The Effects on Well-being of Investing in Cleaner Air in India

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ABSTRACT: Over the past decade, India has experienced rapid economic growth along with increases in air pollution and consequent serious health effects. We examine how policies for air pollution abatement affect well-being in this context by calibrating an overlapping-generations model of economic growth to the Indian experience from 1971 to 2001 and estimating the effects of policy alternatives on measures of wellbeing for the period from 2010 to 2030. In particular, we focus on the effect of policies to reduce ambient fine particulates ($PM_{2.5}$)—which are especially harmful to human health—on growth of the Gross Domestic Product (GDP), the number of deaths, and the human development index (HDI). Our model allows improvements in health to affect economic growth by: (1) decreasing the number of deaths, and therefore changing population age structure; (2) decreasing the number of days of work lost due to illness; and (3) changing the age pattern of personal savings. We consider two scenarios of $PM_{2.5}$ abatement, roughly corresponding to current Indian and European legislation. The net effect in both cases is that GDP growth is virtually unaffected, the number of deaths is reduced, and the HDI is higher. In India, air pollution abatement investments increase well-being.

1. Introduction

Costs of environmental measures, such as those of reducing air pollution, are often seen as an impediment to economic development. This common perception emerges from a narrow focus on the direct costs of mitigation measures. Since these expenditures do not contribute to the value of newly produced goods and services that are traded in markets, they are not counted in gross domestic product (GDP), which, on a per capita basis, is often used as a surrogate for development and even well-being.

However, it is often overlooked that investments in cleaner air also have indirect impacts on economic performance. Lower morbidity due to better air quality will reduce the number of sick days experienced by the working population, and thereby increase productivity.[1] Lower mortality will extend life expectancy, and people who expect to live longer will, in general, accumulate more assets in their working years, thereby increasing capital formation for productive investments.[2–5] Once such indirect effects of investments in cleaner air are taken into account, it is no longer obvious how spending to reduce air pollution will affect GDP.

Moreover, GDP per capita fails to capture other important aspects of well-being, such as health. We develop a more comprehensive perspective to assess the consequences of investments in cleaner air on economic development and human well-being. In particular, we quantify the impacts of such investments on the UN's Human Development Index (HDI),[6] a widely-used metric which combines per capita GDP, longevity and education as three important dimensions of human development. We note that while the HDI improves upon narrow measures of well-being, it still does not tell the whole story. For example, surveys suggest that cleaner air is considered an improvement in the quality of life,[7–9] a source of well-being improvement not considered here.

Our case study focuses on measures to reduce the negative health effects of exposure to fine particulate matter ($PM_{2.5}$) in India. $PM_{2.5}$ comprises particles with an aerodynamic diameter of less than 2.5 microns, which travel far down into the lungs and contribute to a wide variety of ailments, including cardiovascular diseases, vascular inflammation, asthma, lung cancer, atherosclerosis, COPD, emphysema, and chronic bronchitis.[10,11] A wide body of studies demonstrates that these health effects are significant in both industrialized and developing countries.[12–14] For example, about one-third of the increase in life expectancy in US cities between 1980 and 2000 has been attributed to a decline in $PM_{2.5}$ levels;[12] in 2005, outdoor air pollution resulted in an estimated 2.7 million premature deaths worldwide.[15]

We focus on India because of its high and rapidly increasing levels of $PM_{2.5}$ pollution[16,17] and the exceedingly large population at risk. According to our model results, the average person in India is exposed to an annual average concentration of 46 $\mu g/m^3$ of $PM_{2.5}$ from anthropogenic sources,[18] which, when added to an estimated background value of about 7 $\mu g/m^3$ from natural sources, is more than 5 times the World Health Organization (WHO) guideline, which represents the lower end of the range over which significant effects on survival are observed.[11,13] These model-estimated overall concentrations correspond with the latest measured results.[19] In our baseline scenario that considers the envisaged growth in energy consumption without additional air pollution control measures (see Table 4 below), the average concentration of anthropogenic $PM_{2.5}$ will rise to an astounding 116 $\mu g/m^3$ in 2030. This level of pollution would be likely to substantially increase death rates over those that would be observed were the already-high 2010 concentration of $PM_{2.5}$ to be maintained. There would also certainly be significant increases in $PM_{2.5}$-induced morbidity.

Another reason to focus on India is because, given its relatively low economic development status, it faces significant perceived tradeoffs in implementing pollution abatement policies which might be expensive, yet could result in large increases in health and life expectancy and reductions in the burden of disease.[20] A better understanding of the true costs and benefits involved, with respect both to macroeconomics and human well-being, should help inform policy choices in this important context. The goals of this paper are therefore to quantify the likely effects of various policies to reduce ambient $PM_{2.5}$ concentrations resulting from anthropogenic sources and to assess the overall contribution of these policies to well-being. Rapid economic growth and the associated rapid increase of damaging ambient $PM_{2.5}$ makes this determination especially germane at this time.

Section 2 describes our methodology. Section 3 specifies air pollution control scenarios and presents forecast costs and associated ambient $PM_{2.5}$ levels. Section 4 discusses the results for each scenario with respect to components of the HDI. The concluding section examines the limitations of the analysis and presents possible further work.

2. Methodology

Central to our analysis is the linkage of two models that address key aspects of development and human well-being. We employ the Greenhouse Gas – Air Pollution Interactions and Synergies (GAINS) model for Asia[21–23] to estimate current and future emissions of air pollutants in India and their impacts on ambient $PM_{2.5}$ concentrations, as well as the costs of different emission control scenarios. This information is then used in the Simple Economic Demographic Interaction Model (SEDIM)[24,25] to estimate the macro-economic impacts of these investments and to specify how they affect the components of HDI.

2.1 The GAINS model

Our assessment of future levels of precursor emissions of $PM_{2.5}$, abatement costs and ambient $PM_{2.5}$ concentrations are derived from the GAINS model. For this paper, we employ the fuel use and industrial production projections of the World Energy Outlook 2009[16] as an exogenous input to GAINS. For these activity data, GAINS estimates current and future emissions based on emission factors and the extent to which dedicated emission control measures are applied as follows:

$$E_{i,p} = \sum_k A_{i,k} \sum_m x_{i,k,m,p} ef_{i,k,m,p}$$

$$\sum_m x_{i,k,m,p} = 1$$

where *i, k, m, p* stand for Indian states, activity type (production technology), abatement technology, and precursor pollutant, respectively. The analysis considers emissions of primary $PM_{2.5}$, SO_2, NO_x and NH_3 as relevant precursors for ambient atmospheric $PM_{2.5}$. It considers a number of possible emission abatement measures, e.g., for large-scale power stations these include coal cleaning, limestone injection, and various kinds of flue gas desulfurization in addition to a no-control case. $x_{i,k,m,p}$ represents the share of the activity of type k in state i that uses pollution abatement m for pollutant p. Major differences in emission characteristics of specific sectors and fuels are reflected through source-specific emission factors ($ef_{i,k,m,p}$). The database has been extensively verified together with national experts and the emissions model reproduces nationally reported emissions with substantial accuracy.[19]

Based on the detailed sectoral emission inventory described in the previous paragraph, GAINS computes fields of ambient concentrations of $PM_{2.5}$ across India with the help of source-receptor relationships derived from the global chemistry transport model TM5.[26] The TM5 model takes into account the spatial allocation of emissions, weather conditions, and the chemical transformation of precursors, and calculates ambient concentrations of $PM_{2.5}$, which result from (i) primary particulate matter released from anthropogenic sources, (ii) secondary inorganic aerosols formed from anthropogenic emissions of SO_2, NO_x and NH_3, and (iii) particulate matter from natural sources (soil dust, sea salt, biogenic sources).

The mitigation potential for the precursor emissions assessed in this analysis refers to the application of technologies that are currently commercially available on the world market. Each technology, as represented by the *ef* coefficients above, is associated with specific investment and running costs. The principle used to calculate unit costs in GAINS is documented elsewhere.[27–29]

In this paper, we limit our analysis to technical end-of pipe measures, and exclude non-technical mitigation options that involve changes in human behavior and preferences (e.g., using a bus instead of a car). We consider uniform application of additional emission control measures throughout India, and thereby ignore the cost-saving potential from spatially optimized emission control strategies, which could achieve the same environmental benefits at substantially lower costs.[22]

2.2 The SEDIM model

SEDIM is a relatively simple single-sector macroeconomic model that includes realistic demography. In SEDIM, there are three proximate sources of economic growth: growth of the labor force, adjusted for age and educational composition (L_t); growth of the capital stock (K_t); and the growth rate of productivity (A_t). All other factors that influence economic growth—including the impacts of air pollution controls and involved costs—must do so through their effects on one of these.

The structure of the SEDIM model has been presented in prior work.[24,25] Here we discuss only those aspects that are relevant to studying the costs and benefits of $PM_{2.5}$ reductions.

2.2.1 Labor force (L_t)

In SEDIM, the age and educational structure of the labor force are explicitly accounted for. This property makes the model especially pertinent to our research question, since $PM_{2.5}$ reductions affect mortality rates and therefore the age structure of the aggregate and working-age populations. Reductions in population exposure to $PM_{2.5}$ also reduce sick days, thus increasing labor productivity.

2.2.2 Capital stock (K_t)

Variation in exposure to ambient $PM_{2.5}$ affects mortality and morbidity rates. In SEDIM the resulting differences in life expectancy change people's saving decisions and, therefore, the rate at which K_t is accumulated. SEDIM distinguishes between two kinds of capital holders: life-cycle savers and non-life-cycle savers. The first group saves in order to smooth their consumption over their lifetimes. The second group does not, and is predominantly comprised of wealthy individuals, companies, and the government. The saving behavior of life-cycle savers is influenced by their remaining life expectancies and, thus, by policies to reduce $PM_{2.5}$.

2.2.3 *Productivity (A_t)*

The specification of total factor productivity in SEDIM allows countries to approach or recede from their productivity potential. Important variables in the total factor productivity function are the current distance from the productivity potential—the further behind, the faster the convergence—the lagged rate of capital formation, the age and educational structure of the working-age population, the openness of the economy to international trade, and institutional quality variables.

Reductions of ambient $PM_{2.5}$ levels affect the rate of capital formation and the age and educational structure of the population, and, therefore, the rate of total factor productivity growth. Faster growth affects the difference between current total factor productivity and the conditional productivity frontier, and thus future rates of total factor productivity growth.

2.3 Linking GAINS and SEDIM

The GAINS model allows for the application of different levels of emission controls and calculation of resultant emissions, $PM_{2.5}$ concentrations and costs. Using this information as an input, the corresponding macroeconomic effects can be calculated in SEDIM.

2.3.1 Mortality and $PM_{2.5}$

We follow the American Cancer Society's cohort study[13] and re-analysis[12] and specify that the age-specific risk of dying for adults is related to the level of $PM_{2.5}$ as follows:

$$dr^{scen} = dr^{base}(1 + \gamma PM_{2.5}^{scen}) \quad ,$$

where dr^{scen} is the death rate in one of our scenarios, dr^{base} refers to the baseline death rate, and γ is the sensitivity of the death rate to future changes in the level of $PM_{2.5}$. In the baseline, we employ the UN death rates forecasted for India, which implicitly incorporate the effects of $PM_{2.5}$ emissions from non-anthropogenic sources.

In developed countries, where both mortality in general and ambient $PM_{2.5}$ levels are much lower than in India, a 10 $\mu g/m^3$ increase in the concentration of this pollutant has been found to increase relative risk of mortality in adults by 4-6 percent.[13] We adopt the lower—conservative—figure, which has a smaller effect on well-being. The equation above is applied, by single-year age groups, to the population 30 years and older, starting in 2011. Since there are no data for the effects of $PM_{2.5}$ on child mortality, we ignore these effects here.

2.3.2 Morbidity and $PM_{2.5}$

Low air quality also affects L_t through its impact on individual productivity in the form of lost working days and restricted activity days. As a precautionary measure against overemphasizing this effect, we consider only work-loss days and ignore restricted activity days, although the former are considerably less frequent than the latter—thus, we systematically underestimate productivity gains from lower $PM_{2.5}$ exposure. In particular, we follow Hurley et al.,[1] assuming 0.0046 lost working days for every 1µg/m^3 increase in ambient $PM_{2.5}$.

3. Scenarios of future emissions, air quality and health impacts in India

3.1 Scenarios

To parameterize the GAINS and SEDIM models and construct future scenarios, we employ the World Energy Outlook (WEO) 2009 reference projection for India, which assumes the continuation of current trends and practices.[16] In particular, GDP is assumed to increase by a factor of 3.4, accompanied by a doubling in total energy consumption. Most importantly, coal activity as an important source of precursor emissions of $PM_{2.5}$ increases by a factor of 2.4, whereas biomass increases only marginally, by about 9%.

Given this reference projection, we explore three air pollution control scenarios: (1) a baseline stipulating that no additional emission control measures are introduced after 2010 (No Additional Controls—NAC); (2) a scenario assuming the implementation of measures currently specified in Indian air pollution legislation (Indian Current Legislation—ICL), and (3) a scenario simulating the application, in India, of advanced emission control measures, specifically, the current emission standards of the European Union (European Current Legislation—ECL). Main features of the two control scenarios are summarized in Table 1. In both of these, we assume that new control measures are gradually phased in between 2010 and 2019; after 2020, investments are restricted to replacing retiring equipment and to expanding capacity.

Indian Current Legislation (ICL)	European Current Legislation (ECL)
• Controls on dust emissions from the power sector and industry accounting for national emission limit values • Low sulfur liquid fuels for the residential, commercial and transport sectors • Slow penetration of improved cooking stoves using biomass • CNG for buses and three-wheelers in urban areas • Emission limit values for road transport sources up to Euro 4/IV • Emissions of sulfur from the power sector and industry remain uncontrolled	• EU-legislation o stationary sources in the power sector and industry: Proposal for the Industrial Emissions Directive o transport sources: phasing-in EU legislation up to Euro 6/VI for road transport and up to stage IV for non-road sources • German legislation on industrial and small combustion sources when stricter than the EU-wide legislation

Table 1: Current Indian and European legislation for air pollution control and abatement, 2010. Sources: Amann et al., 2008,[18] Amann et al., 2010.[30]

3.2 Emissions and emission control costs

Under the baseline scenario, the growth in energy consumption increases emissions of SO_2, NOx and primary $PM_{2.5}$ by factors of 2.3, 2.4 and 3.2, respectively, between 2010 and 2030 (Table 2). Successful implementation of current Indian legislation would lead to lower increases for all three pollutants—but especially $PM_{2.5}$—of 2.1, 2.2 and 1.1 times current emissions, respectively. Under the most stringent ECL scenario, emissions for all three pollutants would be reduced, by 67% for SO_2, 17% for NO_x, and 33% for $PM_{2.5}$.

Primary emissions of three pollutants, 2010-2030, under three different control scenarios.

Scenario	NAC	ICL	ECL

YEAR	SO_2	NO_x	$PM_{2.5}$	SO_2	NO_x	$PM_{2.5}$	SO_2	NO_x	$PM_{2.5}$
2010	6,755	4,374	5,119	6,755	4,374	5,119	6,755	4,374	5,119
2015	8,658	5,304	7,467	8,468	4,971	5,270	6,927	4,576	4,960
2020	10,500	6,536	10,024	10,116	6,022	5,446	1,591	2,842	3,585
2030	15,541	10,660	16,545	14,515	9,483	5,736	2,218	3,619	3,420

Table 2: Primary emissions of SO_2, NO_x, and $PM_{2.5}$ (kt/year) from 2010-2030 under the baseline (NAC) and two control scenarios.

Implementation of additional emission control measures requires financial resources for installation and operation of pollution control technologies, which must be paid by economic agents. SEDIM considers two different options for allocating costs—our primary results assume that consumers ultimately pay for pollution control, even though the immediate costs of meeting environmental regulations fall mainly on corporations. Analyses of the sensitivity of our results to this assumption not presented here do not alter our main conclusions.

In addition to investments, we also take into account the costs of operating and maintaining pollution abatement equipment, assuming annual operating costs at 10% of the abatement capital in place and a mean lifetime of 20 years. Using this approach, we are able to capture the two phases of policy implementation, i.e., build-up and maintenance.

Additional air pollution control costs as a Fraction of GDP			
YEAR	NAC	ICL	ECL
2010	0.000%	0.151%	0.537%

2015	0.000%	0.154%	0.546%
2020	0.000%	0.153%	0.426%
2030	0.000%	0.116%	0.292%

Table 3: Additional air pollution control costs over the NAC scenario as a fraction of GDP for two emission control scenarios.

Table 3 displays additional air pollution control costs (i.e., investment and operating costs) over those in the baseline scenario as a percentage of GDP. Costs decline in comparison to GDP, largely because of rapid economic growth in India. In the Indian legislation scenario, building up the stock of $PM_{2.5}$ abatement capital costs approximately one- to two-tenths of a percent of GDP per year from 2010 through 2019. Implementing advanced emission controls is over three times as expensive, at around half a percent of GDP per year. In 2030, operating, maintaining, and ensuring that new capital meets legislative requirements costs almost three-tenths of a percent of GDP per year under the ECL scenario, versus just over one-tenth under ICL.

One way to put these pollution abatement policies into perspective is to compare them with other important national priorities. In 2005, India spent about 3.8 percent of GDP on health and 3.2 percent on education (Table 4). Hence, over the first few years of implementation the ECL would cost about four percent of what is being spent on education and roughly five percent of what is spent on health.

India	2000	2001	2002	2003	2004	2005	2006

Health expenditure, total (% of GDP)	-	-	4.5	4.2	4.0	3.8	3.6
Education expenditure, total (% of GDP)	4.4	-	-	3.7	3.4	3.2	-

Table 4: Expenditures on health and education as a percentage of GDP, India, 2000-2006. Source: World Development Indicators, World Bank 2009

The forecasted increase in economic activity without corresponding emission controls would more than double exposure in India from anthropogenic sources by 2030 (Table 5), increasing the population-weighted mean concentration of anthropogenic $PM_{2.5}$ from 46 $\mu g/m^3$ in 2010 to 116 $\mu g/m^3$ in 2030. Full implementation of current Indian emission control legislation would limit the increase to about 50 percent above current levels, while application of advanced emission standards would actually reduce population exposure by about a third. While the reduction in long-term $PM_{2.5}$ concentrations under ICL is significant in comparison with the baseline scenario, the trend is still upward, and ICL is far from achieving the reductions seen under ECL. Note that observed level of ambient $PM_{2.5}$ from anthropogenic sources in 2010 is already well above the WHO guideline of 10 $\mu g/m^3$, even without accounting for natural sources.

	$PM_{2.5}$ Concentration ($\mu g/m^3$)		
YEAR	NAC	ICL	ECL
2010	46	46	46
2015	60	52	38
2020	74	57	30
2030	116	72	31

Table 5: $PM_{2.5}$ concentrations for three emission control scenarios.

4. The impact of emission control efforts on economic growth and human well-being

In order to evaluate the broad consequences of air pollution abatement policies, we consider not only traditionally recognized macroeconomic effects on GDP, but also impacts on the Human Development Index (HDI). The HDI is a composite indicator developed by the UN to provide a more comprehensive measure of well-being than GDP alone. It is derived as the geometric mean of normalized indices of life expectancy at birth, education (educational attainment and school enrollment) and per capita income. As the policy interventions in SEDIM affect only the educational attainment level of the population, but not school enrollment, we slightly modified the methodology used by the UNDP[6] (for details see S4). In the following, we discuss the components of the HDI individually and then the composite indicator as a whole.

4.1 GDP

Table 6 displays the effects of air pollution control scenarios on GDP per capita, GDP per worker, and total GDP, relative to the baseline scenario. Total GDP is expected to be over three times higher in 2030 than in 2010 for all scenarios, corresponding to an average annual growth rate of around six percent.

	YEAR	NAC	ICL	ECL
GDP per capita	2010	4,073	1.000	1.000
	2015	5,514	1.000	1.001
	2020	7,200	0.999	1.000
	2030	11,135	0.996	0.995
GDP per worker	2010	6,713	1.000	1.000
	2015	8,849	1.000	1.001

	2020	11,392	0.999	1.001
	2030	17,308	0.999	1.002
Total GDP (Billions US Int. $ (2000))	2010	4.96	1.000	1.000
	2015	7.16	1.000	1.001
	2020	9.9	1.000	1.003
	2030	16.79	1.001	1.007

Table 6: GDP per capita, GDP per worker and Total GDP under three scenarios, India, 2010, 2015, 2020, 2030. Notes: NAC in 2000 international US$. For ICL and ECL, figures represent the ratio relative to the baseline (NAC) scenario.

The investment in air quality improvements causes trivial changes in GDP per capita, GDP per person of working age, and overall growth of GDP. For example, GDP per capita grows at an average annual rate of 5.16 percent in the baseline scenario, whereas in the control scenarios growth averages about 5.14 percent. Essentially, the air pollution investments envisioned here have no discernible effect on economic growth. These changes in GDP growth in our scenarios incorporate increases in individual productivity resulting from a lower frequency of lost work days. The productivity changes themselves make a relatively small contribution to GDP growth. Had we included productivity effects from restricted-activity days as well, the forecasted decreases in GDP per capita would have been even smaller.

Macroeconomic effects of air pollution control policies can also be evaluated with respect to their impacts on consumption. Two kinds of consumption arise in SEDIM: private consumption as normally defined in economic models (Table 7), and unavoidable consumption of (exposure to) $PM_{2.5}$ (Table 5). Private consumption per capita in 2030 is half of a percent less in the ICL scenario than without new pollution abatement policies. The corresponding average annual rate of growth of private consumption is 5.66 percent in the baseline case and 5.63 percent in ICL. In the ECL scenario, the changes are slightly larger; in 2030, for example, individuals give up around eight-tenths of a percent of their consumption to enjoy cleaner air.

	Year	NAC	ICL	ECL
Consumption per capita	2010	3,065	1.000	1.000
	2015	4,291	0.998	0.993
	2020	5,702	0.997	0.993
	2030	9,213	0.995	0.992

Table 7: Forecasted consumption per capita in three scenarios, India, 2010, 2015, 2020, 2030. Notes: Consumption per capita in NAC in 2000 international US$. Figures for consumption in the control scenarios represent the ratio relative to the baseline (NAC) scenario.

The 2010 concentration of anthropogenic $PM_{2.5}$ is estimated at $46\mu g/m^3$. In the no-control scenario this more than doubles, rising to $116\mu g/m^3$. In ICL, despite pollution control efforts, $PM_{2.5}$ concentrations increase by roughly 20 percent over the period that the stock of pollution abatement capital is being expanded (2010-2019) because of the increased energy use associated with economic growth. During the maintenance phase (2020-2030) $PM_{2.5}$ concentrations increase even more rapidly. Only under the ECL scenario are $PM_{2.5}$ concentrations lower in 2030 than in 2010.

4.2 Longevity

The second component of HDI is longevity. While exposure to pollutants in air will cause substantial premature mortality, life expectancy in India is nevertheless expected to increase—from 70.5 to 74.9 years by 2030—as a consequence of other factors related to economic development, such as improved nutrition, better health care, and access to clean water, among others. This is reflected in the results for the NAC scenario. Even so, life expectancy at birth is more than one year higher in 2030 in the ICL scenario than in the NAC scenario (Table 8). Under ECL, life expectancy in 2030 is 2.8 years higher than for the baseline.

	Year	NAC	ICL	ECL
Life expectancy at birth	2010	70.5	70.5	70.5
	2015	71.8	72.0	72.5
	2020	72.9	73.5	74.4
	2030	74.9	76.2	77.7
Lives saved (1,000s) $Deaths^{base} - Deaths^{scen}$	2010	0	0	0
	2015	0	179	462
	2020	0	423	1,106
	2030	0	1,212	2,528

Table 8. Life expectancy at birth and lives saved per year for three different scenarios, India, 2010, 2015, 2020, 2030.

The number of lives saved per year is calculated as the number of deaths that would have occurred in the baseline scenario minus those that would take place under a particular control scenario. For example, under the ICL scenario, more than 1.2 million fewer people would be expected to die in 2030 than if no $PM_{2.5}$ abatement program had been undertaken. In the ECL scenario, this number more than doubles.

While there is no unique and commonly accepted method for expressing the value of human life in monetary terms, one way to integrate the number of lives saved with the economic cost of air pollution abatement policies is to compute consumption forgone per life saved (Table 9). In 2030, for example, under the ICL scenario, each life saved by reducing $PM_{2.5}$ concentrations results in a decrease in overall private consumption of around \$9,400. To put this figure in perspective, on a per capita basis, each life saved costs 40 millionths of a dollar, equivalent to just 4 billionths of per capita private consumption. In the ECL scenario overall private consumption is over \$12,000 *higher* per life saved than in the baseline case, although per capita consumption is slightly smaller than baseline. This occurs because in this scenario a larger population produces a larger aggregate GDP, but a smaller per capita GDP, than in the NAC scenario. In both control scenarios, the reduction of mortality by providing cleaner air carries costs, but the burden of those costs spread over a large population is quite modest.

	Year	ICL	ECL
Annual consumption forgone to save a life (in 2000 US Int. \$) $\frac{Cons^{base} - Cons^{scen}}{Pop^{scen} - Pop^{base}}$	2010	0	0
	2015	63,205	74,759
	2020	34,199	29,410
	2030	9,426	-12,427
Annual consumption forgone per capita to save a life (millionths of 2000 US Int. \$)	2010	0	0
	2015	54	63
	2020	39	35

	2030	40	29
Proportion of annual consumption each person would have to forgo to save a life (billionths)	2010	0	0
	2015	13	15
	2020	7	6
	2030	4	3

Table 9. Consumption forgone to save a life overall, per capita, and as a proportion of total consumption in three different scenarios, India, 2010, 2015, 2020, 2030. Notes: All prices in 2000 international US$

4.3 Education

Because older cohorts tend, on average, to be less educated, the more deaths are prevented in elderly individuals in a given scenario, the lower the aggregate educational attainment. This is true despite the fact that education in younger cohorts is increasing in all scenarios. If we were to ignore this "negative" effect of increases in longevity, increases in HDI would even be larger than observed. Table 10 summarizes the effect of $PM_{2.5}$ on mean years of schooling. In the NAC scenario, the ongoing expansion of the educational sector in India will lead to a mean increase of roughly 18 months of schooling per capita from 2010 to 2030 (Table 10).

	Year	NAC	ICL	ECL
Mean years of schooling	2010	6.88	1.000	1.000
	2015	7.27	1.000	1.000
	2020	7.65	0.999	0.998
	2030	8.36	0.998	0.995

Table 10. Mean years of schooling in three scenarios, India, 2010, 2015, 2020, 2030. Notes: Mean years of schooling in ICL and ECL scenarios are ratios relative to baseline (NAC) levels. Source of baseline education data: IIASA/VID.[31]

4.4 Summary of effects on HDI

HDI is higher in both the ICL scenario and in the ECL scenario at all time points. In effect, substantial increases in life expectancy at birth outweigh the relatively small decreases in mean years of schooling and per capita GDP that result from air pollution abatement policies. Clearly, well-being, as measured by HDI, is higher when actions are taken to reduce $PM_{2.5}$ concentrations. To achieve equivalent effects on HDI in the absence of additional pollution controls (i.e., as in the NAC scenario), GDP would have to be increased by 29% in 2030.

Decomposition of contributions to to the change in Human Development Index		
	ICL compared to NAC	ECL compared to NAC
GDP per capita Index	-3.5%	-1.8%
Life Expectancy Index	109.%	107.6%
Education Index	-5.5%	-5.9%
Total Change in HDI	100.0%	100.0%

Table 11. Contributions of individual indices to change in the HDI in 2030 under two control scenarios.

5. Discussion

In this study, we investigate the costs and benefits of air pollution policies in India over the next two decades. We find that implementing such policies would increase well-being, as measured by the HDI, because increases in life expectancy outweigh the extremely small economic costs. In our two scenarios, which roughly represent current air pollution legislation in India and Europe, improvements in ambient $PM_{2.5}$ levels—which save over a million lives per year—reduce the average annual rate of per capita GDP growth between 2010 and 2030 by around 2 one-hundredths of one percentage point. Furthermore, much of this reduction is due to the fact that lower $PM_{2.5}$ concentrations keep older non-working adults alive longer.

Assessing the costs and benefits of a cleaner environment is always an empirical matter. Costs and benefits depend on the type(s) of pollution for which actions are being considered and the place and time period of interest. Here, we focus on $PM_{2.5}$, a pollutant with well-known consequences for health and mortality and on India, a country with high current $PM_{2.5}$ levels and high expected rates of growth of $PM_{2.5}$ emissions. Our conclusions might well be different had we considered other pollutants in other places and times.

This paper draws on the disciplines of energy systems modeling, atmospheric dynamics, economics, and demography—the integration of all four in a systems framework is prerequisite to constructing a plausibly realistic picture of the situation in India in the coming years.

The combination of the GAINS and SEDIM models requires a large number of simplifications to make the problem tractable. The costs of $PM_{2.5}$ abatement are calculated on the assumption that emitters do not modify their behavior in response to the new policies. If emitters were to reallocate resources toward less-polluting technologies, for example, the cost of $PM_{2.5}$ reductions would be less than computed here. We did not include the cost of medical care—additional medical expenditures induced by $PM_{2.5}$ pollution act as a kind of tax, reducing both consumption of other goods and savings. Savings reductions, in turn, decrease the rate of capital formation. Had we included the cost of medical care, GDP growth in the ICL and ECL scenarios would have been slightly larger compared with growth under NAC. We also did not include any demand-side effects. If investments in abatement caused the deployment of unemployed or underemployed resources, then the economic cost would be even smaller than we have computed. However, this response is not guaranteed—it is possible that some of the resources needed for abatement investments are in short supply, such that investments would increase the prices of those inputs, leading to a reduction in their use in other sectors. Such considerations are far beyond the scope of this study.

Because technologies included in the analysis are commercially available and well-developed, significant improvements are not expected over the two decades to come. Hence, the model assumes that there will be no technological development and, thus, mitigation effectiveness and costs remain constant over the analyzed period. This assumption, together with the inclusion of only well-developed technologies, makes the assessment of mitigation potential conservative rather than optimistic.

The costs of funding air pollution abatement programs could be distorting, potentially having some (probably small) effect on the incentive to work. This is a complex issue, because the changes in life expectancy that emerge from the SEDIM model could also slightly change these incentives. Modeling such factors was not plausible in the current study. We allowed $PM_{2.5}$ to affect survival rates and health only for adults because data for children is largely unavailable, although $PM_{2.5}$ almost certainly affects the health and survival of children. SEDIM takes into account the costs of educating children. More children imply higher education costs and a greater proportion of the population not of working age, both of which would reduce GDP per capita growth. But expenditures on education are an investment. In the short time span considered here, we would expect mainly to observe the costs of this investment and not the returns. As well, there may be a synergy between better health of children and better educational outcomes. Over the period of forecasting implemented in this study, we expect that the aforementioned considerations would have relatively minor effects that would not affect our overall conclusions.

The results of this work indicate that implementing policies to reduce $PM_{2.5}$ pollution in India would increase well-being, save lives and improve health, with inconsequential effects on the growth rate of GDP and GDP per capita. Furthermore, $PM_{2.5}$ reductions lower anthropogenic contributions to global warming.[32–34] Together, these conclusions strongly indicate that the reduction of $PM_{2.5}$ in India should be high on the priority list of decision makers.

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