The Critical Role of Policy Enforcement in Achieving Health, Air Quality and Climate Benefits from India's Clean Electricity Transition

Wei Peng[1,], Hancheng Dai[2], Hao Guo[3], Pallav Purohit[4], Johannes Urpelainen[5], Fabian Wagner[4], Yazhen Wu[2], Hongliang Zhang[3,6,7]*

[1] School of International Affairs and Department of Civil and Environmental Engineering, Pennsylvania State University, University Park, Pennsylvania, USA

[2] College of Environmental Sciences and Engineering, Peking University, Beijing, China

[3] Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, Louisiana, USA

[4] Air Quality and Greenhouse Gases Program, International Institute for Applied Systems Analysis, Laxenburg, Austria

[5] Energy, Resources and Environment Program, School of Advanced International Studies, Johns Hopkins University, Washington D.C., USA

[6] Department of Environmental Science and Engineering, Fudan University, Shanghai, China

[7] Institute of Eco-Chongming (SIEC), Shanghai, China

*Corresponding author. Email: weipeng@psu.edu, Phone: (+1) 814-865-9408.

ABSTRACT

The coal-dominated electricity system poses major challenges for India to tackle air pollution and climate change. Although the government has issued a series of clean air policies and low-carbon energy targets, a key barrier remains enforcement. Here, we quantify the importance of policy implementation in India's electricity sector using an integrated assessment method based on emissions scenarios, an air quality simulation, and a health impact assessment. We find that limited enforcement of air pollution control policies leads to worse future air quality and health damages (e.g., 14,200 to 59,000 more $PM_{2.5}$-related deaths in 2040) than when energy policies are not fully enforced (8,700 to 5,900 more $PM_{2.5}$-related deaths in 2040), since coal power plants with end-of-pipe controls already emit little air pollution. However, substantially more carbon will be emitted if low-carbon and clean coal policies are not successfully implemented (e.g., 400-800 million tons more CO_2 in 2040). Thus, our results underscore the important role of effectively implementing existing air pollution and energy policy to simultaneously achieve air pollution, health and carbon mitigation goals in India.

1. INTRODUCTION

India faces the dual challenge of improving air quality and curbing carbon dioxide (CO_2) emissions. On the one hand, the country suffers from severe air pollution. In 2017, the nation-wide population-weighted mean exposure to ambient fine particulate matter (i.e., $PM_{2.5}$) was nearly 90 μg/m^3, which led to 0.67 million premature deaths that year[1]. These health impacts likely impose a significant economic burden on the economy; a recent estimate indicates that India loses $150 billion a year due to air pollution[2]. On the other hand, India is currently the third largest CO_2 emitter in the world[3]. As a developing country starting from a low emissions base, the future emissions pathway of India will play a critical role in determining the global climate landscape.

Mitigating air pollution and carbon emissions in India cannot be achieved without tackling its coal-heavy electricity system. Due to the dominance of coal (76% of total generation[4]), power generation currently contributes to about 40% of total CO_2 emissions[5], as well as 53% and 40% of energy-related sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions, respectively[6]. Options to reduce air pollution from the electricity sector include installing end-of-pipe control technologies on coal-fired power plants and replacing coal power generation with cleaner alternatives, notably wind and solar power. The latter approach has the added benefit of reducing carbon emissions and contributing to the low-carbon energy transition.

In recent years, there has been an increasing emphasis on air pollution control and the need for carbon mitigation by the Indian government and other key stakeholders. On the air pollution side, India launched the National Clean Air Program (NCAP) in 2019, which set a target of cutting $PM_{2.5}$ and PM_{10} concentrations in the 122 most polluted cities by 20-30% by 2024 relative to 2017 levels[7]. Regarding carbon mitigation, India has made significant efforts to scale up renewable energy capacity in the recent decade. The share of renewables is already 23% of installed capacity and 9% of generation[4]. Plans have also been announced to continue this renewable energy push, including a target of 500 GW of renewable energy capacity by 2030[8].

However, effective implementation is a key barrier to meeting these targets and enforcing policies. Policy implementation has been particularly challenging in India's electricity sector. To curb air pollutant emissions from the power sector, in December 2015, India issued strict emissions standards for existing and newly built thermal power plants[9]. However, by the first compliance deadline of December 2017, it was found that more than 300 coal power plants continued to violate emission norms[10]. Consequently, the Central Electricity Authority (CEA) extended the deadline for compliance in a phased manner between 2020 and 2024[11]. Yet doubts remain that even with the new deadline, many plants will not be able to comply[12]. To facilitate the low-carbon transition, India not only issued new renewable installation targets[8], but also introduced policies to increase the efficiency of newly built coal-fired power plants (e.g., the Perform Achieve and Trade scheme[13], a flagship programme under the National Mission for Enhanced Energy Efficiency[14,15]). Nevertheless, there is a growing inconsistency between the ambitious government targets and the on-ground efforts of implementation agencies such as the Solar Energy Corporation of India and state electricity distribution companies. For instance, while the government aims to reach 175 GW of renewable capacity by 2022, current capacity stands at 83 GW[4]. Some predict that India will fall short of its stated goal by as much as 42% due to the unstable policy environment[16].

This paper aims to quantify the importance of policy enforcement in India's electricity sector for achieving air quality, health, and carbon mitigation objectives. Conceptually, our focus on the challenge of enforcement is of direct policy relevance given India's institutional context.

Methodologically, we apply a state-of-the-art integrated assessment method to this policy-relevant question, by combining emissions scenarios using the GAINS (Greenhouse Gas – Air Pollution Interactions and Synergies)-South Asia model, an air quality simulation using WRF-CMAQ (The Weather Research and Forecasting Model, coupled with the Community Multiscale Air Quality Modeling System), and a health impact assessment using recent estimates for the exposure-response functions. This framework facilitates the inclusion of air quality, health and carbon mitigation considerations into India's power sector policies, hence going beyond most prior studies that focused either on the carbon challenge[17–19] or on the air pollution crisis[16–22] alone.

2. MATERIALS AND METHODS

For air pollution, we use changes in the WRF-CMAQ simulated concentrations of fine particulate matter ($PM_{2.5}$) to evaluate air quality impacts, and changes in $PM_{2.5}$-related deaths to assess the health implications. For climate, we use changes in CO_2 emissions as a proxy for the climate impacts, while acknowledging that a comprehensive evaluation of these impacts on the climate system (e.g., radiative forcing, precipitation, temperature) will require a climate model as done in other studies[26].

2.1 Policy scenario design

Based on the GAINS-South Asia model[27], we first design a state-level reference scenario (WEO-CLE) from 2015 to 2040 which factors in the policies, measures and targets that have been announced by the Government of India. We then design four scenarios that represent limited implementation of existing air pollution control policies (i.e. WEO-DEL and WEO-FRO) and energy policies (i.e. BAU-CLE and AMB-CLE). As such, the differences between WEO-DEL/FRO and WEO-CLE represent the effects of failing to fully implement existing air pollution policies, while the differences between BAU/AMB-CLE and WEO-CLE represent the impacts of unsuccessful energy policy implementation (including greater electricity demand, inefficient coal use, insufficient renewable penetration, etc.). For all five scenarios, the GAINS-South Asia model estimates the emissions of air pollutants and CO_2 at the state level by multiplying the activity data with technology- and fuel-specific emission factors.

We categorize different policies based on their primary target, even though in reality, many policies simultaneously affect air pollution and carbon emissions. For instance, while the policies to increase renewable energy reduce air pollutants and carbon emissions, we classify them as energy policies since their direct objective is to scale up renewable capacity. Similarly, the Environment (Protection) Rules include policies that are targeted at reducing air pollution in the energy sector, such as mandating end-of-pipe control devices for SO_2, NO_x and PM emissions. We classify them as air pollution policies, based on the same logic that their direct objective is to curb air pollution.

Reference scenario: WEO-CLE. The national total energy projection of this scenario is developed to be consistent with the "New Policy Scenario (NPS)" in the World Energy Outlook 2017[28]. The NPS aims to provide a sense of the direction in which the latest policy ambitions could take the electricity sector. The national energy projection is then allocated across Indian states using the proportional downscaling algorithm reported in Rafaj et al. (2013)[29], which is based on state fractions derived from subnational statistics. We consider the following policies and targets for the power sector: a) Environment (Protection) Rules[9]; b) Universal electricity access by 2025[28,30]; c) Strengthened measures such as competitive bidding to achieve the national target of 175 GW renewable capacity by 2022 (100 GW solar, 75 GW non-solar); d) Expanded efforts to strengthen the national grid, upgrade the transmission and distribution network and reduce aggregate technical and commercial losses to 15%[31,32]; e) Increased efforts to ensure the financial viability of all power market participants, especially transmission and distribution companies[33]. For air pollution control strategies, the WEO-CLE scenario mainly considers the Environment (Protection) Rules 2015[9], which tightened the emission standards for all thermal power plants with especially stringent standards for new power plants installed after 2017.

Scenarios with limited implementation of air pollution policies: WEO-DEL and WEO-FRO. With the same energy projection as WEO-CLE, in WEO-DEL, we assume a 5 to 10-year delay in the implementation of air pollution control strategies (i.e., the penetration rate of end-of-pipe control strategies for each type of power plant in 2020/2025 is the same as that in 2015 for WEO-CLE, and that in 2030/2040 is the same as that in 2025/2030 for WEO-CLE). In WEO-FRO, we assume no further improvements in air pollution control policies after 2025 (i.e., the penetration rates of end-of-control strategies for each type of power plant remains unchanged beyond 2025; essentially "frozen").

Scenarios with limited implementation of energy policies: BAU-CLE and AMB-CLE. With the same penetration rate of end-of-pipe control strategies for power plants, we consider two alternative energy scenarios that assume unsuccessful efforts to scale up renewable generation and/or to improve the efficiency of the coal power fleet. The national energy projections of BAU-CLE and AMB-CLE are based on business-as-usual and ambitious scenarios for the year 2022 and 2040 in the Draft Energy Plan by NITI Aayog of the Government of India[34]. To allocate national total generation to individual states, the spatial patterns of renewable generation are based on the state to national ratios of the 2022 installation targets[35], while those of fossil fuel capacity are assumed to be the same as that in March 2016[36]. The BAU-CLE scenario projects a much more coal-heavy power mix in the future, implying policy failures in achieving renewable installation and generation targets. In both scenarios, we include delays in improving coal plant efficiency by assuming that some of the new coal power plants still use subcritical technology. Essentially, we assume the share of advanced coal technologies (e.g., ultra-supercritical and supercritical coal units) is lower in these two scenarios when compared to the reference WEO-CLE scenario (more details in Supplementary Fig. 4).

Table 1. Summary of five state-level scenarios for the electricity sector

Scenarios		**Energy strategy**		**Air pollution strategy**
		Electricity demand and fuel mix	**Coal plant technology**	
Successful enforcement of both *air pollution* and *energy* policies	**WEO-CLE**	**WEO:** IEA *World Energy Outlook (WEO)* 2017, New Policy Scenario	All new coal power plants use supercritical or ultra-supercritical technologies	**CLE:** Successful implementation of *current legislation (CLE)*, e.g., the emission standards for coal power plants released in 2015
Limited enforcement of *air pollution policies*	**WEO-DEL**			**DEL:** Compared to CLE, 5-10 years *delay (DEL)* in the implementation of control strategy
	WEO-FRO			**FRO:** Compared to CLE, no further changes in implementation rate of control strategy after 2025, i.e. frozen beyond 2025
Limited enforcement of *energy policies*	**BAU-CLE**	**BAU:** NITI Aayog, Government of India, *Business-as-usual (BAU)* scenario	Some new coal power plants still use subcritical technology; others use supercritical or ultra-supercritical technologies	**CLE:** Successful implementation of *current legislation (CLE)*, e.g., the emission standards for coal power plants released in 2015
	AMB-CLE	**AMB:** NITI Aayog, *Ambitious (AMB)* scenario		

2.2 WRF-CMAQ simulation

We use CMAQ v5.0.2 developed by the United States Environmental Protection Agency (U.S. EPA) to simulate surface air quality. A summary of model inputs and the setup is shown in Table 2. Since air quality modeling is computing-intensive, we conduct simulations only for 2015 and 2040. To isolate the effects of implementation failures of power sector policies, we keep future non-power sector activities unchanged from 2015 levels and only change power sector emissions in 2040 (see Section 3.5 for the discussion on uncertainties associated with this assumption). Our assumption to keep non-power emissions at 2015 levels is not meant to represent plausible futures, but a computational method to calculate the marginal effect of policy failures in the power sector. Our analysis hence complements prior work that examined the health effects of India's power sector emissions [22,38–40] and the impacts of multi-sector policy interventions in the future[41].

For 2015, we simulate the whole year. Annual anthropogenic emissions were obtained from the Emission Database for Global Atmospheric Research (EDGAR) at a resolution of 0.1° × 0.1°[3]. Emissions of EDGAR v4.3 for 2010 are scaled to 2015 with scaling factors used in Kota et al. (2018)[25]. Non-methane volatile organic compounds (NMVOC) and PM emissions are mapped to model species based on the SPECIATE 4.3[42] database from the U.S. EPA. An in-house preprocessor is used to generate hourly emissions based on monthly, weekly and diurnal temporal allocation profiles[42]. For 2040, we conduct simulations for four representative months (i.e., January, April, July and October, to represent each of the four seasons). Future anthropogenic emissions from the power sector are adjusted based on state-wise factors modeled by GAINS-South Asia. Within each state, we then allocate emissions to 0.1° × 0.1° grid boxes based on 2015 patterns. The emissions from non-power sectors are kept the same as in 2015 and reported in Supplementary Fig. S1. By using the same meteorological inputs as in 2015, the differences in simulated $PM_{2.5}$ between 2015 and 2040 and across 2040 scenarios are driven entirely by the differences in emissions.

The modeling spatial resolution is 36×36 km, with 27 vertical layers (the depth of the surface layer is 35m). The model uses SAPRC-11[43,44] as the photochemical mechanism and AERO6[45] as the aerosol chemistry mechanism. The model has been improved to predict secondary sulfates and nitrates, as well as secondary organic aerosols (SOA)[46,47]. Meteorological inputs for CMAQ are generated from the WRF v3.7.1 for 2015 with initial and boundary conditions from National Centers for Environmental Prediction (NCEP) FNL (Final) Operational Global Analysis data from the National Center for Atmospheric Research (NCAR) (http://dss.ucar.edu/datasets/ds083.2/). The Meteorology-Chemistry Interface Processor (MCIP) v4.2 is applied to post-process WRF outputs to CMAQ-ready meteorological inputs. The fire inventory from the National Center for Atmospheric Research (NCAR)[48] is used to generate open biomass burning emissions. Biogenic emissions were generated from the Model for Emissions of Gases and Aerosols from Nature (MEGAN) version 2.1[49]. To minimize the impacts of initial conditions on model performance, we exclude results from the first three days of each simulation as a model spin-up period.

Performance of the model application in 2015 is evaluated by comparing simulated and observed data in multiple cities, as reported in Kota et al. (2018)[25]. Supplementary Fig. S2 shows the model domain covering India and surrounding regions.

Table 2. Summary of WRF-CMAQ model inputs and setup

<table>
<tr><td>Model</td><td colspan="2">WRF V3.7.1/CMAQ V5.0.2</td></tr>
<tr><td>Time period</td><td colspan="2">2015: 12 month
2040: Four representative months (January, April, July, October)</td></tr>
<tr><td>Spatial resolution</td><td colspan="2">36km x 36km</td></tr>
<tr><td>Meteorological initial/ boundary condition</td><td colspan="2">2015 FNL (Final) Operational Global Analysis data</td></tr>
<tr><td rowspan="2">Emissions</td><td>2015</td><td>Anthropogenic: Emissions Database for Global Atmospheric Research (EDGAR) version 4.3 in 2010[3], scaled to 2015 based on the scaling factors used in Kota et al. (2018)[25].
Biogenic: MEGAN[49]
Fire: FINN[48]</td></tr>
<tr><td>2040</td><td>Anthropogenic emissions from the power sector: State-level emissions projected by GAINS-South Asia, then allocated to 0.1° × 0.1° grid boxes following 2015 pattern.
Non-power anthropogenic emissions, biogenic emissions, and fire emissions: Same as 2015</td></tr>
</table>

2.3 Health impact assessment

We quantify the mortality impacts due to the exposure to ambient fine particulate matter ($PM_{2.5}$, i.e. particulate matter with a diameter small than 2.5μm). Our focus on the health effects of ambient $PM_{2.5}$ exposure is consistent with prior findings that $PM_{2.5}$ exposure accounts for the majority of long-term health damages and leads to much larger mortality impacts than other types of pollutants (e.g., ozone) in India and worldwide [1,50,51]. We consider six diseases associated with long-term exposure to $PM_{2.5}$, i.e., ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), lung cancer (LC), lower respiratory tract infections (LRI) and diabetes. For each disease, we use the following equation to calculate premature deaths in each state for each scenario:

$$\Delta \mathrm{Mortality}_{d} = \mathrm{I}_{d} \cdot \mathrm{Pop} \cdot (1-\frac{1}{\mathrm{RR}_{d}(c)})$$

The definition and data source for each variable is summarized in Table 3. Note that relative risk (RR) is defined as the ratio of incidence rates between exposed and unexposed populations. (1 – 1/RR) is hence the attributable fraction of deaths due to $PM_{2.5}$ exposure.

As a robustness check, we further consider: a) changing baseline mortality rates in 2040, using the national-level projection from GBD Foresight[52] and cross-state variations in 2015 (Supplementary Materials Section 4); b) alternative exposure-response functions, including non-linear disease-specific functions from the Global Exposure Mortality Model (GEMM)[53] and log-linear functions for all-cause mortality[54] (Supplementary Materials Section 3).

Table 3. Summary of data for health impact assessment

Variables	Definition	Data Source
$\mathrm{I_d}$	Baseline annual mortality rate for disease *d*	For both 2015 and 2040: State-level age- and disease-specific baseline mortality rates in 2015 from GBD India Compare[55] (Supplementary Table S4)
Pop	Exposed population in each state: • For IHD and stroke: Adult population aged 25 and above, by 5-year age group. • For COPD, LC, LRI and diabetes: Total population	For 2015: State-level age-specific and total population in 2015 from GBD India Compare[55]; For 2040: Projected 2040 state-total population from Shared Socioeconomic Pathways #2 (SSP2)[56], assuming the same age structure in all states following the national-level projection (Supplementary Table S1-3).
$\mathrm{RR_d}(c)$	Relative risks (RR) of disease *d* for the respective age groups at the $PM_{2.5}$ levels of c. • For IHD and stroke: Age-specific RR functions	GBD Study[50]

	- For COPD, LC, LRI and diabetes: All-age RR functions.	
c	Annual mean exposures: For 2015: 12-month average of the simulated population-weighted, state-averaged $PM_{2.5}$ concentrations* For 2040: 4-month average of January, July, April and October, as representative months for each of the four seasons	Based on our WRF-CMAQ simulations and population data in 2015

*Population weighted concentrations are calculated as following: $PWC = \frac{\sum c_i \times P_i}{Pop}$, where c_i is the $PM_{2.5}$ concentration in grid i, P_i is the population in grid i, and Pop is the total population in each Indian state. Population data for 2015 is used, based on Population Division 58 (2015) at the Department of Economic and Social Affairs in the United Nations[57].

3 RESULTS AND DISCUSSION

3.1 Impacts on electricity production (Fig. 1)

In all scenarios, electricity demand in India is projected to grow rapidly in the coming decades. In WEO scenarios (i.e. WEO-CLE, WEO-DEL and WEO-FRO), national total electricity generation is projected to grow from 1383 TWh in 2015 to 1883 TWh in 2020, and then to 4480 TWh in 2040. The 2020 projection from WEO is much higher than electricity production in 2018 (1561 TWh), the most recent year for which data is available[58]. This is because WEO assumed an annual average GDP growth rate of 7.7% between 2016-2025, which is higher than real GDP growth rates in recent years (7.0%, 6.1% and 4.2% in 2017, 2018 and 2019, respectively[59]). In comparison, the BAU and AMB scenarios assume that total generation grows to 2341 TWh and 2346 TWh in 2022, and 4682 TWh and 4647 TWh in 2040, respectively. The slightly higher projections in BAU and AMB are primarily because of the higher population and economic growth rates being assumed.

For the 2020- and 2022- time horizon, all scenarios project continued coal dominance, along with a noticeable increase in solar generation. By 2040, while the BAU scenario assumes continued coal dominance (coal share of 57%), the WEO and AMB scenarios project a reduced share of coal at 46-47%. In the meantime, the share of inefficient subcritical coal units is greater in BAU and AMB than WEO (Supplementary Fig. S4), which leads to lower average energy efficiency of the coal fleet and hence, higher emissions per unit of electric output. All scenarios anticipate a rapid expansion of solar and wind energy from now to 2040, though WEO and AMB project more renewable generation than BAU.

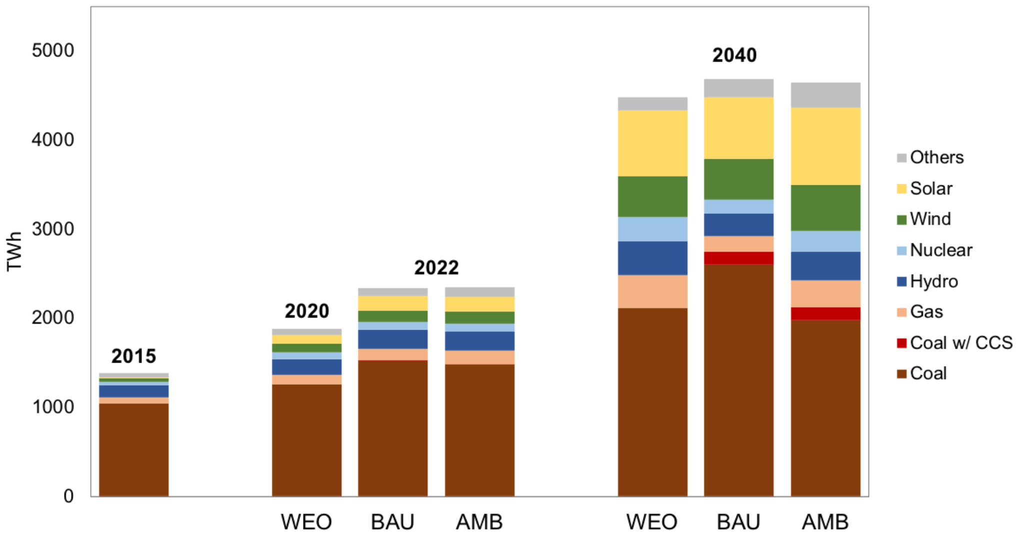


Figure 1. National total electricity generation by source in WEO, BAU and AMB scenarios. The WEO scenario by the IEA makes projections for 2020 and 2040[28], while the BAU and AMB scenarios by NITI Aayog make projections for 2022 and 2040[34].

3.2 Impacts on emissions of air pollutants and CO_2 (Fig. 2)

We highlight two findings. First, power sector CO_2 emissions are significantly affected by energy policies, but not by the implementation of air pollution control policies. Limited implementation of existing energy policies results in more generation from coal (in BAU-CLE), especially from inefficient coal units (in BAU-CLE and AMB-CLE). Quantitatively, in 2040, CO_2 emissions in BAU-CLE and AMB-CLE are 41% and 19% higher than in WEO-CLE, respectively (see Supplementary Fig. S5 for CO_2 emissions by plant type). In comparison, enforcing existing air pollution policies (mainly by installing end-of-pipe controls) has a negligible impact on CO_2 levels. Even if operating end-of-pipe controls reduces plant efficiency by a few percent (see a sensitivity analysis conducted in a previous work[60]), the resulting increase in total CO_2 emissions from the power sector is still minimal.

Second, while the implementation of both air pollution and energy policies affect air pollutant emissions from the power sector, the impacts of air pollution policies are often more pronounced. In particular, 2040 air pollutant emissions are substantially higher if pollution control policies are not made more stringent beyond 2025 (WEO-FRO). Quantitatively, while 2020 emissions in WEO-FRO remain the same as WEO-CLE, 2040 emissions in WEO-FRO are 7.9 times, 0.7 times, and 2.1 times greater than WEO-CLE for SO_2, NO_x and $PM_{2.5}$ emissions, respectively. These results are due to the accelerated implementation of air pollution control technologies between 2025 and 2040 if current policy trends continue, as indicated in WEO-CLE. If the implementation of air pollution policies is delayed by 5-10 years (as in WEO-DEL), 2020 emissions of SO_2, NO_x and $PM_{2.5}$ are 24%, 8% and 6% higher than in WEO-CLE. By 2040, NO_x emissions in WEO-DEL are 48% greater than in WEO-CLE, whereas SO_2 and $PM_{2.5}$ emissions remain the same as WEO-CLE. This trend is driven by our assumption that in the perfect enforcement case (WEO-CLE), NO_x controls (e.g., selective catalytic or non-catalytic reduction) will be implemented more slowly than SO_2 and $PM_{2.5}$ measures (e.g., flue-gas desulfurization and electrostatic precipitators). This is consistent with the pace of current policy discourse. Despite much deliberation on SO_2 control measures over the past decade, action on the installation of NO_x controls remained largely invisible until June 2018[61]. As such, in WEO-CLE, almost all power plants are projected to have SO_2 and $PM_{2.5}$ end-of-pipe controls by 2030. The 10-year delay in WEO-DEL still means full SO_2 and $PM_{2.5}$ control in 2040, but not NO_x control.

In 2020/2022, with limited energy policy implementation and given more fossil fuel-based electricity generation in BAU-CLE and AMB-CLE than in WEO-CLE, SO_2, NO_x and primary $PM_{2.5}$ emissions are about 20% greater. However, by 2040, with SO_2 controls installed in nearly every thermal power plant, power sector SO_2 emissions are minimal and there are negligible differences between different energy pathways (i.e., comparing BAU-CLE and AMB-CLE to WEO-CLE). However, BAU-CLE and AMB-CLE still result in more NO_x and $PM_{2.5}$ emissions when compared to WEO-CLE (for NOx and $PM_{2.5}$ emissions respectively, 26% and 36% greater in BAU-CLE than WEO-CLE, and 12% and 15% greater in AMB-CLE). This is due to greater fossil fuel-based electricity generation and the fact that some old subcritical coal power plants still do not have NO_x/$PM_{2.5}$ end-of-pipe controls.

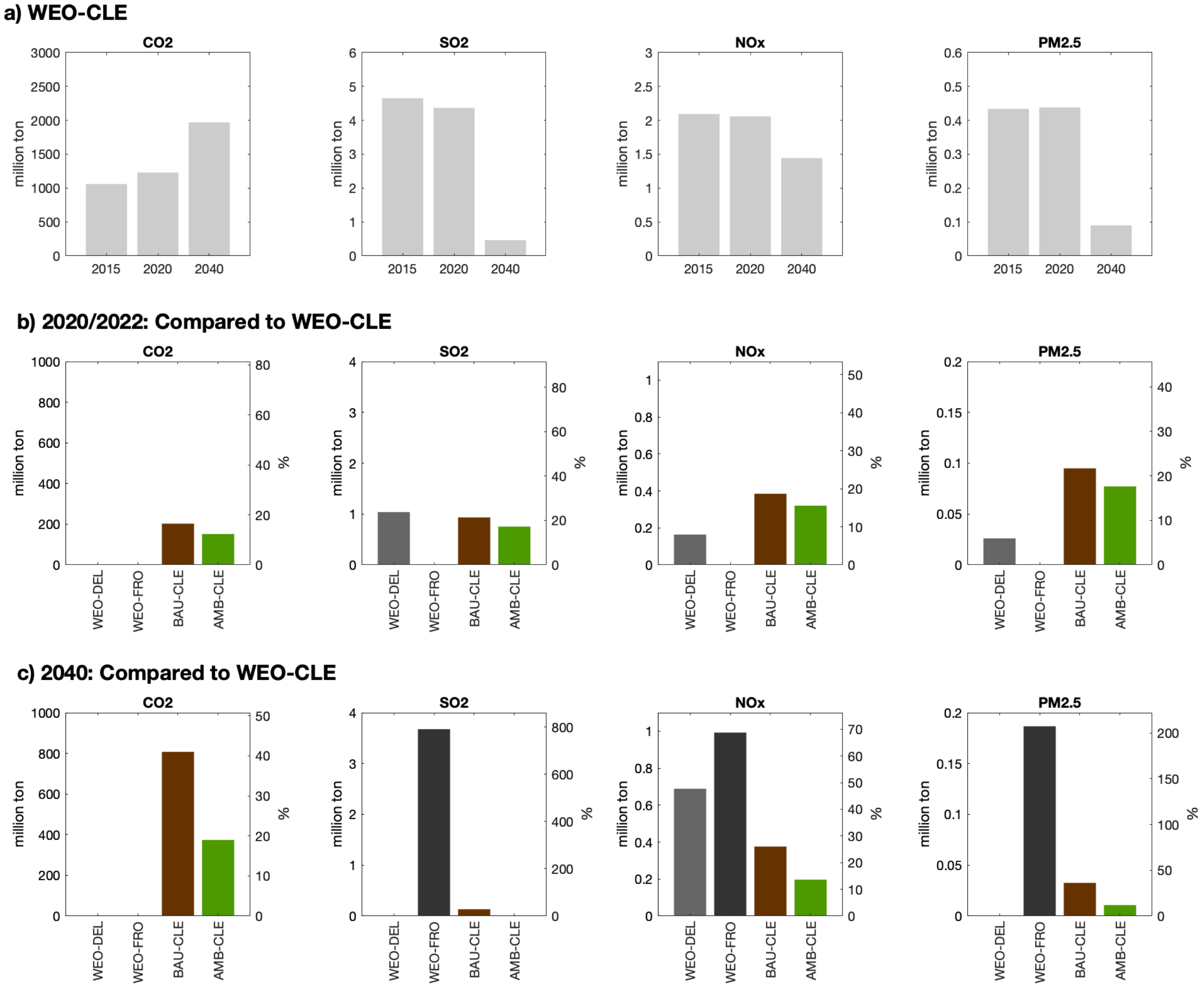


Figure 2. Power sector emissions in the successful enforcement scenario (WEO-CLE, subplot a)**, and the changes for scenarios assuming limited enforcement of air pollution policies** (WEO-DEL and

WEO-FRO) **or energy policies** (BAU-CLE and AMB-CLE) **relative to WEO-CLE in 2020/2022** (subplot b) **and in 2040** (subplot c). Note that the WEO energy projection by IEA is made for 2020 and 2040[28], while the BAU/AMB projections by NITI Aayog are made for 2022 and 2040[34].

3.3 Impacts on surface $PM_{2.5}$ concentrations (Fig. 3)

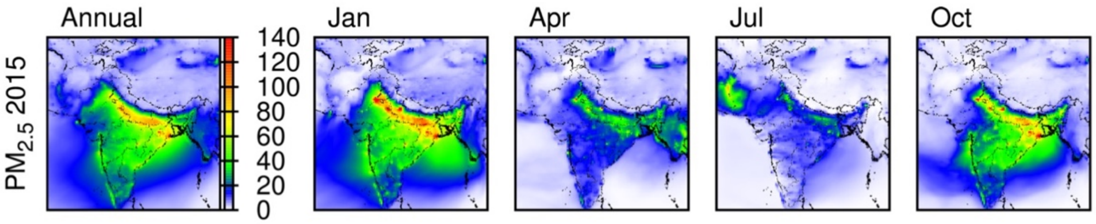
We first validate our WRF-CMAQ modeling by comparing simulated and observed surface $PM_{2.5}$ concentrations in 2015. We find that the model performs well in predicting average concentrations as well as high pollution events[22,25]. For instance, as discussed in Kota et al. (2018)[25], when compared to observations, our simulated $PM_{2.5}$ in 2015 has a normalized mean bias within the range of -0.15 to 0.15 in most Indian cities, which meets the suggested criteria by the U.S. EPA.

Consistent with prior studies[25,41,62–64], we find that $PM_{2.5}$ concentrations are higher during the wintertime and after the monsoon season, but lower during the pre-monsoon and monsoon periods. This pattern is due to greater anthropogenic emissions and unfavorable dispersion conditions during the colder months, and lower emissions and a greater scale of wet deposition during the warmer months. As for the annual average, many places experience a concentration level between 40-60μg/m^3, with states in the Indo-Gangetic plain reaching levels higher than 80μg/m^3.

With successful policy enforcement in WEO-CLE, simulated 2040 concentrations are lower than 2015 levels throughout the country, since air pollutant emissions from the electricity sector are reduced significantly and we assume that non-power emissions remain at 2015 levels (Fig. 3). The annual average $PM_{2.5}$ level in most places in Peninsular India is between 20-40μg/m^3, while in the northern states it lies between 40-60μg/m^3. Hence, our results indicate significant improvements in air quality if both energy and air pollution policies are implemented successfully in India's electricity sector.

When comparing other scenarios to WEO-CLE, the WEO-FRO scenario, in particular, shows a significant increase (i.e., 5-10 μg/m^3) in annual mean PM$_{2.5}$ levels throughout the country. These results are driven by substantially greater air pollutant emissions when pollution controls are not made more stringent beyond 2025. For the other three scenarios, the differences compared to WEO-CLE are generally within the range of 1-2 μg/m^3.

a) Simulated PM$_{2.5}$ concentrations in 2015: Annual mean and monthly mean for four representative months



b) Simulated annual mean PM$_{2.5}$ concentrations in 2040: WEO-CLE and the changes in other scenarios relative to WEO-CLE

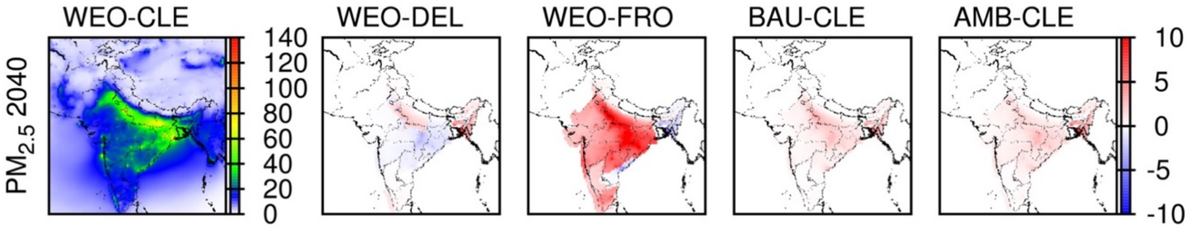


Figure 3. Spatial distribution of ambient PM$_{2.5}$ concentrations (unit: μg/m^3). a) 2015: Annual mean concentration (12-month average) and monthly concentrations for four representative months (January, April, July and October); b) 2040: Annual mean concentration in WEO-CLE, and the difference between the other four scenarios compared to WEO-CLE. The absolute PM$_{2.5}$ concentration in each scenario is presented in Supplementary Fig. S6, and the population-weighted, state-averaged PM$_{2.5}$ concentration is presented in Supplementary Fig. S7.

3.4 Impacts on $PM_{2.5}$-related deaths (Figs. 4 and 5)

We estimate total $PM_{2.5}$-related mortalities to be 0.9 million (confidence interval due to relative risk functions: 0.6 to 1.1 million) in 2015. The leading causes of deaths are ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), and lower respiratory tract infections (LRIs). This estimate is broadly in line with prior studies[1,22]. Under WEO-CLE, $PM_{2.5}$-related deaths increase to 1.3 million (confidence interval: 0.8 to 1.7 million) in 2040. This indicates a 50% increase in $PM_{2.5}$-related deaths from 2015 to 2040, despite a 9% decrease in annual mean population-weighted $PM_{2.5}$ levels (calculated based on state-total population and state-averaged $PM_{2.5}$ concentrations) as a result of decreasing power sector emissions. The main drivers are demographic changes that can play an important role when estimating the past and future health impacts of air pollution in India[65,66]. From 2015 to 2040, the total population is projected to increase by 21% (Supplementary Table S1). Also, due to the effect of aging, the share of the population older than 60 years is projected to increase from 8.9% in 2015 to 17.8% in 2040 (Supplementary Table S2 and S3), further increasing the health burden due to air pollution since the elderly population is more vulnerable. Indeed, when holding demographic factors constant at 2015 levels, we find that the reduction in $PM_{2.5}$ exposure can lead to a 3% decrease in total deaths, indicating that future mortality is significantly affected by demographic changes.

With limited enforcement of air pollution control policies, in 2040, we find 14,200 and 58,900 more cases of premature deaths (or 1.1% and 4.6% higher) in WEO-DEL and WEO-FRO respectively, when compared to WEO-CLE. This finding indicates that the successful implementation of current air pollution policies in the electricity sector is vital for reducing the overall public health burden. Making pollution control policies more stringent over time is especially important.

In comparison, with weak enforcement of energy policy, in 2040, BAU-CLE and AMB-CLE lead to only 8,700 and 5,900 more cases of premature mortality (i.e., 0.7% and 0.5% more deaths) when compared to WEO-CLE. This implies that while energy strategies can affect air pollution levels and the resulting health impacts, these factors are less important than the strict enforcement of proposed air pollution control strategies in thermal power plants.

At the subnational level, under WEO-CLE, the Indo-Gangetic Plain (IGP) in northern India has the most health damages in both 2015 and 2040 (Fig. 5). This region is a hotspot for $PM_{2.5}$ pollution due to high emissions of air pollutants as well as reduced ventilation caused by obstruction from the Tibetan Plateau[64]. It is also a densely-populated region at present and in our 2040 projection. Under limited enforcement of air pollution control policies, the greatest increase in air-pollution related deaths relative to WEO-CLE occurs in these northern states, though the magnitude is much higher in WEO-FRO than in WEO-DEL. Under limited enforcement of energy policies, the increase in $PM_{2.5}$-related deaths relative to WEO-CLE is more spread out throughout the country, since the subnational patterns of renewable installation and coal displacement follow different assumptions in BAU-CLE/AMB-CLE than in WEO-CLE.

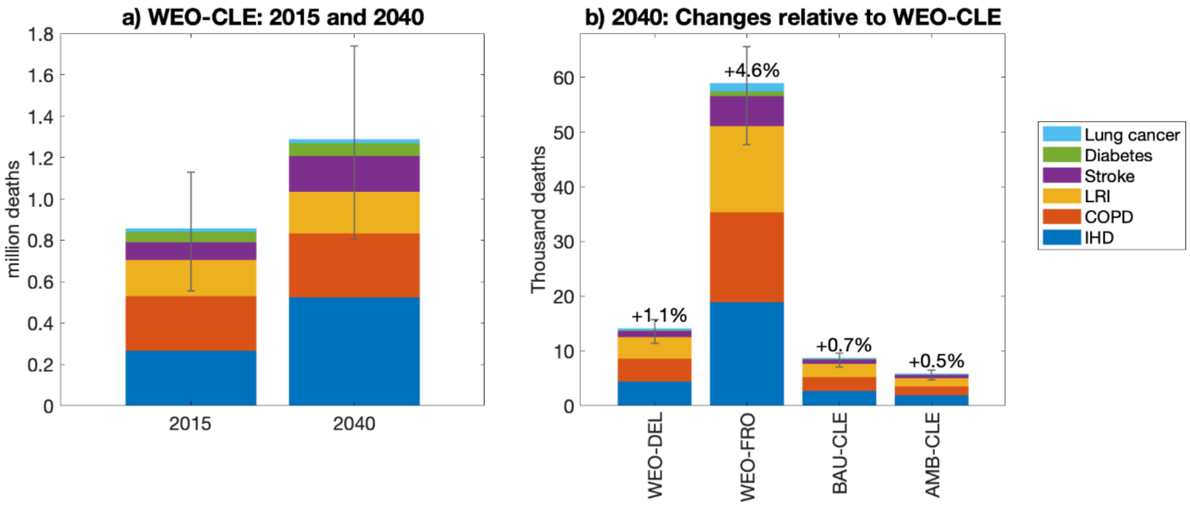
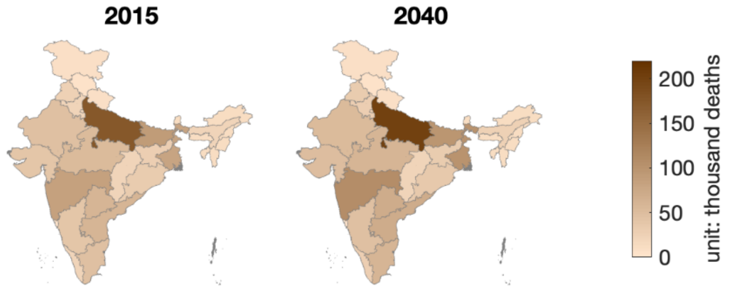
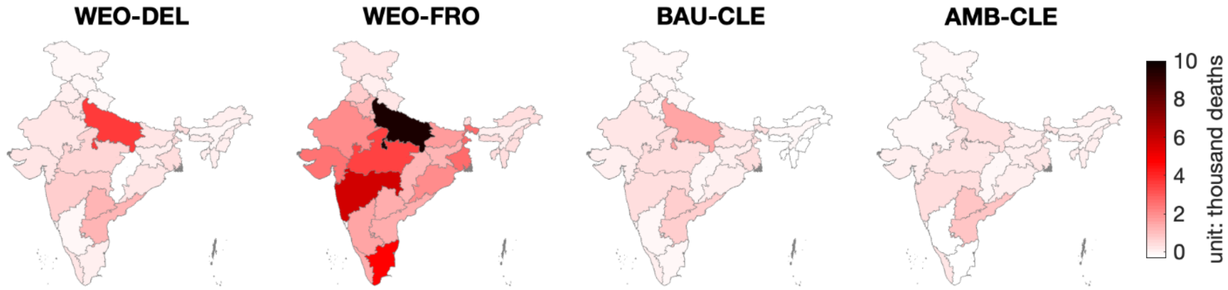


Figure 4. National total $PM_{2.5}$-related deaths: a) for 2015 and 2040 in WEO-CLE, and b) the changes in other scenarios relative to WEO-CLE in 2040. Different colors represent the six different diseases considered this study, i.e., ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), lower respiratory tract infections (LRI), stroke, diabetes, and lung cancer. In panel a), the increase from 2015 to 2040 under WEO-CLE is driven by demographic changes (Supplementary Table S1-3) combined with a decrease in power sector emissions and surface $PM_{2.5}$ concentrations (as shown in Fig. 2a and Fig. 3). In panel b), the changes in other scenarios relative to WEO-CLE in 2040 is driven only by differences in emissions and the resulting $PM_{2.5}$ concentrations.



a) Annual total PM2.5-related deaths in WEO-CLE



b) PM2.5-related deaths in 2040: Changes relative to WEO-CLE

Figure 5. Annual total $PM_{2.5}$-related deaths by state: a) in WEO-CLE: 2015 and 2040; b) in 2040: changes in each scenario relative to WEO-CLE.

3.5 Potential uncertainties

For the health impact assessment, we consider two major factors in our uncertainty analysis: a) changing future baseline mortality rates (Supplementary Fig. S14 and Table S8), and b) alternative exposure-response functions (Supplementary Fig. S9-13 and Table S6-7). Regarding baseline mortality, while the main results above assume the same baseline mortality rates in 2040 as in 2015, the age- and disease-specific baseline mortality rates often decrease over time with growing income levels and an improving healthcare system[66]. When we update the 2040 baseline mortality rates based on the national-level projection from GBD Foresight[52] and current cross-state variations, we find that 2040 $PM_{2.5}$-related deaths under WEO-CLE decrease to 1.2 (0.8 to 1.5) million nationally, which is 9% lower than our main results. However, the relative changes in policy failure scenarios when compared to WEO-CLE are similar to the main results. For instance, national total deaths are 1.2%, 4.8%, 0.7% and 0.5% higher in WEO-DEL, WEO-FRO, BAU-CLE and AMB-CLE scenario, respectively.

For exposure-response functions (Supplementary Materials Section 3, Fig. S9-S13, Table S6-7), while the main results utilize the RR functions for six diseases based on the GBD study, here we consider alternative RR functions for five diseases (i.e., stroke, lung cancer, IHD, LRI and COPD) from the Global Exposure Mortality Model (GEMM)[53]. We find that applying GEMM functions leads to significantly higher estimates of premature deaths than in our main results, which is consistent with prior findings[53]. For instance, total 2040 deaths in WEO-CLE are estimated to be 2.3 (1.7 to 2.7) million with GEMM RR functions, as compared to only 1.3 (0.8 to 1.7) million in our main results. Yet our key finding – that policy failure scenarios always result in more deaths than WEO-CLE, and the highest deaths occur in WEO-FRO –remains robust. In addition, although non-linear RR functions from GBD and GEMM are more consistent with recent epidemiological evidence that marginal mortality risks decrease with increasing $PM_{2.5}$ concentrations at high levels, we also consider the log-linear RR function for all-cause mortality from an earlier study (Pope et al. 2002 [54]), which yields similar findings about the impacts of policy failures.

In addition, there can be two other major uncertainties in our air quality simulations. First, since our goal is to assess the impacts of enforcing electricity sector policies, we only change electricity sector emissions in 2040, and keep non-electricity sector emissions at 2015 levels. However, as studied carefully in our prior study[41], future emissions from other sectors involve a large degree of uncertainty, which can significantly affect future air quality. Due to non-linear interactions between various types of primary emissions to form aerosols, our WRF-CMAQ simulations may under- or over-estimate the changes in $PM_{2.5}$ concentration levels that result from unsuccessful energy policy enforcement. Though a quantitative assessment is beyond the scope of this study, key factors identified in prior studies include local pollution sources (e.g., the availability of SO_2, NO_x, and NH_3 emissions to form secondary aerosols) and meteorological conditions (e.g., relative humidity, wet deposition through precipitation, and wind transport)[25,64]. Second, all power sector emissions are allocated to the surface layer in our simulations, while in reality coal power plants use tall smokestacks. As a result, we may overestimate the effect of coal power plant discharge on surface $PM_{2.5}$ concentrations and human exposure.

3.6 Policy implications and future directions of research

Given the dual challenge of simultaneously curbing CO_2 emissions and air pollution in India, we find that limited enforcement of air pollution control policies leads to worse air quality and more health damages (e.g., 14,200 to 59,000 more $PM_{2.5}$-related deaths in 2040), while the air pollution penalty is less significant when energy policies are not fully enforced (8,700 to 5,900 more $PM_{2.5}$-related deaths in 2040), since coal power plants with end-of-pipe controls already emit little air pollution. However, substantially more carbon emissions will be emitted if low-carbon and clean coal policies are not successfully implemented (e.g., 400-800 million tons more CO_2 in 2040). Further, we observe greater cross-scenario variations in CO_2 impacts than air pollution impacts (see Supplementary Fig. S8 for a combined analysis of air pollution and CO_2 impacts at both, national and subnational levels). This is because while CO_2 impacts are directly influenced by the amount of fossil fuel generation in the future, some level of air pollution control will always exist – even in the delayed or frozen air pollution policy scenarios – since many measures are already taken today.

Our results underscore the critical role of implementing existing air pollution and energy policy to simultaneously achieve India's air pollution, health and carbon mitigation goals. Enforcing air pollution controls can avoid premature deaths from air pollution exposure, even in scenarios dominated by continued coal-fired power generation. Thus, if India cannot reduce or eliminate its reliance on coal, the enforcement of air pollution control is essential to mitigate the country's public health crisis. While limited enforcement of energy policy may not be a major issue for air quality, it will certainly undermine India's efforts to mitigate climate change through low-carbon development as laid out in the Paris Agreement. Thus, the simultaneous achievement of air pollution, health, and carbon mitigation goals will require effective enforcement of both air pollution control and low-carbon energy policies.

For policymakers, our study emphasizes that policy enforcement should be a priority. India's current policy framework is a good start on paper to solve the dual challenges of climate change and air pollution. However, delayed or incomplete enforcement would significantly compromise the policies' efficacy. For the Government of India, the first order of business is to develop strategies that ensure the timely and complete implementation of clean energy and air pollution policies. On air pollution, policy priorities include full enforcement of current emissions standards for all coal-fired power plants and establishment of a real-time monitoring system that allows authorities and citizens to detect and promptly act on violations. In fact, one objective of the National Clean Air Program (NCAP) is to enhance the ambient air quality monitoring network across the country and create a comprehensive and reliable database of this information. In particular, the current push for the Continuous Emission Monitoring System is a step in the right direction. On clean energy, meeting current deployment targets requires reducing investment risks by enforcing power purchase agreements and, over time, developing a more extensive and flexible power market to deal with the intermittency of solar and wind power by balancing supply and demand across the country.

To improve the quantification of air quality, health, and climate implications of power sector strategies, future research should consider integrating the impact assessment approach used in this analysis with power system models. Power system models provide detailed representations of the generation system, transmission system and end-use sectors, and can help develop strategies to link electricity supply and demand decisions, e.g., how much renewable electricity can be integrated when coupled with electric vehicles and heating options. Despite some recent attempts, fine resolution power system modeling requires further development for the Global South including India. A fine temporal horizon would be useful to model the environmental implications of a low-carbon power system. For instance, prior studies on advanced economies utilized hourly or minute-level analyses and found that using thermal generation to balance renewable generation may lead to an emission penalty[67,68].

To advance interdisciplinary policy-oriented research, it is necessary to combine social sciences knowledge regarding political feasibility and implementation challenges with the quantitative modeling utilized in this study. As our study draws attention to policy implementation in India, we highlight three key areas for further interdisciplinary inquiry. First, future studies should investigate drivers of weakly enforced air pollution standards, as well as the institutional weaknesses in the power sector that make renewable energy investment risky (such as rigid power purchase agreements and unreliable payments by electricity distribution companies).

Second, inter-state cooperation is worth further attention. In many Indian states, emission sources that are outside their immediate jurisdiction make dominant contributions to ambient $PM_{2.5}$ pollution[20,69], and these impacts of cross-state air pollution transport are captured by our air pollution simulations. Consequently, most states cannot achieve significant improvements in air quality and reduced population exposure on their own and require coordinated mitigation efforts in nearby regions[70].

Third, due to the geographic mismatch between renewable-abundant states and high-demand states, cross-state transmission is critical to transport renewable power to demand centers. In this case, India's federal structure is an issue, as individual states have considerable authority over power sector investments, pricing, and trade. Developing politically feasible yet effective policy packages that enhance inter-state power trade emerge as an important priority. This design challenge requires understanding the distributional consequences of electricity trading and developing mechanisms that compensate potential losers, thus mitigating political opposition and reaping the gains of an extensive inter-state transmission network.

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