemes (e.g., FAME-II, SATAT, Ujjwala, PAT, AMRUT) to scale up clean technologies across sectors.

- Mobilise climate finance and CSR funds to support low-carbon infrastructure, particularly for clean cooking, electric mobility, sustainable livestock management, and decentralised waste treatment.
- Build robust M&E systems, including real-time emission tracking and remote sensing, to support policy enforcement and adaptive management.

This assessment underscores that Madhya Pradesh has a critical window of opportunity to implement an integrated, science-based emission reduction strategy that delivers clean air, public health improvements, and near-term climate benefits. By pursuing the Recommended Pathway and by addressing existing gaps in high-emission sectors such as livestock, agriculture, and coal mining, the state can position itself as a frontrunner in clean air and climate action, setting a precedent for innovative, sub-national environmental governance in India.

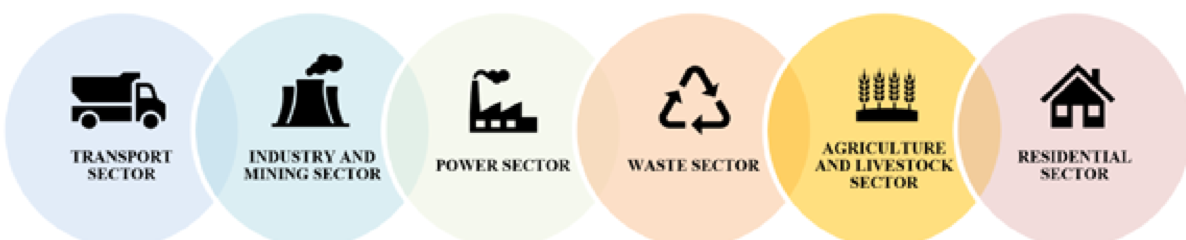
Sectoral Recommendations and Policy Pathways

Madhya Pradesh, with a diverse urban–rural economy and rapidly growing cities, offers a compelling case for state-level action on Short-Lived Climate Pollutants (SLCPs). The state contends with overlapping emission sources: Black Carbon (BC) from household and biomass burning, CH_4 from agriculture and waste, and industrial and transport emissions that elevate PM_{10}/$PM_{2.5}$, SO_2, CO, and ozone precursors, especially in dense urban corridors. As discussed in preceding chapters, addressing non-CO_2 emissions in the state can unlock substantial co-benefits like improved public health, enhanced agricultural productivity, moderated energy demand, and strengthened food and water security – at a time when rising temperatures and heat stress disproportionately affect vulnerable populations (elderly, children, pregnant women, those with chronic illnesses, and socially disadvantaged groups).

To effectively mitigate SLCPs in Madhya Pradesh, a cohesive and strategic approach is essential, particularly one that moves beyond siloed sectoral interventions and embraces integrated, cross-cutting solutions.

As established in the section on spatial analysis, Madhya Pradesh's pollution burden is not spatially homogeneous. Satellite observations reveal four distinct pollution regions with different dominant atmospheric signatures, reinforcing the case that uniform state-level policy must be paired with regional and district-level targeting.

The first step lies in mainstreaming SLCP mitigation into the broader state climate and air quality planning ecosystem. This includes aligning future actions with existing frameworks such as the State Action Plan on Climate Change (SAPCC), the National Clean Air Programme (NCAP), and key flagship schemes like Swachh Bharat Mission (Urban) 2.0, AMRUT, and SATAT. Establishing a state-level SLCP Coordination Cell under the Environment Department can play a crucial role in driving convergence between various government departments and agencies, including those working on energy, urban development, transport, agriculture, and industry.



The sections below further highlight specific sectoral strategies which can be integrated with existing interventions for a comprehensive approach towards mitigation of non-CO_2 emissions.

Transport Sector

The transport sector in Madhya Pradesh is a significant contributor towards NO_x (second highest contributor at 281 kt/yr) and NMVOC emissions (second highest contributing sector at 174 kt/yr) with cascading repercussions for ozone formation. Industrially developed districts in the state like Indore, Bhopal, Gwalior and Jabalpur, particularly show elevated emissions. Satellite NO_2 and VIIRS night-radiance composites independently confirm these urban nodes as elevated combustion zones and trace a continuous emissions signature along the NH-44, NH-46, and NH-30 corridors that connect them.

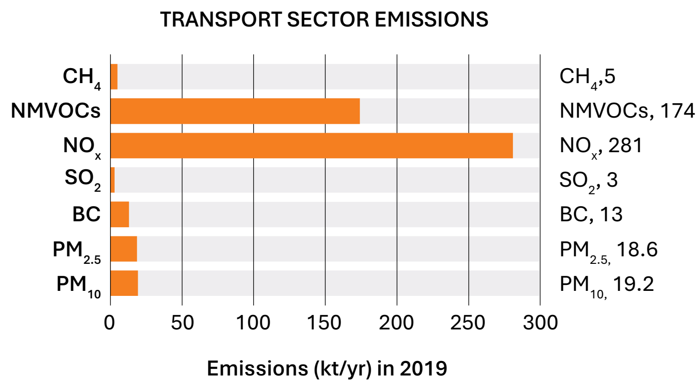


Figure 44: Baseline emissions from the transport sector in 2019

EXISTING POLICY FRAMEWORK

- **MP EV Policy 2025:** Targets 40% new 2-wheeler registrations, 70% 3-wheeler registrations.
- **Inter-city Electric Bus Deployment:** Support clean transport systems.
- **SMART Cities Mission:** Expansion of Bus Rapid Transit Systems and metro rail in Bhopal, Indore, Ujjain, Gwalior, Jabalpur, Satna, Sagar to improve urban mobility.
- **Scheme for Promotion of Ethanol and Biofuel production:** Adhere to national 10% ethanol blending target by 2022, 20% by 2025.
- MP Vehicle Scrappage Policy, Fitness Certification Scheme, Fitness Test Centres, Vehicle Scrapping centre in Chhindwara, Green Tax on older vehicles.

RECOMMENDATIONS

- Introduction of **emissions-weighted fee structure -** linking road taxes and scrappage bonuses to emissions data from BS-VI testing.
- Emissions monitoring through **Portable Emissions Measurement Systems (PEMS) and remote sensing** to enable identification of super-emitters. **Real-time monitoring networks** at toll plazas and high-flow arterials can also feed a public state emissions registry to track fleet composition, EV uptake, and progress toward NCAP-aligned targets.
- Freight-intensive districts such as Dewas, Dhar, Katni, and Rewa can adopt **"Freight Clean Corridors" and diesel control zones** with higher emissions-linked taxes on trucks older than 10 years, time-windowed access to urban areas, emissions screening at logistics hubs, and adoption of cleaner diesel blends (e.g., B6/B7 biodiesel). Freight-

heavy districts should emphasize on strict enforcement of fuel standards, retrofits, and targeted BC/PM controls. Clean corridors should include dedicated rest stops with EV charging, CNG/LNG fueling, and vehicle fitness testing stations to encourage compliance by freight operators.

- Scrappage and retrofitting programs can be scaled through authorized facilities, modelled on Gujarat's large-scale centres at Ahmedabad (36,000 vehicle capacity) and Surat (18,000 vehicle capacity), and linked to purchase incentives for cleaner replacement.

POTENTIAL HURDLES

- Deploying advanced monitoring tools such as PEMS and remote sensing devices entails **high upfront capital costs and ongoing calibration or maintenance expenses.**
- Establishing and operating authorized **scrappage centers—**especially in smaller cities—will require significant **investment in land, equipment, and skilled staff**.
- Expanding EV charging networks in tier-2 and tier-3 cities faces not only **infrastructure funding gaps** but also **grid capacity constraints.**
- Enforcement of LEZs and Freight Clean Corridors may be hampered by **weak on-ground monitoring capacity, resistance from transport operators, and the need for continuous compliance checks.**
- Cleaner diesel fuel supply and biodiesel blending will require close coordination with oil companies, which may **resist operational changes without clear state-level incentives or mandates.**

BEST PRACTICE EXAMPLES

I - Delhi has implemented an Environment Compensation Charge at Delhi's borders for all commercial light duty vehicles and trucks entering Delhi with rates set by axle category.

II - A pilot study in Delhi NCR – organised jointly by the International Council on Clean Transportation (ICCT), Department of Transport, National Capital Territory of Delhi and Gurugram authorities – recently delivered positive results on remote sensing measurements of emissions from on-road vehicles, ensuring vehicles maintain low emissions throughout their life, not just at certification, and help identify super-emitters for corrective action.

III - Indore is already setting best practice examples in the state, accounting for 47,725 electric vehicles (24% percent) out of the 1.94 lakh EVs in the state as of January 2025, according to the VAHAN dashboard.

Way Forward: To ensure that monitoring risks does not falter into a passive exercise without compliance impact, data from real-time monitoring networks should be linked to enforcement actions like automatic fines for gross/high emitters and scrappage eligibility checks. To address fiscal barriers, the state can harness unused allocations from the NCAP, and funds earmarked for the 48 cities under the 15th Finance Commission (15th FC). These can be pooled with state transport budgets to fund priority interventions such as emissions testing infrastructure, LEZ enforcement systems, and urban charging stations. MP could strategically align proposals for the 16th FC cycle to prioritize high-impact strategies, such as citywide remote sensing networks, large-scale scrappage and retrofit subsidies, and cleaner fuel transitions in freight corridors. Public-private partnerships can help spread capital costs, for example, by engaging EV charging providers or retrofitting service companies under revenue-sharing models. Innovation programs such as the Bharat Startup Grand Challenge launched by GoI in partnership with Ather Energy can be leveraged for co-opting such models. MP can also use a fund diversion scheme from fee structures and cess like Delhi, which is funding its EV programme through a dedicated Air Ambience Fund from an environment cess on every litre of diesel fuel sold in Delhi. The state can also tap into private sector logistics and e-commerce players (e.g., Amazon, Flipkart, Delhivery) who are already committing to green fleets. PPP models could accelerate deployment of clean freight solutions in MP. Capacity-building programs, supported by central schemes or climate finance facilities, will be essential to train enforcement officers, municipal transport staff, and local fleet operators in SLCP-focused compliance and maintenance practices, ensuring measures remain effective long after initial deployment.

Industry and Mining Sector

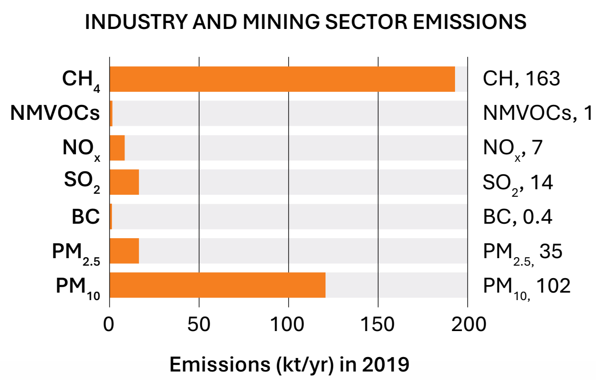


Figure 45: Baseline emissions from the industry and mining sector in 2019

The industrial sector in MP remains a significant source of PM_{10} (102 kt/yr) emissions. CH_4 emissions from coal mining, estimated at 163 kt/year, remain a key concern in districts like Singrauli highlighting the need for effective emission 3control strategies. Indore emerges as a pre-dominant emitter, due to the presence of numerous small- and medium-scale industries using high-emission fuels. Dewas, Sagar, Dhar, Barwani, and Raisen are also key hotspots. Satellite aerosol composites (MODIS MAIAC AOD and Sentinel-5P UVAI) further distinguish three spatially distinct industrial clusters — the Indore-Ujjain-Dewas SME corridor, the Satna-Maihar-Katni limestone and cement belt, and the northern Chambal-Gwalior mixed-source belt — alongside three distinct mining signatures: coal (Singrauli-Anuppur), manganese (Balaghat), and limestone (Satna-Maihar).

EXISTING POLICY FRAMEWORK

- **Madhya Pradesh Industrial Promotion Policy 2025:** Green Industrialization Assistance to encourage cleaner production.
- **Perform, Achieve, and Trade (PAT) mechanism**
- Stack emission standards, Air Pollution Control Devices, and environmental clearance norms, with national directives on continuous emissions monitoring for large units.
- **State Mineral Policy**
- **CAAQMS** in mining areas to track PM_{10}, $PM_{2.5}$, SO_2, and NO_x in real time
- **Central Coal Mine Closure Guidelines**
- **Compensatory Afforestation Programme.**

RECOMMENDATIONS

The state is taking significant strides on addressing non-CO_2 emissions however, certain **gaps** persist such as **reliance on coal and biomass as fuel sources, poor methane/VOC tracking, no targeted emission redressal policies from coal mines, brick kilns or MSMEs and limited incentives for action beyond compliance.**

- Targeted or **phased implementation of community boiler networks in targeted MSMEs clusters** such as Dewas, Dhar and Sagar can aid informed mitigation.
- This should be supplemented by **mandatory coal beneficiation programmes and Industrial Emissions Control Zones** in high-emission districts with stricter norms and financing.
- Green hydrogen integration with a **dedicated transition fund** could also be a key strategy in the coming decade.
- The Industrial Promotion Policy 2025 can be strengthened to include **subsidization of fuel switching, advanced APCDs, and methane/BC reduction retrofits;** and potentially a **Green Performance Scoring system** tied to incentives.
- **A state industrial emissions dashboard** can be considered with real-time CEMS data. Moreover, fuel-mix tracking and hotspot mapping could enable enforcement and transparency.

POTENTIAL HURDLES

- **Fiscal constraints** for implementation of strategies like fuel-switching, advanced pollution control devices, and real-time monitoring—especially for MSMEs with limited borrowing capacity.
- **Technology adoption and maintenance** poses another challenge, with many MSMEs lacking the skills to operate advanced pollution control and monitoring systems.
- **Poor calibration or equipment downtime** can undermine emission control.
- **Monitoring and enforcement gaps** also persist, as CEMS coverage is largely limited to large industries while smaller units and mines escape real-time tracking.
- Stricter norms and SLCP metrics may face **pushback if perceived as cost burdens,** and lack of coordination between industrial promotion, environment, and energy departments can delay execution.

Way Forward: Reallocating part of existing industrial subsidies toward clean fuel adoption, diverting revenues from environmental penalties and mining royalties, blending public funds with CSR contributions and green bonds can help address fiscal constraints. Performance-linked incentives could be tied to verified reductions in $PM_{2.5}$, methane, and black carbon. Setting up cluster-level maintenance hubs, introducing technology leasing models (equipment-as-a-service) where third-party operators manage systems for a fee, and running regular capacity-building programs through industrial associations can help target maintenance issues. Overcoming industrial resistance and policy silos will also be crucial. Market-based incentives—such as linking low-interest loans and land allotment to high "Green Performance Scores" can align economic and environmental objectives. Collectively, the proposed strategies form a multi-pronged approach: regulatory innovation (ETS), stronger oversight, cleaner fuel adoption, and technology upgrades. Implementing them should be prioritized in heavily industrialized districts (Indore, Ujjain, Dewas, Bhopal, etc.) and mining hubs (Singrauli for coal, Katni for cement and limestone, etc.), where air pollution and SLCP emissions are highest.

Power Sector

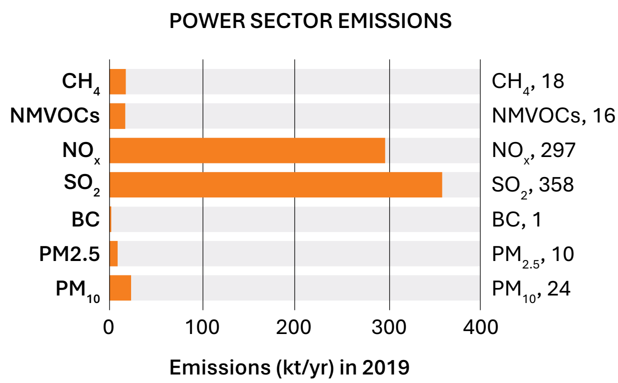


Figure 46: Baseline emissions from the power sector in 2019

As of 2023, 62.5% of the state's power was sourced from coal-based TPPs, down from 81.7% in 2019. The power sector is the largest emitter of SO_2 (358 kt/yr) and NOX (297 kt/yr) in the state. SO_2 emissions particularly contribute to the formation of secondary particulate matter, worsening $PM_{2.5}$ pollution across the region. At an asset level, Gadarwara STPP (58.48 kt) and M.B. Power Ltd (50.29 kt) were identified as the highest SO_2 contributors in the state.

Sentinel-5P SO_2 and NO_2 column composites independently confirm the Singrauli-Anuppur corridor as the dominant point-source cluster in the state, with VIIRS night-radiance data co-locating bright combustion nodes at NTPC Vindhyachal, Sasan, Mahan, MB Power, and Gadarwara.

EXISTING POLICY FRAMEWORK

- 5% **biomass blending requirement introduced in 2024, to be increased to 7% by 2025.**
- Vidhyanchal STPP and Khargone STPP have implemented **FGD systems with 85% efficiency** following national emissions norms
- **MP Renewable Energy Policy 2025:** Aim to generate 50% of electricity from renewable fuels by 2030
- **MP Pump Hydro Storage Scheme and MP Small Hydro Power Policy**
- **Biomass Co-firing Mandate**
- Recent floating solar plant at Omkareshwar and NTPC's planned $23 billion investment in RE Projects.

RECOMMENDATIONS

While the state demonstrates a proactive policy stance in this sector, there remain significant **gaps** in **real-time emissions monitoring and disclosure at a plant-level, grid flexibility, management of demand (through tariffs, smart metering or demand-response incentives) and credit market innovation.**

- Demand-side flexibility could be incentivised through **green Time-of-Day tariffs and a carbon credit mechanism for verified peak shaving** using battery storage or demand response.
- The **government rooftop solar programme** is a strong strategy for creation of carbon-neutral public infrastructure mandates. The state has enormous solar potential (e.g. in Chambal and Bundelkhand regions) and a pipeline of large solar parks.
- Policy should ensure that renewable projects are executed on schedule and integrated reliably via **grid upgrades and storage.**
- **Co-firing biomass pellets** (made from crop waste like paddy straw) in coal boilers can directly reduce coal consumption and cut net CO_2 emissions. This policy would **synergistically support the anti-stubble-burning efforts** in agriculture and reduce black carbon and particulate matter emissions.
- Reducing the overall power demand can allow older peaking power plants (often the dirtiest) to run less. The state can double down on **energy efficiency programs** – e.g. distribution of LED bulbs (following the UJALA scheme's success), efficient agricultural pump sets, and industrial energy audits.
- **Managing peak load** through techniques like off-peak agricultural supply or demand response in industry can avoid firing up outdated captive power units or rental diesel gens, thereby avoiding bursts of SLCPs.
- The state can also explore **innovative financing for efficiency** (such as utility-driven on-bill financing for building retrofits), which has proven effective in other regions for sustained demand reduction.

Way Forward: An integrated policy framework combining renewable energy expansion, pollution control retrofits, demand-side participation, and carbon credit innovation is essential. Concessional finance, regulatory enforcement, and capacity-building will be critical to overcoming cost and infrastructure barriers. In implementing these recommendations, focus should be placed on the higher polluting assets with a high-level of localised emissions, where a holistic intervention could dramatically improve air quality.

Waste Sector

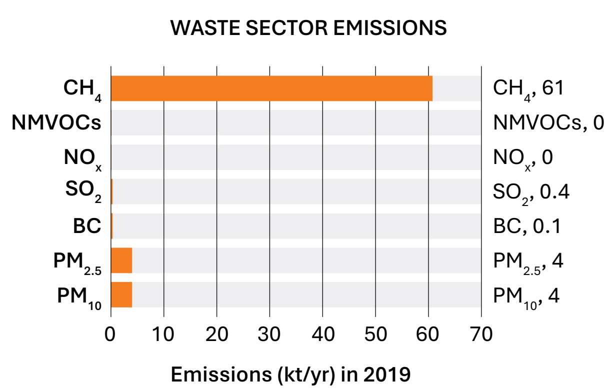


Figure 47: Baseline emissions from the waste sector in 2019

The state has consistently been a frontrunner for setting good practice examples on waste management in the country. Consistent with this, the waste sector contributed 61 kt/year of methane emissions in 2019, accounting for 5% of total CH_4 emissions in the state. Solid waste processing and landfill emissions are the primary sources with urban centres like Indore, Bhopal, Jabalpur and Gwalior identified as significant CH4 emission hotspots. Sentinel-5P CH_4 column composites independently confirm persistent methane enhancement co-located with municipal landfill point data at all four of these cities, alongside secondary hotspots at Ujjain and Rewa.

EXISTING POLICY FRAMEWORK

- **Swachh Bharat Mission:** 97.8% (404) of ULBs have achieved 100% waste segregation, 100% have composting facilities and 373 have operational MRFs, over 6 lakh households in the state are practising home composting and over 11 lakh MT (82% of total) of legacy waste has been remediated via biomining.
- **Climate finance initiatives:** Carbon credit generation through bio methanation.
- **MP Bioenergy Policy**
- **National Biogas Programme:** MPSAIDC has established a target of deploying approximately 3,600 biogas plants by 2023-24, with capacities ranging from 1 to 25 cubic meters.

RECOMMENDATIONS

Certain key gaps in SLCP mitigation identified in the sector include – **continued landfill emissions from unmanaged dumpsites** as gas capture systems remain largely absent, **composting as the dominant mitigation** strategy while **biomethanation remains underused** and lack of **formal RDF offtake agreements** limits diversion of high-calorific dry waste from landfills. Absence of routine methane tracking from landfills, STPs or biogas systems also persists as a monitoring challenge.

- At unremediated open sites, **basic vertical well and blower systems can capture gas for treatment or flaring;** at capped post-bioremediation sites, **modular extraction networks** can supply CBG bottling, gensets, or thermal applications. Where recovery is infeasible, **controlled flaring should be used over passive venting.**
- To utilize high-organic-content waste, the state should **accelerate modular anaerobic digestion (AD) deployment** in both urban and rural areas. Medium-capacity biomethanation units (5–25 TPD) co-located with transfer stations or MRFs can process segregated organics from hotels, markets, and bulk generators, while mini-GOBARdhan plants (1–5 TPD) at gaushalas, mandis, and Gram Panchayats can handle cattle dung and kitchen waste. These systems reduce methane from uncontrolled decomposition, produce CBG for transport and industry, yield bio-slurry for agriculture, create local jobs, and qualify for carbon finance.
- For non-recyclable, high-calorific waste (>1,500 kcal/kg), **scale-up of Waste-to-Energy (WTE) and formalized Refuse-Derived Fuel (RDF) pathways** is essential.
- Long-term RDF supply contracts with cement plants in Neemuch, Satna, Rewa, and Katni should be mandated within a 100-km radius, supported by standardized tipping fees, centralized logistics, and fast-track MPPCB clearances.
- **Biannual methane monitoring at all large dumpsites,** especially in Class-I cities and sites over 10 hectares, using handheld analyzers, drones, and satellite tools (e.g., Sentinel-5P, GOSAT)—following GMI/IPCC Tier 2 protocols—should be mandated, with results integrated into MPPCB audits, ULB ratings, and public portals to support transparency and carbon credit readiness.

BEST PRACTICE EXAMPLES

I - The Indore Municipal Corporation (IMC) became the first civic body in India to generate revenue through carbon credit trading, earning ₹50 lakh from the sale of 1.70 lakh tonnes of CO_2 under the Verified Carbon Standard (VCS) programme of the UNFCCC. Key projects supporting emission reduction include a 600 TPD compost plant, a 35 TPD bio methanation plant at Choithram and Kabitkhedi, and a 1.5 MW solar plant.

Way Forward: District-specific strategies for implementation of different waste management strategies outlined above can help further streamline SLCP mitigation from the waste sector in MP. Active landfill gas (LFG) capture systems should be installed at large legacy dumpsites and newly engineered landfills in Tier-1 and Tier-2 cities such as Gwalior, Jabalpur, and Sagar. These measures cut methane by 70–80%, reduce fire risk, generate revenue via power or carbon credits, and align with SWM Rules 2016, MPPCB Waste Management Rules 2023, and the State Environment Plan's zero-landfill targets. Rollout of AD plants should prioritize Indore, Bhopal, Gwalior, Chhindwara, Jabalpur, Dewas, Sagar, and Ujjain, leveraging the SATAT scheme, SBM-U 2.0, and GOBARdhan for subsidies, PPP facilitation, and guaranteed feedstock supply. The MP Bioenergy Policy remains a key lever for capital subsidy support and viability gap funding. Replicating the 5–7 MW Rewa cluster model in Ujjain, Jabalpur, and Sagar with waste aggregation from 8–10 ULBs can help maximize efficiency for scaling waste-to-energy plants. Moreover, while considering strategies like RDF production, it is important to consider on-ground complications like the recent reports of creation of a plastic lining in cement industries which discourages RDF use. As an alternative, strategies like utilisation of recycled plastic in rural road construction can be considered.

Agriculture and Livestock Sector

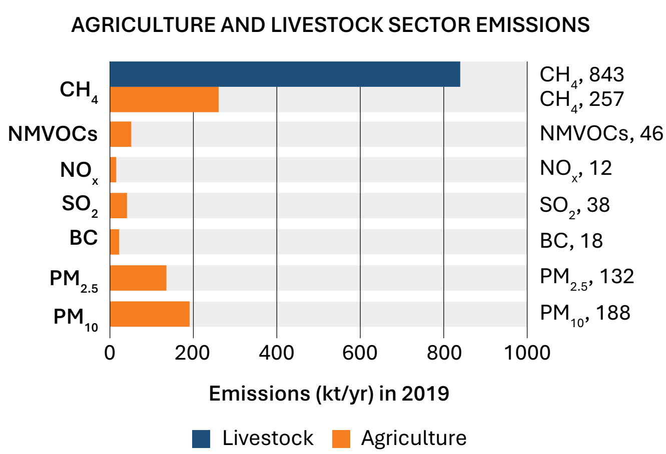


Figure 48: Baseline emissions from the agriculture and livestock sector in 2019

Open burning of agricultural residue remains a major concern, contributing to PM_{10}, $PM_{2.5}$, BC, SO_2, NO_x, and NMVOCS. Hoshangabad, Chhindwara, Seoni, Narsinghpur, and Raisen emerged as the top contributors, together accounting for about 25% of total agriculture residue burning-based BC emitted from the state. Districts like Balaghat, Rewa, Raisen, Mandla, Satna, and Jhabua recorded the highest methane emissions from rice cultivation. However, methane emissions from livestock estimated at 843 kt/year remains the single largest source of CH_4. The leading districts include Sagar, Morena, Rewa, Khargone, Chhindwara, and Satna. FIRMS satellite active-fire detections cluster across these same districts during the October–November kharif harvest window, while elevated CH_4 column densities across the northern agro-residential belt (Morena, Bhind, Gwalior, Tikamgarh, Chhatarpur) reflect the spatially co-located contributions of rice cultivation, livestock, and residential biomass combustion.

EXISTING POLICY FRAMEWORK

- **Direct Seeded Rice implementation policy**
- **Madhya Pradesh Natural Agriculture Development Board**
- **Crop Diversification schemes** like **Mukhya Mantri Krishak Unnati Yojana:** Rs. 850 crore allocated to crop diversification in 2025-26
- **Improved fodder management and balanced cattle feeding strategies** under guidance from NDDB.
- **Gobar Dhan Scheme:** Community level biogas systems
- **Nandishala Scheme, Sammunat Pashu Prajanan Yojana, Gau-Bhains Vansh Prajnan Viniyaman Adhiniyam:** Livestock development schemes

RECOMMENDATIONS

Current programs—like zero-till farming promotion, organic composting, and cattle breed improvement—have not closed key SLCP emission gaps in the state. The absence of a statewide ban on burning, low uptake of residue management equipment and limited livestock feed improvement initiatives remain persistent challenges.

- **Crop Residue Management:** Instituting a **phased ban on crop residue burning** in the state following the model of Punjab and Haryana, starting with the most affected districts.
    1. **In-situ CRM strategies** like adoption of no-till seeders, Super Straw Management Systems, choppers, balers or short-period microbial decomposers.
    2. **Ex-situ utilization strategies** such as – biofuel/ethanol production, redirection towards livestock fodder, briquetting, or fertiliser production like biochar. Ex-situ uses include supplying baled straw to biomass power plants or as fodder/compost.
    3. **Bioenergy integration** like setting up biomass briquetting units or ethanol plants that purchase surplus straw, or creation of dedicated residue collection channels.
- Creating **biochar from crop residue** can also be explored to sequester carbon and avoid emissions. To strengthen innovative efforts for reducing methane emissions from rice cultivation, the MP SAPCC also details techniques like azolla planting which can be explored more proactively.
- **Dedicated feed and fodder management strategy** in the state to improve livestock diets and promote feed additives.
- The state animal husbandry department can partner with ICAR-NIANP and local dairy cooperatives (e.g. Sanchi Milk Federation) to pilot such distribution of **innovative anti-methanogenic feed supplements like Harit Dhara** in high-livestock population districts such as Sidhi and Tikamgarh (can reduce enteric methane emissions by 30–40% in cattle and buffalo when added to their feed).
- Educating dairy farmers on **concentrate feeding, using fortified feed, and avoiding roughage-only** diets will also help, since higher feed efficiency means less methane per unit of milk/meat.
- Encouraging **cultivation of improved green fodder varieties** and proper storage (silage making) to ensure quality feed year-round, reducing reliance on low-nutrition dry crop residues that lead to higher methane output.
- A cross-sectoral emission redressal solution which can be explored is **utilisation of urea molasses-mineral block** (UMMB) licks as cattle feed which also offers an ex-situ CRM strategy. The state could collaborate with institutes like the Madhya Pradesh State Livestock & Poultry Development Corporation on trials for future cost-effective deployment of methane-reducing feed additives like seaweed (Asparagopsis).

Way Forward: District-specific strategies for implementation of the various interventions outlined above can help streamline SLCP mitigation from the agriculture and livestock sector. For example, drought-prone districts like Tikamgarh, Chhatarpur, and Datia are suited for strategies like DSR, while biochar production or applications fits rice-dominant areas like Balaghat and Mandla. Natural farming techniques that use mulching and biochar could be demonstrated in key rice growing districts like Hoshangabad. Dairy-intensive districts like Sagar offer a huge opportunity to turn livestock waste into energy via biogas with critical implications for cross-sectoral emissions reduction. Moreover, uptake of existing strategies needs to be scaled dramatically, and financial incentives are a key mechanism. Equipment-as-a-service models, pay-for-performance programmes, farmer collective aggregation via FPOs and transitional incentive schemes are some financial models which can be explored in the state and have also been detailed in the upcoming draft of the MP SAPCC. For crop diversification, particularly, recent trends in the state show an increase in paddy cultivation in non-traditional districts as diversifying to soybean is not as profitable as growing rice. Diversification alternatives must thus be carefully considered in incentive schemes, leveraging profitable and high-yield crops like jowar. Appropriate financial support and incentives for crop residue management strategies are also crucial. While the economic value of crop residue as a resource has increased more recently, subsidies for CRM technologies must be strengthened. In the livestock sector, the state should support R&D and extension services focusing on long-term solutions like selective breeding for low methane emitting cattle (some breeds or individuals naturally emit less), vaccines that suppress methanogenic archaea in the rumen (an area of active scientific inquiry), and digital tools for diet optimization. Partnering with national institutes and agri-universities in Madhya Pradesh (e.g. JNKVV Jabalpur) can help pilot such innovations in a local context. Cross-departmental coordination, dedicated funding, and sustained farmer outreach—framing benefits in terms of income, soil health, and productivity—are essential for uptake. By combining targeted agricultural practices with livestock feed and waste interventions, Madhya Pradesh can significantly cut SLCP emissions while strengthening the resilience and sustainability of its farming systems.

Residential Sector

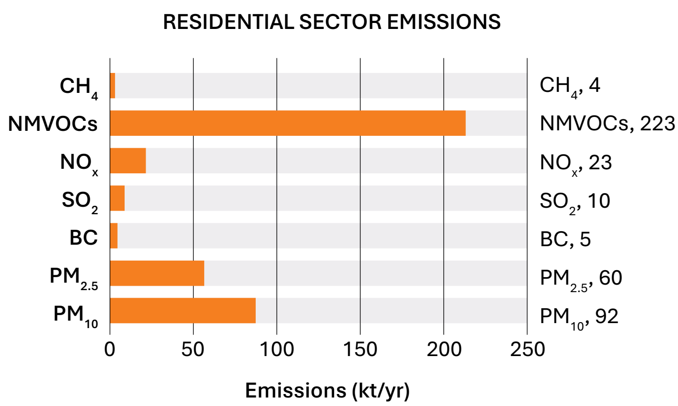


Figure 49: Baseline emissions from the residential sector in 2019

The residential sector in MP is the largest contributor to NMVOCS, primarily from biomass-based cooking and heating. Fuelwood is the dominant source of emissions in most districts, with areas like Dindori, Mandla, Katni, and Balaghat relying on it almost exclusively.

Crop residue use is significant in districts such as Alirajpur and Anuppur, while charcoal-derived carbon plays a notable role in West Nimar and Jhabua. Some districts, including Bhind, Dhar, Morena, and Rajgarh, exhibit a mixed fuel-use pattern, whereas others, such as Mandla and Umaria, rely mainly on biomass. Population-weighted satellite column data shows the highest residential exposure burdens across the northern belt (Sheopur to Singrauli) and the major urban cores; however, this metric systematically underestimates per-household burden in sparsely populated forest districts like Mandla and Dindori, where near-total biomass dependence makes per-capita emission intensities among the highest in the state.

EXISTING POLICY FRAMEWORK

- **Pradhan Mantri Ujjwala Yojana (PMUY):** Free LPG connections to women from BPL families, replacing traditional biomass
- **Promotion of improved biomass cookstoves** in rural areas to enhance fuel efficiency
- **Adoption of Surya Nutan:** A solar cooking technology targeting rural and semi-urban households
- **Madhya Pradesh City Gas Distribution Network Development and Expansion Policy 2025**
- State target to expand to 60 lakh domestic PNG connections and 1207 CNG stations.

RECOMMENDATIONS

- **Challenges** remain in ensuring **consistent LPG usage** as **refill rates are low** among some beneficiaries due to **cost concerns** and in **reaching the last-mile households** in rural, tribal and forested areas. Other barriers to clean fuel adoption include **high LPG refill costs, limited subsidy access, irregular supply chains, and entrenched cultural preferences for biomass cooking.**
- Strengthen last mile LPG connection access to uncovered households with potential refill support for low-income families to ensure 100% clean cooking fuel coverage.
- MP can target high firewood-use areas such as Mandla, Shahdol, and Barwani and utilise satellite-based mapping to identify gaps, and establish micro-distribution points, possibly via women's self-help groups, to overcome last-mile delivery challenges.
- Subsidise a fixed number of refills per year or provide direct benefit transfers during periods of high fuel prices.
- Community-level demonstrations showcasing the health and time-saving benefits of clean cooking. For non-LPG viable areas—remote tribal blocks in Alirajpur, Anuppur, West Nimar, and Jhabua—diversifying clean energy solutions is critical. Household and community-scale biogas digesters can supply cooking, lighting, and even electricity while reducing methane and black carbon emissions.

POTENTIAL HURDLES

- **Behavioural resistance** to LPG adoption.
- **High infrastructure costs** for establishment of strong PNG supply networks.
- **High upfront costs** for adoption of clean cooking alternatives.
- Regular **technical maintenance requirements.**
- **Seasonal production variability** in biomass.
- Uptake of solar cookstoves is challenged by **weather dependence, mismatched cooking schedules, cultural perceptions** and the eventual dependence on **fossil-fuel based electricity.**

BEST PRACTICE EXAMPLES

I - One successful model of LPG expansion is Himachal Pradesh, where building on PMUY, the state implemented its own Himachal Grihini Suvidha Yojana to cover all leftover households; declaring near 100% LPG coverage.

Way Forward: Overcoming the adoption barriers highlighted above requires coordinated measures—financial support, supply-chain strengthening, targeted outreach, and behavior change programs—to ensure sustained clean fuel use. Solutions include offering capital grants or concessional loans, training local technicians to provide maintenance services, and promoting cooperative feedstock pooling from multiple households. Solar cookstoves can further reduce biomass dependence, but their uptake is challenged by weather dependence, mismatched cooking schedules, and cultural perceptions. These can be addressed through hybrid cooking models (solar plus LPG or biogas), improved cooker designs with insulation, and pilot programs demonstrating popular local dishes prepared with solar methods. Integrated strategies combining adoption of LPG expansion with biogas and solar cooking can yield the greatest environmental and health benefits. Success will depend not only on financial incentives and infrastructure investment but also on sustained awareness campaigns, culturally sensitive engagement, and robust monitoring to track adoption and performance. By combining targeted LPG rollout, urban PNG expansion, decentralised biogas systems, and solar cooking in a district-specific manner, Madhya Pradesh can significantly reduce residential sector emissions, improve public health, and advance its climate and energy security goals.

Cross-Sectoral Interventions

Building on the strategies outlined above, it is equally important to recognize the opportunity for cross-sectoral integration that leverages synergies across waste, agriculture, energy, and industry. For example, dry municipal solid waste, currently a significant source of methane when dumped, can be processed into refuse-derived fuel (RDF) and co-fired in cement kilns. This not only diverts waste from landfills but also reduces black carbon emissions from fossil fuel substitution in the industrial sector. Cities like Indore and Bhopal, with established material recovery and waste segregation systems, are particularly well positioned to pioneer such models. Similarly, crop residues that would otherwise be burned in the open—contributing heavily to black carbon pollution—can be aggregated and processed for biomass energy production or compressed biogas (CBG) units. Paddy-dominant districts like Hoshangabad and livestock-heavy regions such as Sehore offer high potential for such agricultural-waste-to-energy transitions. These integrated models could be further strengthened by linking outputs across sectors. For instance, slurry from biogas plants can be used to produce organic fertilizers, supporting sustainable agriculture, while energy generated from decentralized biomethanation units in urban areas could power local electric vehicle (EV) charging stations—creating a virtuous cycle of emissions reduction.

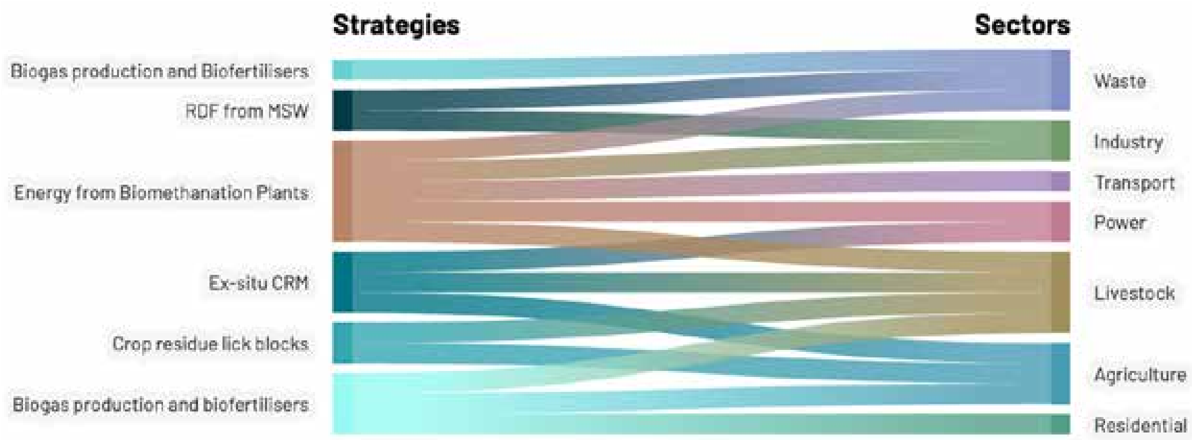


Figure 50: Proposed cross-sectoral policy interventions for mitigation of non-CO_2 emissions in Madhya Pradesh

Institutional Capacity Building: At the institutional level, a major priority should be capacity building. Urban Local Bodies (ULBs), rural panchayats, and district line departments need technical training and planning support to effectively implement and monitor SLCP mitigation activities. Customized toolkits, decision-support systems, and training modules should be developed to help them incorporate emissions reduction targets into local development plans.

Climate Financing: Across sectors, financing remains a persistent challenge, but multiple options can be pursued. The state can strategically pool resources from centrally sponsored schemes like SBM-U 2.0, XV Finance Commission grants, and the National Livestock Mission. Simultaneously, proposals that emphasize co-benefits—such as improved health outcomes or livelihood creation—can be developed to access international climate finance through mechanisms like the Green Climate Fund (GCF) or the Global Environment Facility (GEF). Public-private partnerships (PPPs) – such as Indore's PPP-based green waste processing plant in Bicholi Hapsi – offer another pathway, particularly in waste valorization and agri-residue supply chains, where private sector involvement can unlock efficiencies and innovation.

Engagement and Awareness: Public engagement will also be critical in driving behavioral shifts, particularly around waste segregation, adoption of clean cooking technologies, and resistance to open burning. State-wide awareness campaigns, supported by community-based organizations and self-help groups, can play a transformative role in ensuring last-mile uptake and sustained impact. Finally, the role of innovation and localized technology development cannot be overstated. Collaborations with local academic institutions, technical universities, and startups in Madhya Pradesh can support the customization and scaling of affordable technologies like improved cookstoves, small-scale digesters, and pelletizers. Innovation hubs and pilot demonstration zones in select districts can serve as testing grounds for new models and technologies.

The way forward for SLCP mitigation in Madhya Pradesh lies in transitioning from isolated interventions to integrated, cross-sectoral action. With coordinated governance, community participation, institutional capacity, and resource mobilization, the state can lead by example in demonstrating how climate and development goals can be met together—creating cleaner air, healthier communities, and more resilient ecosystems.

Annexures

Residential

The basic equation employed for emission estimation from the residential sector is,

$$E_p = \sum_{a=1}^{n} \sum_{f=1}^{6} Pop_{(a,f)} \times C_{(a,f)} \times EF_{(f,p)}$$

Where, [Ep]R is the emission of a particular pollutant (p) from the residential sector, Pop(s,f) is the population using a particular fuel (f), C(s,f) = Region (rural/urban) specific per capita consumption of a particular fuel for cooking activity, EF(f,p) = Emission factor of the particular pollutant (p) of the particular fuel type (f). Six major fuels those are used in the residential households for cooking purpose is included in this emission inventory preparation – a) Fuel wood, b) dung cake, c) crop residue, d) coal, e) kerosene and f) LPG. Population of Madhya Pradesh during 2019 was taken from population projection report for India and states (MoHFW 2020).

State specific monthly per capita consumption of different fuels (Cs,f) in the rural and urban areas of Madhya Pradesh is taken from NSSO (2014) report and assessment report on primary survey on household cooking fuel usage and willingness to convert to LPG (PPAC 2016). Electricity used in the residential sector has no reported emission of air pollutants, so it is not considered during the preparation of present emission inventory.

NSSO (2014) reports household consumption of various amenities during 2011-2012. However, there is significant growth in household LPG usages after 2011, these affects the biomass and kerosene uses pattern in the residential sector. The biomass and kerosene consumption and use in the residential sector 2019 were re-estimated by incorporating the growth rate of LPG consumers.

District level LPG consumption (2015 to 2019) information provided by Food, Civil Supplies and Consumer Affairs department, Government of Madhya Pradesh were used to estimate the growth trend of LPG usage in the state. Accordingly, an annual LPG consumption growth of 9.2% has been considered for Madhya Pradesh. The increase of number of households using LPG is then uniformly distributed to adjust the number of fuelwood, crop residue, dung cake and kerosene using households during 2019. The growth of LPG coverage and consumption showed significant improvements in urban areas where 92% of households were dependent on LPG for cooking. However, considering similar LPG consumption growth (9.2%) in rural areas, less than 10% of households is estimated to have access to clean cooking facility and majority of the population was still relying on traditional biomass fuel (mainly fuelwood) as primary energy source to meet their cooking needs.

Fuel specific emission factors of different pollutants (EF(f,p)) are taken from Datta and Sharma (2014) and Pandey et al. (2014)

Table 43: Emission factors (g/kg) of different pollutants from different fuel types used in the residential sector

Pollutant	Fuelwood	Crop Residue	Dung Cake	Coal	Kerosene	LPG
$PM_{2.5}$	4.6	5.7	4.4	4.04	3	0.35
PM_{10}	6.77	8.6	10.5	8.26	3.6	0.35
SO_2	0.8	0.7	0.6	15.33	0.4	0.4
NO_x	1.7	1.8	1	2.16	1.3	2.9
CO	66.5	64	78.6	59.46	43	2
NMVOCs	15.89	8.5	24.1	10.5	17	19*
BC	0.4	0.3	0.4	0.00826	0.6	
CH_4**	5.16	4.32	6.65	4.4	0.56	0.28

* Pandey et al. (2014); others were adopted from Datta and Sharma (2014)

NA: Not available; ** Danish Emission inventories for stationary combustion plants 2018, Danish Centre of Environment and Energy

Estimated Fuel consumption

Annual consumption of different types of fuels for cooking activity in the residential households of Madhya Pradesh during 2019 is illustrated in Figure 51. Fuel specific consumption pattern revealed that fuel wood is majorly used as energy source in residential households for cooking activity followed by dung cake, LPG and crop residue. Annual consumption of fuel wood, dung cake, LPG and crop residue was estimated as 11145 kt, 1061 kt, 756 kt and 579 kt respectively. While, annual consumption of coal and kerosene was estimated as 2 kt and 1 kt respectively owing to very less usage in Madhya Pradesh.

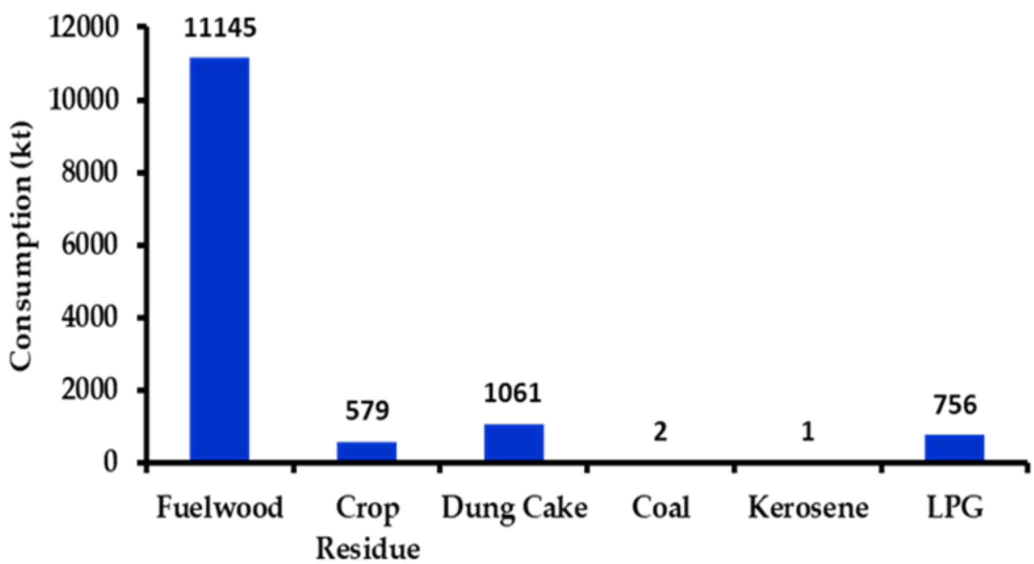


Figure 51: Estimated annual consumption of different types of fuel for cooking activity in the residential households of Madhya Pradesh during 2019

Estimated emission of different pollutants

The activity data of different fuels is fed into above equation along with the fuel specific emission factors of different pollutants (EF(f,p)) (Table 44) to calculate the emission (kt) of different pollutants from the use of different fuel types in residential households of Madhya Pradesh during 2019.

Table 44: Emission (kt) of different pollutants from the residential cooking activity in Madhya Pradesh

Pollutant	Fuelwood	Crop Residue	Dung Cake	Coal	Kerosene	LPG
$PM_{2.5}$	51.27	3.30	4.67	0.01	0.00	0.26
PM_{10}	75.45	4.98	11.15	0.02	0.00	0.26
SO_2	8.92	0.41	0.64	0.03	0.00	0.30
NO_X	18.95	1.04	1.06	0.00	0.00	2.19
CO	741.14	37.05	83.43	0.12	0.03	1.51
NMVOCs	177.09	4.92	25.58	0.02	0.01	14.37
BC	4.46	0.17	0.42	0.00	0.00	0.00
CH_4	57.51	2.50	7.06	0.01	0.00	0.21

Transport

The equation to estimate vehicular tailpipe emission in the transport sector is,

$$\mathrm{E_p} = \sum_{c=1}^{n}\sum_{s=1}^{4} VKT_{c,s} \times EF_{c,s,p} \times \varepsilon_{c,s} \times n_c$$

Where, Ep is the total emission of a pollutant (p); c is the type of vehicle; s is the emission control norm (BSI to BSIV); VKT is the daily Vehicle Kilometre travelled by vehicle type c; EF is the emission factor of pollutant p and ε is the percentage of vehicle under an emission control norm (s) and n is the total number of vehicles in vehicle type c. The methodology of calculating emissions from the sector is explained in (Figure 45)

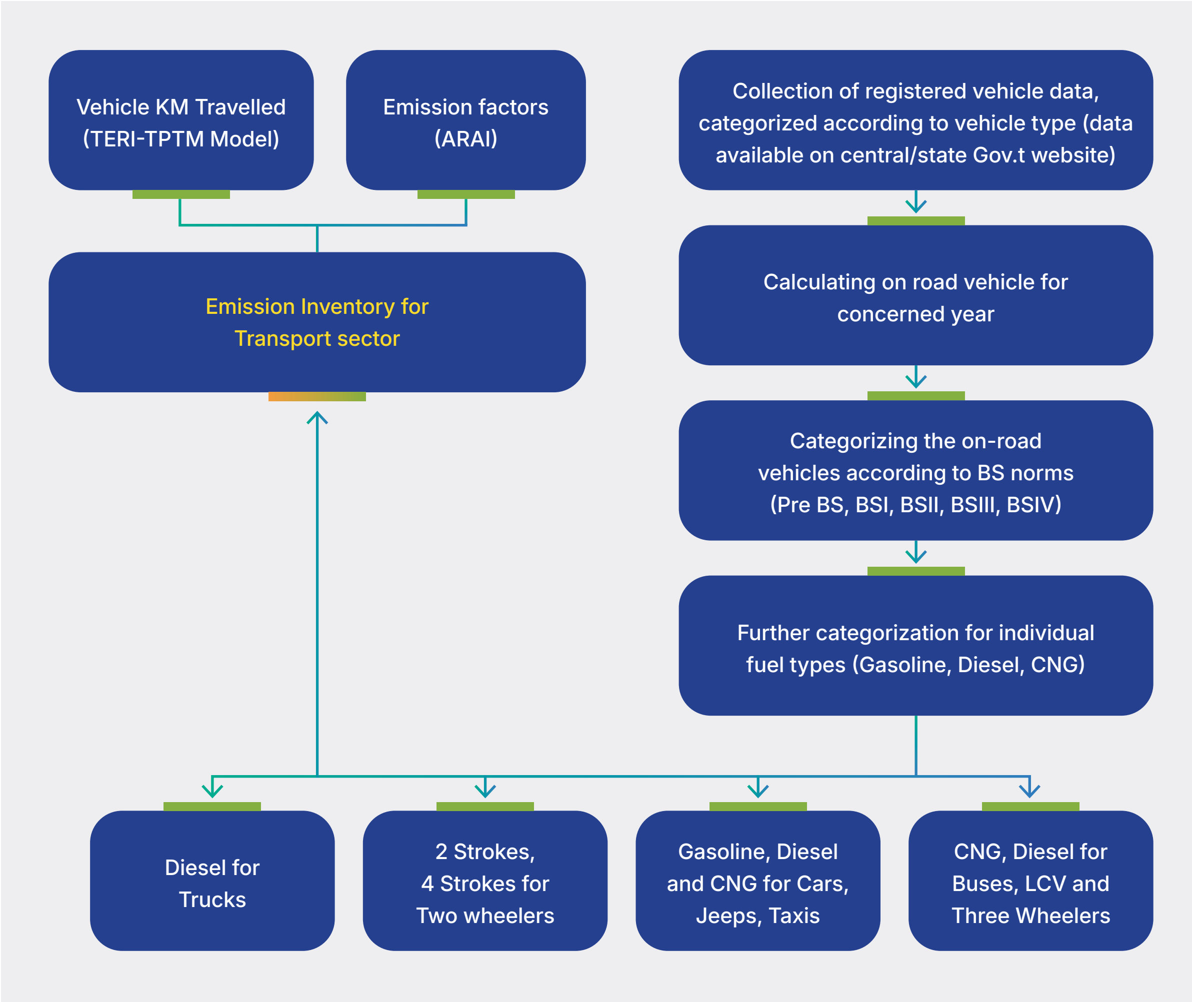


Figure 52: Methodology for estimating emissions from the transport sector

The estimated state level annual Vehicle Kilometre Travelled (VKT) of different categories of vehicle during 2019 was adopted from the TERI-Transport Model (TERI-TPTM) (Table 45). The model first estimates the total transport demand in Madhya Pradesh, which is an aggregation of the projected passenger and freight demand, defined as the annual Billion Passenger Kilometres (BPKM) and Billion Tonne Kilometres (BTKM) respectively.

Passenger Demand (BPKM): For arriving at the total passenger demand a multi- step approach is followed. Firstly, the vehicle ownership is projected based on socio-economic variables such as GDP and population. The vehicle ownership is then disaggregated for urban and rural areas. Further, based on the assumptions of fuel type, fleet utilisation and vehicle occupancy for different vehicle segments (two wheelers, three wheelers, four wheelers, buses and rail) the annual BPKM is calculated for both urban and rural areas separately. Lastly, the total annual BPKM at pan India level is arrived at by the summation of urban and rural BPKM.

Freight Demand (BTKM): For arriving at the total freight demand, a similar approach is followed with the differentiating factor being the consideration of sectorial GDP in the estimation of commercial vehicle ownership. The total annual BTKM is computed as an aggregation of BTKMs of LCVs and HCVs.

Table 45: TERI-TPTM Model Simulated Daily VKT of Different Types of Vehicles

VKT (Km/day)	2W	3W	Car	LDV	HDT	HDB
2019	23	135	61	81	237	191

2W: 2-wheeler; 3W: 3-wheeler; LDV: Light Duty Vehicle; HDB: Heavy Duty Bus; HDT: Heavy Duty Truck.

It was assumed that, after introduction of one BS emission norm, the vehicles under lower BS emission norm were not sold in the market. The lifespan for private (2W, 3W, Cars) and commercial (Trucks, Buses, LMV, Tractors) vehicles was assumed as 15 and 20 years, respectively. This was used to estimate the total number (n) of different types of vehicles under different emission norms during a particular year from the cumulative annual registered vehicle data published by the MoRTH (2020) for Madhya Pradesh. The emission factors (EF) of PM10, $PM_{2.5}$, NO_X, SO_2, hydrocarbon, CO, BC, and CH_4 for this exercise were adopted from ARAI (2008) and IPCC (2006).

Table 46: Emission Estimates in kt/year from the Transport Sector in Madhya Pradesh

Vehicle Type	PM_{10}	$PM_{2.5}$	BC	NO_X	SO_2	NMVOCs	CO
Truck	6.04	5.85	4.12	113.4	0.50	56.5	31.90
Tractor/Trailer	0.78	0.75	0.53	14.02	0.03	4.67	3.90
Bus	0.62	0.60	0.42	12.59	0.86	0.43	4.58
Cars	0.74	0.71	0.50	18.52	0.57	5.25	18.54
MUVs	0.32	0.31	0.22	4.33	0.001	0.69	1.82
2 wheelers	6.78	6.57	4.62	62.22	0.24	92.5	136.2
3 wheelers	0.37	0.35	0.25	2.47	0.36	1.02	2.53
LCVs	3.52	3.41	2.40	53.31	0.78	12.79	24.53
Totals	19.2	18.6	13.1	280.9	2.6	174	224.1
	CH_4 (Estimated based on fuel's calirific value)						
Transport	4.8						

Industry

The approach for estimating emissions from the industrial sector used in this study is based on the activity data of fuel consumption in the manufacturing processes and the type of fuel consumed. Emissions of PM10, PM2.5, SO2, NOX, NMVOCS, BC, and CH4 into the ambient atmosphere mainly occur during combustion. The data concerning fuel consumption and the APCDs installed is obtained from the MPPCB, providing a comprehensive insight into fuel usage patterns in the industrial sector.

The emissions from the industrial sector are estimated using the fuel consumption data and emission factor; the following is the equation to estimate industrial emissions:

$$E_p = C_f \times (f,p) \times (1-\eta)$$

Where Ep represents the emission of pollutants p, Cf is the fuel consumption in the industry, EF is the emission factor of the pollutant p of the fuel consumed f, and η denotes the efficiency of the APCD deployed in a specific industry. By systematically assessing industrial emissions, this study aims to provide insights into the air pollution challenges in Madhya Pradesh and support the development of effective air quality mitigation strategies.

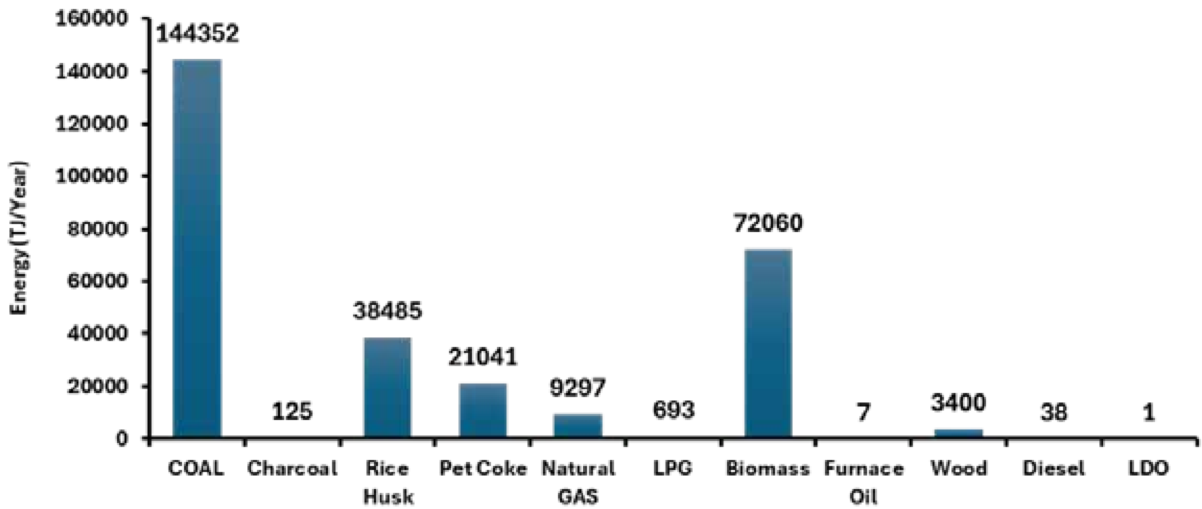


Figure 53: Estimated annual consumption of various types of fuel in the industry sector of Madhya Pradesh during 2019

The manufacturing industries in Madhya Pradesh exhibit a distinct fuel consumption pattern, with coal being the predominant energy source, accounting for approximately 50% of the total fuel usage. This heavy reliance on coal significantly contributes to air pollution and greenhouse gas emissions. Biomass constitutes around 39%, reflecting some level of renewable energy adoption, though its share remains much lower than coal. Liquid fuels such as furnace oil, Light Diesel Oil (LDO) and diesel together account for 0.016%, primarily used in specific industrial operations. Petroleum coke (pet coke) contributes 7%, and while its usage is relatively lower, its high carbon intensity makes it a significant pollutant. Other fuels, including natural gas and alternative fuels (LPG, Charcoal), make up the remaining 3.49%. This distribution highlights the urgent need for cleaner energy alternatives and improved fuel efficiency in Madhya Pradesh's industrial sector to mitigate environmental and health impacts.

Estimated emissions of different pollutants

The activity data of different fuels is fed into above equation along with the fuel specific emission factors of different pollutants (EF(f,p)) (Table 47) to calculate the emission (kt) of different pollutants from the use of different fuel types used in the industries of Madhya Pradesh Pradesh during 2019.

Table 47: Emission Factors (Kg/t), (Kt/PJ), (T/PJ) of Different Pollutants from Different Fuels Used in Industries in Madhya Pradesh

Emission Factor (Kg/t)	Pet Coke	Charcoal	Wood	Diesel	Furnace Oil	Natural gas	LPG	Coal	LDO	Rice Husk	Bagasse
PM_{10}	3.73	200	17.3	0.24	2.592	0.0001216	2.1	187.6	0.24	5.3	8.1
$PM_{2.5}$	2.13	70	15.743	0.216	1.73664	0.0001216	2.1	65.66	0.216	3.445	5.265
SO_2	13.46	9.75	0.2	9.405	37.68	0.0000096	0.4	9.75	33.858	0.11	0.18
NO_X	3.82	12	1.3	1.2	6.6	0.0016	1.8#	4.5	1.2	0.19	0.36
CO	2.73	160	126.3	0.6	0.6	0.001344	0.252#	0.3	0.6	14.05	12.39
VOCS* (kT/PJ)	0.01	0.01	0.015	0.004	0.005	0.003	0.002	0.01	0.004	0.015	0.048
BC* (T/PJ)	0.519	0.519	8	0.11	0.744	0.007	0.013	4	0.11	14.2	14.2
CH_4* (kT/PJ)	0.01	0.01	0.01	0.003	0.003	0.0471	0.001	0.001	0.003	0.003	0.011

*Sources: SA Six cities, CPCB, Coal: based on ash content and sulphur content for PM and SO_2, Rice Husk: M Irfan et.al 2014, *Gains Asia, #Kg/10^6 m^3*

Emissions (Kt/year) of various pollutants for different fuels from Industries in the state of Madhya Pradesh are shown in Table 48.

Table 48: Emission Estimates in kt/year from the Industry Sector in Madhya Pradesh

	PM_{10}	$PM_{2.5}$	SO_2	NO_x	NMVOCs	BC	CH_4
PetCoke	0.15	0.10	1.78	0.51	0.08	0.00	0.04
Charcoal	0.05	0.02	0.01	0.01	0.00	0.00	0.00
Wood	0.18	0.19	0.01	0.04	0.02	0.01	0.01
HSD	0.01	0.02	0.00	0.25	0.05	0.00	0.02
FO	0.03	0.02	1.36	0.24	0.01	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.08	0.09	0.00	0.09
LPG	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coal	62.64	25.58	10.85	5.01	0.32	0.12	0.03
LDO	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Rice husk	1.00	0.75	0.07	0.12	0.14	0.11	0.02
Bagasse	2.04	1.55	0.15	0.30	0.85	0.20	0.16
TOTAL	**66.10**	**28.23**	**14.24**	**6.56**	**1.58**	**0.44**	**0.38**

Mining

There are different processes in which emissions occur during mining such as mining activities, mine fires and coal/lignite burning. Once the overburden is removed, drilling and blasting actions are performed to reach the lignite seam. The charging of holes with the explosive results in the release of carbon di oxide. Drilling of coal/lignite also results in the release of methane gas along with other toxic elements. After the excavation coal gets loaded on dumpers and will be carried to the coal preparation plant unit. Fugitive emissions of PM are the major causes of air pollution from mines. All major activities (overburden removal, drilling, blasting, crushing, hauling, loading, transportation, etc.) carried out in the mines produce a lot of dust. Opencast mining has a more severe impact on air quality compared to underground mining, with high levels of suspended PM associated with opencast mines. Several studies have repeatedly reported that as high as 50–80% of the total dust emitted in open cast coal mines can be attributed to vehicular movement on unpaved haul roads, followed by loading and unloading of dumpers.

The activities responsible for pollution in and around coal mine areas are drilling, blasting, overburden loading and unloading, coal loading and unloading, haul roads, transport roads, stock yards, exposed overburden dumps, coal handling plants, exposed pit faces, presence of fire, exhausts from heavy earth moving machinery, crushing of coal to a convenient size in the feeder breaker and workshop (Ghose and Majee, 2000a).

In this study, we have estimated fugitive emissions from:

- Overburden (topsoil) removal, its loading, unloading and transportation
- Loading, unloading and transportation of coal

Emissions from overburden removal and transportation

The emissions occurred during the process of overburden removal, it's loading and unloading is estimated based on the equation 2.

EOB = OBR × EF .... (2)

Where,

E_{OB} is the fugitive emissions due to overburden removal, loading and unloading

OB_R is the quantity of overburden removed

E_F is the emission factor

Quantity of overburden removed per year is collected from Coal directory 2019-2020. EF developed by Ghose (2004) is used for estimation of Emissions (Table 49)

Table 49: EF and estimated emissions from overburden removal, its loading and unloading

Mining activity	PM emission factor (kg/t)	Emissions (kt/year)		
		PM	PM_{10}	$PM_{2.5}$
Topsoil removal	0.029	29.64	14.82	2.96
Loading of overburden	0.018	18.39	9.19	1.84
Unloading of overburden	0.001	1.022	0.511	0.102
Total		**49.06**	**24.53**	**4.90**

Emissions from transport of overburden were estimated based on the total quantity of overburden removed annually, capacity of truck used to carry the overburden, distance travelled by each truck and emission factor using equation 3.

ETOB = (OBR / CT) × DT × EF .... (3)

Where ET_{OB} is the emission, OB_R is the quantity of overburden removed, C_T is the capacity of the truck used to carry overburden, DT is the distance travelled by the truck, and EF is the emission factor.

The information on the quantity of overburden removed length of the haul road, and the capacity of the truck were assumed to be based on TERI's past studies, and the emission factor developed by Ghose is used to estimate emissions. Table 50 represents the selected EF and estimated emissions from transport of overburden.

Table 50: EF and estimated emissions from overburden removal, its loading and unloading

Mining activity	PM emission factor (kg/VKT)	Emissions (kt/year)		
		PM	PM_{10}	$PM_{2.5}$
Transportation of overburden	2.25	13.53	6.77	1.3528

Emissions from loading, unloading and transport of coal

Eq. (2) and (3) will be used to estimate emissions from loading, unloading and transportation of coal. Instead of the total overburden removed, the total coal produced will be used for the estimation. The estimated emissions from loading, unloading and transporting of coal are depicted in Table 51.

Table 51: EF used and estimated emissions from loading, unloading and transport of coal

Mining activity	PM emission factor (kg/t)	Emissions (kt/year)		
		PM	PM_{10}	$PM_{2.5}$
Loading of coal	0.014	1.76	0.88	0.17
Unloading of coal	0.033	4.15	2.077	0.41
Transport of coal	2.25 (kg/VKT)	3.414	1.70	0.34
Total		**9.32**	**4.66**	**0.93**

Methane (CH_4) emissions from coal mining activities in India for the year 2019–2020 were estimated using coal production data obtained from the Coal Directory of India. The estimation considers emissions from three primary sources within the coal mining process: surface mining, underground mining, and post-mining activities. To ensure consistency with national reporting protocols, emission factors used for the calculations were adopted from India's Fourth Biennial Update Report (BUR-4) submitted to the United Nations Framework Convention on Climate Change (UNFCCC).

Methane emissions were calculated using a Tier 1 approach, in line with the 2006 IPCC Guidelines, which employs default emission factors applied to activity data. The general equation used for estimating emissions is:

CH_4 Emissions = $\sum i(Pi \times EFi)$

where Pi is the quantity of coal produced (in million tonnes) from mining type i—namely surface, underground, or post-mining—and EFi is the corresponding emission factor (in m3 CH_4 per tonne of coal) for each mining type.

The total national coal production for 2019–2020 was disaggregated based on the relative shares of mining methods in Madhya Pradesh (MP), one of the major coal-producing states in India. According to available data, approximately 96% of coal in MP is extracted through surface mining, while 4% is mined underground . These proportions were assumed to be representative of the broader national mining profile for the purpose of this estimation and were applied to the total coal production to determine the quantities extracted by each method.

Emission factors (Table 52) sourced from India's BUR-4 were applied to the respective production volumes. Surface mining and underground mining emissions were calculated separately using their respective emission factors. Post-mining emissions, which result from the release of methane during the handling, processing, and transportation of coal, were estimated by applying a distinct emission factor across the entire coal production, regardless of the method of extraction, in accordance with BUR-4 guidelines.

Table 52: CH_4 Emission Factor

Operation (Mining / Post mining)	Methane emission factor (m_3/tonne)	
	Surface mining	Underground mining
Mining	1.18	13.08
Post Mining (Handling)	0.15	2.15

India. (2024). ***India. Biennial Update Report (BUR). BUR 4.*** United Nations Framework Convention on Climate Change. https://unfccc.int/sites/default/files/resource/India%20BUR-4.pdf

Table 53: CH_4 Emissions (Kt/Year)

Processes	Emissions
Surface	102
Underground	44
Post Mining	
Surface	13
Underground	3
Total	**162**

Power Plant

Emissions from coal-based thermal power plants are estimated based on the amount of coal consumed in the year 2019. Coal consumption serves as the activity data, while emission factors for coal combustion in thermal power plants (TPPs) are applied to calculate emissions. Coal consumption data for 2019 was obtained from the Central Electricity Authority (CEA) for each power plant. Additional information, including ash content, sulfur content, and details on air pollution control devices (APCDs), was obtained from the CEA database and reports from Madhya Pradesh Power Generating Co. Ltd.

As discussed earlier, both imported and domestic coal consumption were considered to estimate emissions. Emission factors for various pollutants were derived from multiple sources, including the AP42 guidelines, the GAINS Asia database, and the AR6 report.

The equations used for estimation of emissions (SPM and Gases) from coal-based power plant are,

$$[E_{PM}]_c = \sum_{(a=1)}^{n} [P_c]_a \times [A_c]a \times (1 - fb_r) \times \mathbf{M} \times (1 - RE_a)$$

$$[E_{Pg}]_c = \sum_{(a=1)}^{n} [P_c]_a \times EF_{pg} \times (1 - RE_a)$$

Where, E_{PM} is the emission of particulates, E_{Pg} is the emission of gaseous pollutants, [Pc]a is annual coal consumption in plant a, [Ac]a is ash content of coal in TPP a, fb_r is the ratio of bottom ash to fly ash, M is the particulate mass fraction (0.75 for PM_{10} to total particulates and 0.4 for $PM_{2.5}$ to PM_{10}), REa is the efficiency (%) of installed air pollution emission control equipment at TPP and EFpg is the emission factor of the particular gaseous pollutant (p) from TPP.

Estimated emissions of different pollutants

The emission factors for particulate matter and gas pollutants used for calculation of emissions from domestic coal and imported coal are provided in Table 54.

Table 54: Emission factor for coal-based power plants as per AP-42, USEPA, AR6 report and Gains Asia database

Pollutants	Emission Factor	Unit
SPM	Coal consumption (Kt/year) * {(1-bottom ash (%)) * (1-ESP efficiency (%)}	kt
PM_{10}	70% of SPM	kt
$PM_{2.5}$	40% of PM_{10}	kt
SO_2	19.5* S*	kg/t
NO_X	4.5	kg/t
NMVOCs	0.015	Kt/PJ
CH_4	0.274	kg/t
BC	12% of $PM_{2.5}$	kt

*The ash content of domestic coal ranges from 27.6% to 37.5% (CEA, MPPGCL), while imported coal has 10% ash content and 20% sulfur content (CEA). Bottom ash was considered as 20%, based on the average value from MPPGCL data.

Emissions for various pollutants from various thermal power plants and Industrial captive thermal power plants in the state of Madhya Pradesh are shown in ***Table 55***

Table 55: Emissions (Kt/year) from the coal based thermal power plants in Madhya Pradesh state during the year 2019.

Utility-Scale Thermal Power Plants	PM_{10}	$PM_{2.5}$	SO_2	NO_X	NMVOCs	CH_4	BC
Amarkantak TPP	1.69	0.68	32.52	21.92	1.18	1.33	0.08
Bina TPP	0.59	0.23	10.18	6.86	0.37	0.42	0.03
Nigrie STPP	1.11	0.44	22.81	15.37	0.83	0.94	0.05
Jhabua Power Ltd, BarelaTPP	0.89	0.36	15.52	10.46	0.56	0.64	0.04
M.B. PowerLtd, Jaithari Anuppur, TPP	2.89	1.16	50.29	33.90	1.82	2.06	0.14
Mahan Energen Limited, TPP	1.08	0.43	20.61	13.89	0.75	0.85	0.05
Khargone STPP	1.18	0.47	3.25	14.59	0.78	0.89	0.06
Gadarwara STPP	3.07	1.23	58.48	39.42	2.12	2.40	0.15
Sanjay Gandhi TPP	1.79	0.72	39.42	26.57	1.43	1.62	0.09
Sasan TPP	2.30	0.92	40.02	26.98	1.45	1.64	0.11
Satpura TPP	0.44	0.18	10.23	6.90	0.37	0.42	0.02
Shree Singaji TPP	1.37	0.55	24.33	16.40	0.88	1.00	0.07
Vindhyachal STPP	3.85	1.54	9.21	41.39	2.22	2.52	0.18
Industrial Captive Power Plants							
A.C.C. Ltd, TPP (Captive)	0.14	0.06	2.46	1.66	0.09	0.10	0.01
Birla Corporation Ltd, TPP (Captive)	0.07	0.03	1.17	0.79	0.04	0.05	0.00
Grasim Industries Limited, TPP (Captive)	0.14	0.06	2.44	1.64	0.09	0.10	0.01

Utility-Scale Thermal Power Plants	PM_{10}	$PM_{2.5}$	SO_2	NO_x	NMVOCs	CH_4	BC
HEG Limited, TPP (Captive)	0.22	0.09	3.07	2.07	0.11	0.13	0.01
Hindalco Industries, Mahan Aluminum, TPP (Captive)	0.34	0.13	6.43	4.34	0.23	0.26	0.02
Sidhi Cement Works, TPP (Captive)	0.11	0.04	1.95	1.31	0.07	0.08	0.01
Ultra Tech, TPP (Captive)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vardhman Fabrics, TPP (Captive)	0.09	0.04	1.61	1.08	0.06	0.07	0.00
Vardhman Yarns, TPP (Captive)	0.10	0.04	1.75	1.18	0.06	0.07	0.00
Total	**23.46**	**9.38**	**357.73**	**288.71**	**15.49**	**17.58**	**1.13**

Captive power plants can be considered part of the power sector because many are connected to the grid and supply a significant amount of power to the state. This integration makes their emissions a crucial component in estimating total emissions from the power sector. In this analysis, emissions are categorized from industrial captive thermal power plants (ICPPs) and utility-scale thermal power plants (USTPPs). In Madhya Pradesh, combined emissions from ICTPPs and USTPPs are 23.46 kt of PM_{10}, 357.73 kt of SO_2, and 1.13 kt of BC annually.

Among USTPPs, Vindhyachal STPP (3.85 kt) and Gadarwara STPP (3.07 kt) emitted the highest PM_{10}, while Gadarwara STPP (58.48 kt) and M.B. Power Ltd (50.29 kt) released the most SO_2. Although ICPPs emit lower amounts individually, their combined emission 0.11 kt of BC—are non-negligible, with Hindalco Industries (0.02 kt) as the largest contributor. Other pollutants, including NO_x, NMVOCS, and CH_4, also contribute significantly to the state's emissions from thermal power plants.

DG Sets

According to the Ministry of Petroleum and Natural Gas (MoPNG) annual reports, diesel consumption in Madhya Pradesh grew at a compound annual growth rate (CAGR) of 5.3% between 2008 and 2019. The latest data from the Petroleum Planning and Analysis Cell (PPAC, 2021) indicates that diesel generator (DG) sets account for approximately 2.5% of the state's total diesel consumption across various sectors. The industrial sector leads with a 0.9% share, followed by agricultural pumps (0.6%), the commercial sector (0.5%), mobile towers (0.3%), and the residential sector (0.2%). The emission inventory for DG sets in 2019 was estimated using diesel consumption (activity data) and emission factors from sources including AP-42 (USEPA), Bond et al. (2004) for black carbon (BC), and the AR6 report for methane (CH_4). Sector-specific fuel consumption was calculated by analyzing the total annual diesel consumption in Madhya Pradesh and the proportion of each sector's fuel usage. Annual diesel consumption data were obtained from MoPNG reports, while sector-specific consumption shares were based on the PPAC report (2021).

Further, emissions are estimated using equations X and Y.

Ed = Fd x Cald **eq. X**

EDG = Ed x EF **eq. Y**

Where, Ed is the total energy equivalent of the diesel fuel consumed by DG sets annually, Fd is total fuel consumed by DG sets annually, Cald is the calorific value of diesel which is 45.5 MJ/Kg.

Tailpipe emission control devices and technologies are not included in current emission estimates. According to expert interviews and literature reviews, there is limited data on the number of diesel generator sets equipped with these devices. But better devices to control emissions from exhaust pipes have been made and are expected to be used more in the future and accounted in alternate scenario for all the sectors except agriculture pumps. Pollutant-wise emission factors represented in Table 56.

Table 56: Emission factor for DG sets as per AP-42, USEPA, Bond et al. 2004 and AR6 report

Pollutants	Emission Factor (g/Joule of energy)
PM_{10}	133.3
$PM_{2.5}$	113.31
SO_2	124.7
NO_X	1896.3
CO	408.5
$NMVOC_S$	154.8
CH_4	3
BC	74.8

**Conversion of ng/J → g/Kg = 0.0036*

Emissions for various pollutants in the state of Madhya Pradesh are shown in **Table 57.**

Table 57: Emissions (Kt/year) from the operation of diesel generators in different sectors in Madhya Pradesh state during the year 2019.

	PM_{10}	$PM_{2.5}$	SO_2	NO_X	CO	$NMVOC_S$	CH_4	BC
Agri Pump sets	0.13	0.11	0.12	1.89	0.41	0.15	0.00	0.07
Mobile towers Dg sets	0.07	0.06	0.06	0.95	0.20	0.08	0.00	0.04
Power generation (industrial DG sets)	0.20	0.17	0.19	2.84	0.61	0.23	0.00	0.11
Power generation (Commercial DG sets)	0.11	0.09	0.10	1.58	0.34	0.13	0.00	0.06
Power generation (Residential DG sets)	0.04	0.04	0.04	0.63	0.14	0.05	0.00	0.02
Total	**0.55**	**0.47**	**0.52**	**7.88**	**1.70**	**0.64**	**0.01**	**0.31**

Crematoria

Emissions from the cremation sector are estimated based on the total amount of wood used during cremation rituals. Wood consumption is calculated using key demographic factors, including the total population of Madhya Pradesh, the crude death rate, and the proportion of Hindus, Jains, and Sikhs in the state. For the baseline inventory year 2019, population data was taken from the projected population report of the Census, while the religious composition was sourced from Census 2011. The crude death rate (6.5) was obtained from the Sample Registration System (SRS) Bulletin 2020.

The wood consumption per cremation was taken from the NEERI report 2019 (Short Term and Localized Air Pollution Control System). By combining these parameters, the total wood burned was estimated, serving as the foundation for calculating emissions from the cremation sector. Emissions were quantified using equations_X.

Ep = (P2019 X F X DR X 350) X EF

Where P2019 is the total population of Madhya Pradesh, F is the fraction of Hindus, Sikhs and Jains, DR is the crude death rate i.e. 6.5 (per thousand population), EF is the emission factor and 350 is average wood consumption in KG for one cremation.

The emission factors were adopted from Akagi et al. (2011) and the Scientific Report from DCE ***(Danish Centre for Environment and Energy (2018)).*** The compiled emission estimates (Kt/year) and emission factors are presented in the following table 58.

Table 58: Emission factor used & Estimated Emissions from Crematoria Sector

Pollutant	Emission factor (G/Kg)	Emissions (Kt/year)
PM_{10}	18.5	3.18
$PM_{2.5}$	9.1	1.56
SO_2	0.4	0.07
NO_X	2.55	0.44
CO	93	15.97
$NMVOC_S$	51.9	8.91
BC	0.52	0.07
CH_4	5.16	0.89

Agricultural Residue Burning

Emission inventory of different pollutants from the burning of different crop residues in the cropland has been developed by following the IPCC (2006) inventory preparation guideline. The primary crops considered for inventory preparation are rice, wheat, maize, sugarcane and cotton. These crops have been selected as they are prone to burning across the country, as mentioned in different published literature along with National Policy for Management for Crop Residues (NPMCR). Emission from the in-situ burning of crop residue is calculated using the equation below,

$$\mathrm{Epol} = \sum_{S=1}^{35} \sum_{D=1}^{n} \sum_{C=a}^{n} Pa \times Ra \times fDa \times fBa \times EFpol \times Bf$$

Where, Epol = Emission of a particular pollutant (pol) (g); Pa is the total production of a particular crop (C) in a particular district (D) of the state (S) in kilogram (here only Madhya Pradesh has been taken); Ra is the fraction of residue generated for the production (Pa) of the particular crop (a); fDa is the fraction of dry matter in the residue of the particular crop (a); fBa is the combustion efficiency of crop residue that is burnt, Bf is the burning fraction of the crop estimated based on MODIS FRP data, and EFpol is the emission factor of the particular pollutant (g/Kg). Emission estimation equation does not show controls as there are no direct emission control measures for control of agricultural burning emissions at the fields. However, burning fractions are to be reduced by implementing in-situ and ex-situ measures.

The seasonal district-wise production data (Pa) of different crops was collected from the Department of Agriculture Cooperation and Farmers' Welfare (DAC&FW), Ministry of Agriculture, and Government of India for the year 2019. Different crops' residue to crop fractions (Ra) has been replicated as in Datta and Sharma (2014). The dry matter fraction in different crop residues (fDa) replicates as reported by Aerosol and Air Quality Research. The combustion efficiency (fBa) of different crop residues is used as reported in Turn et al. (1997) (Table 59).

Table 59: Coefficients of Different Crop Residues to Estimate the Emissions of Different Pollutants

Co-efficient	Rice	Wheat	Cotton	Maize	Sugarcane
Residue to Crop ratio (Ra)[a]	1.59	1.70	3.00	2.00	0.40
Dry fraction of residue (fDa)[b]	0.86	0.88	0.80	0.90	0.90
Combustion efficiency (fBa)[c]	0.89	0.86	0.90	0.92	0.68

[a] Datta and Sharma (2014); [b] Jain et al. (2014); [c] Turn et al. (1997)

The burning fraction (Bf) has been calculated from the MODIS Fire Radiative Power (FRP) data. The FRP dataset of the NASA's MODIS (aqua and tera) satellites is also used to identify the crop residue burning locations at grids over the state boundary during crop harvesting seasons of 2019. This is further employed to spatially allocate the emissions. The MODIS active fire products provide fire detections at the satellite overpass times. Terra and Aqua respectively cross the equator at approximately 10:30 a.m. and 1:30 p.m. local time during daytime and 10:30 p.m. and 1:30 a.m. during nighttime. The MODIS Level 2 active fire products (abbreviated MOD14 for Terra and MYD14 for Aqua) contain for each fire pixel the detection time, geographical coordinate, confidence (low, nominal, and high), fire radiative power (units: MW per pixel), brightness temperature at the MODIS band 21 (3.660–3.840 µm) and band 31 (10.780–11.280 µm), and average brightness temperature of the surrounding non-fire pixels at bands 21 and 31. The FRP estimates in MODIS Collection 6 (C6) active fire product are retrieved following the method developed by Wooster et al. (2003). The FRP products retrieved from MODIS C6 datasets were plotted on GIS along with LULC (land use and land cover) MODIS products for the study year. The FRP's detected over agricultural land use area were extracted for further analysis, as it is assumed that rest of the FRP's being detected may represent some other form of burning. This extracted data has been used to estimate yearly FRP detected in each district of the country. The maximum FRP value detected in any district of the country since the availability of the data i.e., 2001 has been assumed where almost 70% of the residue is being burnt.

Estimated methane emissions from rice crop land of Madhya Pradesh during 2019-20 were 0.26 kt **(Table 60).** During the estimation of methane emission, it was considered that there were no direct methane emissions from other crops like maize, wheat, sugarcane and Cotton as there was no continuous waterlogging condition during cultivation process of these crops.

Table 60: Total Agriculture-related Emissions in Madhya Pradesh in 2019 (kt/yr)

District	PM_{10} (kt)	$PM_{2.5}$(kt)	BC(kt)	CO(kt)	SO_2(kt)	NO_X(kt)	$NMVOC_S$(kt)	CH_4 (kt)
AGAR MALWA	1.74	1.18	0.17	14.23	0.32	0.11	0.11	0.00
ALIRAJPUR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ANUPPUR	0.36	0.28	0.04	2.98	0.11	0.02	0.28	0.01
ASHOKNAGAR	3.56	2.41	0.36	29.09	0.66	0.22	0.30	0.00
BALAGHAT	0.92	0.69	0.10	7.49	0.28	0.06	0.68	0.03
BARWANI	2.47	1.76	0.15	15.75	0.42	0.21	1.78	0.00
BETUL	3.44	2.61	0.29	25.47	0.70	0.23	0.97	0.00
BHIND	1.84	1.27	0.19	15.08	0.39	0.12	0.40	0.00
BHOPAL	1.95	1.33	0.19	15.91	0.37	0.12	0.19	0.00
BURHANPUR	0.85	0.60	0.05	4.39	0.12	0.10	0.82	0.00
CHHATARPUR	3.67	2.48	0.37	30.00	0.67	0.23	0.23	0.00
CHHINDWARA	13.07	10.06	0.82	93.61	2.74	0.78	6.51	0.00
DAMOH	1.88	1.30	0.19	15.46	0.39	0.12	0.39	0.01
DATIA	3.95	2.74	0.42	30.87	0.74	0.30	0.58	0.01
DEWAS	5.27	3.59	0.52	42.94	0.97	0.33	0.43	0.00
DHAR	8.19	5.62	0.61	57.05	1.38	0.65	4.17	0.00
DINDORI	0.21	0.16	0.02	1.69	0.06	0.01	0.13	0.01
GUNA	4.16	2.85	0.40	33.84	0.77	0.26	0.38	0.00

District	PM_{10} (kt)	$PM_{2.5}$(kt)	BC(kt)	CO(kt)	SO_2(kt)	NO_x(kt)	$NMVOC_s$(kt)	CH_4 (kt)
GWALIOR	4.53	3.17	0.47	36.97	1.00	0.29	1.26	0.01
HARDA	3.02	2.05	0.30	24.63	0.55	0.19	0.24	0.00
HOSHANGABAD	11.84	8.43	1.15	95.25	2.54	0.74	3.07	0.01
INDORE	4.20	2.84	0.42	34.36	0.76	0.26	0.28	0.00
JABALPUR	6.69	4.72	0.68	54.62	1.50	0.42	1.97	0.01
JHABUA	0.55	0.39	0.04	3.84	0.10	0.04	0.31	0.00
KATNI	3.69	2.63	0.39	30.37	0.90	0.23	1.44	0.01
KHANDWA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
KHARGONE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MANDLA	1.54	1.16	0.16	12.48	0.43	0.10	0.92	0.02
MANDSAUR	4.09	2.77	0.41	33.44	0.75	0.25	0.29	0.00
MORENA	1.39	0.94	0.14	11.34	0.26	0.09	0.13	0.00
NARSINGHPUR	7.01	5.19	0.84	43.61	1.01	0.94	1.02	0.01
NEEMUCH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NIWARI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
PANNA	1.59	1.11	0.16	13.02	0.35	0.10	0.43	0.02
RAISEN	8.16	5.70	0.84	66.86	1.78	0.51	2.09	0.00
RAJGARH	3.02	2.07	0.29	24.55	0.56	0.18	0.28	0.00
RATLAM	3.16	2.15	0.30	25.19	0.57	0.20	0.47	0.02
REWA	5.32	3.77	0.56	43.78	1.26	0.33	1.88	0.00
SAGAR	5.32	3.61	0.53	43.49	0.98	0.33	0.40	0.02
SATNA	6.16	4.33	0.64	50.62	1.41	0.39	1.92	0.00
SEHORE	6.75	4.65	0.67	55.15	1.33	0.42	1.01	0.01
SEONI	11.72	9.14	0.86	90.56	2.75	0.58	4.67	0.01
SHAHDOL	0.57	0.42	0.06	4.67	0.16	0.04	0.34	0.00
SHAJAPUR	3.93	2.65	0.39	32.18	0.71	0.25	0.25	0.00
SHEOPUR	3.53	2.46	0.36	28.98	0.77	0.22	0.90	0.00
SHIVPURI	3.96	2.72	0.40	32.45	0.79	0.25	0.62	0.01
SIDHI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
SINGRAULI	1.95	1.40	0.19	15.90	0.46	0.12	0.71	0.00
TIKAMGARH	2.33	1.58	0.23	19.11	0.42	0.15	0.15	0.00
UJJAIN	7.89	5.33	0.79	64.60	1.43	0.49	0.50	0.01
UMARIA	0.08	0.06	0.01	0.65	0.02	0.00	0.04	0.00
VIDISHA	5.98	4.05	0.60	48.95	1.10	0.37	0.48	0.00
Total	187.52	132.44	17.76	1477.50	37.73	12.36	46.41	0.26

Livestock and Manure Management

The formula applied to calculate methane (CH_4) emissions from livestock and manure management is as follows:

$$\textbf{Emissions} = N_{(T)} * EF_{(T)} * 10^3$$

Where, Emissions = methane emissions (kg/year),

$EF_{(T)}$ = emission factor for the defined livestock population, kg CH_4/head/year

$N_{(T)}$ = the number of head of livestock species

T = species/category of livestock

For estimating emissions from livestock and manure management, default IPCC emission factors were applied (Table 61).

Table 61: Emission Factors used for Estimating Emissions from Livestock and Manure Management

Category	Sub-Category	Age Group	Methane Emission Factor	
			Enteric Fermentation (kg CH_4/head/year)	Manure Management (kg CH_4/head/year)
Indigenous Cattle	Dairy Cattle	Indigenous	28.00	3.50
	Non-Dairy Cattle (indigenous)	0–1 year	9.00	1.20
		1–3 years	23.00	2.80
		Adult	32.00	2.90
Crossbred Cattle	Dairy Cattle	Cross-bred	43.00	3.80
	Non-Dairy Cattle (cross-bred)	0–1 year	11.00	1.10
		1–3 years	26.00	2.30
		Adult	33.00	2.50
Buffalo	Dairy Buffalo		50.00	4.40
	Non-Dairy Buffalo	0–1 year	8.00	1.80
		1–3 years	22.00	3.40
		Adult	44.00	4.00
Sheep	Non-Dairy		5.00	0.20
Goat	Non-Dairy		5.00	0.22
Horses and Ponies	Non-Dairy		18.00	2.19
Donkeys	Non-Dairy		10.00	0.90
Camels	Non-Dairy		46.00	2.56
Pigs	Non-Dairy		1.00	4.00
Poultry	Non-Dairy		0.00	0.00

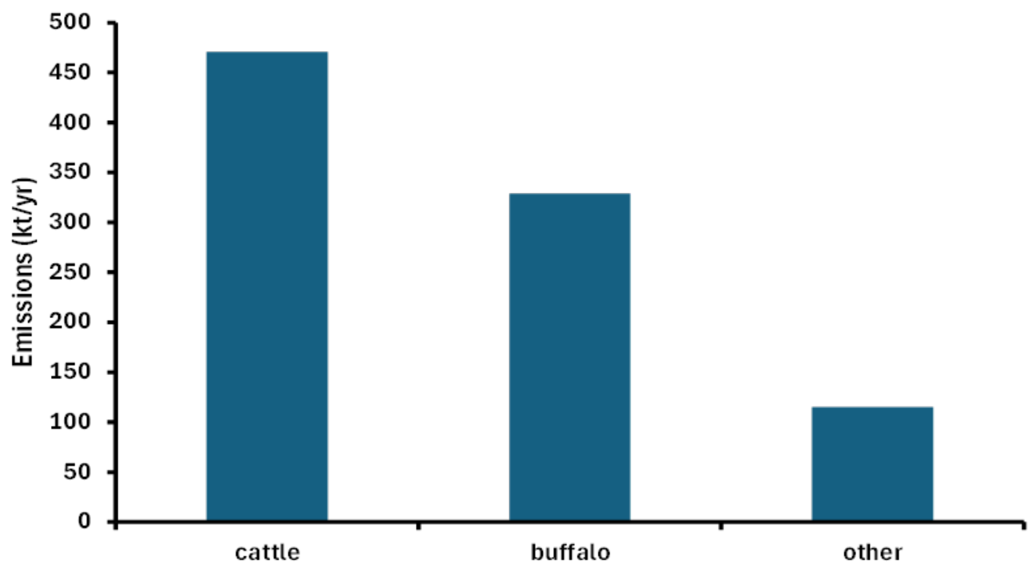


Figure 54: Methane Emissions from Livestock Enteric Fermentation in MP in 2019

Construction

The quantification of emissions from the construction sector is derived by assessing the total land area allocated for construction and demolition (C&D) activities. This estimation integrates the Gross State Value Added (GSVA) for the construction sector in Madhya Pradesh, as documented in the RBI Handbook (2023), along with the per-acre land valuation to approximate the spatial extent of active development. To enhance the temporal accuracy of cost estimations, an inflation-adjusted methodology is employed. Expert assessments indicate that the average construction expenditure per acre in 2016 was Rs. 984 lakhs. To account for cost escalation over time, the Construction Cost Index (CCI) sourced from the Construction Industry Development Council (CIDC), India is utilized. The CCI, benchmarked to a base year of 2007 (index value = 100 Rupees), facilitates the derivation of inflation-adjusted construction costs for 2019. This revised cost parameter is then applied to estimate the total active construction area, thereby enabling a more precise computation of emissions associated with sectoral activities.

After estimating the construction cost per acre, the GSVA for the construction sector is divided by this cost to quantify the total developed area for the base year. The mathematical expression used for the area calculation is described below:

AST = GSVAST / Ca

Where, AST represents the total area under construction during a year, GSVAST denotes the Gross State Value Added from construction activities for that year and Ca refers to the construction cost per acre of land for the respective year.

Below mentioned equation is used for emission estimation for construction or demolition sector.

Ep = Ac * T * Ef

Where, Ep signifies the suspended particulate emissions.

Ac = Activity data or total area under construction or demolition

T= Activity duration for construction or demolition for a site

*Rainy months (RM) are not considered in activity duration

Ef = Emission Factor (tons/acre/month)

The emissions of Suspended Particulate Matter (SPM) from construction activities are estimated using an emission factor of 1.2 tons/acre/month (Source: EPA). As per USBR (2002), PM_{10} emissions resulting from overburden removal and bulldozing during construction account for 35% of the total particulate matter emissions, while $PM_{2.5}$ constitutes 6% of the total SPM (Ahuja et al., 1989; Houck et al., 1989, 1990). The respective emission factors and estimated emissions are detailed in the **Table 62.**

Table 62: Emission Factors and Estimatted Emissions from Construction Activities

Year	2019	Emission Factor	SPM	PM_{10}	$PM_{2.5}$
Construction cost (INR Lakhs)	1000	1.2 tons/acre/month	52.66	18.43	3.16
Estimated area under construction (Acre)	4388				

Satellite Data Products and Technical Specifications

This report presents the 2019 Sectoral Spatial Analysis for Madhya Pradesh, report consists of a curated stack of Sentinel-5P/TROPOMI atmospheric retrievals (from European Space Agency), MODIS MAIAC aerosol optical depth 0.47 µm (NASA), VIIRS nightlights (NASA), and SEDAC population layers (NASA & COLUMBIA).

Sentinel 5p/TROPOMI Level 3 products provide total column averaging kernels for individual retrievals with further information in individual sections.

All Satellite products were aligned at EPSG CRS:6933 (NSIDC EASE-Grid 2.0 Global) resampled temporally with monthly median and spatially by mean (for all raster annual composites) and should not be mistaken for ground level concentrations.

SEDAC (Population Grids)

The Socioeconomic Data and Applications Center (SEDAC) Gridded Population of the World (GPW), version 4, revision 11 source dataset contains a Population Density product that provides estimates of population density at five-year intervals, we have used the estimates for the year 2020 on a 30 arc-second (~1 km at the equator) grid. Population density is obtained by dividing the population count grid for a given target year by the gridded land area. The GPW population count is generated using input from tabular census data that identifies the number of persons by administrative area and digital census administrative boundary data. This dataset was produced by CIESIN at Columbia University with primary support from the National Aeronautics and Space Administration for the Socioeconomic Data and Applications Distributed Active Archive Center (DAAC) for the Earth Observing System Data and Information System (EOSDIS).

Technical Details

Population estimates are distributed to a 30 arc-second (~1km) grid using an areal-weighting method. The input geographic boundaries were obtained from multiple sources including national statistical offices, national mapping agencies, and the Global Administrative Areas (GADMv2) dataset. A water mask was also applied to ensure that areas of water and permanent ice were not included in distributed population counts. The annual exponential growth rates applied to determine population estimates in the target years were defined using the population count from the previous census, the population count from the current census, and the number of years between the two records.

The dataset is limited by the availability and quality of census data. Additionally, there may be small underestimates in the gridded population for some areas due to the decision to exclude geographically undefined populations such as the homeless or those with boat homes. Taken from Doxsey-Whitfield (2015)

Table 63: SEDAC Technical Specifications

Attribute	Value
Temporal Extent:	**2000 - 2020**
Temporal Resolution:	**Annual, every 5 years**
Spatial Extent:	**Global**
Spatial Resolution:	**30 arc-seconds (~1 km at equator)**
Data Units:	**Number of persons per square kilometer (persons/km²)**
Data Type:	**Research**
Data Latency:	**5 years**

Satellite Products

TROPOMI (Tropospheric Monitoring Instrument) is a cutting-edge satellite instrument aboard the European Copernicus Sentinel-5 Precursor (S5P) satellite, launched in October 2017. It plays an essential role in gathering data that helps scientists to better understand atmospheric processes and environmental changes. TROPOMI's high-resolution data contributes to global efforts in monitoring air quality, tracking climate trends, and protecting the ozone layer, making it a key tool for advancing environmental science and policy worldwide.

Satellite Working

TROPOMI is an imaging spectrometer. It measures the solar radiation that is backscattered by the Earth and the atmosphere. By measuring the backscattered radiation for many wavelengths, TROPOMI can derive the concentration of different gases in the atmosphere. TROPOMI can observe the entire Earth in a single day and provides data with a spatial sampling of approximately 3.5 × 5.5 km for most of the data products and 7 × 5.5 km for the shortwave infrared data products.

1. METHANE

Sentinel-5P OFFL CH4: Offline Methane

Methane (CH_4) is, after carbon dioxide (CO_2), the most important contributor to the anthropogenically enhanced greenhouse effect. TROPOMI aims at providing CH_4 column concentrations with high sensitivity to the Earth's surface, good spatio/temporal coverage.

Filtering on qa_value > 0.5 removes all pixels considered bad. Some pixels with too low methane concentrations are still present:

- Single TROPOMI overpasses show stripes of erroneous CH_4 values in the flight direction.
- Not all pixels above inland water are filtered.
- Uncertainties for the CH_4 is only based on the single sounding precision due to measurement noise.

2. SULFUR DIOXIDE

Sentinel-5P OFFL SO2: Offline Sulfur Dioxide

S5P/TROPOMI samples the Earth's surface with a revisit time of one day with unprecedented spatial resolution of 3.5 × 7 km which allows the resolution of fine details including the detection of much smaller SO_2 plumes

The qa value is adjusted before running harpconvert to satisfy all of the following criteria:

- snow_ice < 0.5
- sulfurdioxide_total_air_mass_factor_polluted > 0.1
- sulfurdioxide_total_vertical_column > -0.001
- qa_value > 0.5
- cloud_fraction_crb < 0.3
- solar_zenith_angle < 60

3. NITROGEN DIOXIDE

Sentinel-5P OFFL NO2: Offline Nitrogen Dioxide

Nitrogen oxides (NO2 and NO) are important trace gases in the Earth's atmosphere, present in both the troposphere and the stratosphere. The TROPOMI NO2 processing system is based on the algorithm developments for the DOMINO-2 product. This retrieval-assimilation-modelling system uses the 3-dimensional global TM5-MP chemistry transport model at a resolution of 1×1 degree as an essential element.

4. FORMALDEHYDE

Sentinel-5P OFFL HCHO: Offline Formaldehyde

Formaldehyde is an intermediate gas in almost all oxidation chains of non-methane volatile organic compounds (NMVOC), leading eventually to CO_2. The seasonal and inter-annual variations of the formaldehyde distribution are principally related to temperature changes and fire events, but also to changes in anthropogenic activities. HCHO concentrations in the boundary layer can be directly related to the release of short-lived hydrocarbons, which mostly cannot be observed directly from space.

5. CARBON MONOXIDE

Sentinel-5P OFFL CO: Offline Carbon Monoxide

Carbon monoxide (CO) is an important atmospheric trace gas for understanding tropospheric chemistry. In certain urban areas, it is a major atmospheric pollutant. TROPOMI on the Sentinel 5 Precursor (S5P) satellite observes the CO global abundance exploiting clear-sky and cloudy-sky Earth radiance measurements in the 2.3 µm spectral range of the shortwave infrared (SWIR) part of the solar spectrum. TROPOMI clear sky observations provide CO total columns with sensitivity to the tropospheric boundary layer. For cloudy atmospheres, the column sensitivity changes according to the light path.

6. UV AEROSOL INDEX

Sentinel-5P OFFL AER AI: Offline UV Aerosol Index

The AAI is based on wavelength-dependent changes in Rayleigh scattering in the UV spectral range for a pair of wavelengths. The difference between observed and modelled reflectance results in the AAI. When the AAI is positive, it indicates the presence of UV-absorbing aerosols like dust and smoke. It is useful for tracking the evolution of episodic aerosol plumes from dust outbreaks and biomass burning. The wavelengths used have very low ozone absorption, so unlike aerosol optical thickness measurements, AAI can be calculated in the presence of clouds. Daily global coverage is therefore possible.

Table 64: Sentinel-5P/TROPOMI product bands, ranges and resolutions

Name	Units	Min	Max	Native Resolution	Description	Revisit
CH_4_column_ volume_mixing_ ratio_dry_air	Mol fraction	1285*	2405*	7 km x 7 km	Column-averaged dry air mixing ratio of methane, as parts-per-billion	2 days
SO_2_column_ number_density	mol/m²	-0.4051*	0.2079*	~7 km x 3.5 km	SO_2 vertical column density at ground level, calculated using the DOAS technique.	Daily
NO_2_column_ number_density	mol/m²	-0.00051*	0.0192*	~7 km x 3.5 km (native); ~10 km aggregated	Total vertical column of NO_2 (ratio of the slant column density of NO_2 and the total air mass factor).	Daily
tropospheric_ HCHO_column_ number_density	mol/m²	-0.0172*	0.0074*	3.5 km x 5.5 km	Tropospheric HCHO column number density.	Daily
CO_column_ number_density	mol/m²	-34.43*	5.71*	~7 km x 7 km	Vertically integrated CO column density.	Daily
UVAI -absorbing_ aerosol_index	Unitless	-21*	39*	~7 km x 3.5 km	A measure of the prevalence of aerosols in the atmosphere.	Daily

7. MODIS MAIAC AOD

MAIAC is an advanced algorithm which uses time series analysis and a combination of pixel- and image-based processing to improve accuracy of cloud detection, aerosol retrievals and atmospheric by Alexei Lyapustin and Yujie Wang (2022)

The MAIAC atmospheric products include AOD, column water vapor and smoke injection height at 1km resolution. Over the ocean, MAIAC retrieves AOD and fine mode fraction and reports the water-leaving reflectance.

Table 65: Technical Specifications Aerosol Optical Depth

Attribute (AOD)	Value
Band Name	Optical_Depth_047
Wavelength	0.47 µm (470 nm)
Units	Dimensionless
Native Range	-100 to 8000
Valid AOD Range	Approximately 0.0 - 8.0
Spatial Resolution	1 km
Temporal Resolution	Daily
Projection	Sinusoidal Grid

8. FIRMS

The near real-time (NRT) active fire locations are processed by LANCE using the standard MODIS MOD14/MYD14 Fire and Thermal Anomalies product. Each active fire location represents the centroid of a 1km pixel that is flagged by the algorithm as containing one or more fires within the pixel. The data are rasterized as follows: for each FIRMS active fire point, a 1km bounding box (BB) is defined; pixels in the MODIS sinusoidal projection that intersect the FIRMS BB are identified; if multiple FIRMS BBs intersect the same pixel, the one with higher confidence is retained; in case of a tie, the brighter one is retained.

8(a). MODIS Active Fire Products

Each MODIS active fire/thermal hotspot location represents the center of a 1km pixel that is flagged by the algorithm as containing one or more fires within the pixel. Combined (Terra and Aqua) MODIS NRT active fire products (MCD14DL) are processed using the standard MOD14/MYD14 Fire and Thermal Anomalies algorithm. VIIRS FIRMS datasets from SUOMI NPP are also taken for analysis.

8(b). VIIRS (375m) Active Fire Products

Each VIIRS active fire/thermal hotspot location represents the centre of a 375m pixel. The VIIRS data complement the MODIS fire detections, but the improved spatial resolution of the 375 m data provides a greater response of fires over relatively small areas and has improved nighttime performance. VIIRS NRT 375 m active fire products are from: Suomi NPP (VNP14IMGTDL_NRT)

9. Open Street Map

OpenStreetMap is an editable map database built and maintained by volunteers and distributed under the Open Data Commons Open Database License. All map data are free to download by anyone via multiple methods. The Road Hierarchy used from OSM is - Trunk / National Highways (from state LULC); Primary; Secondary; Tertiary and Service roads.

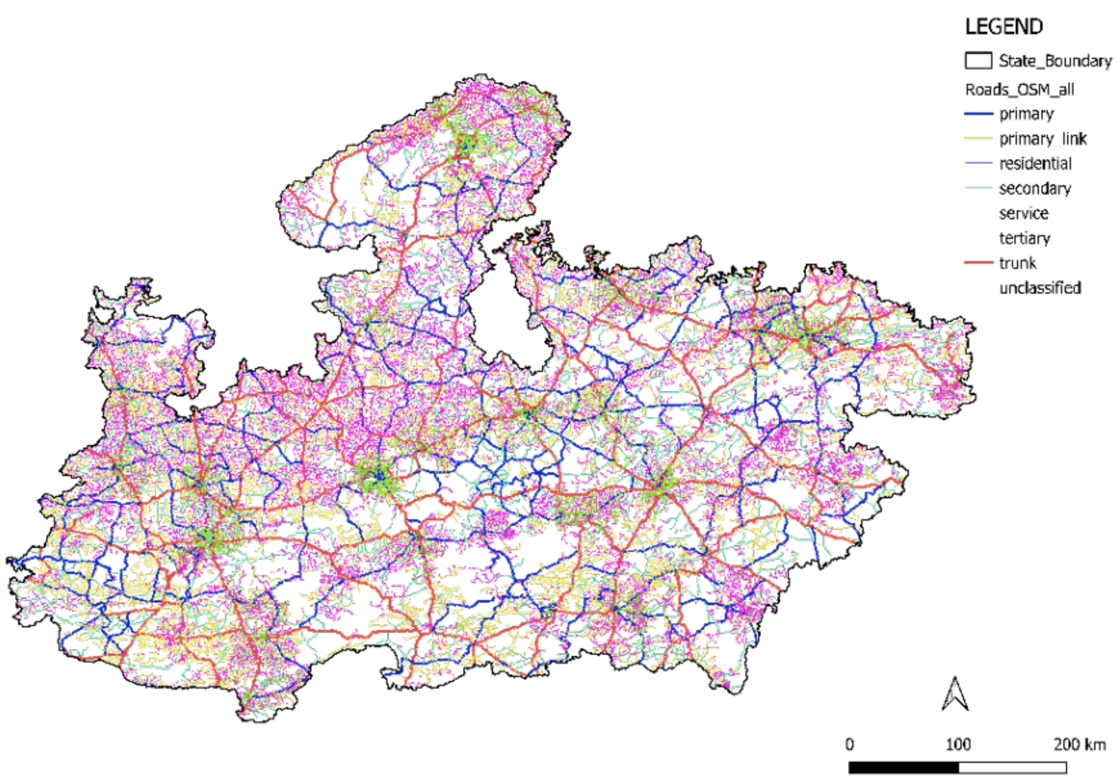


Figure 55: Open Street Map Road Network Inventory Madhya Pradesh

Table 66: Road Network - Open Street Map

Sr	class	Length (km)
1	primary	11764
2	residential	63134
3	secondary	22856
4	service	8767
5	tertiary	43842
6	trunk	13073

10. VIIRS Night Lights

'NOAA/VIIRS/DNB/ANNUAL_V21'

Annual global VIIRS nighttime lights dataset is a time series produced from monthly cloud-free average radiance grids spanning 2013 to 2021.

An initial filtering step removed sunlit, moonlit and cloudy pixels, leading to rough composites that contains lights, fires, aurora and background. The rough annual composites are made on monthly increments and then combined to form rough annual composites. We use the twelve-month median composite for maximum. Background areas are zeroed out using the data range (DR) calculated from 3×3 grid cells. The DR threshold for background is indexed to cloud-cover levels, with higher DR thresholds in areas having low numbers of cloud-free coverages.

Table 67: Technical Specifications VIIRS Maximum Radiance Band

Name	Units	Native Resolution	Description
Maximum	nanowatts/sr/cm^2	463.83 meters	Maximum DNB radiance values.

11. PADDY FIELDS DATASET

Paddy fields at 30 m resolution are taken from Shaoping Li et;al (2025) a study for developing on the Global Crop Dataset-Rice (GCD-Rice) dataset to map rice cultivation across multiple seasons.

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For more information

Gateway Research, First Floor, N-122 Panchsheel
Park, Malviya Nagar New Delhi , India–110 017
Web: gatewayresearchinstitute.org
Tel: 011-35062638