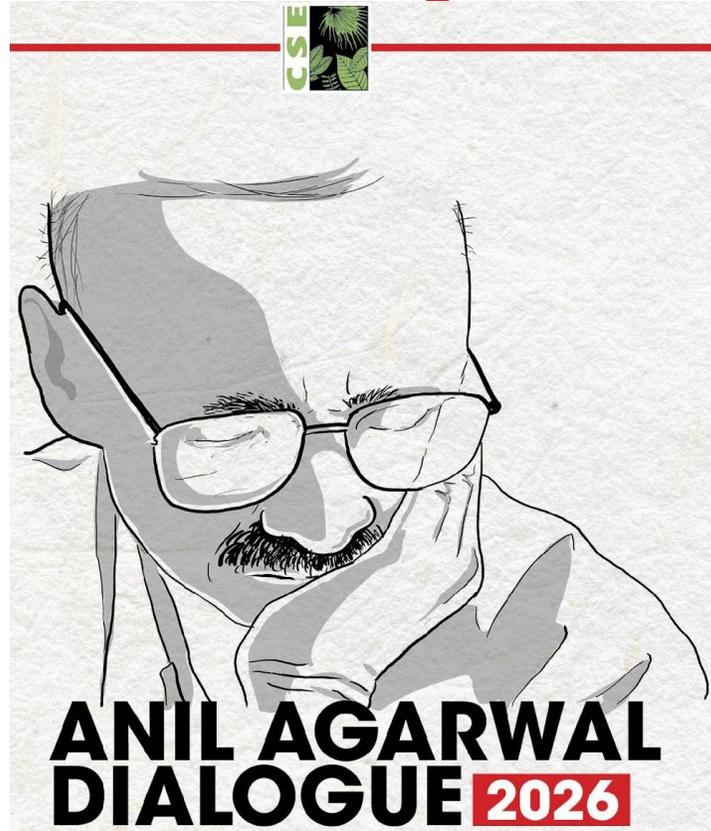


Estimating Air Pollution and Apportioning its Sources -- the Science of Doing an Inventory



Sri Harsha Kota

*Professor, Department of Civil & Environmental Engineering
and Co-Ordinator & Chair CoE in Clean Air*

IIT Delhi

*Introduction to the
Urban & Regional
Air Quality
Management
(URAM) Group*



Academic Qualifications

B.E.

- Civil Engineering at CBIT, Osmania University, Hyderabad.
- 2003-2007

M.S.

- Civil Engineering at Texas A&M University, College Station, USA.
- 2007-2009
- Thesis: *“Modeling Air Quality Near Freeways Using a Three Dimensional Eulerian Model”*

Ph.D.

- Civil Engineering at Texas A&M University, College Station, USA.
- 2009-2014
- Dissertation: *“Using Local and Regional Air Quality Modeling and Source Apportionment Tools to Evaluate Vehicle and Biogenic Emission Factors”*

PG Diploma in Environmental Law and Policy from National Law University, Delhi (2016-2017)

~18 years experience in air quality management



Professional Appointments

Professor

Department of Civil & Environmental Engineering
Indian Institute of Technology Delhi

Coordinator & Chair Professor

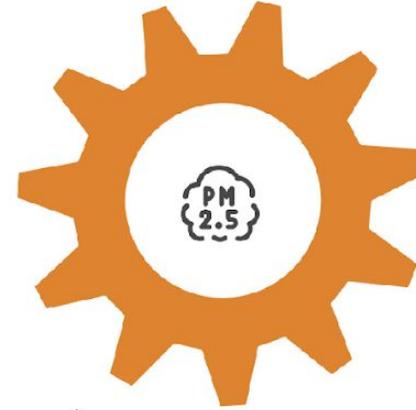
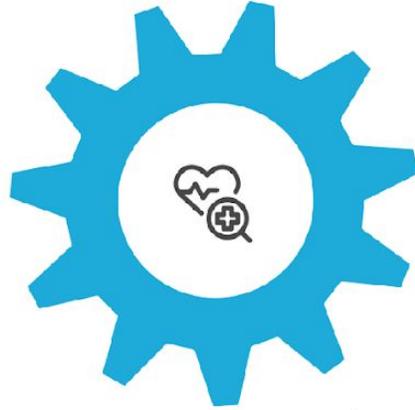
Centre of Excellence for Research in Climate
Change and Air Pollution

Associate Dean (Infrastructure)

Indian Institute of Technology Delhi

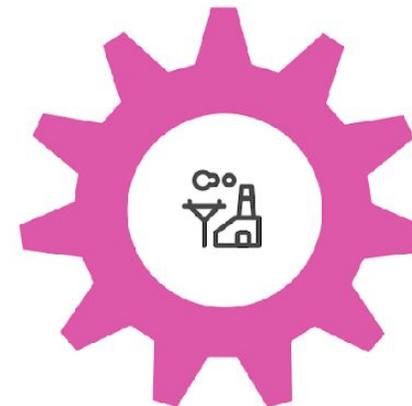
Major Areas of Research

Exposure,
Health Impacts
& Societal
Costs



Air Quality
Modelling &
Policy
Evaluation

Air
Pollution
& Plants



Multi-Sectoral
Emission
Inventories

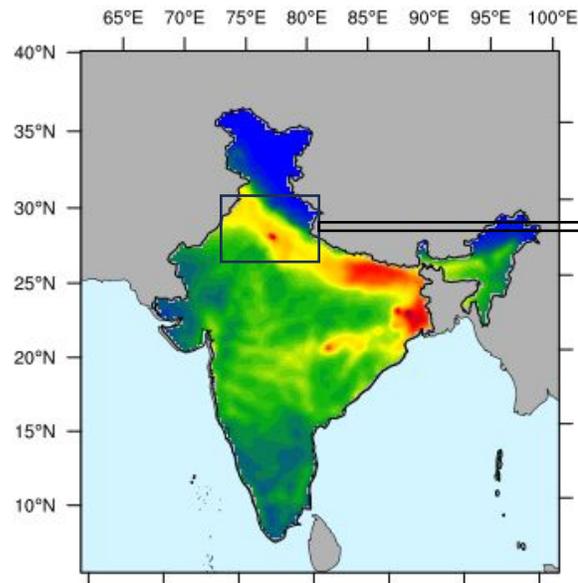
Urban and Regional Air Quality Management (URAM) Contribution

Integrated National ↔ Regional ↔ Urban ↔ Hotspot Modeling

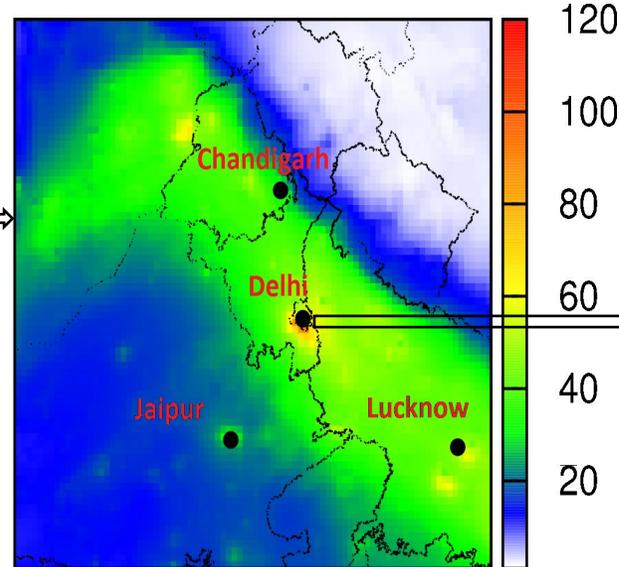
Novelty in CTM based Source-Apportionment

Clean Air Action Plans for
~10% Non-Attainment Cities in India

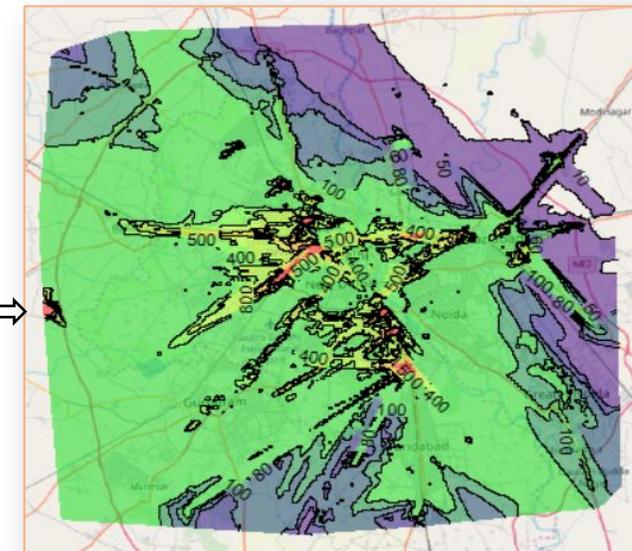
Clean Air Action Plans Resulted in
Redevelopment of City Master Plans



National



Regional



Urban/Hotspot

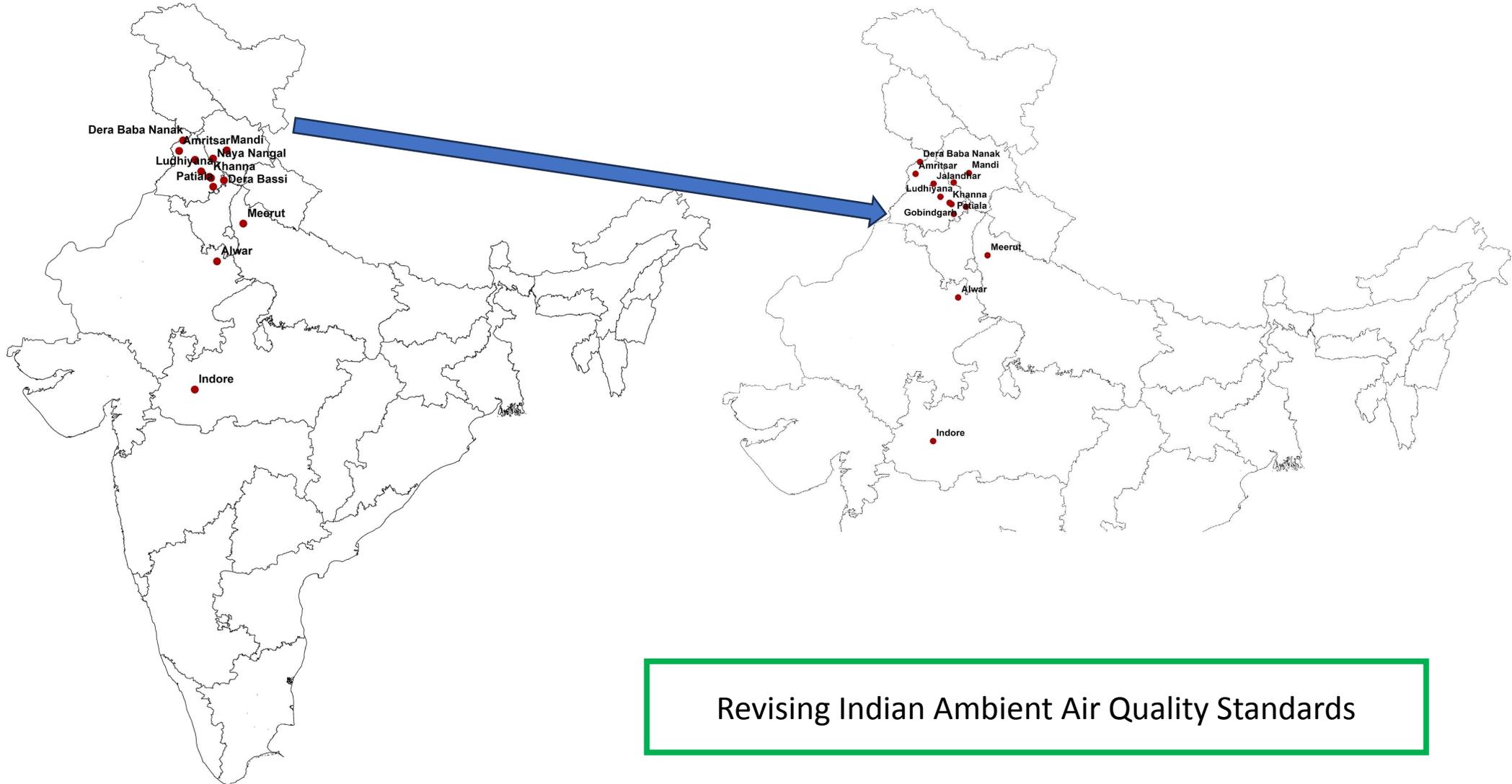
Operational Air Quality Forecasting
Systems for Delhi

High Resolution Sector-Specific Emission
Inventories

Urban and Regional Air Quality Management (URAM) Contribution

Clean Air Action Plans for
~10% Non-Attainment Cities in India

Clean Air Action Plans Resulted in
Redevelopment of City Master Plans



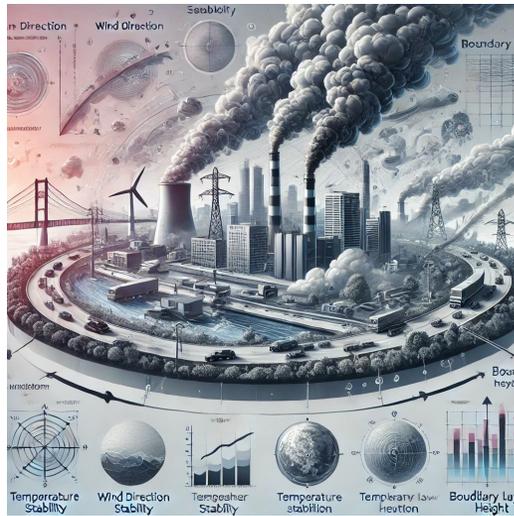
Revising Indian Ambient Air Quality Standards



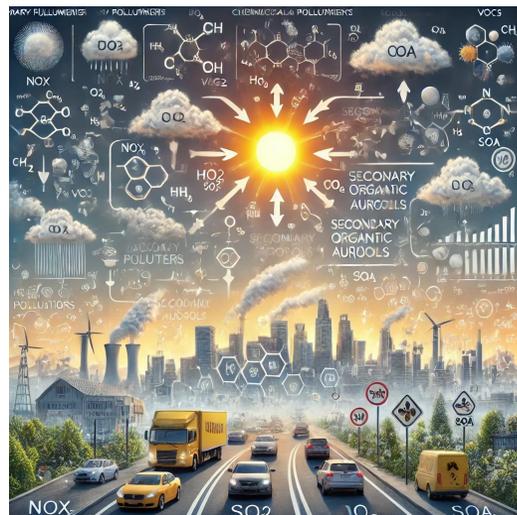
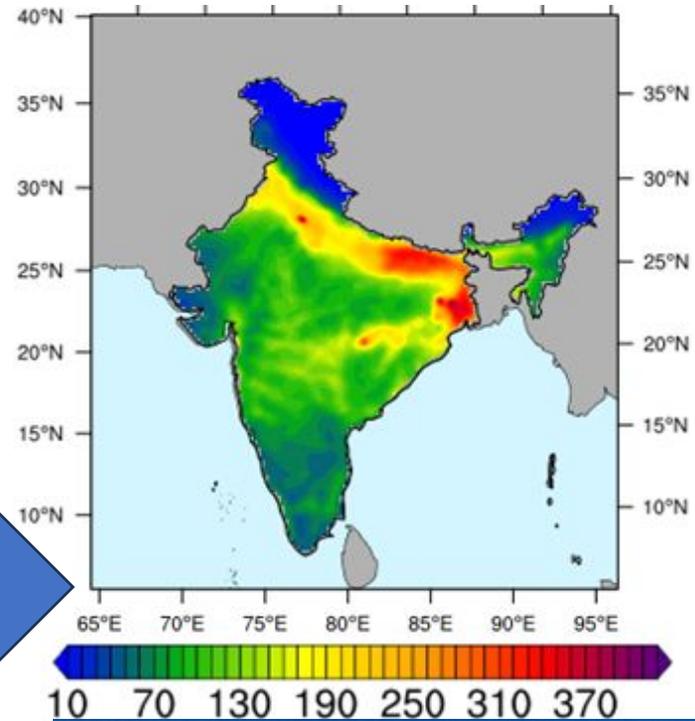
Introduction to Source Apportionment



Emissions → Chemical Transport → Concentrations



Meteorology, LULC, Chemistry



Types of Air Quality Data

GROUND MONITORING

- Air Quality Stations
- Sensor Networks
- Local Measurements

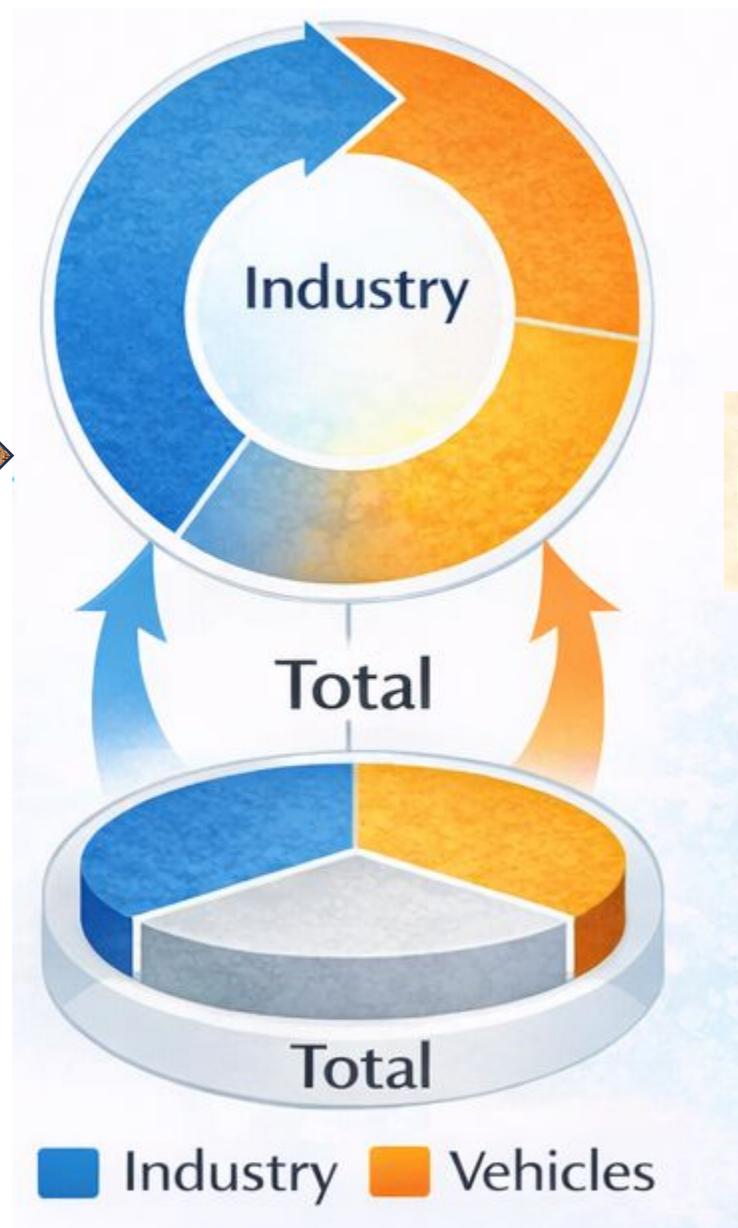
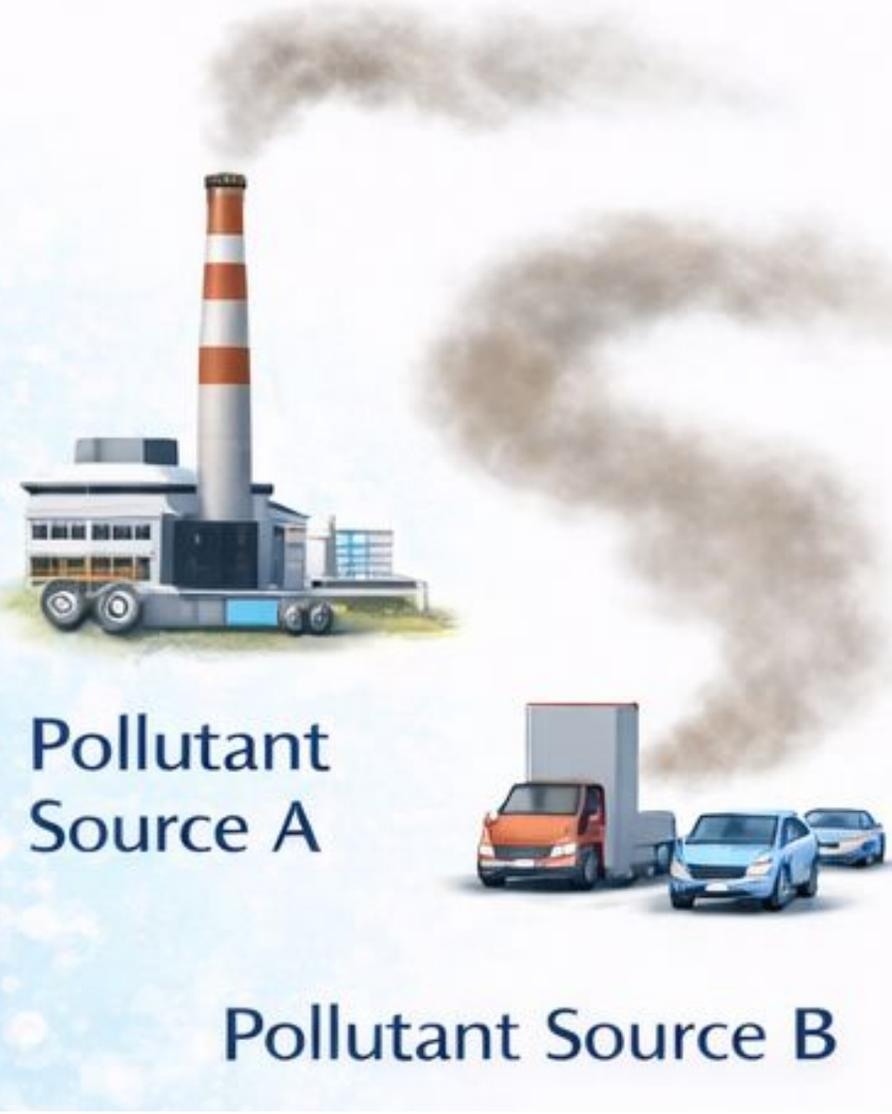
REMOTE SENSING

- Satellite Observations
- Aerial Drones
- Global Coverage

MODELING

- Forecast Models
- Pollution Simulations
- Predictive Analysis

What is Source Apportionment?



Two common methods:
□ Receptor Modeling
□ Dispersion based SA

Receptor Modelling



Ridge Pattern



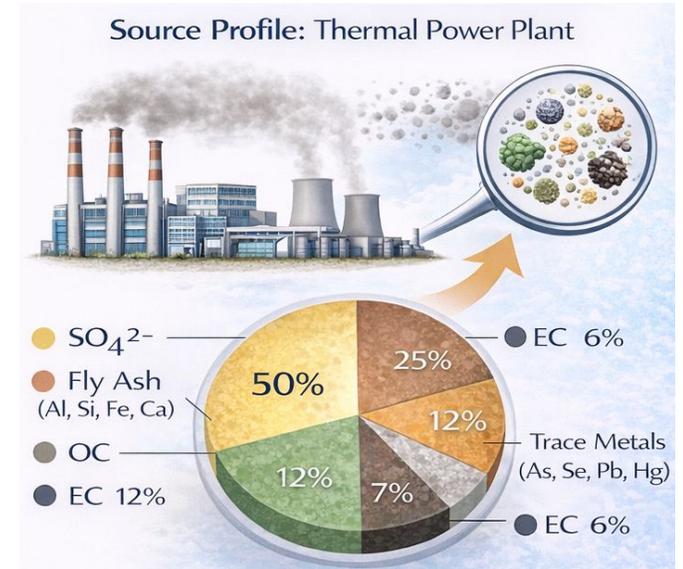
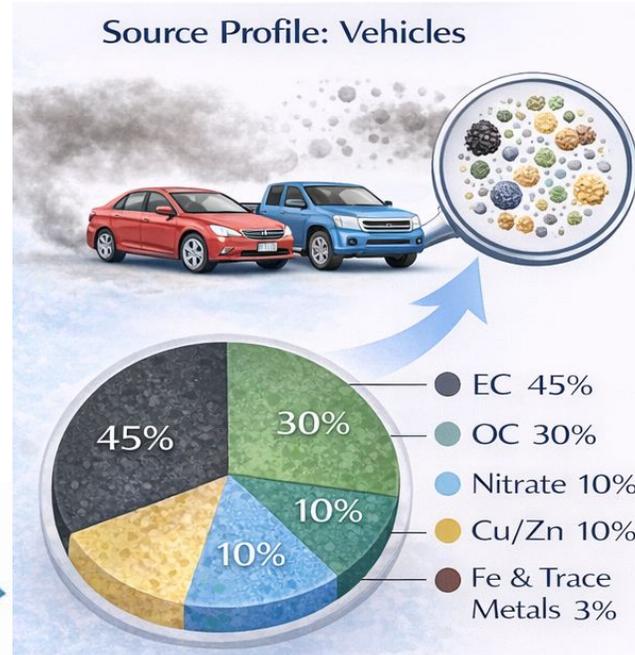
Unique Identity



Biometric Verification

Uniqueness enables Identification

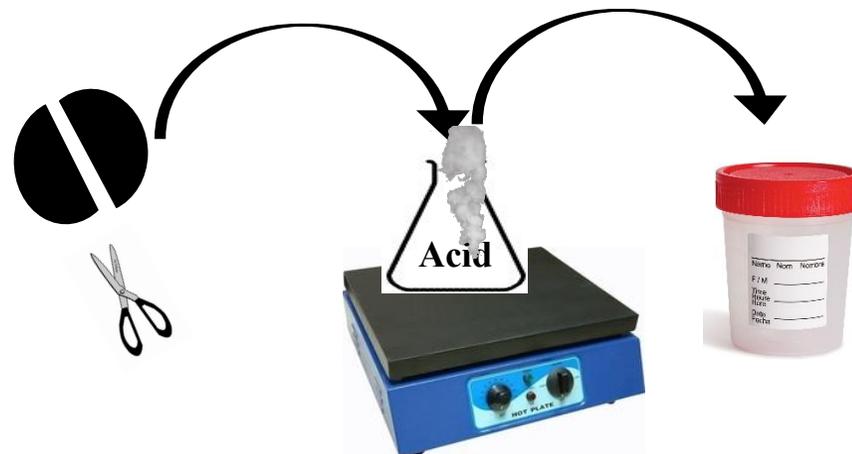
No two individuals share identical fingerprints.



Just as biometric systems rely on unique ridge patterns, atmospheric science identifies emission sources using distinctive chemical signatures



Receptor Modelling



X (Measured Species)
[$\mu\text{g}/\text{m}^3$]

G (Mass Load)
[$\mu\text{g}/\text{m}^3$]

F (Profile)
[%]

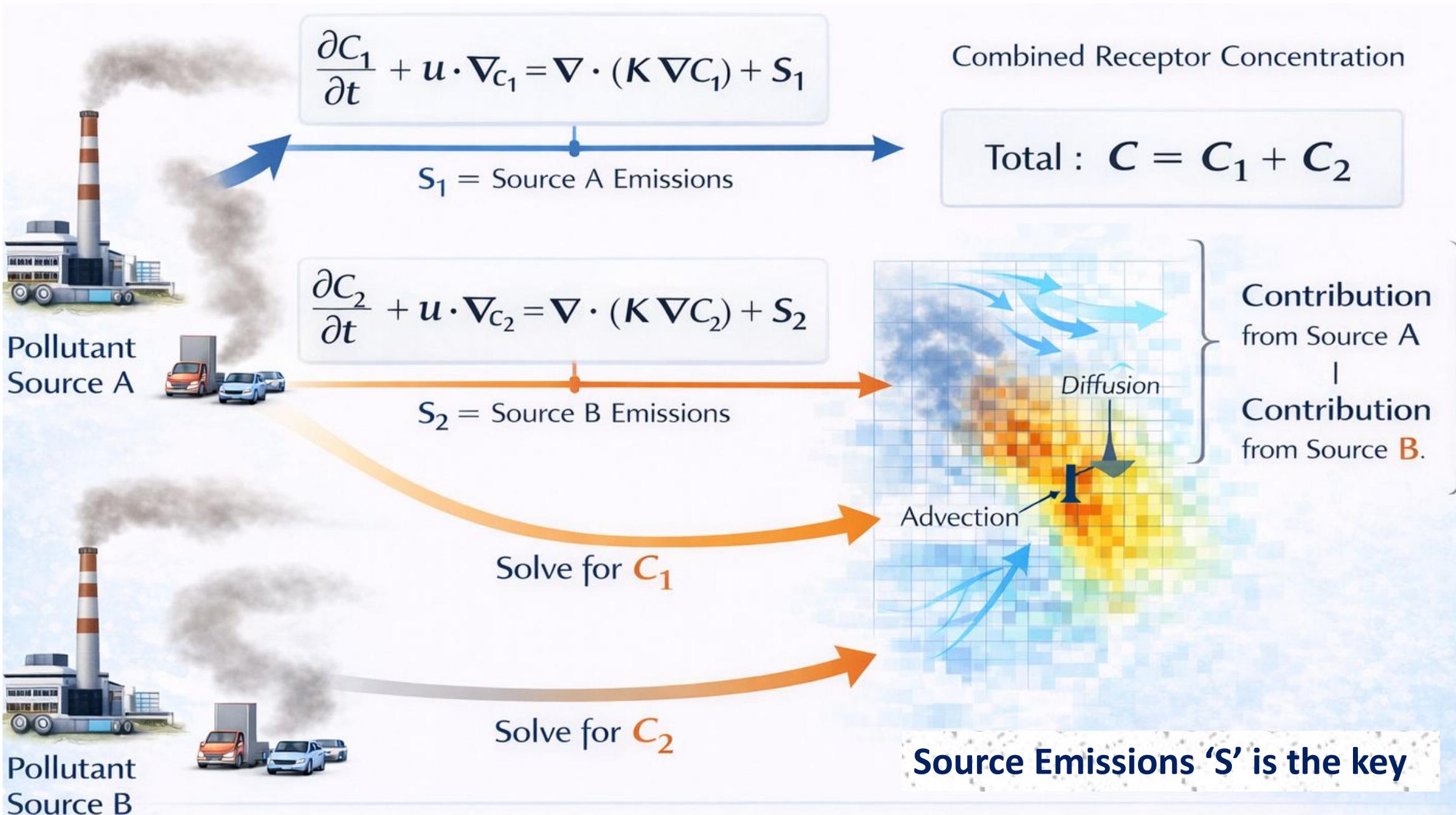
	Fe	OC	BC	Sulfate	Nitrate
Sample 1 (Roadside)	8.4	37.6	25.0	15.0	14.0
Sample 2 (Industrial)	3.2	13.6	8.8	47.5	27.0
Sample 3 (Mixed)	6.0	26.5	17.5	30.0	20.0

	Vehicles	Power Plant
Sample 1 (Roadside)	80	20
Sample 2 (Industrial)	15	85
Sample 3 (Mixed)	50	50

×

	Fe	OC	BC	Sulfate	Nitrate
Vehicles	10	45	30	5	10
Power Plant	2	8	5	55	30

Dispersion Based



High Resolution Sector-Specific Emission Inventories



Road Transport



Residential Combustion



Thermal Power Plants



Agriculture



Restaurant

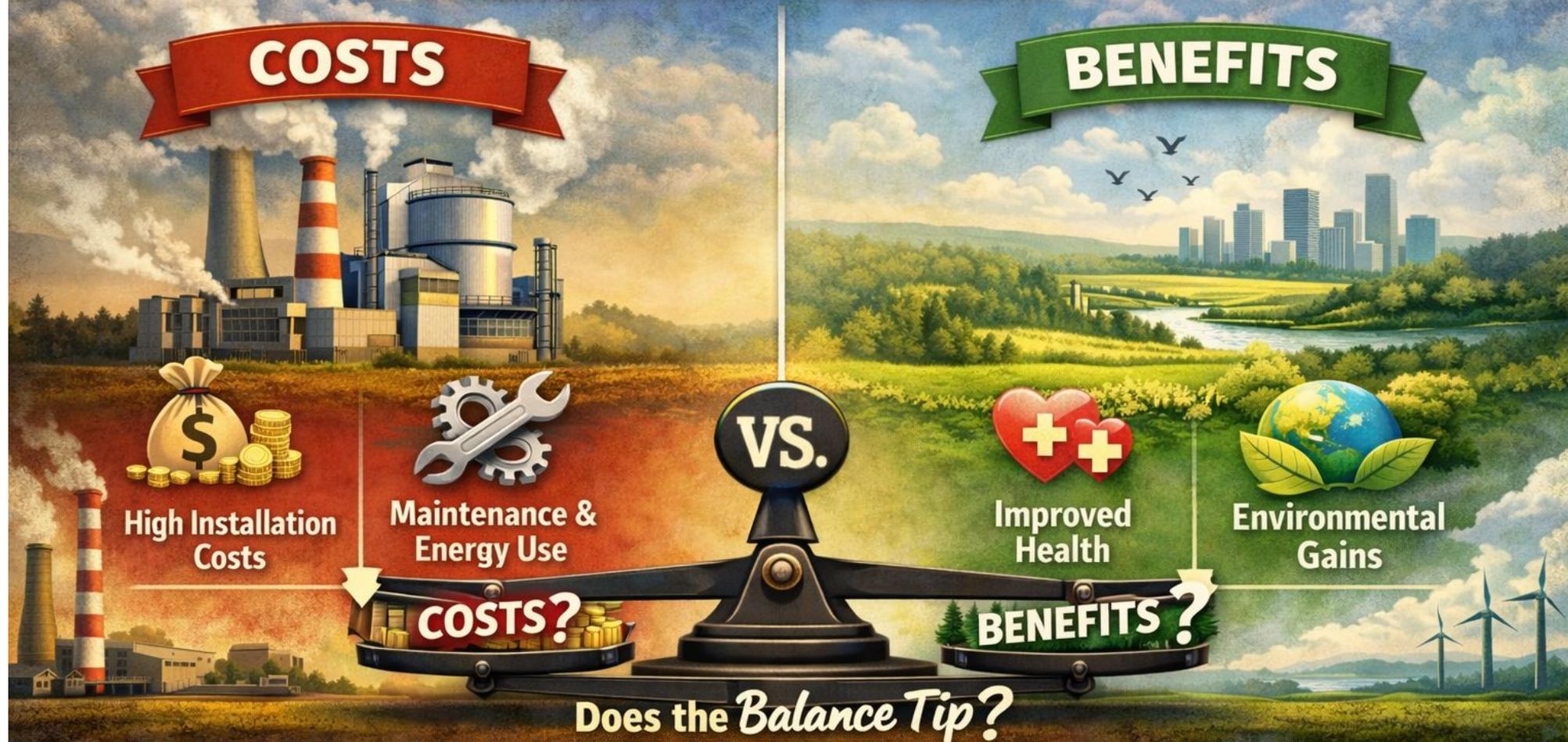


Industry

Case Study-Thermal Power Plants

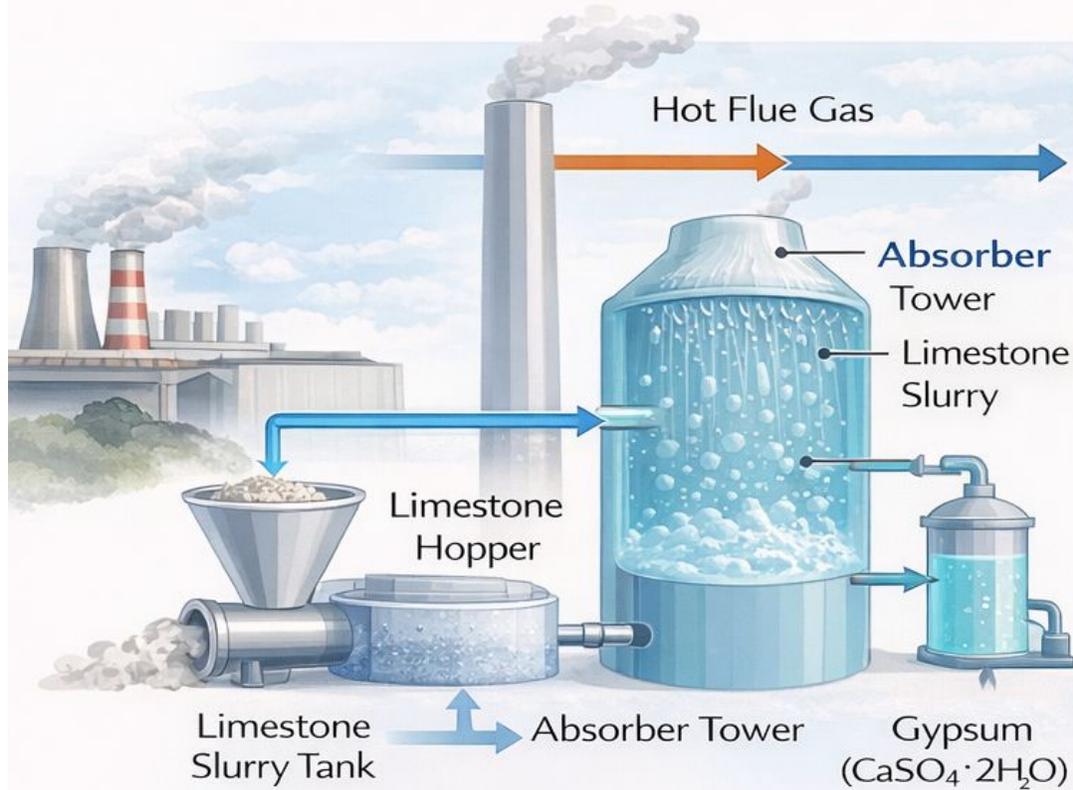
Cost-Benefit Analysis of FGD in Thermal Power Plants

Is FGD Worth the Investment?



Wet vs. Dry Flue Gas Desulfurization (FGD)

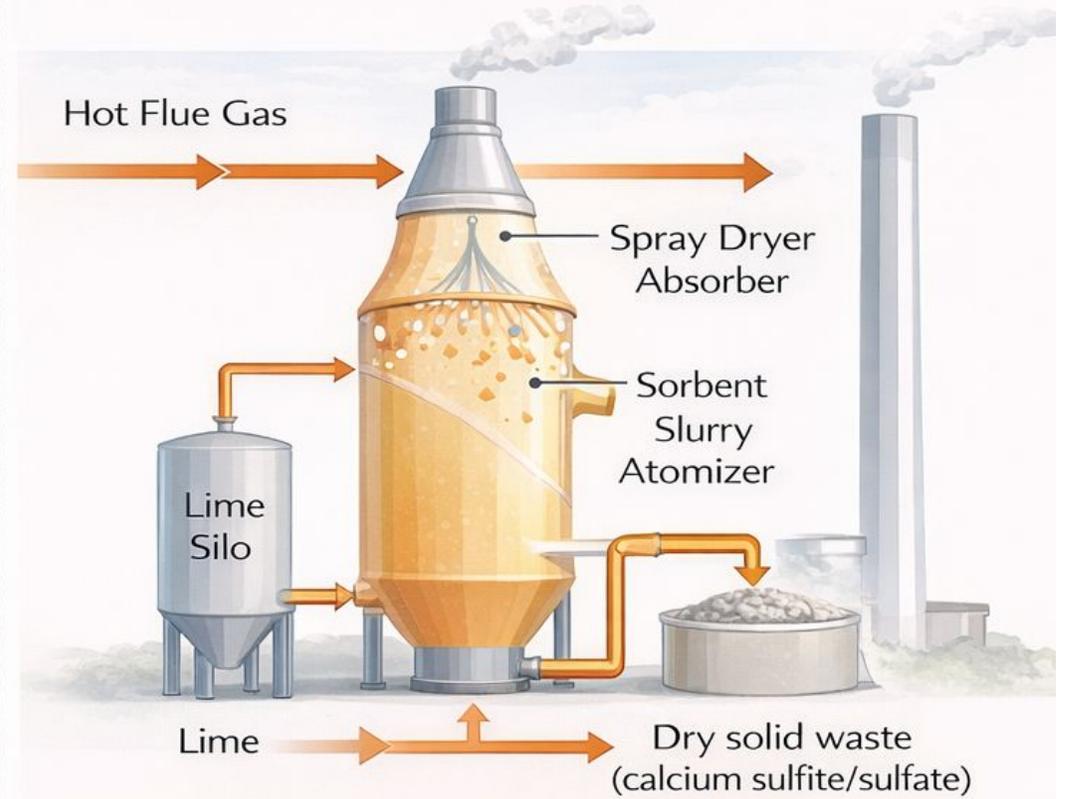
Wet FGD



Reagent: Limestone slurry (CaCO₃)

- **Byproduct:** Gypsum (CaSO₄·2H₂O)
- **Typical:** Removal: 90-98%
- **Large units** (>400 MW)
- **Removal efficiency**

Dry FGD

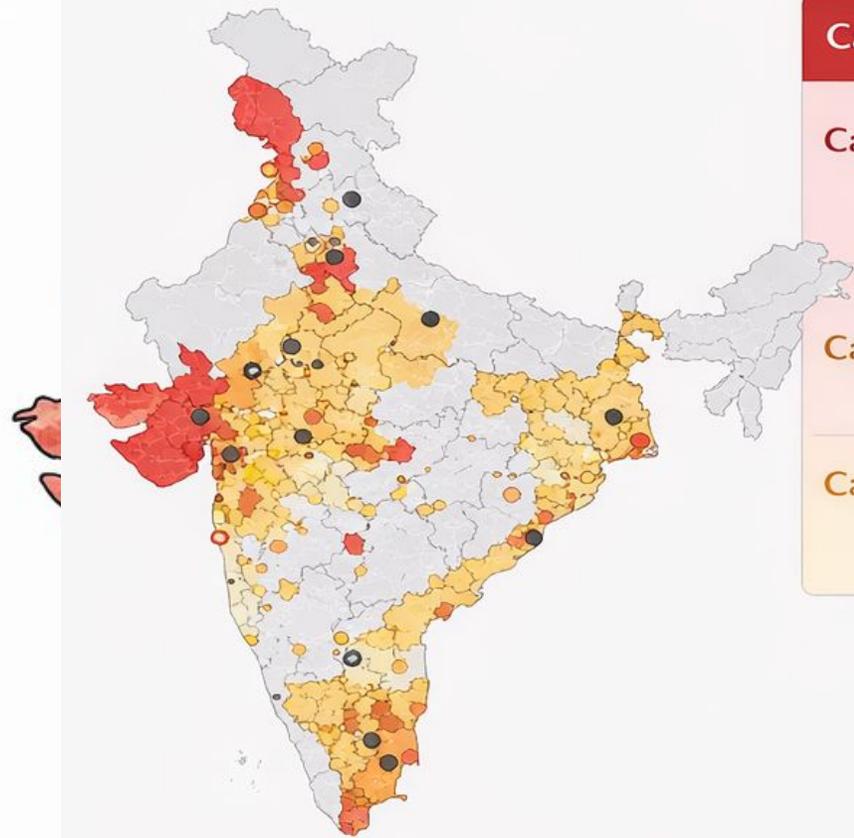


Reagent: Lime / sodium bicarbonate

- **Byproduct:** Dry solid waste (calcium sulfite/sulfate)
- **Typical:** Small-medium units (<400 MW)
- **Removal efficiency: 60-90%**

India's Revised FGD Compliance Framework (MoEF&CC, 2024)

(MoEF&CC Notification G.S.R. 465(E), 11 July 2025)



- Category A
- Category B
- Category C
- All other TPPs

Category A	Location Criteria	Revised Compliance Framework
Category A	Within 10 km of NCR or cities with population ≥ 1 million	Compliance by 31 December 2027
Category B	Within 10 km of Critically Polluted Areas (CPAs) or Non-Attainment Cities	Case-by-case applicability based on Central Government review
Category C	All other thermal power plants	Exempt from SO ₂ standards Stack height compliance by 31 December 2029

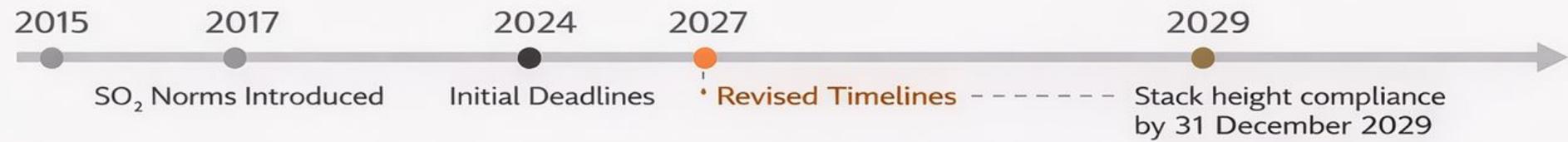
Compliance Issues Issued

0.40 Unit penalty

Environmental Compensation for Delayed Compliance

Non-Compliant operation beyond the Timeline

0-180 days	181-365 days	366 days and beyond
₹0.20	₹0.30	₹0.40
181-365 days	₹0.30	₹0.40
366 days and beyond	₹0.40	₹0.40

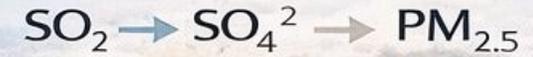


Motivation of this study

**Coal-dominated power sector
→ high SO₂ emissions**

- 🔥 Largest industrial SO₂ source in India
- ▶ Major contributor to sulfate & secondary PM_{2.5}
- 👤 Central challenge for air-quality management

Air pollution burden → major public-health impact

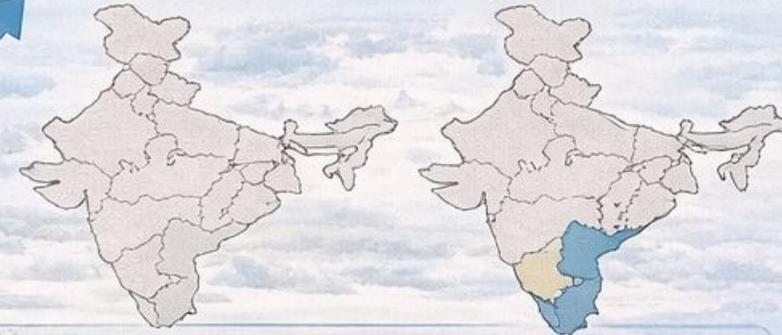


- ▶ Large population exposure in power corridors
- ▶ Substantial cardiopulmonary health risk

This Study

- ▶ Plant-resolved techno-economic framework
- ▶ Region-specific input costs & tariffs
- ▶ WRF-Chem air-quality modelling
Integrated health valuation

Key research gaps



**Strong mandate,
slow implementation**

Nationwide FGD mandate
(2015; revised 2024)

Plant-resolved techno-economic framework

- ▶ Region-specific input costs & tariffs
- ▶ WRF-Chem air-quality modelling
- ▶ Integrated health valuation

● Objective: Identify where sulfur control delivers the highest societal returns

Key research gaps

- ▶ National-average cost assumptions dominate
- ▶ Retrofit complexity



SO₂ Emissions

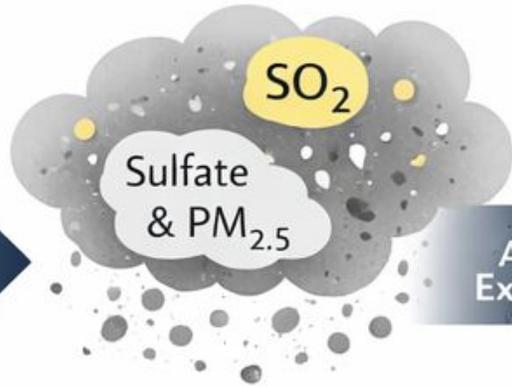
Air Pollution

Population Exposure

Health Impacts



SO₂ Emissions



Airborne Exposure



Health Effects



Respiratory Disease

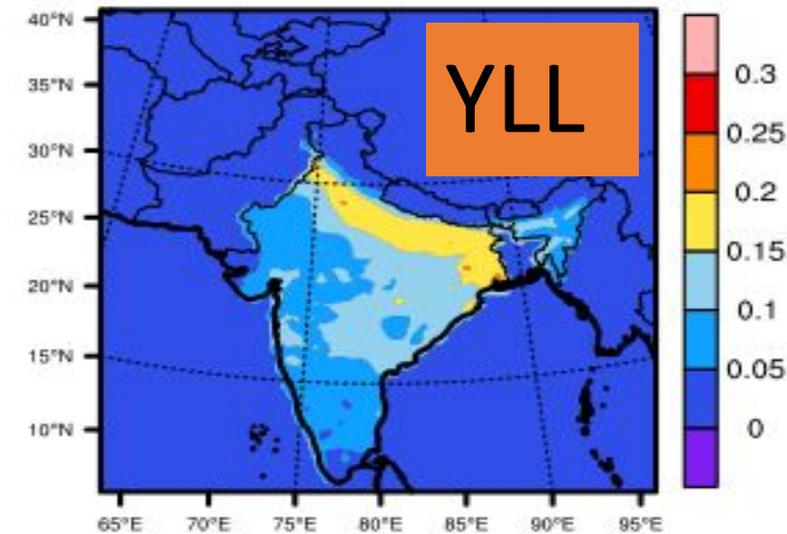
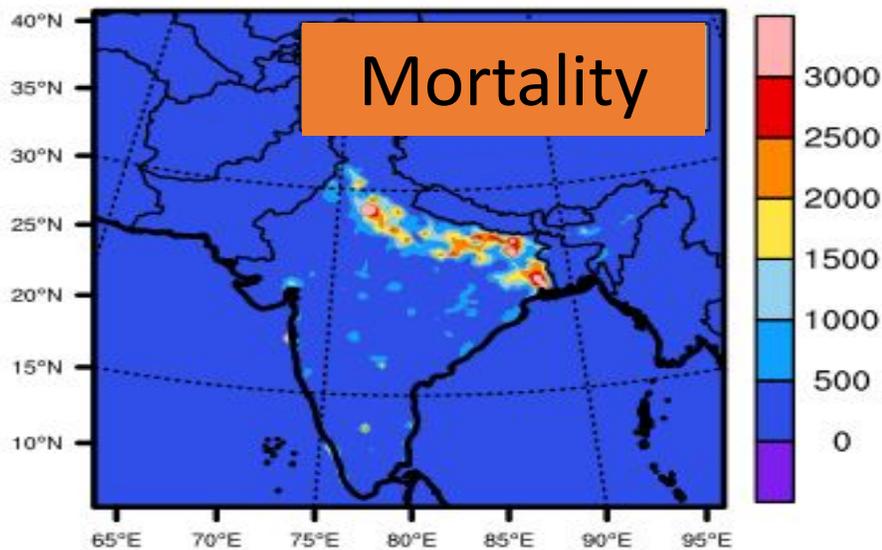
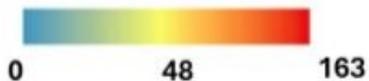
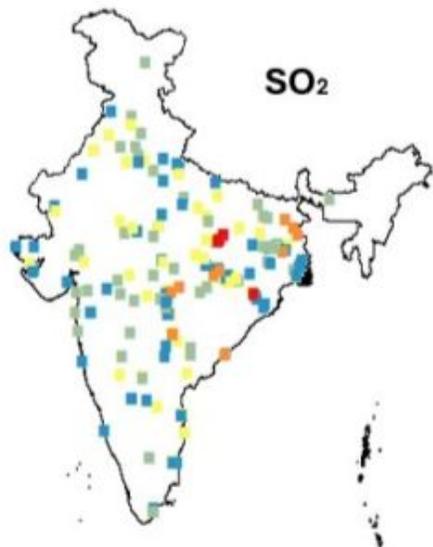


Cardiovascular Disease



Premature Mortality

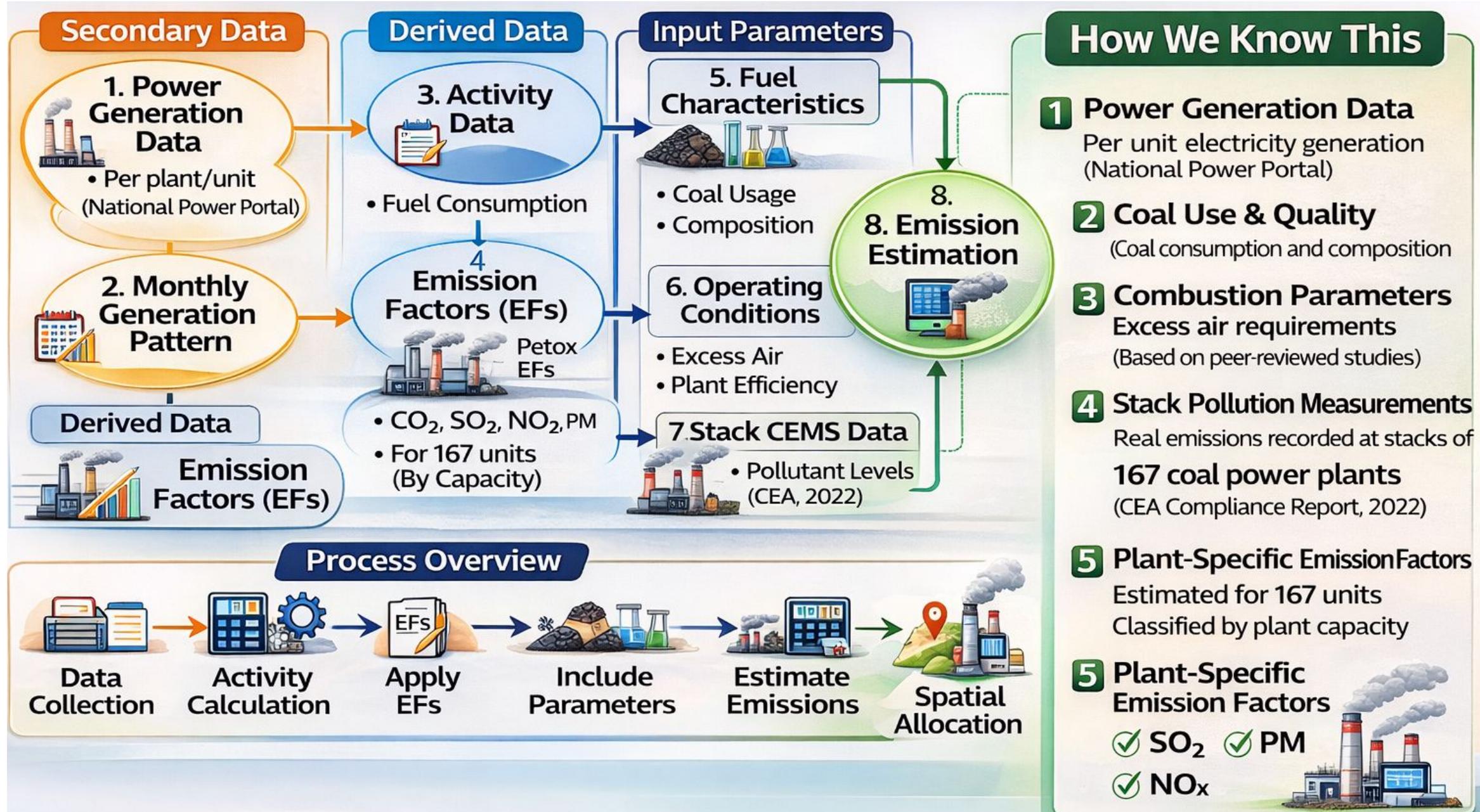
Coal-Fired Power Plant



Emissions



Methodology



Emission Factors

Capacity (MW)	PM _{2.5} (g/kWh)	SO ₂ (g/kWh)	NO _x (g/kWh)	SO ₂ (g/kWh) (FGD)
100-250	0.40	4.40	2.19	2.82
250-500	0.14	4.12	2.30	1.43
500-600	0.26	4.60	2.11	0.73
≥ 600	0.18	3.47	1.73	0.33

Emissions

State	PM _{2.5} Emissions	SO ₂ Emissions	NO _x Emissions
Andhra Pradesh	16.390	243.494	118.282
Assam	1.959	21.546	10.724
Bihar	16.161	214.771	106.969
Chhattisgarh	35.321	545.507	273.965
Gujarat	17.840	222.146	110.618
Haryana	7.104	118.674	58.367
Jharkhand	8.604	136.514	65.533
Karnataka	7.891	133.179	66.125
Madhya Pradesh	36.855	530.392	263.517
Maharashtra	28.667	490.198	250.434
Odisha	13.171	253.549	123.470
Punjab	6.804	111.994	56.275
Rajasthan	19.157	234.178	116.602
Tamilnadu	18.132	258.844	124.658
Telengana	11.665	218.212	103.934
Uttar Pradesh	44.510	610.259	301.484
West Bengal	21.167	350.584	177.628



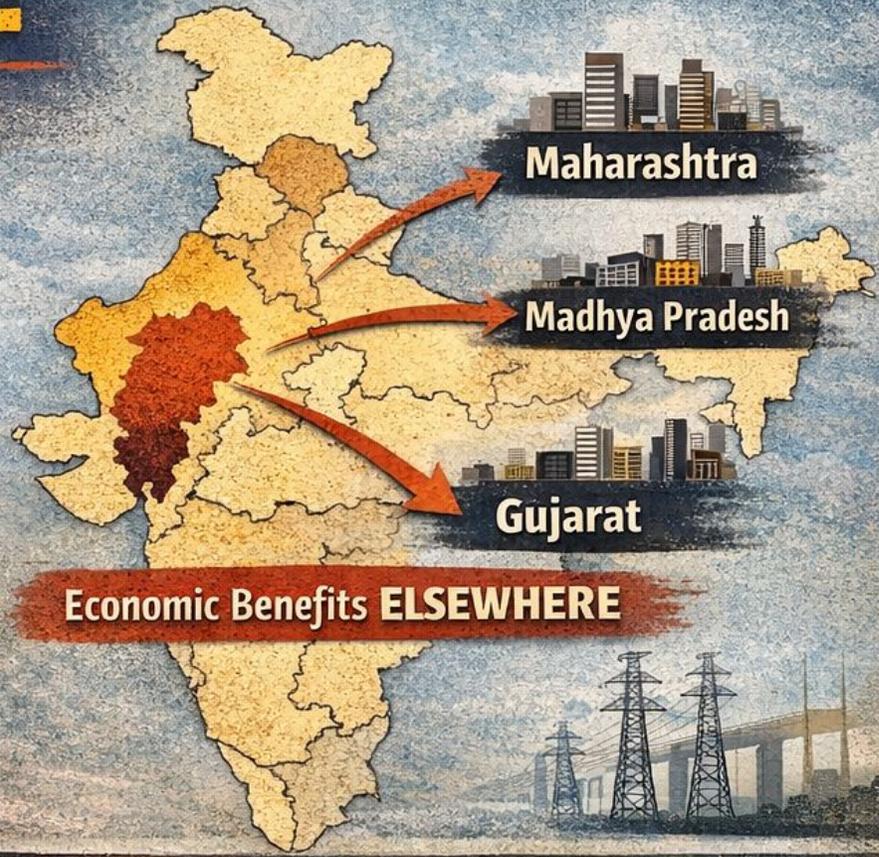
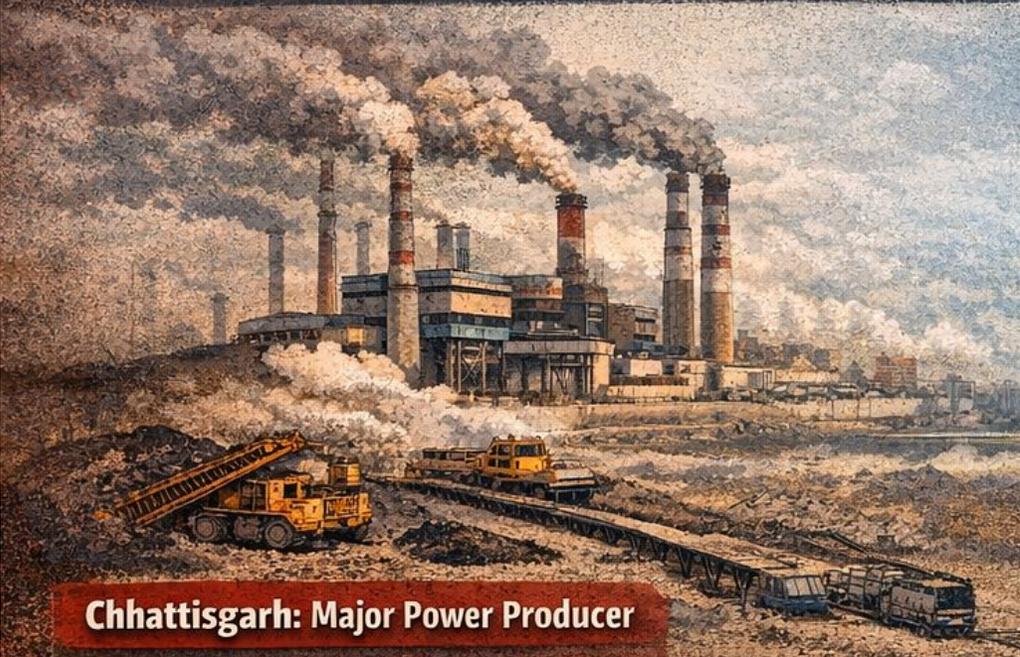
Ecologically Unjust!

Majority of Power EXPORTED to

Chhattisgarh Powers Other States, Bears the Pollution

PM_{2.5} per GSDP (kg/lakh)

400
300
200
100
0



Chhattisgarh: Major Power Producer

- ✓ 139,255 MU Electricity Generated
- ✓ 1178 kg Per Capita Emissions
- ✓ 869 kg Per GSDP Emissions

CHHATTISGARH SUFFERS

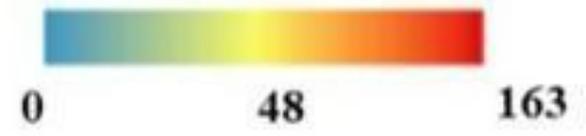
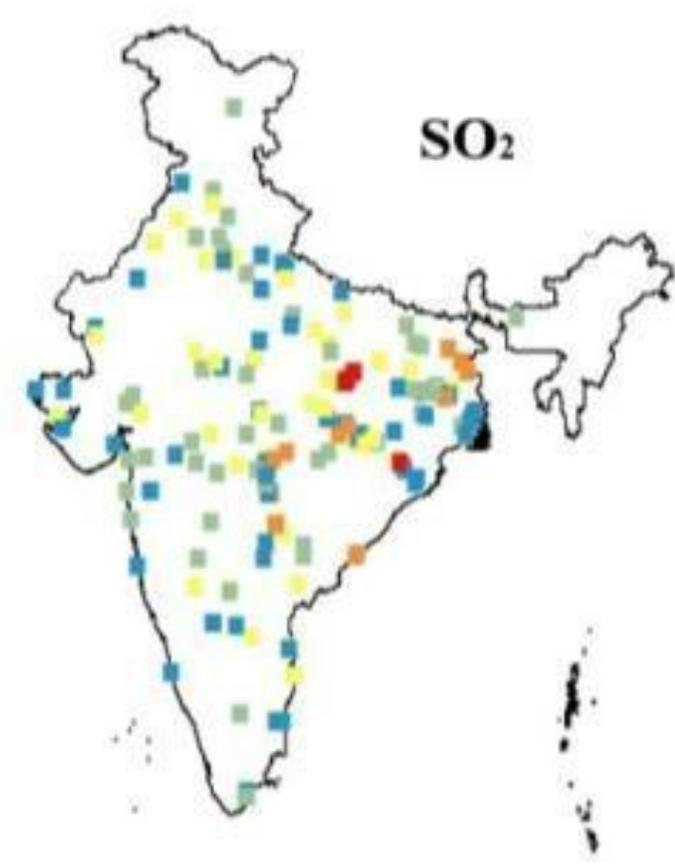
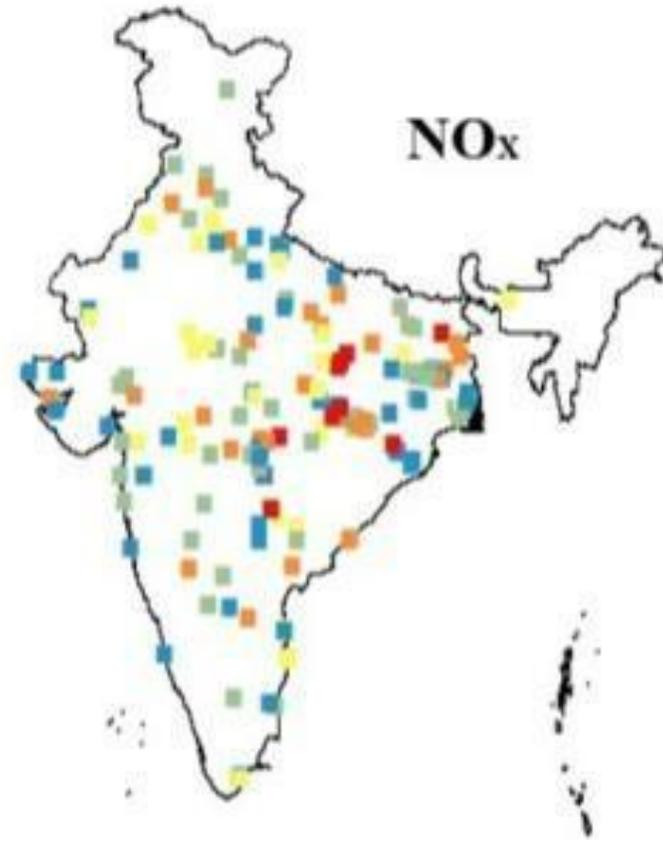
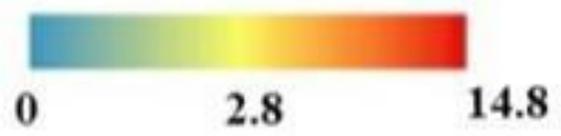
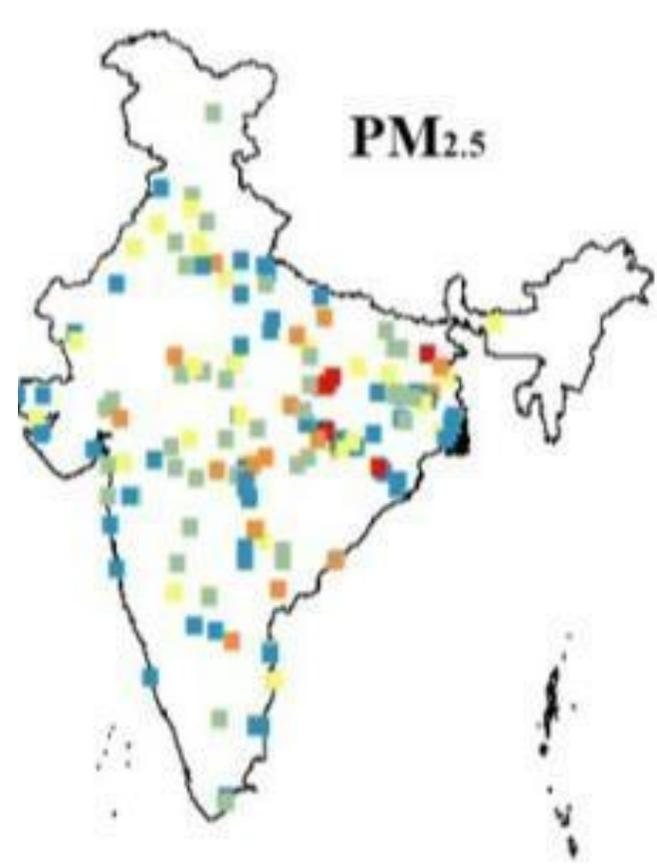
- ✓ Polluted Air
- ✓ Land Degradation

OTHER STATES GAIN

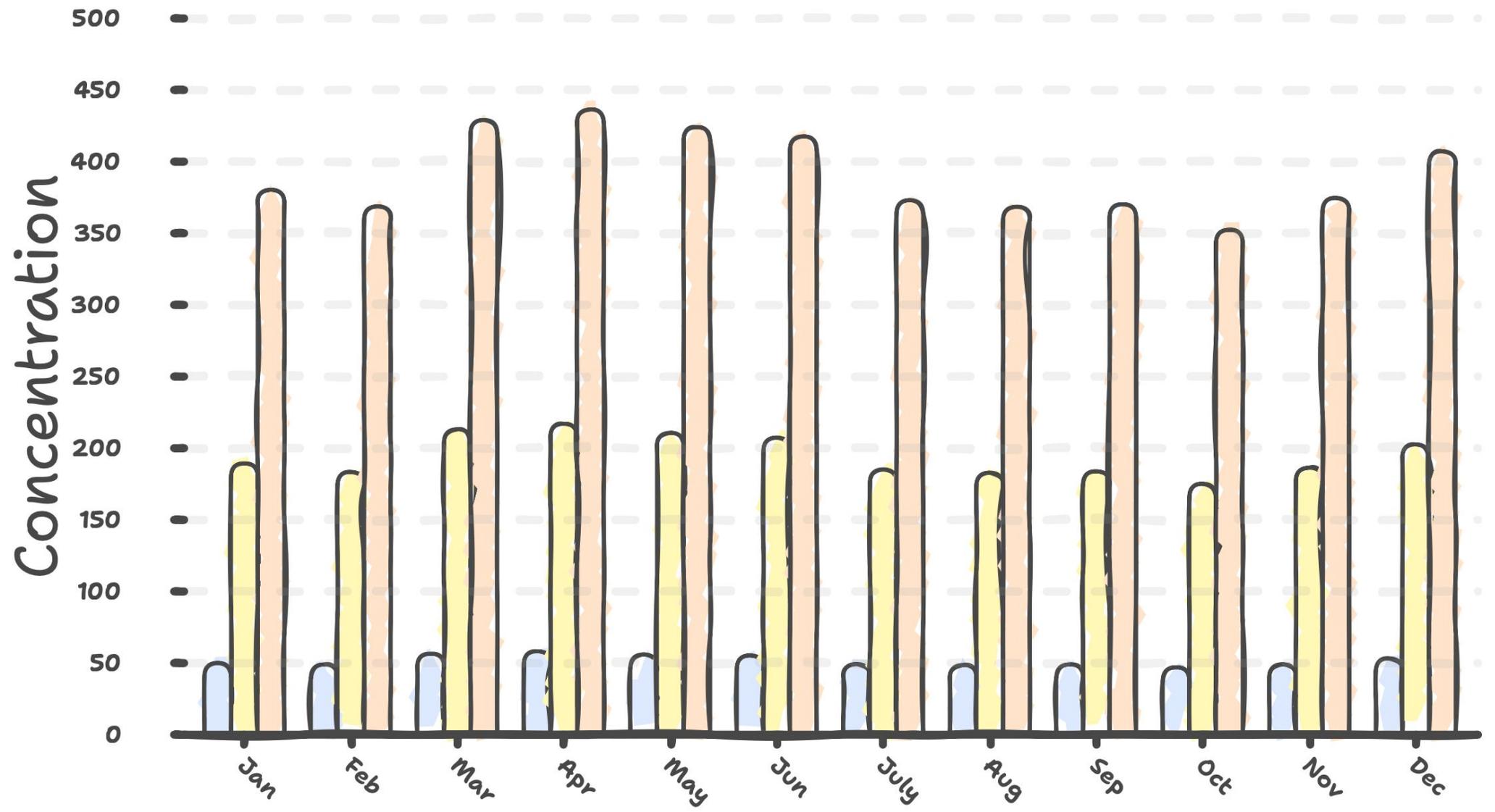
- ✓ Cheap Electricity
- ✓ Industrial Growth

Who Bears the Burden? Emission Here, Prosperity There





○ PM10 ○ NOx ○ SO2

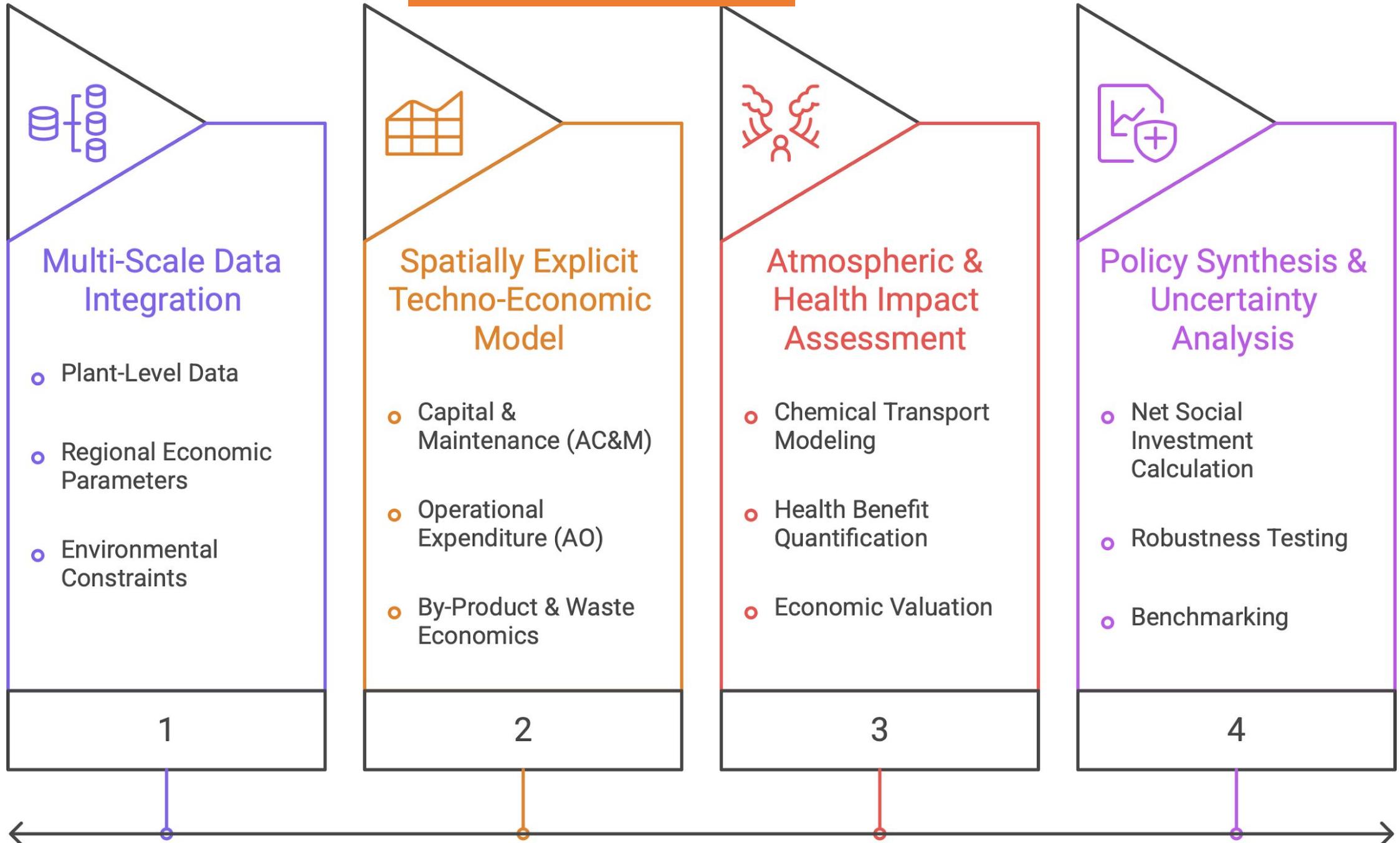


Month

Cost-Benefit Calculations



Detailed Methodology



Spatially-Explicit Techno-Economic Model

Capital Cost (CC)

Determined by Boiler Capacity (BC) and Retrofit Factor (RF)

Maintenance Cost (MC)

Percentage of Capital Investment

Electricity Cost (EC)

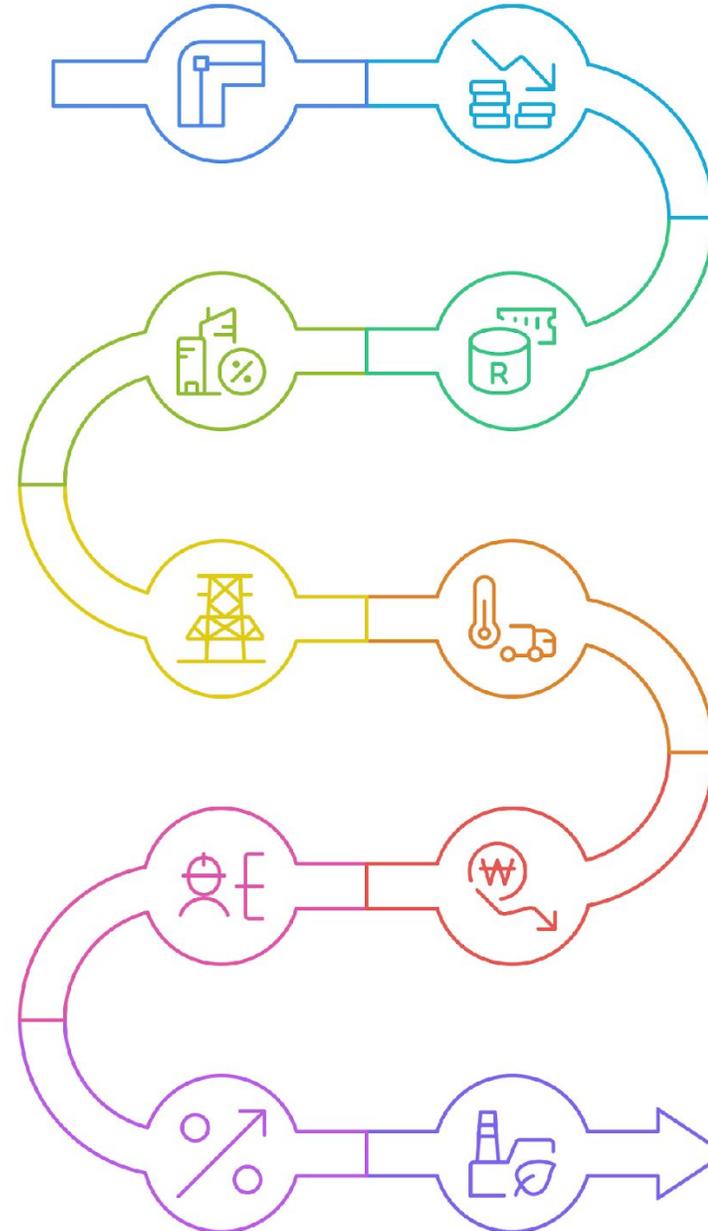
Auxiliary Power Consumption (Aux FGD) multiplied by State-Specific Electricity Price

Labour Cost (LC)

Complexity Factor and State-Specific Minimum Labour Wages

Gypsum Revenue

80% Utilization Rate and Gypsum Price



Annualization

Total Capital Cost (CC) annualized using Capital Recovery Factor (CRF)

Depreciation (DC)

Sorbent Cost (SC)

Water & Waste Water Treatment Cost

Total Cost

Parameters	Sugathan, Bhangale et al. 2018	Zhang, Luo et al. 2023	GAINS model	Yang, Zhang et al. 2018	USEPA model	Present study
1. Annualized Capital and Maintenance Cost						
Relative flue gas volume	X	X	✓	X	X	✓
Retrofit factor	X	X	✓	X	✓	✓
Fixed cost (Capital Cost)	✓	✓	✓	✓	✓	✓
Variable cost (Financial Cost)	X	✓	✓	✓	✓	✓
Maintenance cost	✓	✓	✓	✓	✓	✓
Salvage Value	X	✓	X	✓	X	✓
1. Annualized Operation Cost						
Auxiliary power FGD	✓	✓	✓	✓	✓	✓
Power specific cost	X	X	X	X	X	✓
Plant specific labor demand	X	X	X	X	X	✓
Stratified Labor cost	X	X	X	X	X	✓
Sorbent (limestone) demand	✓	✓	✓	✓	✓	✓
Transportation cost	X	X	X	X	X	✓
Region specific sorbent cost	X	✓	X	✓	X	✓
Water usage	✓	✓	✓	✓	✓	✓
The water consumption rate	✓	✓	✓	✓	✓	✓
Net gypsum cost	X	X	X	X	X	✓
Landfill disposal cost	X	X	✓	X	✓	✓
Revenue cost	X	X	X	X	X	✓
Waste water treatment cost	X	X	X	X	✓	✓



Name of State	Limestone cost PG NRE Sources		PG RE Annual av. Price (₹) Sources (%)		Av. Cost of NRE (₹/KW/h)	Av. Cost of RE (₹)		
	(%)		(%)			skilled Power (₹/KW/h)	Semi-Skilled Power (₹/KW/h)	Unskilled Power (₹/KW/h)
India		679.31						
Andhra Pradesh	0.75		0.25		4.71	437.72	422.02	404.03
Assam	0.90	1170.20	0.10		5.14	383.25	306.6	262.8
Bihar	0.99	483.00	0.01		4.26	403.00	330.00	318.00
Gujarat	0.69	478.75	0.31		3.44	371.80	363.30	355.30
Haryana	0.95	621.88	0.05		3.99	350.80	318.18	295.64
Jharkhand	0.98	502.13	0.02		4.04	451.39	342.43	326.86
Karnataka	0.47		0.53		4.29	587.86	542.23	500.74
Madhya Pradesh	0.91	476.67	0.09		3.44			
Maharashtra	0.86	436.63	0.14		4	436.92	383.92	350.96
Rajasthan	0.71	590.54	0.29		3.94	477.14	510.87	542.20
Tamil Nadu	0.72		0.28		3.73	326.00	366.00	416.00
Telangana	0.80	474.75	0.20		3.92	445.56	411.06	381.06
Uttar Pradesh	0.95	442.63	0.05		4.38	283.00	271.00	259.00
West Bengal	0.94	519.61	0.06		3.55	394.08	391.54	388.23
Tamil Nadu		481.04				461.18	429.03	400.88
Telangana		474.75				451.65	403.19	366.54
Uttar Pradesh		474.75				414.00	377.00	342.00

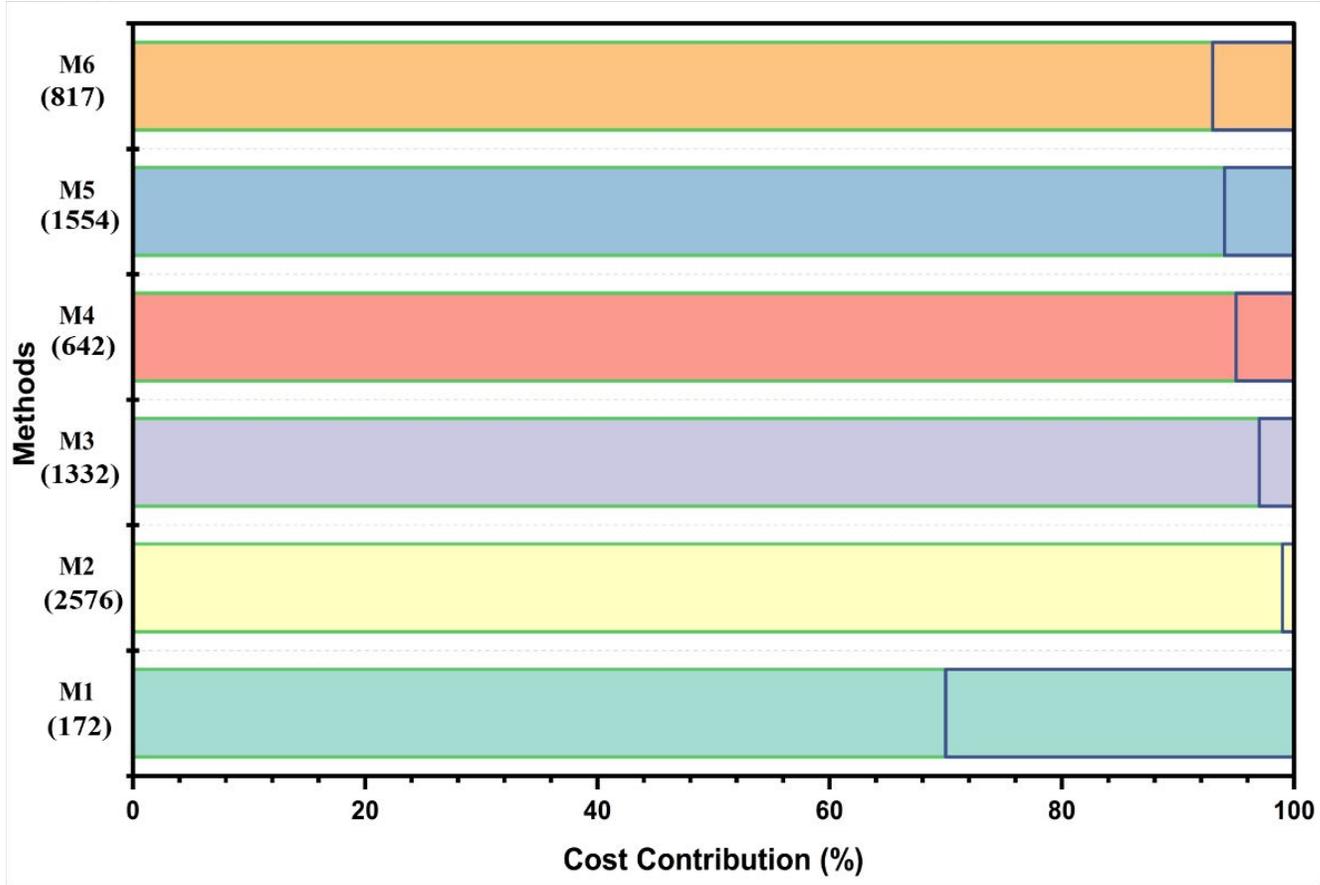


Results & Discussion



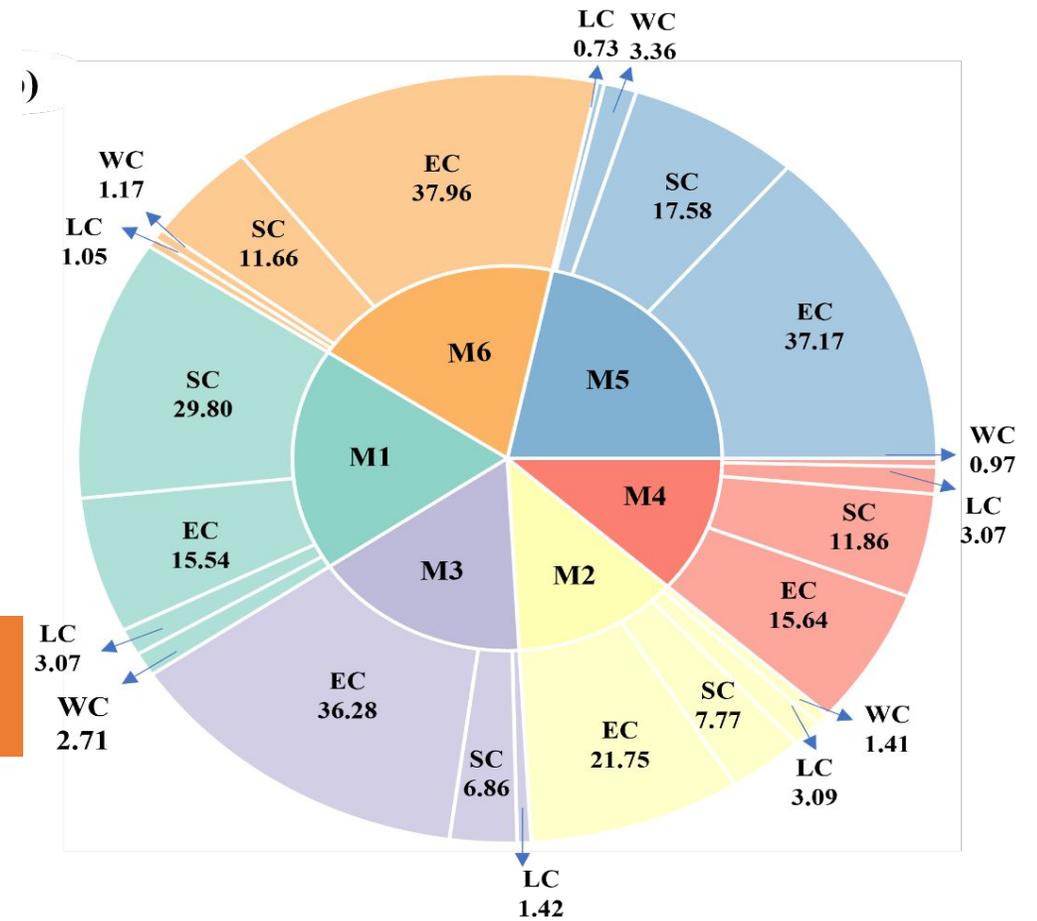
(a) AC&M

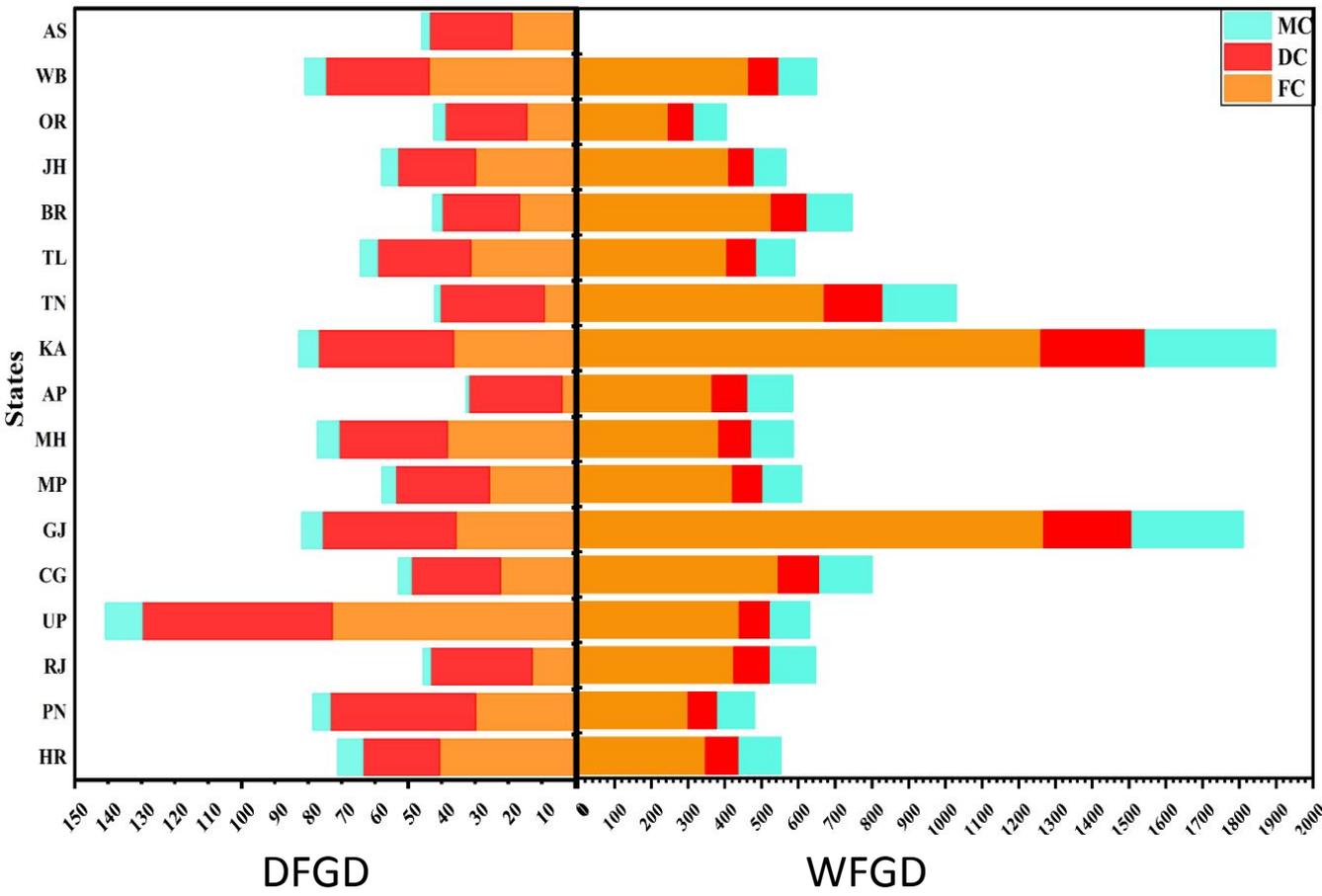
AO



Annualized capital and maintenance (AC&M) and annualized operation (AO) costs.

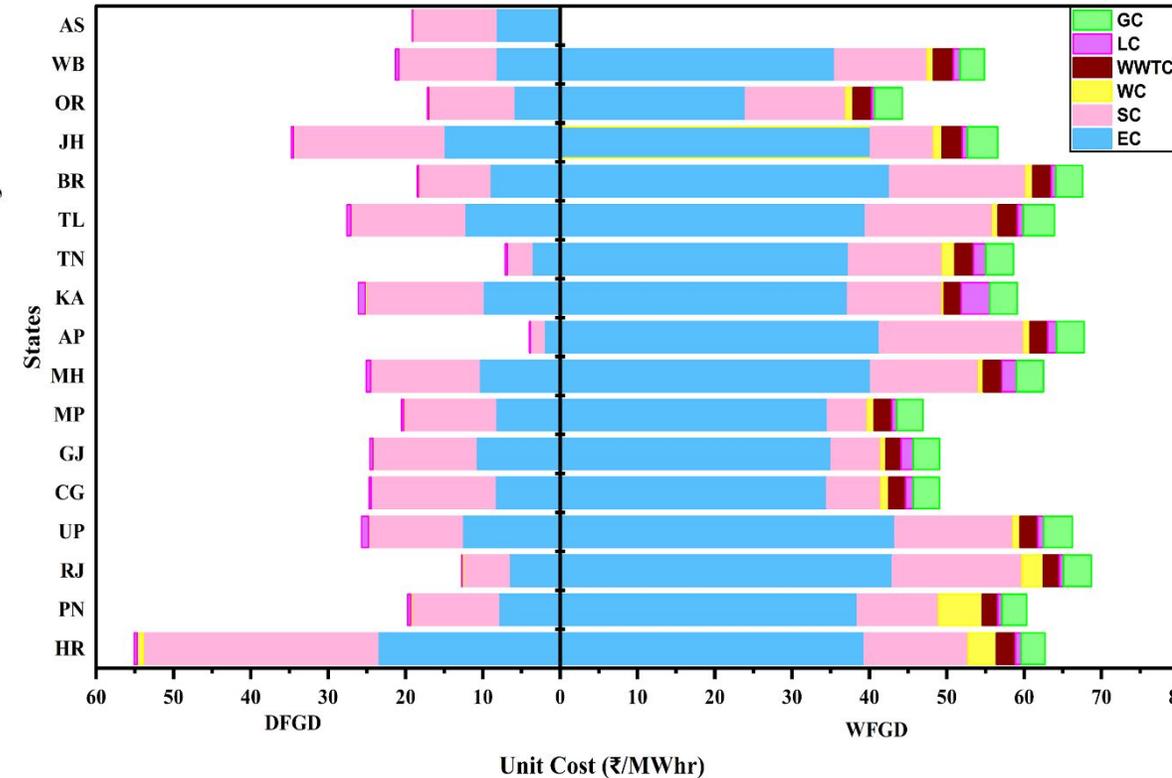
Breakdown of AO sub-costs including electricity (EC), sorbent (SC), labour (LC), and water (WC). Units in ₹/MWh.





Capital Cost (Maintenance+ Depreciation+ Financial) ₹/MWh

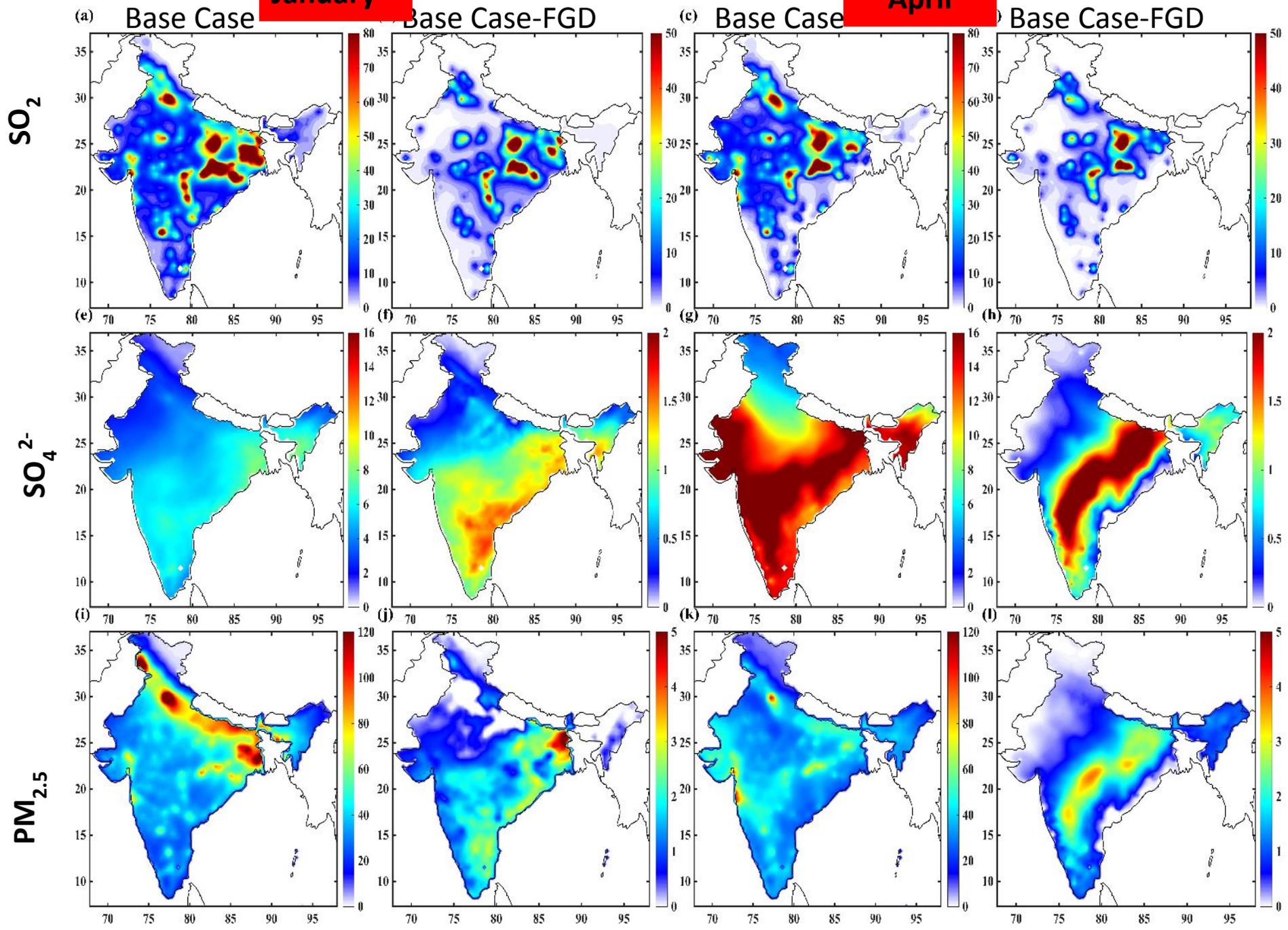
Operation Cost (electricity (EC), sorbent (SC), labour (LC), and water (WC)) ₹/MWh



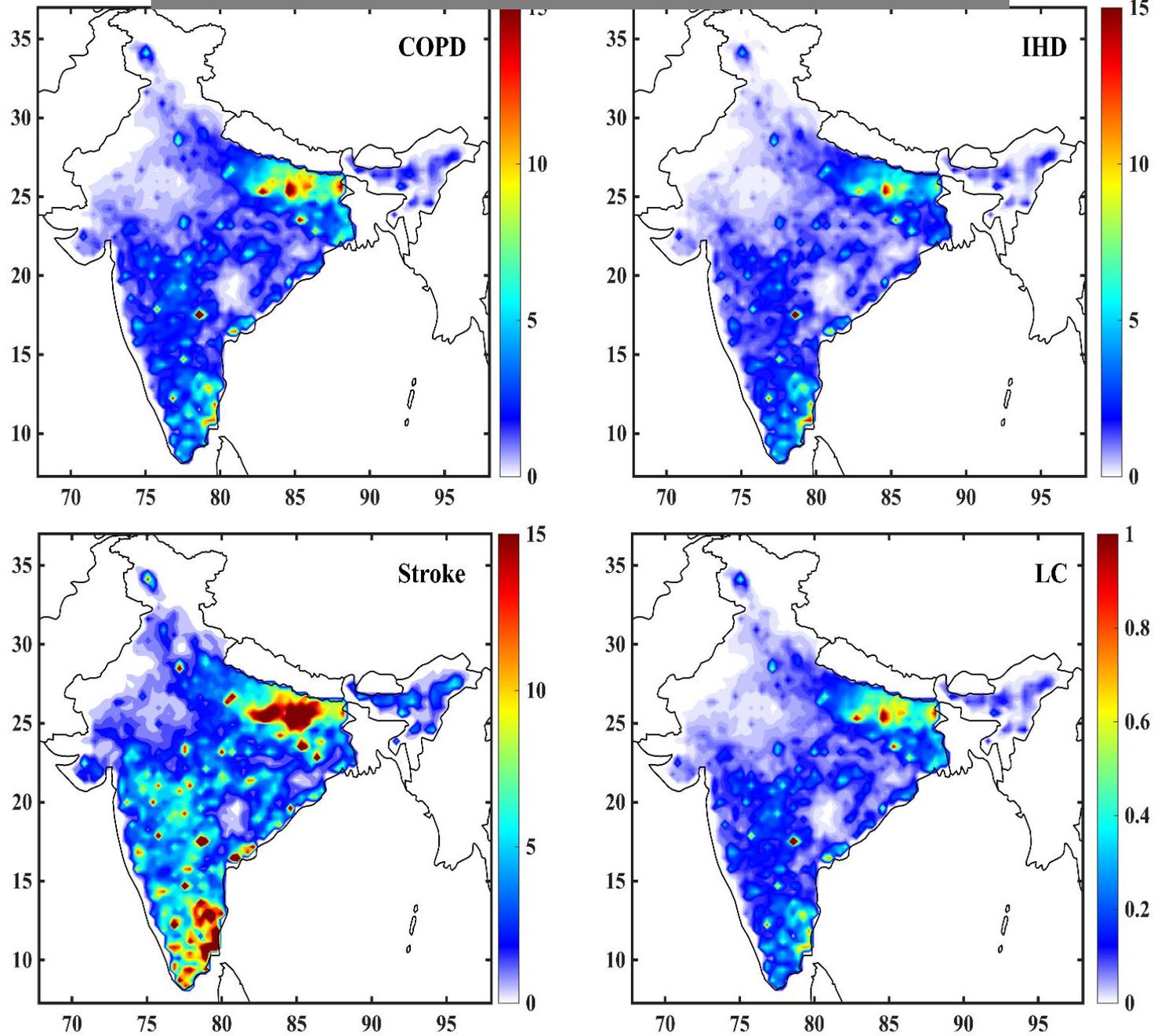
Air Quality Benefit due to FGD deployment

January

April



Reduction in Premature Mortality



FGD COSTS: NITI VS CEA

Why Do Cost Estimates Differ So Widely?

NITI AAYOG

2024 ESTIMATE

₹1.40 Cr/MW

- ✓ TAXES, DUTIES EXCLUDED
- ✓ OPPORTUNITY COST EXCLUDED



UNIFORM NATIONAL COST PER MEGAWATT



CEA

NORMATIVE TECHNICAL ESTIMATE

2015 NORMS (REGULATED SINCE 2019)

COST PER MEGAWATT VARIES BY UNIT SIZE

195–250 MW	₹0.45 Cr/MW
300 MW	₹0.43 Cr/MW
500 MW	₹0.40 Cr/MW
800–830 MW	₹0.37 Cr/MW

DIFFERENCE: 3–4X HIGHER ESTIMATE



COST DECREASES WITH ECONOMIES OF SCALE

- Impacts electricity tariff calculations
- Influences cost-benefit analysis
- Affects discourse on FGD deadlines

- Impacts electricity tariff calculations
- Influences cost-benefit analysis
- Spotlighting energy vs environment policy debate

BOTH EXCLUDE TAXES & OPPORTUNITY COST

NITI Ayog
crore MW
CEA (₹0.30
crore MW



Conclusions

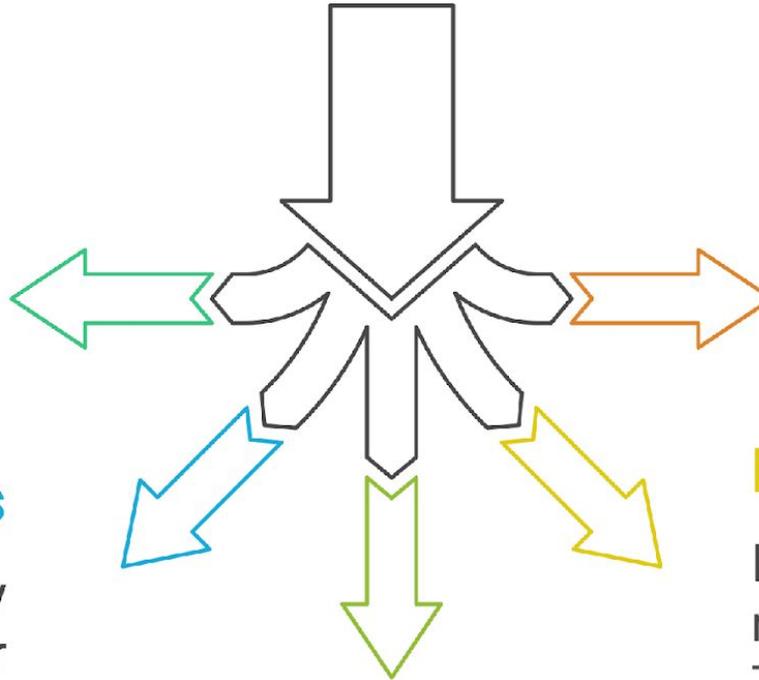
FGD Deployment

Air-Quality Improvements

~40% reduction in SO₂ emissions improves air quality.

Health Benefits

Decreased PM_{2.5} related mortality by ~0.15 lakhs/year



Rollout Strategies

Differentiated, risk-based rollout strategies are preferable.

Regional Heterogeneity

Net Cost varies from \$770 million in UP to -\$170 million in Tamil Nadu

Economic Implications

~26-80% reduction in net cost by inclusion of monetized health co-benefits



Urban and Regional Air quality Management (URAM)



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