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Climate and air pollution implications of potential energy infrastructure and policy measures in India

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ABSTRACT

India is a rapidly developing economy with interrelated air quality, sustainable development, and climate change mitigation goals. There are unique challenges to achieving each of these goals as well as potential tradeoffs among them. This study examines the implications of possible future energy, climate, and air pollution control policies and measures in India through 2050. We take a scenario approach using the GCAM global energy-climate-land model combined with the Hector simple climate model and the TM5-FASST air quality source-receptor model to examine energy, climate and air quality outcomes. Reducing use of traditional biomass in buildings can reduce primary carbonaceous particulate emissions well below 2015 levels. However, policies that are more ambitious than current plans would likely be required to reduce SO_2 and NO_x emissions well below 2015 levels. Among single policy cases considered, pricing of greenhouse gas (GHG) emissions and expansion of natural gas infrastructure have the largest impacts on overall energy system changes relative to the reference scenario. Ambitious air pollution control and GHG policies lead to the largest reductions in air pollution concentrations and radiative forcing, respectively. However, ambitious air pollution control and GHG policies differ in the extent to which they support or impede other policy objectives. Forcing increases due to reduced aerosols from ambitious air pollution policies can be mitigated, at least in part, by applying air pollution control and GHG policies together.

1. Introduction

India has some of the worst air quality in the world, making its improvement a high priority for the Indian government as evidenced by the launch of the National Clean Air Programme in January 2019 [18]. More than 99% of the population is exposed to ambient $PM_{2.5}$ concentrations greater than the World Health Organization's annual mean ambient concentration guideline of 10 μg/m^3, with more than 50% of the population exposed to concentrations greater than India's own annual National Ambient Air Quality Standard (NAAQS) of 40 μg/m^3 [21].

Projected increases in energy consumption, particularly fueled by coal, create challenges for attaining climate and air quality goals. Coal dominates India's energy system, comprising 75% of electricity generation and 37% of industrial final energy use in 2015 ([12]; **Fig. S14**). Coal combustion in the electric power and industrial sectors contributes to CO_2 and air pollutant (particularly SO_2 and NO_x) emissions. India faces dual challenges in the industrial sector of transitioning out of highly polluting informal industries (e.g. brick-making; food and agricultural processing) and decoupling emissions from output when expanding formal industries to meet sustainable industrialization goals. The transportation sector, largely composed of internal combustion engine (ICE) vehicles, contributes approximately one third of India's total NO_x emissions, despite a relatively small share (16% in 2015) of total final energy use ([12]; **Fig. S14**). To mitigate air pollution, the Indian government has introduced regulations on power plants, industries, vehicles and fuels, and agricultural waste burning (see Section 2.1). Incentives for electric vehicles (EVs) have also been adopted (see SI section S2.4).

Sixty percent of final energy in India's buildings sector is estimated to be traditional biomass ([12]; **Fig. S14**), largely for cooking, which is a major contributor to air pollution. To increase access to cleaner, more

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convenient cooking and lighting technologies, the government has subsidized liquefied petroleum gas (LPG) connections to low-income households and invested in rural electrification. Increasing access to modern energy can also improve health and welfare for reasons that extend beyond air quality, for example by reducing the time women and girls spend collecting biomass [20]. One result of these efforts is decreasing consumption of highly polluting kerosene used in the residential sector [12, 19].

Related to energy access and other societal objectives, the Indian government has stated its intent to increase the share of natural gas in primary energy [14]. The Indian government has also introduced goals for expansion of renewable energy as part of its nationally determined contribution (NDC) towards global greenhouse gas emission reductions along with goals for overall carbon intensity reductions [8]. India also has experience with environmental taxation, for example through its coal tax, which stands at approximately $3/ton CO_2 (International Institute for Sustainable Development [15], 2018).

When considering multiple goals simultaneously, it is important to consider that energy and environmental goals can interact, with action on one goal potentially impeding or supporting progress on another. For example, addressing air quality by reducing reliance on coal in the power and industrial sectors could exacerbate climate change by decreasing SO_2 emissions, due to its cooling effect. On the other hand, addressing climate change with an economy-wide GHG price could support air quality goals by reducing coal consumption, although it could also impede access to modern energy and exacerbate residential air quality if modern fuels become more costly and lead to continued use of traditional fuels [22, 23].

These issues have been explored globally by Rafaj et al. [22], who quantified the implications of an integrated approach to achieving energy-related SDGs. Rao et al. [23] linked several integrated assessment models (including the Global Change Analysis Model, GCAM) to the global source-receptor air quality model TM5-FASST to assess air quality implications of global climate mitigation. Vandyck et al. [30] employed a similar approach and quantified the value of health-related air quality co-benefits of climate policy across regions (including India) and sectors in multiple models, estimating a broad range of co-benefits (both positive and negative) across sectors and regions.

Focusing on India, Venkataraman et al. [32] developed a sectoral-level emissions inventory for 2015 and projections of emissions and $PM_{2.5}$ concentrations through 2050 under different air pollution mitigation pathways. Purohit et al. [21] explored the extent to which Indian air quality standards could be achieved under different air pollution and climate change mitigation pathways, using GCAM to determine energy outcomes, and GAINS [16] to determine emissions and corresponding health and environmental impacts. Previous studies using GCAM have explored the effects of economy-wide carbon prices and more targeted energy system policies, such as energy efficiency [5], renewable energy technologies [28], and low-carbon technologies [27] on energy and climate outcomes in India. Other models, such as TIAM-UCL, have been used to evaluate the role of renewables and CCS [1] and the possibility of carbon trading [9] as part of India's contribution to global climate change mitigation.

This study aims to understand the implications of energy infrastructure, climate change, and air quality policy measures on energy and environmental outcomes in India through 2050 separately and in combination. In contrast to previous studies, we design a larger set of scenarios structured to examine specific technology and policy dimensions relevant to India, taking into account recent trends. We define reference and ambitious pathways over four dimensions (air pollution control, GHG pricing, natural gas infrastructure expansion, and passenger vehicle electrification) in order to examine a range of potential policies and technology trends. We focus on plausible pathways, as opposed to extreme scenarios (e.g., no further policy action or maximum feasible air pollution controls). We use an integrated energy system model (GCAM), a simple climate model (Hector), and an air quality source-receptor model (TM5-FASST) to examine changes in energy, emissions, climate forcing, and air pollutant concentrations through 2050.

The rest of the paper is organized as follows. Section 2 describes the methods, specifically the GCAM, Hector, and TM5-FASST models, and introduces the scenarios, including the underlying policy context guiding their development. Section 3 contains results and discussion of our reference scenario, and selected policy cases in terms of key energy and environmental outcomes. Section 4 concludes with a summary of insights, caveats and potential future directions.

2. Methods

2.1. Linked modeling approach

This study uses three models to examine the energy, climate and air quality implications of possible future scenarios of the Indian energy system. As shown in **Fig. 1**, a modified version (SI section S4) of the Global Change Analysis Model version 5.2 (GCAM) is used to project energy system changes, as well as GHG and air pollution emissions [3, 4]. GCAM is an open-source global model that represents interactions between energy, water, agriculture, land use, the economy, and climate systems. The energy system is disaggregated into 32 regions, with India as its own region.

GHGs and other climate forcers from GCAM are used to estimate radiative forcing changes using Hector 2.0, a simple climate model [11]. Hector includes non-linear relationships between emissions and concentrations, concentrations and radiative forcing, and radiative forcing and global mean surface temperature.

We also evaluate implications for surface air pollutant concentrations by using the TM5-FAst Scenario Screening Tool (TM5-FASST) source-receptor model to produce estimates of population-weighted average $PM_{2.5}$ and surface ozone levels across India [29]. TM5-FASST provides a rapid method of estimating air pollutant concentrations and has been used in a number of other studies [23, 25, 30]. We evaluate the air pollution and climate implications of various policy cases for changes in India emissions only, holding emissions from all other regions at their reference levels. More details about the three models and the linkages between them are provided in SI section S1.

2.2. Scenarios and policy context

This study uses a scenario approach, defining "reference" and "ambitious" pathways along four dimensions: air pollution emissions controls (AP), greenhouse gas emissions pricing (GHG), natural gas infrastructure expansion (NG), and passenger vehicle electrification (EV). The reference case consists of the reference pathway for each dimension, which is intended to capture existing policies and plausible future trends in policy and technology through 2050. The reference pathways incorporate some amount of policy delay or incomplete implementation, consistent with what has been observed to date. Ambitious pathways represent a greater push towards specified energy or environmental goals beyond current trends, including new or ratcheted policies, but not to the level of maximum feasible implementation. A summary of the reference and ambitious pathway assumptions is shown in Table 1. Further details for each scenario are given in SI Section S2, which draws on Purohit et al. (2018) and a review of recent policy developments and trends.

We examine ambitious action along just one dimension (single policies), as well as along multiple dimensions (combination policies). This allows us to investigate the effects of each dimension individually as well as potential interactions. In each of the single policy cases we combine the ambitious policy pathway in the relevant dimension with the reference pathway in all other dimensions. For example, in the AP case, we combine the ambitious AP pathway assumptions with the reference GHG, NG and EV pathway assumptions. In combination policy cases, we combine assumptions from several ambitious pathways. For

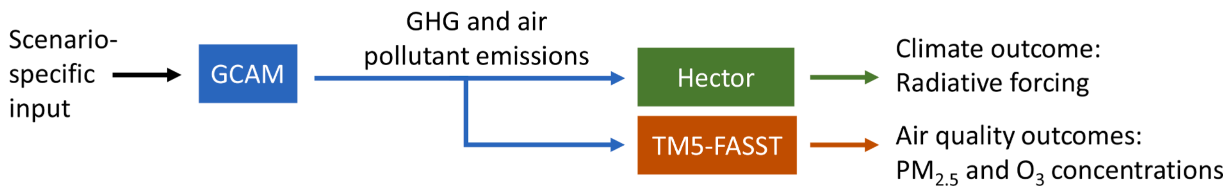

Fig. 1. Models used in this study and their linkages.

example, in the GHG_AP case, we combine the ambitious GHG and AP pathway assumptions with reference NG and EV pathway assumptions. These policy cases are compared to the reference case. We recognize that policy objectives overlap and real-world policies are not limited to the aspects we have included in our policy definitions here.

The AP dimension consists of assumptions in the electric power, transportation, industry, buildings and agriculture sectors regarding air pollutant emissions controls and other technology or fuel changes. As of 2020, progress towards meeting current emission limits for existing thermal power plants has been slow, with SO_2 and NO_x limits originally set for 2017 now pushed back to December 2022-2024. It is possible that many plants will also miss this deadline. For NO_x the original compliance limits for plants built in 2003-2017 were challenged in court and subsequently relaxed in August 2019. Furthermore, there remains a possibility that NO_X limits on plants built after 2017 could also be relaxed.

Given this context, in the reference AP pathway we assume that plants built through 2025 are retrofitted to meet the current regulatory limits (as of mid-2020) for SO_2 and NO_x by 2033 (see SI section S2.1.1), thereby assuming up to 11 years of delay, with plants thereafter built in compliance. For NO_x, the limit for new plants built after 2017 is set higher than the original policy standards, which assumes that these limits are also relaxed. The SO_2 limit for plants built after 2040 ratchets down to an "ultra-low" level (currently implemented in China). There is no analogous future strengthening of NO_x limits in the reference AP pathway.

In the ambitious AP pathway, all existing plants are assumed to meet their respective regulatory limits for SO_2 and NO_x by 2025 (up to 3 years of delay), and plants thereafter are built in compliance. For NO_x, the limit for new plants built after 2017 stays at the currently regulated (more stringent) value. For SO_2, the limit for plants built after 2010 is ratcheted down to the post-2017 SO_2 limit level by 2035 (these post-2010 vintage plants are assumed to be retrofitted). The SO_2 and NO_x limits are both assumed to ratchet down to "ultra-low" standards for plants built after 2035. Faster retirement of existing coal plants is also assumed.

In the transportation sector, the reference AP pathway assumes that emissions from new vehicles (two- and three-wheeler, passenger four-wheeler, and light- and heavy-duty trucks) are consistent with the Bharat Stage VI standards, which parallel the Euro 6 standards. The ambitious AP pathway assumes a faster phase-in of Bharat VI standards on various modes and improved compliance (see Table 1 and SI section S2.1.2). We note that we have assumed that emission standards are applied across the vehicle sector, but information on implementation is incomplete, particularly for freight transport.

In the industrial sector, the reference pathway assumes that emission factors for processes that utilize coal and refined liquids decrease by 2050. A more rapid decrease in emission factors is assumed in the ambitious AP pathway to reflect a greater focus on air pollution controls and industrial process modernization (see SI section S2.1.3). In addition, the ambitious AP pathway assumes a faster transition away from industrial biomass.

In the buildings sector, the reference AP pathway assumes that air pollutant emission reductions occur through both an increase in the use of improved cookstoves, represented by modest decreases in emission factors, and switching away from traditional biomass and coal in the residential and commercial sectors. These assumptions are intended to represent current government LPG subsidies and programs to increase rural electrification. The ambitious AP pathway assumes greater impact in both these dimensions (see SI section S2.1.4). Finally, we assume less agriculture waste burning on fields in the ambitious AP pathway, reflecting changing practices and policies.

The GHG dimension consists of assumptions about GHG pricing. There is no price on GHGs in the reference pathway, but India's current GHG emissions intensity **(Fig. S12)** and non-fossil electric capacity targets as part of its NDC are met in the reference pathway. In the ambitious GHG pathway, an economy-wide price is applied to all GHGs globally (to avoid emissions leakage effects across borders). This price path starts at 10 \$/tCO2e in 2025, rises to 20 \$/tCO_2e in 2030 and increases by 5% annually to 53 \$/tCO_2e in 2050, a level comparable to the price in the European ETS in 2021 [24] and considerably higher than India's coal tax, which is equivalent to ~3 \$/ton CO_2 (see SI section S2.2). For comparison, we also consider a high GHG price pathway, that reaches 184 \$/tCO2e in 2050. The high GHG price case is included to illustrate how air quality and climate outcomes respond to a higher GHG price level consistent with a global 2°C target.

As discussed in SI Section S2.3, India has had difficulty increasing natural gas consumption due to a combination of pricing policy and infrastructure constraints. In the reference NG pathway, total natural gas consumption is constrained to increase at a rate similar to recent historical trends. In the ambitious NG pathway, this constraint is eliminated after 2035 and NG consumption is determined by market competition.

India has established goals to manufacture and deploy higher numbers of EVs and has introduced subsidies for EVs and charging infrastructure. In addition, several states have enacted policies to promote the deployment of EVs. However, there is uncertainty as to whether these policies are sufficient to drive large-scale deployment of EVs (see SI Section S2.4). The EV dimension explores the implications of two EV deployment cases. The reference EV pathway reflects a market without any interventions to incentivize EVs, although EV costs are assumed to decline over time following recent global trends. The ambitious EV pathway assumes a set of technology and policy developments such that all new passenger vehicles sold by 2035 are electric and are at cost parity with internal combustion engine vehicles (ICEVs) by that point.

3. Results and discussion

3.1. Energy system and emissions trends

In this section, we examine energy system and emission results across the reference (REF) scenario and four main policy cases (GHG, AP, GHG_AP, and NG). We also note insights from the higher GHG price sensitivity case (GHG_hi) and the addition of expanded natural gas infrastructure on top of other main policies explored (GHG_NG, AP_NG, and GHG_AP_NG). With the exception of transportation final energy, our EV case has limited impacts on energy and environmental outcomes, and therefore, we show EV results in the SI (Figs. S19-S20).

3.1.1. Reference (REF) scenario

India's energy system is expected to grow significantly over the next

Table 1
Description of reference and ambitious pathways across the four scenario dimensions. Single policy cases are developed by combining the ambitious pathway specification for one dimension with the reference pathways in the other dimensions. Combination policies combine ambitious pathways in two or more dimensions with the reference pathways in the remaining dimensions. The reference case assumes the reference pathway in all four dimensions. Table S2 in the SI lists all cases and, for each case, indicates which dimensions use reference vs. ambitious assumptions.

	Reference Pathway	Ambitious Pathway
Air Pollution Emission Controls (AP)	Current emission reduction plans across the economy, with some amount of delay and incomplete implementation.	Greater levels of ambition across power, transportation, industry, buildings, and agriculture sectors.
Electric Power Generation	Existing plans are put largely into place, with up to 11 years of delay. NO_x standards weaker than 2015 regulations. Subsequent tightening of standards for SO_2 only.	Existing plans are put into place as planned, with up to 3 years of delay. NO_x standards consistent with 2015 regulations. Subsequent tightening of standards for both SO_2 and NO_x. Faster retirement of existing coal plants.
Transportation	New vehicles: 92% fully Bharat VI-compliant and 8% non-compliant starting in 2020 for passenger 4W and in 2025 for all other modes. Fuel sulfur is Bharat-VI compliant starting in 2020.	New vehicles: 97% fully Bharat VI-compliant and 3% non-compliant starting in 2020 for all modes. Fuel sulfur is Bharat-VI compliant starting in 2020.
Industry	Emission factors from coal and refined liquids start decreasing in 2030 (*e.g.,* coal BC EF declines by 54% from 2010 levels by 2050).	Emission factors from coal and refined liquids start decreasing in 2025 and achieve stronger control levels by 2050 (*e.g.,* coal BC EF declines by 70% from 2010 levels by 2050).
Buildings	Gradual phase out of traditional biomass (9% of buildings final energy in 2050). Slower uptake of improved biomass cookstoves (10% penetration in 2050).	Faster phase out of traditional biomass (4% of buildings final energy in 2050) along with faster uptake of LPG as cooking fuel. Faster uptake of improved biomass cookstoves (35% penetration in 2050). Faster phase out of residential and commercial coal.
Agriculture	37% relative decrease in agriculture waste burning by 2050.	60% relative decrease in agriculture waste burning by 2050.
Greenhouse Gas Emissions Pricing (GHG)	No price on any greenhouse gas emissions.	Price on all GHG emissions: 10 $/tCO_2e$ in 2025, 20 $/tCO_2e$ in 2030 and increasing by 5% annually to 53 $/tCO_2e$ in 2050. ***Higher sensitivity case (GHG_hi):*** Price on all GHG emissions: 5 $/tCO_2e$ in 2020 increasing linearly to 184 $/tCO_2e$ in 2050.
Natural Gas Infrastructure Expansion (NG)	Access to natural gas continues to be limited through 2050 with moderate growth in overall natural gas consumption.	Gradual relaxation of infrastructure constraint over time, with natural gas consumption unconstrained by infrastructure after 2035.
Passenger Vehicle Electrification (EV)	No constraints on vehicle choice.	No new sales of passenger ICEVs (two- and three-wheelers, light-duty vehicles, and buses) after 2035 (phased in).

several decades. Total primary energy in the REF scenario grows from 34 EJ in 2015 to 69 EJ in 2040 and 83 EJ in 2050 **(Fig. S18).** This growth in primary energy is lower than the growth in IEA WEO 2019's Current Policies Scenario (CPS), which projects 86 EJ of primary energy in 2040 [13], due largely to lower traditional biomass in residential buildings and lower oil in transportation in our projections. In comparison, Venkataraman et al. [32] project energy demand around 100 EJ for a scenario without regulations beyond 2015, 80 EJ for a scenario with promulgated regulations (by 2018) included, and 60 EJ for a scenario that includes ambitious regulations beyond those already promulgated, including a complete phase out of traditional biomass by 2050. Purohit et al. [21] project primary energy demand around 100 EJ by 2050. Our REF case fossil fuel and industrial process (FFI) CO_2 emissions grow from 2200 $MtCO_2$ in 2015 to 4700 $MtCO_2$ in 2040 and 5500 $MtCO_2$ in 2050 **(Fig. 3e)**. Emissions are slightly lower than those in IEA's CPS, which projects emissions of 5500 $MtCO_2$ in 2040.

Electricity generation grows around five-fold from 1400 TWh in 2015 to 6700 TWh in 2050 in the REF case **(Fig. 2a).** In 2040, electric generation is projected to be 5000 TWh, close to the 4600 TWh in WEO 2019's CPS [13]. Coal generation continues to dominate, which leads to increasing CO_2 emissions from this sector **(Fig. 3e)**, but other technologies, notably solar PV and wind, make up a larger share of total generation by 2050. Due to the timing of air pollution control installations, SO_2 and NO_x emissions both peak in 2020 before declining **(Fig. 4)**. Further ratcheting of SO_2 emission controls on new power plants to ultra-low standards results in a 72% decrease in electric SO_2 emissions from 2015 levels by 2050 **(Fig. 3a)**. Due to weaker long-term NO_x standards, electric NO_x emissions only decrease by 16% from 2015 levels by 2050 **(Fig. 3b)**.

Transportation sector energy consumption is small relative to other sectors, but it grows nearly three-fold from about 3 EJ in 2015 to about 8 EJ in 2050 in the REF case **(Fig. 2d)**. Despite the increase in transportation demand, transportation sector NO_x emissions decrease after 2030 due to most new vehicles complying with more stringent standards **(Fig. 3b).** Consequently, transportation NO_x emissions make up only 16% of total NO_x emissions in 2050.

In the industrial sector, final energy roughly triples from 11 EJ in 2015 to 35 EJ in 2050 in the REF case **(Fig. 2b)**. Electricity, coal, refined liquids and natural gas consumption expand, with coal making up a third of the total in 2050, leading to continued increase in CO_2 emissions **(Fig. 3e)**. The modest reference case SO_2 and NO_x controls for industry (see SI section S2.1.3) result in growing industrial emissions while electric power sector emissions decrease (albeit more modestly for NO_x). The net result is that total SO_2 and NO_x emissions in 2050 are only slightly lower than 2015 levels, by 26% and 11% respectively **(Fig. 3a and 3b; Fig. 4)**.

Final energy in buildings grows from about 9 EJ to 14 EJ in the REF case between 2015 and 2050 **(Fig. 2c)**. There is a significant expansion of modern energy technologies, with a seven-fold growth of electricity (in cooling and aggregated other loads) and a transition away from traditional biomass. Kerosene, which was widely used for residential lighting and a source of carbonaceous particulate matter – black carbon (BC) and organic matter (OM) – is phased out by 2020 consistent with the observed decline in kerosene from 1999 to 2017 ([12]; SI section S4.1). This is responsible for half of the reduction in BC emissions from buildings between 2015 and 2030 **(Fig. 3c)**, with the other half largely from traditional biomass phaseout. Most of the decline in BC emissions and nearly all of the decline in OM emissions between 2030 and 2050 is attributable to the assumed phase-out of biomass cookstoves, along with an assumed increase in efficiency in those that remain (see SI Section S2.1.4). Although traditional biomass plays a large role in the energy system today, it is projected to be less than 10% of building final energy by 2050, at which time total BC and OM emissions are 66% and 56% lower than their 2015 levels **(Fig. 3c and 3d)**. These reductions are considerably larger than the relative reductions in total SO_2 and NO_x emissions **(Fig. 4)**.

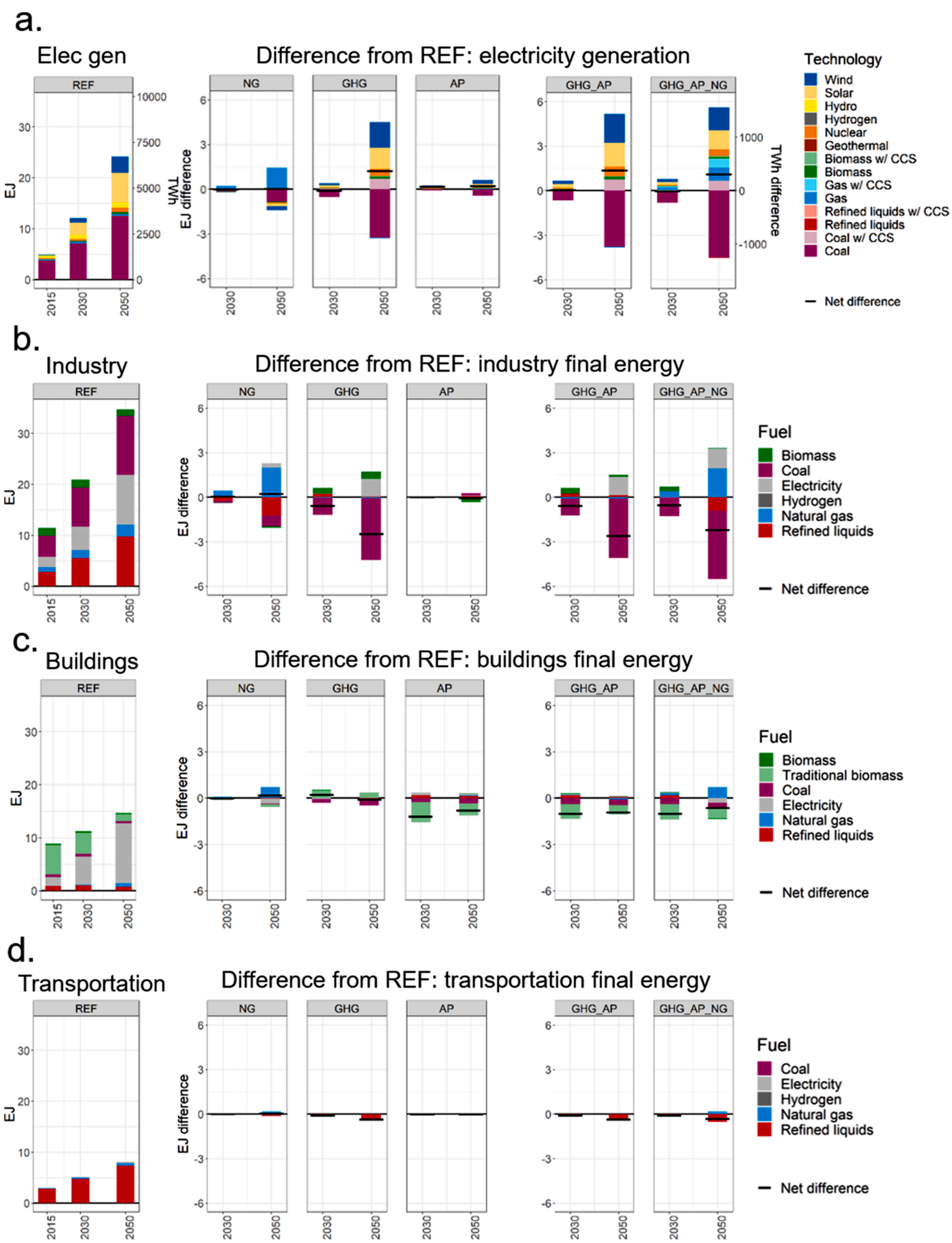

Fig. 2. (a) electricity generation; (b) industry final energy; (c) buildings final energy; (d) transportation final energy by technology/fuel. The left panel in each graph shows the growth in the reference (REF) scenario between 2015 and 2050. The middle set of panels show the difference between the indicated scenario for three single policy cases (NG, GHG, AP) and REF (Scenario - REF) in 2030 and 2050. The right set of panels show the difference for two of the combined cases (GHG_AP and GHG_AP_NG).

Some of the trends in air pollution emissions in our REF case have been observed in other studies. For example, in a scenario with current (as of 2018) air pollution policies, Purohit et al. [21] find that SO_2 emissions are 15% lower in 2050 than 2015 levels, while NO_x emissions are 31% higher in 2050 than 2015 levels. These trends are due largely to increasing industrial emissions (for both SO_2 and NO_x) and roughly flat electric NO_x emissions. Purohit et al. also find that policies in the residential sector can deliver large decreases in PM emissions, but that increasing industrial PM emissions could counteract this reduction (see SI section S2.1 for discussion of PM vs. BC and OM emissions). Venkataraman et al. [32] find that under current and promulgated policies, overall air quality further deteriorates by 2030 and 2050. In contrast,

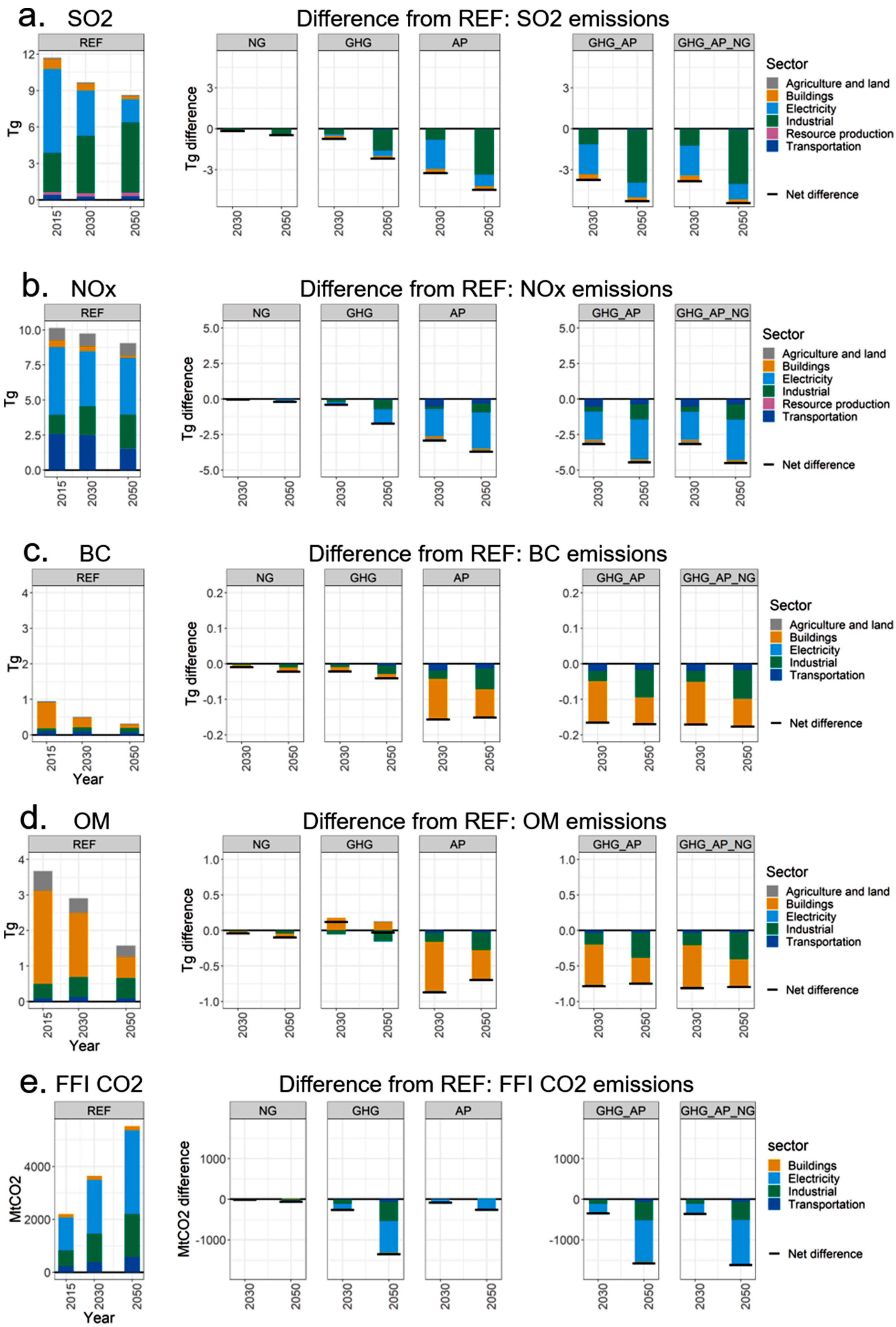

Fig. 3. Emissions of (a) SO_2, (b) NO_x, (c) BC, (d) OM (e) and CO_2 from fossil fuel combustion and industrial processes (FFI) by sector. The left panel in each graph shows the growth in the reference (REF) scenario between 2015 and 2050. The middle set of panels show the difference between the indicated scenario for three single policy cases (NG, GHG, AP) and REF (Scenario - REF) in 2030 and 2050. The right set of panels show the difference for two of the combined cases (GHG_AP and GHG_AP_NG). Sectoral definitions are given in SI Table S1. OM is defined as 1.3*non-biomass OC + 1.8*biomass OC, in line with the definition in [16].

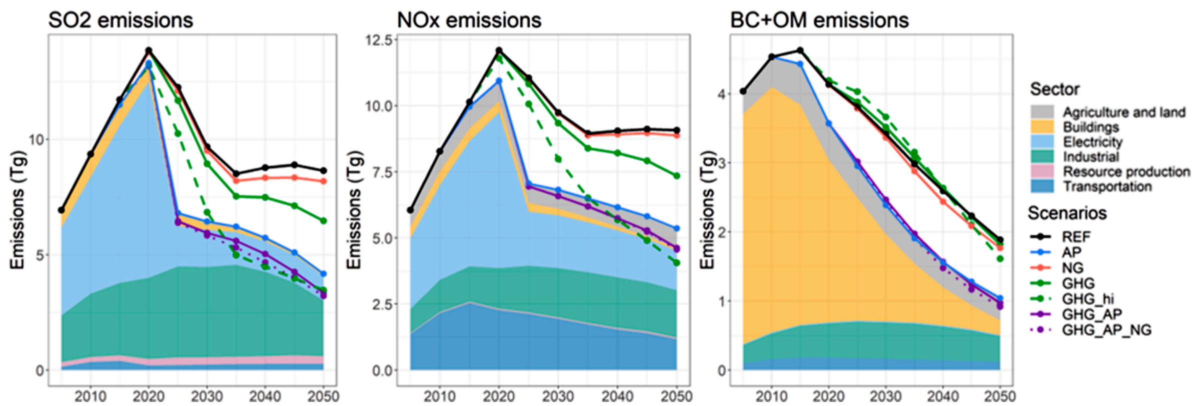

Fig. 4. Panels show, from left-to-right, SO_2, NO_x, and BC+OM emissions for the REF, AP, NG, GHG, GHG_AP and GHG_hi scenarios from 2005 to 2050. Shaded area shows the sectoral breakdown of emissions in the AP case. See Fig. S23 for sectoral breakdown of emissions in the REF case. Sectoral definitions are identical to Fig. 3. BC+OM is calculated as BC + 1.3*non-biomass OC + 1.8*biomass OC, in line with the definition in [16].

our REF scenario projects improving air quality by 2050 because we account for policy actions beyond those currently promulgated, assuming a continuation of recent trends.

3.1.2. Ambitious air pollution emission controls (AP)

In the AP case, by 2050, there is a 64% reduction in SO_2 emissions and a 46% reduction in NO_x emissions from 2015 levels (Fig. 4), larger than the REF reductions in all periods (**Fig. 3a and 3b**). The greatest differences are in 2025, largely because current power sector regulatory limits and compliance timelines are assumed to be followed without significant delay. In the AP case, industrial NO_x emissions peak around 2040 and industrial SO_2 emissions fall below 2015 levels by 2050, resulting in deeper reductions across sectors compared to REF. CO_2 emissions decline by 260 $MtCO_2$ in the AP case relative to REF due to faster coal plant retirement (**Fig. 3e**).

BC and OM emissions in the AP case are 45% and 44% lower than in the REF case in 2050, largely driven by reductions in the industrial and buildings sectors (**Fig. 3c and 3d**). The AP case has the largest impact on the buildings sector of all the single policy cases. In the residential sector, greater deployment of clean cooking fuels in the AP case leads to additional substitution of LPG for traditional biomass compared to the REF case in all periods **(Fig. S15).** In the commercial buildings sector, there is additional substitution of electricity for coal compared to REF **(Fig. S16)**. The aggregate effects of residential and commercial building fuel shifts are shown in **Fig. 2c.** In the industrial sector there is a shift away from highly polluting biomass and coal-fueled informal industries towards cleaner technologies (e.g., coal boilers with lower emission factors; see **Fig. S1-2**; **Fig. 3a-d**).

3.1.3. Greenhouse gas emissions pricing (GHG)

The largest changes in the GHG case occur in the electric power and industrial sectors because of the large shares of coal in these sectors that become less economic as the GHG price rises. CO_2 emissions decline by 1400 $MtCO_2$ relative to REF by 2050, mostly in the power and industrial sectors (**Fig. 3e).** In the power sector, solar PV, wind, nuclear, and CCS technologies together displace 26% of the REF case coal generation in 2050, with the largest share coming from wind and solar PV (**Fig. 2a).** There is also a net increase in electricity generation from increased electrification in the industrial sector compared to the REF case in 2050 (**Fig. 2b**). These industrial and electric power sector responses result in 45% and 28% lower SO_2 and NO_x emissions, respectively, by 2050 relative to 2015. These reductions are smaller than in the AP case (**Fig. 4**). When the GHG price is considerably higher (GHG_hi), there is more reduction of SO_2 and NO_x emissions than in the AP case **(Fig. S23),** due to the much higher phase-out of coal.

With an economy-wide price on GHGs, industrial and residential traditional biomass usage does not decrease as quickly relative to REF because biomass is assumed to be CO_2-neutral and is therefore less costly relative to other fuels whose delivered prices increase under a GHG price (**Fig. 2b; Fig. S15;** net building effects in **Fig. 2c**). In the industrial sector, this implies a slower transition out of biomass-fueled informal industries. In the residential sector, there is a slower transition out of traditional biomass for cooking and less uptake of LPG, coal, and electricity. This leads to higher residential OM emissions relative to REF in 2030 (**Fig. 3d**), which is offset over time by decreases in industrial OM emissions from coal use. These changes in OM emissions in the GHG case are robust to the level of the GHG price **(Fig. S22)**, suggesting that an idealized GHG policy, if not combined with other policies or actions, could slow access to modern energy and exacerbate air pollution in some sectors [23].

3.1.4. Combined AP and GHG policies (GHG_AP)

The energy system responses in the GHG_AP case are largely additive from those seen in the GHG and AP cases individually. In the power sector, 31% of REF case coal generation in 2050 is displaced by renewables and CCS technologies (**Fig. 2a),** due to both faster coal retirement under an ambitious air pollution control policy and coal becoming less economic under a GHG price. In the industrial sector, there is increased electrification and coal phase out compared to REF due to the GHG price. There is more phase out of industrial biomass in 2050 compared to the GHG case due to ambitious air pollution emission controls (**Fig. 2b**).

In the buildings sector, the GHG and AP cases individually have opposite responses in the rate of traditional biomass phase out compared to REF (**Fig. 2c**). However, because the GHG response is economic, while the AP response is due to policy assumptions, when combined, nearly all of the accelerated phase-out of traditional biomass observed in the AP case still occurs (**Fig. 2c**). As a result, OM emissions are 49% lower under GHG_AP compared to REF (**Fig. 3d**). This suggests that combining a GHG price with policies that result in households switching to cleaner, modern energy forms (as assumed in the AP case) can reduce the air pollutant "rebound" effect of increased traditional biomass use under an economy-wide GHG price.

The SO_2 and NOx reductions in the GHG_AP case are 71% and 54% lower than 2015 levels in 2050 (**Fig. 3a and b**), larger than the reductions in both the AP and GHG cases individually. CO_2 emissions decline by 1600 $MtCO_2$ relative to REF by 2050, slightly larger than reductions in the GHG case. Meanwhile, BC emissions reductions relative to REF are similar to those in the AP case (**Fig. 3c**). This is because of overlap between both AP and GHG policies in reducing industrial coal emissions (see further discussion of overlap in section 3.2).

3.1.5. Natural gas infrastructure expansion (NG)

The NG case leads to greater natural gas consumption, displacing future expansion of other fuels roughly in proportion to their REF case use. This displacement is initially small, growing larger by 2050, as the constraint on natural gas infrastructure is relaxed. Natural gas displaces about 6% of electricity generation from other sources and about 4% of final energy from other fuels in the end use sectors in 2050 relative to the REF case, although there is minimal change in transport (Fig. 2; **Fig. S17**). In addition, there is a slight increase in electricity consumption in the industrial sector resulting from lower electricity prices, a consequence of more abundant natural gas and decreased electricity demand in buildings.

India's currently stated goal of 15% natural gas in the primary energy mix by 2030 is not fully realized in the NG case, due to a combination of near-term constraints and continued long-term competition with other fuels and technologies. The share is projected to be 7.5% by 2030 and 13% by 2050 (see SI section S2.3, **Fig. S13**). CO_2 emissions decline by 59 $MtCO_2$ in the NG case relative to the REF case in 2050, smaller than in either the GHG or AP case (Fig. 3**e**) because natural gas displaces both higher- and lower-emitting fuels. Similarly, reductions in air pollutant emissions relative to REF in the NG case are much smaller than in the AP and GHG cases (Fig. 4) and the net radiative forcing relative to REF is negligible (Fig. 5), findings consistent with the multi-model study of McJeon et. al. [17].

The addition of expanded natural gas infrastructure on top of other policies, as in the GHG_AP_NG shows an additive energy system response, in that more natural gas substitutes for other fuels present under GHG_AP (Fig. 2). We note that gas CCS is deployed in the GHG_AP_NG case because we allow gas CCS as a technology when there is expanded natural gas infrastructure, and it becomes economic under a GHG price. Despite the differences in energy system trends, the climate and air quality outcomes are similar with and without expanded natural gas infrastructure, as seen in Fig. 6, comparing AP_NG, GHG_NG, and GHG_AP_NG to their counterparts without NG. This suggests alternative routes to the same environmental outcomes. Although we do not estimate the costs of the policies considered here, other studies have shown that abundant natural gas can lower the cost of climate policy [10, 34].

3.2. Climate and air quality outcomes

We now examine how two of the key metrics, population-weighted average $PM_{2.5}$ concentrations (from TM5-FASST) and radiative forcing (from Hector), change relative to the REF case under AP, GHG and combined GHG_AP policies, as well as under the high GHG price sensitivity (GHG_hi and GHG_hi_AP) (Fig. 6). Among single policy dimensions, AP and GHG cases each result in the largest changes by 2050 relative to REF along their primary policy dimension. However, they differ in the extent to which they support or impede other policy objectives.

While reducing $PM_{2.5}$ concentrations, the AP case (filled blue circle) leads to an increase in radiative forcing relative to REF. As a result of the decrease in SO_2, BC and OM emissions, the population-weighted average $PM_{2.5}$ concentration is reduced by 26% (6.3 μg/m^3) relative to the REF case by 2050. Net radiative forcing increases relative to REF by 2050 due to reductions in cooling aerosols driven by lower SO_2 emissions, and to lesser extent, lower OM emissions (**Fig. 5**). This forcing increase is partially offset by reductions in forcing from BC, tropospheric O_3 (due to lower NO_X emissions) and, to a lesser extent, CO_2, by 2050. In general, surface ozone responses are similar to those of $PM_{2.5}$ and are discussed in SI Section S6.

On the other hand, the GHG cases (green circles) simultaneously reduce 2050 radiative forcing and $PM_{2.5}$ concentrations relative to REF. Net reductions in radiative forcing are predominantly due to the reduction in CO_2 emissions from reductions in coal use (**Fig. 5**). These decreases are partially offset by increases in radiative forcing due to SO_2 emission reductions. In 2030, the change in net radiative forcing is close to zero, but by 2050, there is a net reduction in radiative forcing, as CO_2 reductions eventually dominate **(Fig. S25).** The higher GHG price sensitivity case (GHG_hi, open green circle) leads to greater CO_2 reductions and consequently larger decreases in net radiative forcing relative to REF by 2050.

The base GHG price case (filled green circle) reduces population-weighted $PM_{2.5}$ concentrations by 10% (2.4 μg/m^3) compared to the

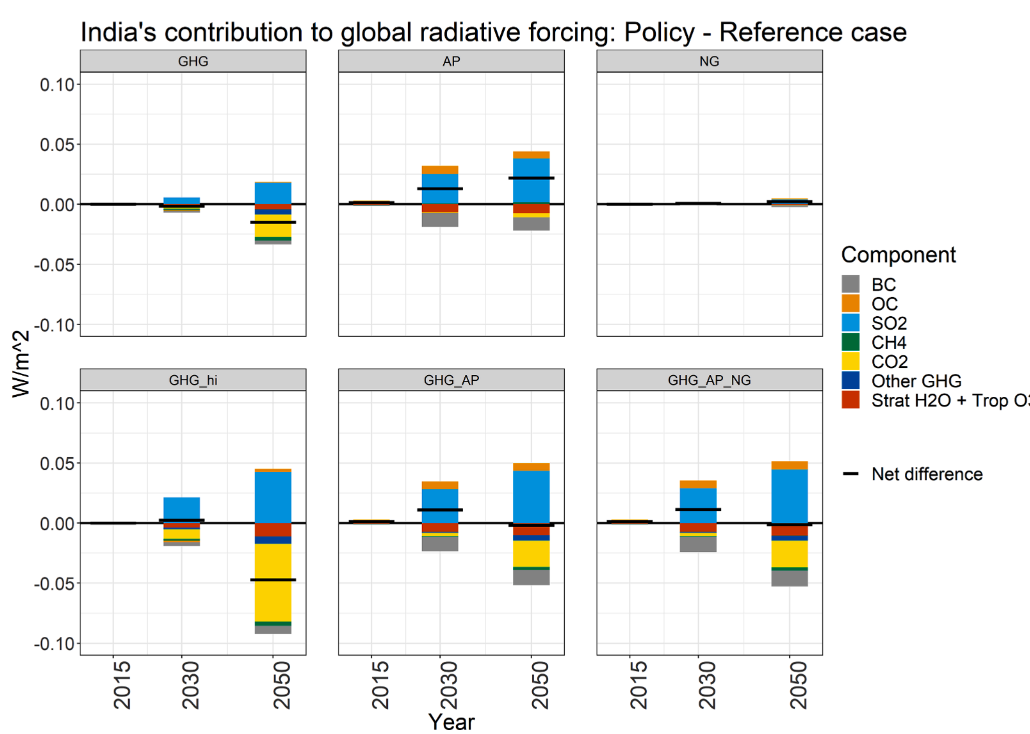

Fig. 5. India's contribution to global radiative forcing in 2050, expressed as changes from the reference case (REF) in the GHG, AP, NG, GHG_hi, GHG_AP, and GHG_AP_NG scenarios, estimated by running the Hector simple climate model with only India emissions changed for each case. OC indicates forcing by anthropogenic primary OM emissions.

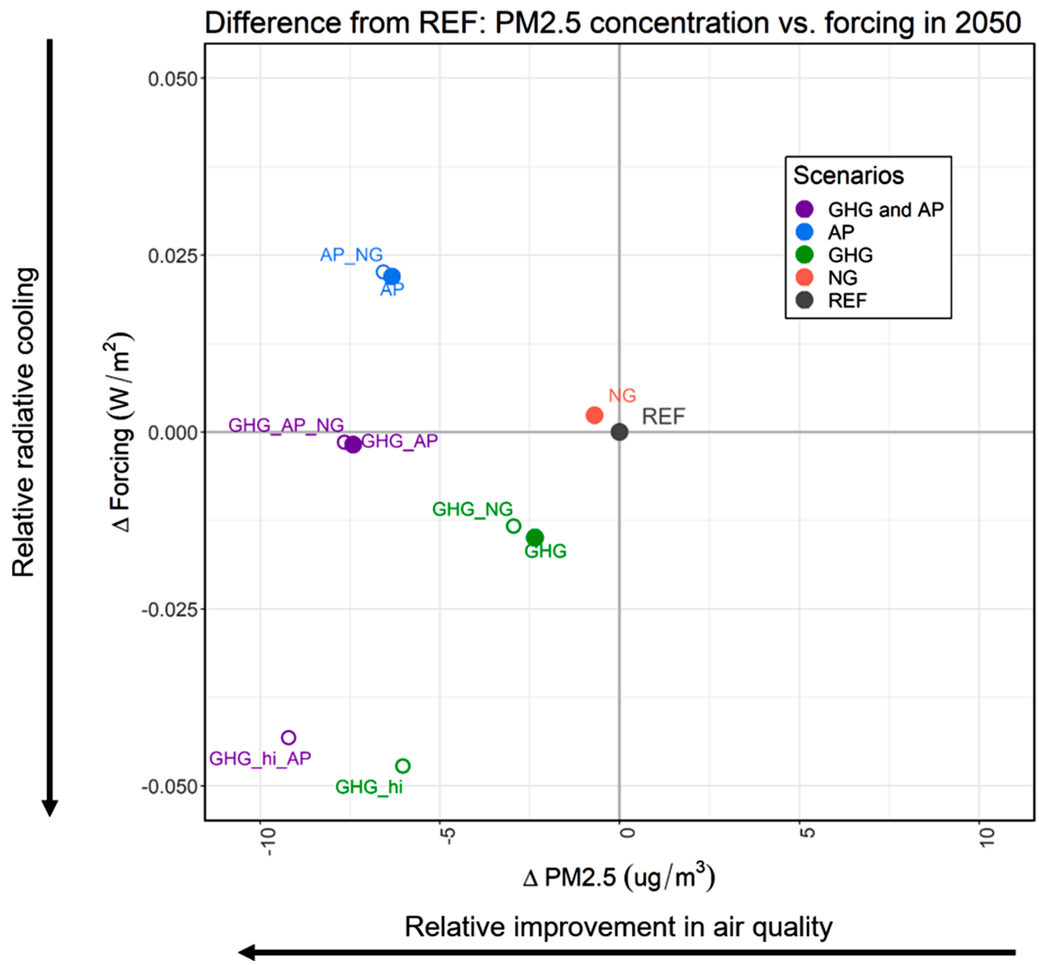

Fig. 6. Population-weighted average PM 2.5 concentration (primary + secondary) in India (μg/m^3) vs. India's contribution to global radiative forcing (W/m^2) in 2050. Both are expressed as changes from the reference case (REF). Results are shown for GHG, AP, NG, and GHG_AP as filled circles and for sensitivity cases with the addition of NG or a higher GHG price onto a base scenario as open circles.

REF case. This is less $PM_{2.5}$ reduction than in the AP case, while the higher GHG price case leads to a $PM_{2.5}$ reduction that is closer to the AP case (and a higher level of O_3 reduction, **Fig. S27**). This suggests that a stringent GHG policy can deliver air quality outcomes comparable to those resulting from policies targeting air quality directly, consistent with other findings in the literature [21, 23, 33].

Combining AP and GHG together (GHG_AP, filled purple circle) leads to more $PM_{2.5}$ reduction relative to REF than either the GHG or AP case alone in 2050. $PM_{2.5}$ reductions in the GHG_AP case are only 15% smaller than the sum of the $PM_{2.5}$ reductions in the GHG and AP cases separately. This indicates that there is only a small overlap in the effects of these two policy cases because these reductions largely occur in different sectors and fuels. In the GHG case, net $PM_{2.5}$ reduction occurs largely through decreased industrial coal use. In the AP case, $PM_{2.5}$ reductions occur largely through phase-out of traditional biomass cooking fuels and informal industries, as well as SO_2 emission controls in industry. The small overlap occurs because AP and GHG cases both reduce industrial coal emissions relative to the REF case by 2050 (**Fig. 3a, c, d**), either by moving to formal industries and adding controls (AP) or fuel switching (GHG). When fuel switching occurs, there is less remaining coal to which controls can be added. The same is true to a lesser extent in the power sector. As the GHG price increases, there is more overlap in $PM_{2.5}$ reductions between the GHG and the AP cases (less difference between GHG_hi_AP and GHG_hi than GHG_AP and GHG along the x-axis in Fig. 6). With higher GHG prices, the impact of air pollution controls declines as more coal is removed from the system for climate mitigation.

Interactions between policies also affect climate forcing outcomes. In 2050, the forcing increase relative to REF for the AP case is mitigated when AP and GHG are applied together (GHG_AP) as SO_2 forcing increases are offset by GHG forcing decreases (**Fig. 5; Fig. S25).** The stringency of the GHG price determines the net change in forcing. Under the high GHG price case, forcing in 2050 is not significantly impacted by additional air pollution controls (GHG_hi vs. GHG_hi_AP) because most new coal consumption in 2050 is from plants with CCS, which have intrinsically low SO_2 emissions, meaning fewer emissions that would be impacted by air pollution controls.

In addition to the differences in 2050, there are significant differences in the time paths of radiative forcing (**Fig. S26**), with air pollution assumptions having a dominant effect out to at least 2030. This result follows in part from the assumption that AP emission controls are applied in the near term, whereas fuel switching occurs more slowly in the GHG case. In addition, there are differences in the responses of the relevant physical systems (air pollution concentrations immediately respond to emissions, whereas forcing also depends on GHG concentrations, which are mediated by biogeochemical cycles).

4. Conclusions

This study has examined the energy and environmental implications of different potential policy and infrastructure pathways related to India's air quality, sustainable development and climate change mitigation goals. We find that future SO_2 and NO_x emissions mostly depend on the pace at which emission controls in the electric and industrial sectors are implemented. A continuation of current policies and trends (REF case), including slower implementation in the power sector, and lack of stringent controls in the industrial sector, would limit the extent to which SO_2 and NO_x emissions drop much below 2015 levels by 2050. However, more ambitious air pollution controls (AP case) could reduce SO_2 and NO_x emissions below even 2010 levels. In the buildings sector, efforts to improve modern energy access and therefore decrease the use of traditional fuels (as assumed in the REF case) could greatly reduce BC and OM emissions well below recent levels, thereby improving household air quality [7] although potentially at the expense of increasing CO_2 emissions.

Among single policy interventions considered, expanded natural gas infrastructure and comprehensive GHG price cases (GHG) result in the largest energy system (fuel and technology) changes, although air pollution (AP) and electric vehicle cases have significant changes in specific sectors. Air pollution control policy and GHG pricing lead to the greatest reductions in air pollution emissions and radiative forcing, respectively, with the magnitude of forcing reduction varying with the GHG price. An air pollution control policy in isolation increases radiative forcing due to a reduction in SO_2 emissions. Similarly, an idealized GHG policy, if not combined with other policies or actions, could slow access to modern energy (by raising delivered energy prices), which could increase air pollution emissions from some sectors.

These forcing and air quality tradeoffs can be mitigated by combining air pollution control and GHG policies together. Furthermore, combining AP and GHG together achieves more $PM_{2.5}$ reduction relative to REF than either policy alone, because reductions largely occur in different sectors and fuels. There is a small overlap due to coal removal under both policies. There is less impact from ambitious air pollution controls when there is a very stringent GHG price as coal consumption drops in response to the GHG price. This suggests that carefully combining GHG and air pollution control policies will be important for improving India's air quality while also reducing GHG emissions.

Passenger vehicle electrification and natural gas infrastructure expansion have smaller impacts on air quality and climate than the other policies considered. In contrast to regions like the EU or the US, India has a much lower share of transport in final energy. We find, therefore, that policies targeting end uses other than transportation can have a larger impact.

There are several important caveats to consider when interpreting results from this study. First, results from a forward-looking modeling study such as this one depend on the quality of the initial energy and environmental data, which in some cases, is sparse or not robust across sources. Second, this study did not take into account effects of the COVID-19 pandemic, which may have a large impact on energy and environmental trends across sectors in the near term but is unlikely to change the types of long-term trends and interactions examined in this paper. Third, in a rapidly growing economy, different assumptions about projected growth rates in key sectors, which are also quite uncertain, can lead to material differences in outcomes by 2050. For this reason, this study has focused on differences between policy cases and a plausible reference case to illustrate the potential direction and magnitude of change associated with particular policy interventions, recognizing the reference case itself is subject to significant uncertainty. Fourth, we do not consider the relative costs of implementing each policy intervention, so cannot evaluate the costs of any particular policy measure or combination of measures.

Finally, this study has examined the Indian energy system at a broad sectoral level in order to consider a wide range of potential policy actions and to highlight interactions across sectors. However, GCAM does not provide information about sub-national outcomes and more detailed sectoral models are likely to provide additional insights. Similarly, TM5-FASST is a source-receptor model, not a spatially-explicit atmospheric chemistry and transport model and, therefore, does not represent non-linear interactions such as sulfur/nitrogen aerosol formation tradeoffs [2, 6, 26, 31] or non-linear responses of ozone to changes in precursor compounds. As such, results from this study could be used to inform more detailed analysis of particular policies, sectors or regions within India using more focused modeling tools.

The findings from this study, along with the known limitations stated above, indicate several possible directions for future work. Improved historical energy and emissions data, with greater sectoral and regional resolution, would provide a stronger basis for future projections. Alternative projections for growth in key sectors could be used to examine the sensitivity to the reference pathway assumptions. Greater detail in key sectors, such as buildings (rural versus urban, and disaggregation of lighting, air-conditioning and cooking services) or industry (greater disaggregation of industrial sub-sectors), or further sub-national disaggregation would provide a more granular picture of possible responses. Coupling more disaggregated information to highly resolved atmospheric chemistry and transport models could enhance understanding about air quality outcomes in regions most likely to be affected by air pollution and thus by policies that control air pollution.

Data statement

GCAM version 5.2 is publicly available at https://github.com/JGCRI/gcam-core/releases/tag/gcam-v5.2. The input files necessary to fully replicate these results are available at https://doi.org/10.5281/zenodo.4477861.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2021.100067.

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