



Integrating climate, air, and health goals: the impact of efficient cooling policies in India

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Abstract

Air conditioning in buildings is a significant contributor to electricity demand in developing countries and is expected to increase significantly in the coming years. This increase will lead to higher greenhouse gas (GHG) emissions, air pollution, and related impacts. In India, the energy use due to room air conditioners (RACs) is estimated to cause 18%, 9%, and 8% of fine particulate matter (PM_{2.5}), nitrogen oxides (NO_x), and sulphur dioxide (SO₂) emissions, respectively. These emissions contribute to 5% of power sector PM_{2.5} concentrations in India and were attributable to 5748 air pollution-related deaths in 2017. If no technological improvements are made, India's RAC energy demand is expected to increase from 56 Gigawatt (GW) in 2017 to 289 GW in 2046, attributable to 39,072 deaths annually by 2046. However, implementing the Indian Cooling Action Plan (ICAP) could reduce RAC demand and associated pollution by 60%. Stricter standards for coal-based power plants, in accordance with National Clean Air Programme (NCAP), could also reduce air pollution from RACs by 50%. An integrated approach including ICAP, NCAP, and Intended Nationally Determined Contributions (INDCs) could lead to a compounded overall reduction of 84% in PM_{2.5} concentrations from RACs, with 33,047 lives saved annually in 2046.

Keywords Air pollution · Climate change · Cooling · Room air conditioner · Health impacts · Integrated policy · Heating

Introduction

Room air conditioning has become an essential need in several parts of the world. About 1.6 billion air conditioners are currently used worldwide (IEA 2018a). The demand is expected to grow with rising temperatures due to climate change, economic status, and population growth. A developing country like India had about 40 million operating room air conditioners (RACs) in 2017. With the growth in income levels and additional stressors of climate change, the demand for cooling will increase this RAC stock to approximately 350 million units in 2037 (ICAP 2019).

Alongside its benefits, the cooling sector has a significant environmental footprint. It generates huge energy demand, serving as a substantial source of greenhouse gas (GHG) and air pollutant emissions globally. Air conditioners worldwide consume over 2000 Terawatt-hour (TWh) of electricity every year, equivalent to two and a half times the total electricity use in Africa (IEA 2018b). Over a fifth of the electricity used in buildings is for cooling, with space cooling in buildings responsible for 50% or more of residential peak electricity demand (IEA 2018b). This increasing demand presents unique challenges for developing countries, where electricity generation remains heavily reliant on fossil fuels, contributing to a global scenario where 62.7% of electricity is generated from fossil fuels (Statistical Review of World Energy 2020).

The emissions associated with fossil fuel combustion have profound implications for climate change (Kumar et al. 2022), affecting weather patterns (Singh et al. 2023; Badrzadeh et al. 2022), crop yields, and overall environmental health (Hatfield and Prueger 2015; Parry 1992; Pariyar et al. 2020; Shestakova et al. 2020). Recognizing this, many countries have implemented energy efficiency measures

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as a strategy for both energy security and GHG mitigation (Haines 2017). These measures, however, offer more than just climate benefits; they can also reduce exposure to air pollution (Bloomberg and Aggarwala 2008) and contribute to improved regional-scale air quality and human health (Bell et al. 2008; Nemet et al. 2010; Zhang et al. 2017). Beyond human health (Chaudhary et al. 2023; Chaudhary et al. 2022), ambient air pollution adversely impacts agricultural productivity (Sembhi et al. 2020) and the built environment (Rahman et al. 2023; Agarwal et al. 2020; Wilkinson et al. 2012).

Climate change and air pollution are interconnected. While climatic patterns play an important role in defining the air quality of a region, atmospheric aerosols also have the potential to impact regional scale weather patterns (Myhre et al. 2014, 2012; Lohmann and Feichter 2005). Addressing these issues separately, as is often the case in most countries, can lead to reduced cost-effectiveness, weaker policies, and implementation delays. These challenges are typically addressed through isolated interventions by different departments at the policy, governance, and institutional levels. However, adopting an integrated and coordinated approach has the potential to maximize social, health, economic, and environmental benefits at an optimized cost.

This study proposes and employs an integrated approach known as the Integrated Energy-Emissions-Air Quality-Health Model (IEEAHM) to assess and account for the co-benefits associated with improving energy efficiency in the energy-intensive room air conditioning (RAC) sector. Specifically, we aim to address the following questions for India as a case study, representing a developing country with a rapidly growing demand for RACs:

- 1) What is the contribution of RACs to GHG emissions and air pollutant emissions inventory?
- 2) What is the share of RACs in deteriorating air quality and its health implications?
- 3) What is the future of RACs in different growth scenarios, and what are the effects of various energy efficiency improvement measures?
- 4) What is the overall impact of integrating energy efficiency, climate change control, and air pollution control strategies on RAC's contributions to emissions, air quality, and human health?

The findings of this study are poised to drive integrated strategies in the RAC sector, facilitating coordinated actions that enhance energy efficiency, improve air quality and health, and reduce GHG emissions. This research not only addresses the pressing challenges within the cooling sector but also offers valuable insights into the broader applicability of the IEEAHM approach to assess the co-benefits of energy efficiency strategies across various sectors.

The novelty of this work lies in its use of an integrated model (i.e. IEEAHM) that comprehensively evaluates the linkages between energy, emissions, air quality, and health impacts attributable to the RAC sector. This approach allows us to identify not only direct but also indirect benefits, paving the way for a more holistic understanding of the impacts of energy efficiency measures. By showcasing the practical significance of this integrated approach, this study underscores its potential to guide policy and decision-makers in achieving sustainable and coordinated improvements in the RAC sector. The review of the literature suggests that there are limited studies on country level assessments, evaluating co-benefits of integrated strategies for improving sectoral efficiencies, mitigating climate change reducing air pollution and improving human health. Khaiwal et al. 2021, state the use of an integrated model to understand climate, health, and environmental drivers for better clean household energy. Another study done for the European Union (EU) assessed climate policies in the EU and their effect on fine Particulate Matter (PM_{2.5}) and health effects (Pisoni et al. 2023). Reis et al. 2022, devised and put into action a comprehensive modeling framework that integrates air quality and climate considerations for optimizing investments in both structural and end-of-pipe solutions. The aim was to effectively address air pollution while concurrently achieving the temperature goals outlined in the Paris Agreement, specifically targeting the objectives of limiting global warming to 1.5°C and 2°C. In a recent study, ApSimon et al. 2023, employed a United Kingdom integrated assessment model (UKIAM) to formulate proposed targets for reducing PM_{2.5} as outlined in the United Kingdom (UK) Environment Act. The study assessed various emission scenarios until 2050, highlighting the potential health and other environmental benefits associated with these reductions. In a study conducted by Limaye et al. 2023, they assessed air quality levels in Ahmedabad and examined health co-benefits in various contexts by incorporating data on climate, energy, cooling, land cover, air pollution, and health. The results indicated that implementing climate change response policies at the city level could yield significant co-benefits for air quality and public health. It is important to note that the study focused solely on evaluating the impacts at the city scale and specifically on the variations in emissions of air pollutants. This study is one of the first in the context of developing countries to use a systematic modeling approach to address this issue and propose a scientific modeling framework for developing cost-optimized integrated policies and action plans at the national scale in India.

Methods

The study methodology is outlined in Fig. 1. Essentially, different models were integrated to understand how RACs

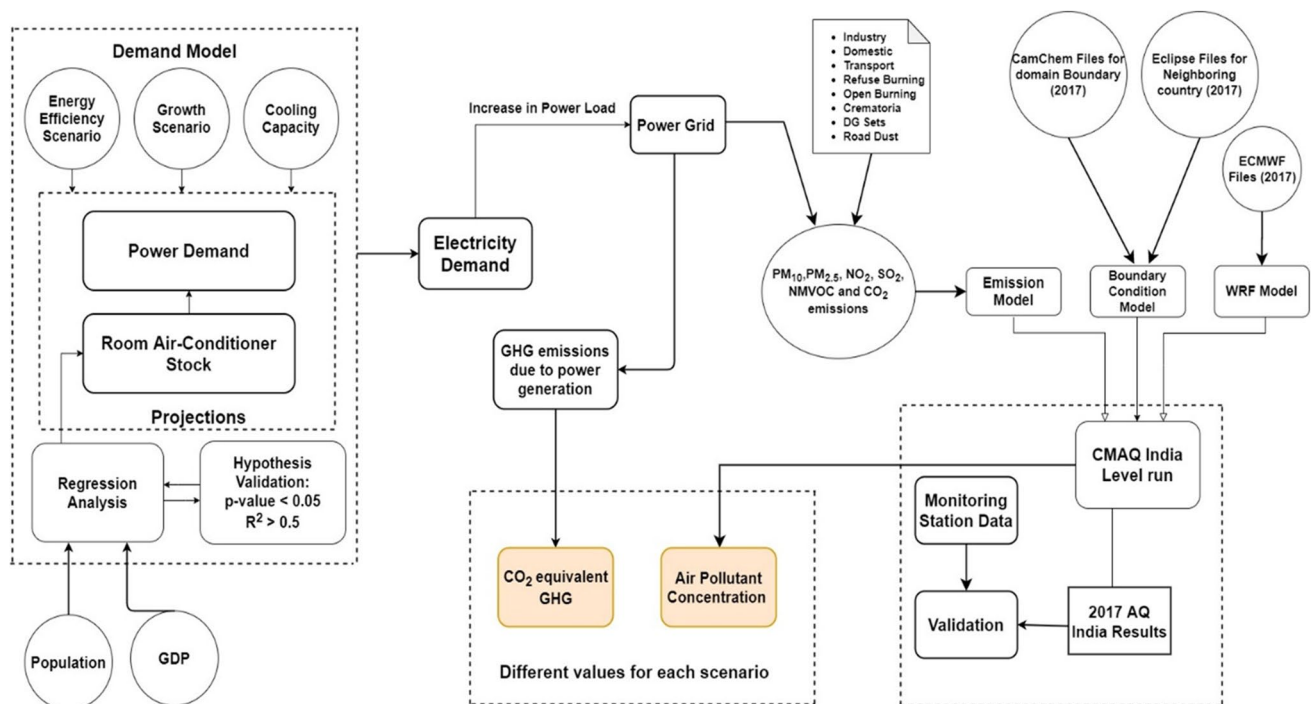


Fig. 1 Broad methodology of the IEEAHM model

are expected to affect energy needs, GHG emissions, air quality, and health, especially in India during 2017 to 2046. This study suggests the IEEAHM approach for an integrated assessment of energy efficiency, air pollution, and GHG emissions from the RAC sector in a large developing country like India. The methodology involves estimating electricity demand for RACs under various alternative future scenarios and using these estimates to determine the resulting GHG and air pollutant emissions, primarily caused by power generation. Additionally, how air pollutant emissions impact air quality and, consequently, human health were evaluated. This was achieved through the utilization of a validated scientific United States Environmental Protection Agency (US-EPA) approved model (and established relationships between pollutant exposures and health outcomes. Initially, estimates were made for the energy consumption of RACs in India, considering their contribution to the overall energy mix. Subsequently, GAINS (Greenhouse gas – Air pollution Interactions and Synergies) Asia model (Amann et al. 2011) was employed to compute the air pollutant emissions specifically attributed to these air conditioners. These emission data are then input into the validated Community Multi-Scale Air Quality Model (CMAQ) (Singh et al. 2021) to estimate the proportion of population weighted $PM_{2.5}$ concentrations in India attributable to RACs, which serves as a crucial indicator of exposure to air pollution in the country. For the future, a business-as-usual (BAU) scenario is developed to estimate RAC electricity demands and associated

emissions of GHGs and air pollutants. Alternative scenarios were also created based on the Indian Cooling Action Plan (ICAP), India's Intended Nationally Determined Contributions (INDCs), and the National Clean Air Program (NCAP) to assess their impacts on electricity demand from the RAC sector and their effects on GHG emissions and air quality. Please note that uncertainty in emission inventories, modeling uncertainty are always present in such models, and they have been discussed in detail in Singh et al. 2021. Health impact dose response curve is international standard and not indigenous and hence may have a small uncertainty. The results of these uncertainties were also calculated in Chaudhary et al. 2022; the results were satisfactory and have been explained in the cited paper.

Scenarios

In the analysis, two main economic growth projections for India: the “reference” and “aspirational” scenarios were considered, both linked to India's projected Gross domestic product (GDP) figures from the India Energy Security Scenarios (IESS) report (IESS 2023). The reference scenario assumes GDP growth ranging from 6.2 to 4.7% between 2017 and 2046, while the aspirational scenario is more optimistic, projecting growth from 8.1 to 5.6% over the same period. In addition to economic growth, we explore different technological advancement scenarios.

Frozen technology (FT) This scenario assumes no significant energy efficiency improvements, with the efficiency rating (Indian Seasonal Energy Efficiency Ratio (ISEER)) for air conditioners remaining at 3.72 from 2019 to 2046.

Standards & Labelling (S&L) In this scenario, we anticipate a 2.76% yearly improvement in the ISEER, based on current trends until 2029. Afterward, we assume a two-stage change: a 1.70% increase starting in 2030 and a 1% increase from 2040.

ICAP This scenario represents a more aggressive push for efficiency if the efficiency improvement rate would grow at double the rate of the S&L scenario. This leads to a reduction in cooling energy needs by 25–40%.

INDC This scenario assumes that by 2030, 40% of India's power needs will be met by non-fossil sources, potentially resulting in reduced GHG and air pollutant emissions.

NCAP This scenario is based on stricter pollution controls for power plants, requiring the installation of Flue Gas Desulfurization (FGD) units to control sulphur dioxide (SO₂) and Selective Catalytic Reduction (SCR) for Nitrogen Oxides (NO_x) control. Under this scenario, we assume that all coal-run power stations in India will have installed advanced pollution control technologies by 2024.

Based on these five scenarios, we examine a total of eighteen combinations, encompassing various regulatory regimes. We estimate carbon dioxide (CO₂) emissions and PM_{2.5} concentrations for each scenario within the RAC sector in India, as mentioned in Figure S1. These eighteen scenarios result from the combination of three different technology scenarios for the RAC sector (FT, S&L, and ICAP), two GDP-based growth scenarios (reference and aspirational), scenarios related to GHG control through the penetration of renewables (INDC) and pollution control in the power sector (NCAP) (Figure S1).

Estimation of RAC stock

The literature review suggests top-down modeling approaches, including regression and econometric analysis for long-term electricity demand projections or forecasts (Esteves et al. 2015, Negi and Kumar 2018).

We used a linear regression model developed to derive the number of RACs per 1000 population in India based on GDP per capita level, using Equation S1. Statistical validation of the regression model is carried out based on *p*-value and *r*² parameters. The *p*-value of 0.05 and *r*² of more than 0.9 are considered satisfactory. In our model, the variable values are found to be well below the value of 0.05 and shows that the

independent variable lies within the 95% confidence interval levels of our analysis. The *r*² and adjusted *r*² values are found to be about 0.99, depicting satisfactory performance of the regression model.

The validated linear regression model within the S-Curve (sigmoid function) is used to evaluate the number of RACs per 1000 population. Equation-S1 estimates the number of RACs per 1000 population in a particular year. This model is used to estimate RACs per thousand population in India based on future projections of GDP per capita, which are adopted based on the India's GDP growth analysis done by National Institute for Transformational India's (NITI Aayog) in 2023 (IESS 2023). The RACs stock is then estimated using the population growth projections for India (World Bank 2020). India resembles China, Brazil, and Indonesia in terms of population growth and economic growth pathways. A report shows that the RAC markets of Brazil and Indonesia have not saturated yet with penetration rates of 16% and 9%, respectively (IEA 2018a). The share of RAC installed household is still low for Brazil and Indonesia, but, on the other hand, China has 60% of households with RACs. The current penetration level of RACs in India is also low (below 10%) (ICAP 2019), and hence, a similar saturation level (*S* = 950) to that observed in China has been assumed. We anticipate that India may reach a situation like China in terms of RAC penetration levels in the coming decades. The growth trajectory of India's RAC sector is assumed to be like that of China. Hence, the value of 950 for the saturation level is assumed in line with China's RACs penetration level in 2046 (Karali et al. 2020).

Estimating electricity demand from the RAC sector

Based on the econometric modeling of the RAC stock above, we have analysed the impact of RACs stock on the electricity demand. The electricity demand is estimated under the three- technology-based energy efficiency scenarios (FT, S&L, and ICAP) based on ISEER projections. This energy efficiency ratio projection assumes to be constant in the FT scenario, while it grows by 171% to reach 6.37 in the S&L scenario and by 290% to reach 10.79 by 2046. The life of a RAC unit is assumed to be ten years. In this study, we have considered efficiency degradation under all three energy scenarios. Degradation in the efficiency of the equipment is assumed to occur at a rate of 2% annually, without rigorous and regular maintenance and servicing of the equipment (Matson et al. 2002, Hendron 2006, Fenaughty et al. 2018). The most common problems associated with RACs are improper refrigerant charge and evaporator coil airflow. Other issues include non-condensable refrigerants, suction line flow restriction, and fouled outdoor condenser coils (Fenaughty et al. 2018). All these problems with RACs lead to deterioration in the efficiency of the equipment due to

operations over its lifetime. The benefits of regular servicing in the RAC sector have been accounted for under the ICAP scenario only. Further, we have assumed that expert servicing will be gradually introduced from the year 2021 and will become accessible to the whole stock of RAC by the year 2024. Efficiency depreciation in the RAC stock under the ICAP scenario is considered only 0.5% annually due to expert servicing as specified in the ICAP.

Space cooling makes a significant contribution to the peak power demand in India. Phadke et al. (2014) have shown that the average heat index pattern during the summer months is very similar across geographic regions in India. The space cooling demand has a high coincidence factor (the probability of appliance use coinciding with system peak demand across India). This study assumed the peak coincidence factor of 0.7 for India, in line with Phadke et al. (2014). The average cooling capacity of the RAC stock has been taken as 1.328 tons, based on the 2019 market share of various available RAC cooling capacities in India. There are transmission and distribution (T&D) losses associated with the power supply, which create a large gap between the demand and generation of electricity. Apart from the T&D losses, electricity is also consumed by auxiliary equipment, and both of these factors are taken into account to estimate the electricity demand on the generation side. The current T&D losses in India stand at ~20% (Energy Statistics 2019). Historical data suggests that the T&D losses have decreased annually in India since the last decade and are projected to decrease further in the coming years (Pachouri et al. 2019). This study assumed that the T&D losses would decrease linearly to 10%, and auxiliary consumption would reduce to 3% in 2046 from the 2019 levels. Using this, the electricity demand at the generation end under various scenarios of energy and growth is estimated for the RAC sector. An annual operation of 1600 h is assumed in this study for the RAC units (Kumar et al. 2018).

Estimation of GHG emissions from RACs

Based on the electricity demand from the RACs sector, the power generation and associated GHG emissions are estimated. The power sector in India is majorly dependent on coal. While slowly, the share of renewable energy is growing in India, in the medium-term, coal can be expected to be the primary source of electricity generation in India (National Power Portal—<https://npp.gov.in/>). The considerable electricity demand of the RAC sector and refrigerants in the form of Hydrochlorofluorocarbons (HCFCs) demand could add to the emissions of GHGs and air pollutants. They are also known as short-lived climate pollutants.

There are two types of emissions from the RAC sector, namely, direct and indirect emissions. The direct emissions occur from the release of refrigerants from the RAC

equipment over its lifetime. The release of refrigerants can happen from leakages and intentional or unintentional discharges (Calm 2006). The refrigerants are considered GHGs, and an earlier generation of refrigerants was classified as ozone-depleting substances. Severe consequences of ozone depletion are being averted through the global adherence to the successful adoption of the Montreal Protocol (Calm 2002). In this study, we have not included estimates of the GHG potential of refrigerant emissions.

Indirect emissions occur from the operational use of the RAC equipment over its lifetime. Estimating indirect GHG emissions is done using electricity demand projections and the grid emission/weighted average emission factor for CO₂. The weighted average emission factor is the average CO₂ emitted per unit of electricity generated in the grid. It is calculated by dividing the absolute CO₂ emissions of all power stations by the total generation from all sources. According to the Central Electricity Authority, India (<https://cea.nic.in/?lang=en>), the CO₂ emission rate in India was 0.721 kg CO₂/Kwh in the year 2015 and is projected to reduce to 0.524 kg CO₂/Kwh in 2026. In this study, we have taken the emission factor to be 0.7 kg CO₂/Kwh in the year 2019, which decreased linearly in time to the value of 0.3 kg CO₂/Kwh in the year 2046 to account for the penetration of renewables in the power sector. Over the years, renewable energy generation technologies will penetrate, and power generation in India is expected to be less emission intensive (Pandve 2009). In this study, we have not considered the direct emissions from the RAC sector and have accounted for the indirect emissions only.

Estimating air quality co-benefits

To estimate air quality co-benefits of reduced electrifying consumption and GHG emissions from the RAC sector, we used Community Multiscale Air Quality (CMAQ version 5.3.1) model. CMAQ is a first-principles state of the art scientific computer model that comprehensively represents the most critical processes affecting air quality and atmospheric chemistry. In the air quality model, emissions from various sources are fed along with terrain and meteorological inputs. CMAQ uses an extensive mechanism of atmospheric chemical reactions to predict the chemical production and loss of several pollutants as they are carried downwind from their sources (US EPA, 2014). The broad methodology used to apply this model has been described in Fig. 1. This study uses an already customized (for Indian conditions) and validated version of the CMAQ model based on published emission inventories of pollutants from various sectors. Singh et al. (2021) validated the CMAQ model to estimate PM_{2.5} concentrations in the Indian domain. The model was successfully used to find the primary and secondary fractions of particulate matter in India. The same model and

methodology has been used in this paper to estimate the air pollution levels of 2017.

Multi-sectoral, multi-pollutant inventory developed by Singh et al. (2021) for 2016 has been projected for 2017 at a resolution of $36 \times 36 \text{ km}^2$. Air pollutant emission inventory was based on the energy consumption of each of the contributing sectors (e.g. transport, power, industries, etc.) using the GAINS ASIA model (Amann et al. 2011). Fuel and technology onset and control measures in different sectors have also been accounted in the estimation of air pollutant emissions. Meteorological data and boundary conditions (to account for atmospheric pollution transport from outside of India) were also fed into the CMAQ model at the same resolution. Weather Research Forecasting (WRF (version 3.9.1)) model was used to estimate the meteorological conditions for the year 2017 using the European Centre for Medium-Range Weather Forecast's (ECMWF) ERA5 (ECMWF Reanalysis v5) archived dataset (Berrisford et al. 2011) at six hourly intervals. To account for the transport of pollutants from outside of the study domain, boundary conditions were produced from the Community Atmosphere Model with Chemistry (CAM-chem) model (Buchholz et al. 2019). Emissions of ammonia (NH_3), which is a primary gas responsible for the secondary particulate formation, emissions of ships, and emissions from neighbouring countries like Pakistan, Nepal, Sri Lanka, Myanmar, Bangladesh, etc., which fall within the study domain are taken from ECLIPSEv5 database of IIASA (2014).

The CMAQ model was run for the whole year 2017, and model predicted $\text{PM}_{2.5}$ concentrations were validated (Figure S5) against the actual ground observations taken from the Central Pollution Control Board of India (<https://app.cpcbcr.com/ccr/#/caaqm-dashboard-all/caaqm-landing/data>). The validated model is used in this study to assess pollutant concentrations attributable to the RAC sector for the years 2017 and 2046. To estimate the contributions from the RAC sector, all other inputs (emissions of other sectors, meteorological conditions, terrains, boundary conditions, etc.) of WRF-CMAQ have been kept constant for future years. The model runs were performed for different technology and growth scenarios of the RAC sector while keeping all other variables constant. Changes in India-wide annual average $\text{PM}_{2.5}$ concentrations were estimated for different scenarios of RAC energy demand in India.

Developing emission inventory of the RAC sector

Emissions of the RAC sector is estimated using energy demands generated in the year 2017's alternative future scenarios. The power demand for RACs is generated from both conventional and non-conventional energy sources. In 2018, 80.42% (Energy Statistics 2019) of power in India was generated from fossil fuel-based sources. Coal consumption

in the power sector in India is taken from the Coal Directory of India (<http://www.coalcontroller.gov.in/pages/display/16-coal-directory>), which is fed into the GAINS model to estimate emissions of air pollutants like $\text{PM}_{2.5}$, NO_x , and SO_2 from the power sector in India. The share of RAC stock in India's total coal-based power consumption is used to estimate the share of RACs in total emissions of different air pollutants. Air pollutants emissions are projected for 18 alternative scenarios based on the change in RAC energy loads, dependencies of coal in power stations, and implementation of emission control norms in power plants.

Estimating air quality and health co-benefits

This study has assessed the impacts of air pollution on human health in different scenarios envisaging the implementation of air pollution control strategies in the country. The health effects of exposure to atmospheric $\text{PM}_{2.5}$ have been quantified. The approach for estimating health is broadly the disease burden estimation (in terms of avoided mortality) or estimating the health benefit due to the implementation of control strategies. The input to this health impact modeling exercise is the ambient annual average $\text{PM}_{2.5}$ concentrations derived from the CMAQ Model. The study then quantified the positive health impact of different scenarios (consisting of various interventions) in terms of decreased risk of mortalities. The associated avoided deaths and savings due to improved air quality were analysed based on the change in $\text{PM}_{2.5}$ concentrations in different scenarios for 2017 and 2046. Based on the population's exposure, health impacts were quantified in terms of disease-specific mortality attributable to ambient $\text{PM}_{2.5}$ concentrations. The study estimated the mortalities attributable to five diseases, cardiopulmonary diseases (COPD) (above 30), lung cancer (LC) (above 40), ischemic heart disease (IHD) (above 25), lower respiratory infections (LRI) (below 5), and stroke (all age groups) caused due to high ambient particulate matter concentrations. The health impact is captured through the integrated exposure risk function (IER) developed by Burnett et al. (2014). These IERs are employed to estimate the relative risks attributable to $\text{PM}_{2.5}$ exposure for the five endpoints. The coefficients of each disease have been estimated using the data for $\text{PM}_{2.5}$ and the relative risks for 4042 data points provided by Apte et al. (2015). The coefficients estimated for LRI, COPD, and LC are the same for all the age groups. However, there exist age-modified risk models for IHD and stroke. Epidemiological studies of risk factors for both IHD and stroke indicate that the relative risk (RR) declines with the logarithm of age, reaching one between 100 and 120 years. Thus, age modification to the RR s has been considered, and the IER has been fitted for each age group separately.

Any global assessment of the mortality risks associated with ambient PM_{2.5} is contingent on assumptions about the shape of concentration–response (*C – R*) relationships for the full range of conditions experienced by the global population. There is evidence of a supra-linear *C – R* function where the marginal effects of exposure decline with increased exposure. Recent analyses from studies of PM_{2.5} ambient air pollution, second-hand cigarette smoke exposure, and active cigarette smoking provide further evidence that the exposure–response function is not linear throughout the range of potential exposures (Pope et al. 2015), rather it flattens out when exposure is extended to very high levels (Fig. 2). The excess risk for the assumed supra-linear *C-R* function illustrated in Fig. 3 is as shown in Equation S2.

The data of the population was taken from the Census 2011 and then extrapolated for 2017 and 2046. The reported average annual disease incidence rate for the five endpoints had been derived from the Global Burden of Disease (GBD)

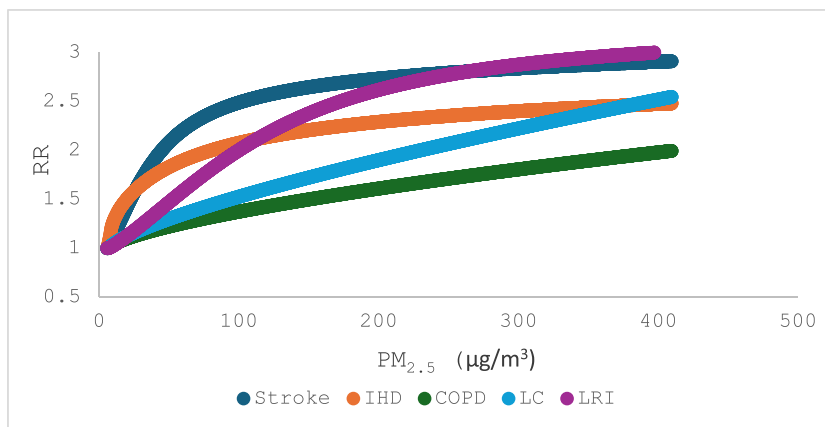
database for the year 2020 (Vos et al. 2020) and assumed to be constant for the future years.

Results

India's growing appetite for RAC units is evident. As of 2017, a total of 40 million RAC units were in use across the country. Given the current adoption rate at a mere 10%, this figure is anticipated to increase tremendously, potentially reaching 350 million units by the year 2037–38 (ICAP 2019).

This estimated surge of RACs in India corresponds well with Kumar et al.'s (2018) projection that India's cooling energy demand will double by 2027. Meeting this demand will necessitate the establishment of new power generation facilities. However, if India leans towards fossil fuel-based power plants, the subsequent increase in GHG emissions

Fig. 2 Concentration–response function for PM_{2.5} for five individual endpoints



Reference - INDC + ICAP + NCAP

Aspirational - INDC + ICAP + NCAP

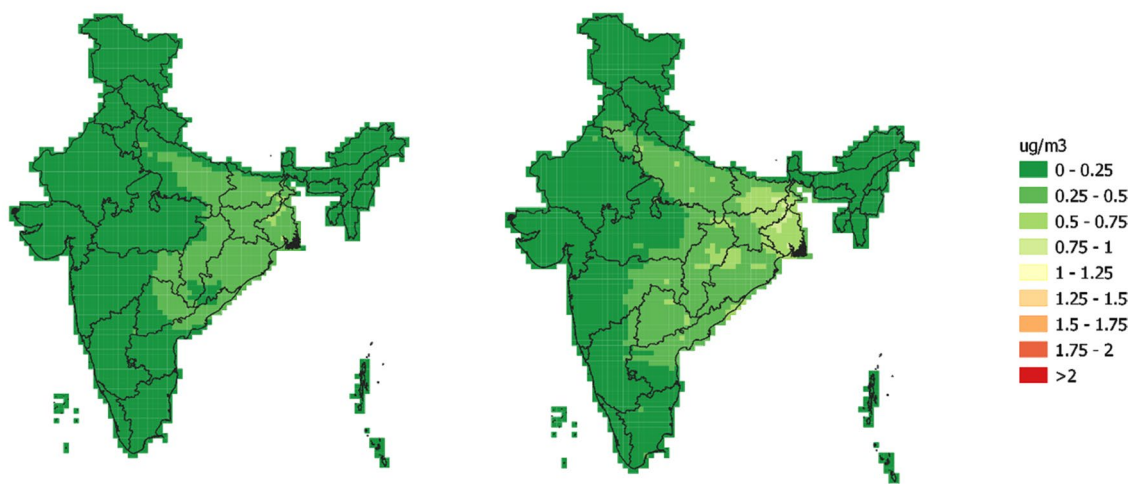


Fig. 3 PM_{2.5} concentration due to RAC—INDC+ICAP+NCAP policy results in two growth scenario

and air pollutants could be alarming. Compounding this, a large number of its urban areas already breach national ambient air quality standards. Consequently, augmenting RAC-associated emissions from coal-powered plants will not only increase India's GHG contributions but will also exacerbate the already subpar air quality.

In this context, the importance of energy efficiency emerges as paramount, especially within the RAC sector. A study (Phadke et al. 2014) underscores this, indicating a potential energy savings of roughly 100 TWh by 2030 through strategic energy efficiency measures in the RAC sector. To provide some perspective, this saving is tantamount to averting the need for 100 new coal-fired power plants, each with a 500-megawatt (MW) capacity.

Future RAC stocks and energy consumption

RAC Stock Projections: The outcome of regression modeling predicts a robust increase in RAC stock in India for the upcoming decades. Specifically, by 2046, under a standard reference scenario, the RAC stock could witness a rise to over 265 million units. This figure is nearly seven-fold compared to the stock in 2017. However, when we consider a more ambitious or “aspirational” scenario, the RAC stock exhibits even steeper growth, potentially touching 402 million units by 2046. This represents a ten-fold increase compared to the 2017 figures.

Energy consumption forecasts

The energy demand of RACs under various scenarios—namely FT, S&L, and ICAP was thoroughly examined. The FT scenario, which posits no substantial technological advancement, anticipates a surge in power demand within the RAC sector of over 400% in the reference context. This would mean an escalation from 56 GW in 2017 to an overwhelming 289 GW by 2046. However, the projections under the S&L and ICAP scenarios are more optimistic. Both these scenarios project diminished power demands due to the implementation of energy-efficient technologies. By 2046, the ICAP scenario anticipates a drop in power demand to 187 GW and 283 GW for reference and aspirational settings, respectively, when contrasted against the FT scenario. Fast forwarding to 2037, the tail-end of the ICAP policy duration, both the S&L and ICAP scenarios predict impressive energy consumption reductions—30% and 54%, respectively. This reduction surpasses the ICAP's stipulated goal, which aims for a 25–40% reduction in cooling energy demands in the RAC sector. Under the ICAP scenario, when set against the S&L scenario, the energy conserved equates to the generation capacity of 225 and 149 power plants of 500 MW each for the reference and aspirational scenarios, respectively.

Figure S2 graphically represents the projected electricity demands for the RAC sector at the generation end. Notably, under the ICAP scenario, the forecast indicates a significant drop in electricity consumption. By 2046, we can anticipate a reduction of 299 TWh in the reference scenario and an even more substantial decrease of 453 TWh in the aspirational scenario when compared to the FT scenario.

This sharp decline in electricity demand, as visualized in the ICAP scenario, underscores the transformative potential of adopting energy-efficient measures in the RAC sector. It not only results in energy conservation but also paves the way for countries, especially developing nations like India, to effectively achieve their INDCs. Moreover, this aligns with India's commitment to the global environmental cause, reinforcing its dedication to the stipulations of the Paris Agreement.

Emissions of GHGs and air pollutants

Emission models provided the foundation for our calculations of CO₂ and air pollutants (namely PM_{2.5}, NO_x, and SO₂) emanating from power generation tailored for RACs. Through these models, the electricity demands estimated for distinct scenarios were translated into equivalent GHG emissions (expressed in CO₂ equivalents (CO₂e)). Indirect emissions from the RAC sector, resultant from fossil fuel-driven electricity production, were charted across various economic growth and energy efficiency scenarios, as seen in Figure S3. The baseline emissions in 2017 from the RAC sector in India are estimated to be 62.72 MT of CO₂e. Under the FT energy scenario, this is projected to increase to 138.7 MT (+221%) and 210.3 MT (+335%) in reference and aspirational growth scenarios by 2046, respectively. The rate of GHG increase will plateau after 2040 due to the enhanced energy efficiency of the new RAC stocks. Even in the aspirational growth scenario, India's RAC-based CO₂e emissions will peak in 2044 to 211.1 MT, in the most pessimistic energy efficiency (FT) scenario, while in the optimistic ICAP scenario, it will peak early in the year 2036 to the level of 88.2 MT.

The S&L energy scenario shows a decrease of about 39% in GHG emissions (CO₂e) with respect to the FT scenario in 2046, under both the growth scenarios. By 2046, the ICAP scenario shows a massive decrease of 64.7% with respect to the FT energy scenario.

Moreover, factoring in power generation, coal type, and efficiencies of emission control, emissions of key air pollutants associated with the RAC sector were estimated. PM_{2.5} emissions play a direct role in elevating primary ambient PM_{2.5} concentration levels. Concurrently, SO₂ and NO_x function as precursors, fostering secondary particulate formation that in turn also contributes to PM_{2.5} concentrations. For the year 2017, the RAC sector's emissions in India for PM_{2.5}, NO_x, and SO₂ were tallied at 10.83, 101.2, and

244.81 kT/year respectively. Our findings point to a surge in PM_{2.5} emissions by 4.4-fold and 6.7-fold in reference and aspirational scenarios respectively between 2017 and 2046. Both the S&L and ICAP models present the advantage of diminished air pollutant emissions tied to the RAC sector. When matched against the FT scenario, reductions of 40% and 60% are projected for 2046 under the S&L and ICAP models. In the same year, the reference growth scenario under all three models (FT, S&L, and ICAP) projects 44–48% lower pollutant emissions compared to the aspirational growth scenarios. For a comprehensive view of emission trends under S&L and ICAP, Figure S4 offers more detailed insights.

Co-benefits of energy efficiency, climate change, and air pollution control programs

Three parallel initiatives are running in India, which have implications by the RAC sector: cooling sector energy efficiency improvement, climate change mitigation, and air pollution control. ICAP aims to reduce energy consumption from RACs. National Plan for Climate Change (NAPCC) envisions an enhanced share of renewables in power generation (INDC), which indirectly reduces GHG (and hence, air pollutant) emissions attributable to the RAC sector. Similarly, the National Clean Air Program (NCAP) plans to adopt stringent power plant air pollutant emission standards (NCAP 2019) and can help to reduce the RAC sector air pollutant emissions.

As its commitment through its first INDCs, India plans to enhance the share of non-fossil-based sources in its power generation to 40% by the year 2030 (MoEFCC 2015). In 2017, India was using 20% non-conventional energy sources to produce energy (Energy Statistics 2019), and it needs to cut CO₂e further by 20% to meet INDC goals. This INDC scenario, even in the pessimistic FT scenario, shows an additional reduction of ~20% air pollutant loads in both economic growth scenarios. INDC scenario integrated with S&L and ICAP scenarios show a 40–61% decrease with respect to the FT scenario.

Stringent emission control standards for coal-based power plants will require the installation of control devices such as selective catalytic reduction and flue-gas desulphurization, causing a 50%, 80%, and 90% reduction in PM_{2.5}, NO_x, and

SO₂ emissions from stacks calculated using GAINS ASIA Model. These reductions are considered to create the NCAP scenario, which when integrated with the S&L and ICAP, shows a 40–60% reduction, with respect to FT scenario. The NCAP scenario individually indicates a decrease of 37%, 74%, and 87% for PM_{2.5}, NO_x, and SO₂ emissions, respectively, with respect to INDC scenario in all three FT, S&L, and ICAP control technology cases for the year 2046. Refer to Table S1 for actual emissions of PM_{2.5}, NO_x, and SO₂ for 2046 and 2017 used to analyze the above data.

Impact of RAC on ambient PM_{2.5} concentrations and associated health impacts

Pollutant emissions are fed into the CMAQ model to estimate ambient PM_{2.5} concentrations over India, validated for different cities against actual observations in 2017 (Figure S4). Using the model, the India-wide annual average population-weighted PM_{2.5} concentrations are estimated to be 58.4 µg/m³ for 2017. Based on the contribution of RACs to power generation, the contributions by the RAC sector in the ambient PM_{2.5} concentration are estimated to be 0.19 µg/m³ (0.33%). We found that the spatial distribution of PM_{2.5} concentrations is uneven due to the locations of power plants and meteorological influences. The highest contribution of the RAC sector in annual average PM_{2.5} concentrations is 0.72 µg/m³ in the states of Bihar and Jharkhand. In West Bengal, the highest concentration attributable to the RAC sector reached 1.33 µg/m³ in January. In the aspirational growth FT scenario, the India-wide and spatial-peak annual concentration attributable to the RAC sector will increase to 1.49 and 10.23 µg/m³ in 2046, respectively.

ICAP and S&L can reduce the India-wide PM_{2.5} annual averages by 40% and 60%, respectively, with respect to base case. Individually, the INDC and NCAP scenarios can further reduce the concentrations by 20% and 50%, respectively, in 2046 with respect to the base case. Table 1 shows the estimated PM_{2.5} concentrations attributable to the RAC sector in different scenarios, and Figure S6 shows the spatial plots of India in these scenarios.

Using established dose–response relationships, we estimated about 0.82 millions mortalities in India attributable to ambient PM_{2.5} exposures in 2017, which is close to the estimates of Balakrishnan et al. (2019). The share of the

Table 1 Estimated PM_{2.5} (µg/m³) concentrations attributable to the RAC sector in India in different scenarios in the year 2046

Scenarios	Reference			Aspirational		
	FT	S&L	ICAP	FT	S&L	ICAP
Base	1.04 (7.10)	0.61 (4.16)	0.41 (2.79)	1.49 (10.23)	0.89 (6.08)	0.60 (4.14)
INDC	0.82 (5.62)	0.48 (3.26)	0.32 (2.16)	1.19 (8.17)	0.70 (4.81)	0.47 (3.24)
NCAP	0.52 (3.55)	0.30 (2.08)	0.20 (1.40)	0.75 (5.12)	0.44 (3.04)	0.30 (2.07)

*Note—Values are India averaged for 2046 with peak PM_{2.5} value in India written inside bracket

RAC sector in population-weighted PM_{2.5} concentrations in different scenarios has been used to estimate mortalities attributable to the RAC sector. We estimate that out of 0.82 millions mortalities, 5748 mortalities were attributable to the RAC sector in 2017. The mortalities are projected to increase in the two growth scenarios (FT reference and aspirational scenarios) to 39,072–58072 by 2046. S&L and ICAP scenarios can reduce the estimated mortalities to 22,749 and 15,224 compared with the FT scenario (reference growth) and 34,219 and 23,182 (in aspirational growth). In the best possible scenario, an overlap of ICAP, NCAP, and INDC, a reduction of 33,047 and 49,043 mortalities can be seen in reference and aspirational scenario with respect to FT scenario.

Integration of energy efficiency, climate, and air pollution control programs

We find that the energy efficiency (ICAP), climate change control (INDC), and air pollution control (NCAP) programs individually provide benefits in terms of reduction of GHG and pollutant emissions. However, integrating them can show enhanced benefits from the RAC sector. For the RAC sector, we estimated that combining the three, GHG emissions are reduced by 136 MT (~65%), PM_{2.5} emissions by 60%, PM_{2.5} concentrations from 1.50 to 0.60 $\mu\text{g}/\text{m}^3$, and mortalities attributable to RAC sector by 49,043 (about 84%) in 2046, with respect to the aspirational growth-FT scenario. Spatial maps of air pollution due to RAC with all 18 scenarios are presented in Figure S6. Spatial maps of India for the year 2046 with integrated energy efficiency, climate change control, and air pollution together for economic growth scenarios are presented in Fig. 3.

Implications of the global scenario

To understand the implications of the growth of the RAC sector in developing countries in the global scenario, we

made a comparison of RAC demand, average efficiency ratings of RAC, CO₂e emissions from the electricity/heating sector, and PM_{2.5} emissions from the power sector for different countries (as shown in Table 2). We found that India has comparatively low RAC demand per million people presently. However, the absolute numbers are close to the whole of the European Union. China has ~1.6 times more RAC demand than the other four regions combined, while Japan has the highest RAC demand per million people. The average efficiency rating in India is comparatively lower than the rest of the lot, which is expected to improve by 2037 with the help of the ICAP mandate, making India at par with the rest of the world. This mandate makes ICAP essential, and there is a need for its faster implementation. Due to dependence on coal, the absolute CO₂e emissions from the power sector in India are more than that of Japan and close to the EU but are still much lower in terms of per capita levels. India has higher PM_{2.5} emissions from power sector than the USA, EU, and Japan but lesser than China, showing the dependence on high ash coal (Amann et al., 2011). High per capita RAC demand in China and low average efficiency ratings in India could lead to high CO₂e emissions and PM_{2.5} emissions from the existing coal-based power plants in these two countries. The controls at power stations can be improved, reducing PM_{2.5} emissions even if coal is continued. However, to reduce CO₂ and local pollution, faster adoption of renewables is the way to go.

Discussion and conclusion

This study looks at the expected rise in air conditioning units in India, a trend that mirrors global increases as cities expand and living standards go up. This growth presents challenges, particularly in terms of energy consumption and meeting climate change targets, like challenges faced by other developing countries. The study highlights the critical role of enhancing energy efficiency in air conditioners, notably

Table 2 International Scenario of AC's efficiency and Power sector emissions

Country	RAC demand (2017)		Average efficiency ratings (2020)	CO ₂ e emission from Electricity/Heating sector (2017)		PM _{2.5} emissions from Power sector (2015)	
	Total (thousand)	Thousand RAC/million people		Total (MtCO ₂ e)	tCO ₂ e/capita	Total (kT)	tPM _{2.5} /million people
USA	7958	24.48	4.2	2064.52	6.35	56.9	175.01
China	43,487	31.39	4.4	4904.12	3.54	836.7	603.97
Japan	8924	70.41	5.2	589.35	4.65	14.8	116.77
Europe	5943	13.30	5.3	1161.54	2.6	NA	NA
India	5138	3.82	3.2	1157.77	0.86	521.6	387.45
Reference	JRAIA (2019)		IEA (2020)	Climate Watch Historical GHG Emissions (2021)		Amann et al. (2011)	

through initiatives like the ICAP. Such improvements are recognized as key to reducing climate impact and cutting down fossil fuel reliance for energy. It also points out that adopting these energy efficiency measures could lead India to significantly lower its GHG emissions and pollution from air conditioners, aligning with the Paris Agreement's climate change mitigation goals. These conclusions support existing research advocating for the shift towards cleaner, more efficient technologies for environmental benefits. Health is another important aspect covered in the study, showing that reducing air conditioner pollution could improve air quality and result in fewer health issues and pollution-related deaths. This discussion is part of a larger conversation on how energy policies can greatly affect public health. Furthermore, the study compares India's situation with that of other countries, highlighting India's unique challenges and opportunities in improving air conditioner efficiency and reducing emissions. This comparison underscores that this issue is global, encouraging international cooperation and shared learning to tackle these challenges. In summary, the anticipated increase in air conditioning units in India is expected to have considerable impacts on energy use, the environment, and health. However, focusing on making air conditioners more efficient, this study presents a viable solution to these challenges, offering insights that are relevant not just for India but for other countries facing similar situations.

This study determined that RAC systems contributed 4.86% in share of India's power sector, and 0.29% in total ambient $PM_{2.5}$ concentrations in 2017. This contribution is associated with approximately 5,748 mortalities in India, attributable to pollutant emissions from power plants catering to the electricity demands of the RAC sector. Projections indicate a significant increase in the pollutant contribution from the RAC sector, potentially enhancing climate and human health impacts. Past studies have indicated a variety of climate and health impacts linked to enhanced GHG emissions, emissions of short-lived climate pollutants and toxic air pollutants. It is anticipated that RAC units will grow by 363 million, resulting in 147.56 MT of CO_2e emissions, 84 kT of $PM_{2.5}$ emissions, and an increase of 1.49 $\mu g/m^3$ in ambient $PM_{2.5}$ levels, leading to an estimated 58,072 attributable mortalities by 2046 (FT scenario in aspirational growth).

India has taken three key independent initiatives aimed at improving energy efficiency in the cooling sector, mitigating climate change, and controlling air pollution. The IEEAHM was utilized to assess these initiatives, highlighting potential integrated strategies that could yield co-benefits in terms of reduced air pollution and health impacts. The study's analysis of three scenarios (ICAP, NDC, NCAP) suggests a potential average reduction of 84% in $PM_{2.5}$ concentrations in India, which could prevent 33,047 attributable mortalities in the FT scenario under reference growth.

The study further underscores the advantages of integrating various ongoing programs focusing on energy efficiency, climate change, and air pollution control. Acknowledging the co-benefits of these programs can encourage developing countries to elevate their ambitions and implement them with greater enthusiasm and stringency. This approach may enable these countries to use cost optimization methods to identify strategies offering maximum co-benefits. Given the interconnected nature of energy efficiency, GHGs, and air pollution, synergistic effects through aerosol-climate linkages are anticipated, potentially improving health and overall quality of life. Moreover, the study indicates that incorporating ICAP alongside NCAP and NDCs holds the potential to assist the country in reaching diverse targets outlined in the United Nations' Sustainable Development Goals (SDGs). The study's analysis unequivocally demonstrates that adopting this strategic approach will contribute to the realization of SDG 3 by diminishing air pollution and fostering a healthful environment for everyone. Simultaneously, it aligns with SDG 7 by enhancing energy efficiency and facilitating access to clean, sustainable energy. Furthermore, the strategy supports SDG 13 by fortifying the national response to climate change and actively participating in global endeavours to mitigate increases in global temperatures.

Specific steps recommended for integrating plans in India or similar developing countries include:

- A detailed assessment of individual plans needs to be carried out through a joint evaluation of the nodal implementation agencies to identify key strategies which can provide significant co-benefits.
- An inter-departmental/ministerial task force needs to be formed to evaluate the cost-effectiveness and prioritize the strategies considering all possible co-benefits.
- The task force should assess the possibilities of enhancing the stringencies of actions by revising standards or timelines considering the enhanced benefits through integration.
- The task force should revise the implementation plans to work in a mission mode and regularly track the progress.
- A mass awareness program needs to be launched to make the relevant stakeholder and public aware of the co-benefits and seek their support and cooperation.
- A third-party assessment needs to be carried out to assess the overall benefits accrued and the costs saved.

Limitations of the study include the exclusion of several other potential co-benefits, such as improvements in agricultural productivity, reduced aerosol-climate impacts, and enhanced employment opportunities. Additionally, the assessment assumes uniform implementation of strategies across India, a factor that could be further refined to account for regional variations. The spatial distribution

of benefits, especially in a large country like India, may vary significantly and hence, warrants further evaluation. In future work following this research, it would be beneficial to explore regional variations in the implementation of energy efficiency strategies across India, extend the analysis to other key sectors of the economy, and investigate the long-term impacts on public health and the environment. There is also a need to assess the role of emerging technologies in enhancing energy efficiency, evaluate the effectiveness and enforcement of current policies, and conduct comprehensive cost–benefit analyses of integrated strategies. Additionally, studying the impact of public awareness on the success of these strategies, exploring the co-benefits on agricultural productivity and employment, delving into aerosol-climate linkages, and comparing India's approaches with global practices would provide deeper insights and more effective solutions for energy efficiency and pollution control. We acknowledge that a complex modeling study, like this, may have inherent uncertainties and underlying assumptions in terms of input data, modeling limitations and uncertain geopolitical global and regional scenarios. We have ensured use of the best possible published information as input data, state-of-the-art well-established models, and validated projections for this study. We agree that there could still be uncertainty in the analysis but directionally, we are confident of the results of this study and feel that the policymakers could use this for informed decision making.

In future work following this research, it would be beneficial to explore regional variations in the implementation of energy efficiency strategies across India, extend the analysis to other key sectors of the economy, and investigate the long-term impacts on public health and the environment. There is also a need to assess the role of emerging technologies in enhancing energy efficiency, evaluate the effectiveness and enforcement of current policies, and conduct comprehensive cost–benefit analyses of integrated strategies. Additionally, studying the impact of public awareness on the success of these strategies, exploring the co-benefits in agriculture and employment, delving into aerosol-climate linkages, and comparing India's approaches with global practices would provide deeper insights and more effective solutions for energy efficiency and pollution control.

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Author contribution Shivang Agarwal: Writing—original draft, Data Analysis.

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Karan Mangotra: Supervision – Cooling and GHG.

Sumit Sharma: Conceptualization, Writing—original draft, Supervision.

Data availability Availability of data and material dataset

Used as input is available on the public domain.

<https://app.cpcbcr.com/ccr/#/caaqm-dashboard-all/caaqm-landi ng/data>—Modeled AQ datasets was validated from data available on public portal of Central Pollution Control Board, India

<https://gains.iiasa.ac.at/>—Emission model

<https://github.com/USEPA/CMAQ/releases>—Air Quality model (open source) code

<https://github.com/wrf-model/WPS/releases>—Meteorology model code (open source)

Emissions data available in Singh et. al., 2021

Declarations

Competing interests The authors declare no competing interests.

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