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A complete transition to clean household energy can save one-quarter of the healthy life lost to particulate matter pollution exposure in India

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Abstract

Exposure to fine particulate matter (PM_{2.5}) is a leading contributor to the disease burden in India, largely due to widespread household solid fuel use. The transition from solid to clean fuels in households has the potential to substantially improve public health. India has implemented large initiatives to promote clean fuel access, but how these initiatives will reduce PM_{2.5} exposure and the associated health benefits have not yet been established. We quantified the impacts of a transition of household energy from solid fuel use to liquefied petroleum gas (LPG) on public health in India from ambient and household PM_{2.5} exposure. We estimate that the transition to LPG would reduce ambient PM_{2.5} concentrations by 25%. Reduced exposure to total PM_{2.5} results in a 29% reduction in the loss of healthy life, preventing 348 000 (95% uncertainty interval, UI: 284 000–373 000) premature mortalities every year. Achieving these benefits requires a complete transition to LPG. If access to LPG is restricted to within 15 km of urban centres, then the health benefits of the clean fuel transition are reduced by 50%. If half of original solid fuel users continue to use solid fuels in addition to LPG, then the health benefits of the clean fuel transition are reduced by 75%. As the exposure–outcome associations are non-linear, it is critical for air pollution studies to consider the disease burden attributed to total PM_{2.5} exposure, and not only the portion attributed to either ambient or household PM_{2.5} exposure. Our work shows that a transition to clean household energy can substantially improve public health in India, however, these large public health benefits are dependent on the complete transition to clean fuels for all.

1. Introduction

Fine particulate matter (PM_{2.5}) exposure is a leading contributor to disease burden in India, associated with 8% (95% uncertainty interval, UI: 7–9%) of healthy life lost (disability-adjusted life years, DALYs) (India State-Level Disease Burden Initiative Air Pollution Collaborators 2019). The majority of the air pollution disease burden in India is from ambient PM_{2.5} (APM_{2.5}) exposure (55% of DALYs), with

a substantial contribution from household PM_{2.5} (HPM_{2.5}) exposure (41% of DALYs) (GBD 2017 Risk Factor Collaborators 2018). Household solid fuel use is also the dominant source (22–56%) of APM_{2.5} concentrations in India (Chafe *et al* 2014, Lelieveld *et al* 2015, Butt *et al* 2016, Silva *et al* 2016, Karagulian *et al* 2017, Conibear *et al* 2018, Guo *et al* 2018, GBD MAPS Working Group 2018, Gao *et al* 2018, Upadhyay *et al* 2018, Reddington *et al* 2019, Chowdhury *et al* 2019a). The implication is that more than half of the loss of

healthy life associated with air pollution exposure in India is attributed to household solid fuel use (GBD 2017 Risk Factor Collaborators 2018).

Incomplete combustion of solid fuels leads to substantial emissions of toxic air pollutants (Naeher *et al* 2007, Gordon *et al* 2014, Adetona *et al* 2016). Epidemiological studies have found that a transition from solid to clean fuels in Indian homes can improve respiratory and cardiovascular outcomes (Arlington *et al* 2019, Sukhsohale *et al* 2013, Lewis *et al* 2017, Hystad *et al* 2019, Balmes 2019). Up until 2015, 700 million people across India primarily used solid fuels, a number that has not changed for several decades (Smith 2017a). Residential solid fuel use includes a wide range of fuels including firewood, charcoal, and animal dung. Past solid fuel interventions in India, such as the National Programme on Improved Chulhas and the National Biomass Cookstoves Initiative, focused on clean and efficient combustion of biomass in 'improved cookstoves' (Venkataraman *et al* 2010, Smith and Sagar 2014). However, the penetration of these stoves remained lower than aimed (Smith 1993, Hanbar and Karve 2002, Government of India 2011) and the emission reductions of these improved cookstoves are more limited in the field than laboratory studies suggest (Sambandam *et al* 2015, Aung *et al* 2016, Pope *et al* 2017, Grieshop *et al* 2017).

Since 2015, three programmes have promoted liquefied petroleum gas (LPG) access to poor households (Mittal *et al* 2017). The Pratyaksh Hanstantrit Labh scheme directly pays fuel subsidies into individuals bank accounts (Smith 2017b, Ministry of Petroleum and Natural Gas 2018c). The Pradhan Mantri Ujjwala Yojana scheme aims to provide connections to distributors and enable access to subsidised LPG to 80 million poor households by 2020 (Dabadge *et al* 2018, Goldemberg *et al* 2018, Ministry of Petroleum and Natural Gas 2018a, 2018b, 2019). The 'Give it up' scheme aims to persuade middle-class households to give up their fuel subsidies which are then redirected to poor households (Government of India 2018). The combined aims of these programmes are to provide clean cooking to 80% of all households by 2019, and 90% by the early 2020s (Goldemberg *et al* 2018). The Ujjwala scheme's aim to provide LPG access to 80 million poor households was achieved ahead of schedule in September 2019. The Ujjwala scheme is now in hiatus with a updated version in development (Harish and Smith 2019). Following these programmes, and the continued growth of LPG use for the middle-class without subsidies, the number of solid fuel users is likely to decline.

The transition to clean household energy has the potential to substantially improve public health in India, dependent on access and usage (Gould and Urpelainen 2018, Tripathi and Sagar 2019, Kar *et al* 2019, Pattanayak *et al* 2019, Harish and Smith 2019). Access is essential and these LPG programmes have overcome various access issues, such as supply

chain distribution problems, connections, and financial access for many. Access alone is not sufficient for a complete transition to clean household energy, as continued usage is required replacing solid fuel use. Usage issues, such as continual affordability, awareness, and stacking with solid fuels, can be common after access is achieved, potentially offsetting public health benefits (Lewis and Pattanayak 2012, Rehfuess *et al* 2014, Pillarisetti *et al* 2014, Lozier *et al* 2016, Clark *et al* 2017).

The potential of these LPG programmes to reduce total PM_{2.5} (TPM_{2.5}, i.e. APM_{2.5} and HPM_{2.5}) exposure and the associated disease burden have not yet been established. We used a regional chemical transport model with a novel residential emission inventory to explore how hypothetical transitions to clean household energy could change TPM_{2.5} exposure and the loss of healthy life under different access and usage scenarios. We do not attempt to evaluate the impact of specific ongoing clean household energy programmes.

2. Methods

2.1. Model description

Simulations were conducted using the Weather Research and Forecasting model online-coupled with Chemistry (WRF-Chem) version 3.7.1 (Grell *et al* 2005), incorporating various model improvements, including updated anthropogenic emissions, aqueous chemistry, and a more complex secondary organic aerosol scheme. Detailed information on the model setup is provided in supplementary table 1 (stacks.iop.org/ERL/15/094096/mmedia) and the supplementary methods. Simulations were for the year of 2016 with one month spin-up. The model domain covered South Asia at 30 km (0.3°) horizontal resolution.

Anthropogenic emissions of black carbon (BC), organic matter (OM), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NO_x), other PM_{2.5}, and sulphur dioxide (SO₂) for residential biomass (wood, dung, and crop residues for cooking, space heating, and water heating), residential LPG (including biogas), residential kerosene, and residential lighting are for 2010 from a new residential inventory for India (Lam and Bond 2020). These emissions were produced at 1 km spatial resolution based on village surveys of energy services required, then aggregated to 0.25° × 0.25° horizontal resolution. Emission factors for the residential sector were completely reassessed to include field-measured emission factors that have recently become available. Residential kerosene use is diminishing in India without the need for further incentives.

Anthropogenic emissions of BC, organic carbon (OC), NMVOC, NO_x, other PM_{2.5}, and SO₂ for open burning, power plant coal (thermal), industrial coal (heavy and light), brick production, transportation

Table 1. Household energy scenarios (Lam and Bond 2020).

Scenario	Description
BASELINE	A counterfactual scenario representative of 2015 before these LPG programmes begun. Household solid fuel use based on energy use characteristics with emissions informed by village and town data in the 2011 census and other sources (Government of India 2011, Lam and Bond 2020).
ALLLPG	Energy services currently met with biomass were completely replaced by fuels with LPG-equivalent energy and emission characteristics for cooking, water heating, space heating services, and zero-emission electric sources for residential lighting. The residential emissions here do not account for LPG leakages at point of use or in the delivery system. This scenario reflects the theoretical potential of a complete transition to clean household energy, assuming complete coverage and adoption. We do not attempt to simulate specific LPG programmes in India. We note that there are currently no clean-fuel interventions for space, water, and fodder heating.
URB15	An access scenario, where energy transition characteristics of ALLLPG but only for households within 15 km from urban areas. This scenario considered that programmes have limited effectiveness outside of urban areas, driven by a variety of factors, including plausible access to commercially distributed fuels.
STATE50	An access scenario, where emission reductions in URB15 were applied evenly across each state. Anthropogenic emission totals were the same within the URB15 and STATE50 scenarios, but the spatial distributions were different.
EMIS50	A usage scenario, where all households were assumed to have access to LPG (as in ALLLPG) but households continued to use solid fuels 50% of the time (stacking) in addition to using LPG. Residential emissions were estimated as 50% of residential emissions from the BASELINE scenario added to the residential emissions from the ALLLPG scenario. The extent of stove stacking was a conservative approximation of the recently updated CEEW dataset of energy access across 6 Indian states (Jain <i>et al</i> 2018).

(on-road gasoline/compressed natural gas, on-road diesel, and railways), distributed diesel (agricultural tractors, agricultural pumps, and diesel generator sets), and other sources (informal industry, trash burning, and urban fugitive dust) were taken from (Venkataraman *et al* 2018) as used by the Global Burden of Disease from Major Air Pollution Sources study for 2015 at $0.25^\circ \times 0.25^\circ$ horizontal resolution (GBD MAPS Working Group 2018, Venkataraman *et al* 2018). Anthropogenic emissions of carbon monoxide (CO), ammonia (NH₃), acetylene (C₂H₂), and methane (CH₄) were from the Emission Database for Global Atmospheric Research with Task Force on Hemispheric Transport of Air Pollution version 2.2 for 2010 at $0.1^\circ \times 0.1^\circ$ horizontal resolution (Janssens-Maenhout *et al* 2015).

2.2. Household energy scenarios

To understand the impacts of interventions to replace solid fuel use with LPG, we completed annual simulations using five different emission scenarios (table 1). Household energy scenarios were split by access and usage issues, relative to a complete transition.

Figure 1 shows the annual anthropogenic emission totals from these scenarios. In the BASELINE scenario, residential biomass makes a substantial contribution to anthropogenic OC and NMVOC emissions. Power plant and industrial coal use dominate anthropogenic emissions of other chemical components of PM_{2.5}, SO₂, and NO_x. Anthropogenic dust, open burning, and trash burning contribute strongly to anthropogenic PM_{2.5} emissions. Transportation and distributed diesel contribute heavily to anthropogenic NO_x and NMVOC emissions. Under

the ALLLPG scenario, total BC emissions are reduced by 47%, and OC emissions by 77%, contributing to a 44% reduction in total primary PM_{2.5} emissions relative to the BASELINE. There are also substantial reductions in NMVOC (28%) emissions, while SO₂ and NO_x emissions are reduced by less than 2%. Applying the spatial constraint to the intervention as in URB15, resulted in half the emission reduction that was achieved in ALLLPG. The stove stacking scenario in EMIS50 resulted in similar total emission reductions to URB15, but with different spatial patterns.

2.3. Model evaluation

Model evaluation was conducted using measurements obtained from OpenAQ (OpenAQ 2019). Following Manning *et al* (2018), sites were accepted for evaluation when there was more than 16 h of data per day, more than 50 d of data, and when hourly-mean PM_{2.5} concentrations were greater than $5 \mu\text{g m}^{-3}$ (93% acceptance). Measurements were aggregated to annual-means. There were 34 OpenAQ measurement sites in India for 2016 that passed this criteria. We compared the same days in the model as there are data in the measurements. The normalised mean bias factor (NMBF) and the normalised mean absolute error factor (NMAEF) were used to evaluate the model (Yu *et al* 2006). The measurements from OpenAQ were primarily collected from the Central Pollution Control Board (Ministry of Environment and Forests 2018). To increase the sample size of measurement sites for evaluation, these were combined with the World Health Organization Global Ambient Air Quality Database for measured

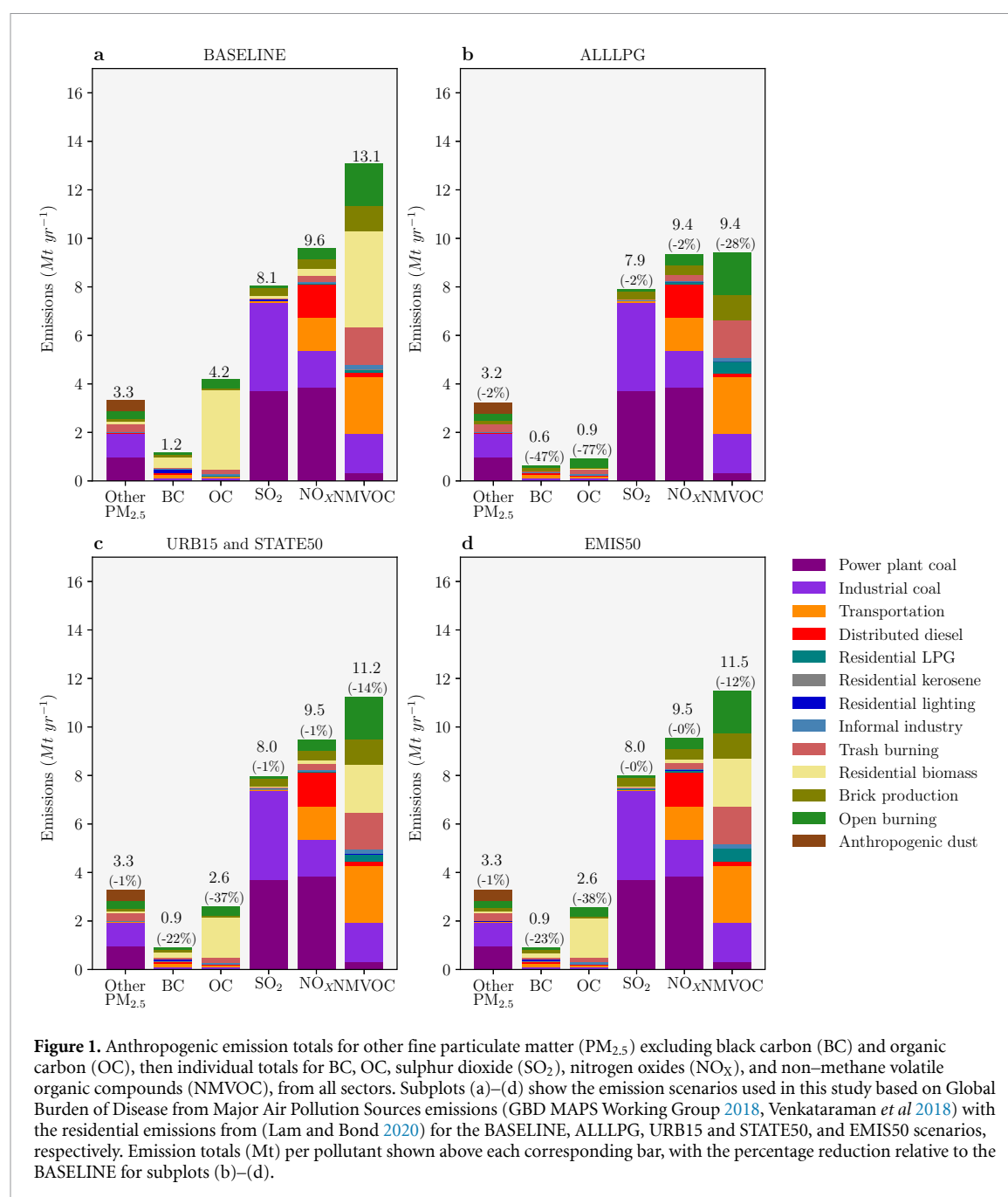


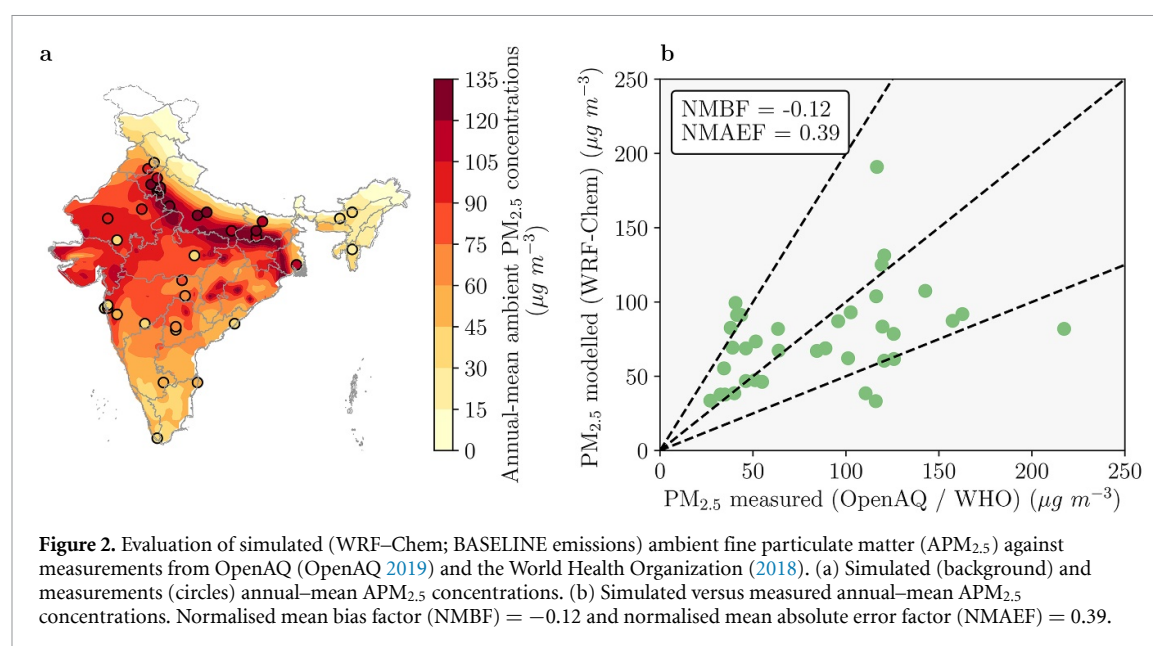
Figure 1. Anthropogenic emission totals for other fine particulate matter (PM_{2.5}) excluding black carbon (BC) and organic carbon (OC), then individual totals for BC, OC, sulphur dioxide (SO₂), nitrogen oxides (NO_x), and non-methane volatile organic compounds (NMVOC), from all sectors. Subplots (a)–(d) show the emission scenarios used in this study based on Global Burden of Disease from Major Air Pollution Sources emissions (GBD MAPS Working Group 2018, Venkataraman *et al* 2018) with the residential emissions from (Lam and Bond 2020) for the BASELINE, ALLLPG, URB15 and STATE50, and EMIS50 scenarios, respectively. Emission totals (Mt) per pollutant shown above each corresponding bar, with the percentage reduction relative to the BASELINE for subplots (b)–(d).

annual-mean PM_{2.5} concentrations in 2016 (World Health Organization 2018).

The model captures the spatial variation and magnitude of annual-mean APM_{2.5} concentrations across India, with greatest concentrations over the Indo-Gangetic Plain (figure 2). The model slightly underestimates observed APM_{2.5} concentrations (NMBF = −0.12 and NMAEF = 0.39). Our previous work used a similar model configuration and similarly underestimated measured APM_{2.5} concentrations (Conibear *et al* 2018a). Overall, the simulated APM_{2.5} concentrations show adequate skill to address questions of relative change in long-term APM_{2.5} concentrations over India.

2.4. Health impact assessment

All the health impact assessments were for the same year (2015) to remove confounding influences of changing population size, population age, and baseline mortality rates. The health impact assessment estimated the disease burden attributable to PM_{2.5} exposure using population attributable fractions (PAF). Intervention-driven variations in exposure were used to predict associated variations in outcome. This study followed the approach of the Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) 2017 (GBD 2017 Risk Factor Collaborators 2018). The GBD2017 apportioned the disease burden attributable to TPM_{2.5} between APM_{2.5}



and HPM_{2.5} for solid fuel users and non-solid fuel users following relationships in supplementary table 2. The proportional PAF allowed for the individual disease burdens to be additive, due to the joint effects of APM_{2.5} and HPM_{2.5} being considered on single integrated exposure-response (IER) function per disease. The primary metrics used in the health impact assessment are the annual number of premature mortalities (MORT) and the rate of DALYs per 100 000 population, i.e. the total loss of healthy life. Detailed information on the methodology for the health impact assessment for APM_{2.5} and HPM_{2.5} are in the supplementary methods, where supplementary figure 1 shows the HPM_{2.5} concentrations and supplementary figure 2 shows the IER. The epidemiological data underlying health impact assessments are rapidly developing and a range of uncertainties remain (see supplementary methods). Recent developments to the IER for GBD2017 allow a better understanding of the combined impacts of household and ambient PM_{2.5} exposure. As the main results of this paper are comparative, future epidemiological developments that influence the absolute disease burdens will not impact the comparative lessons drawn from this paper.

3. Results and discussion

3.1. Current disease burden associated with PM_{2.5} exposure in India

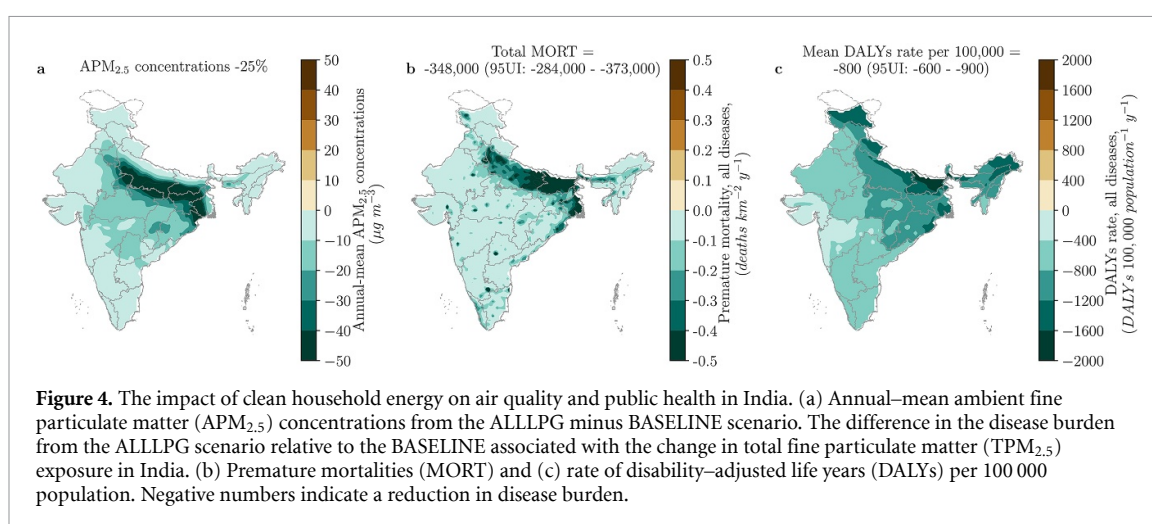
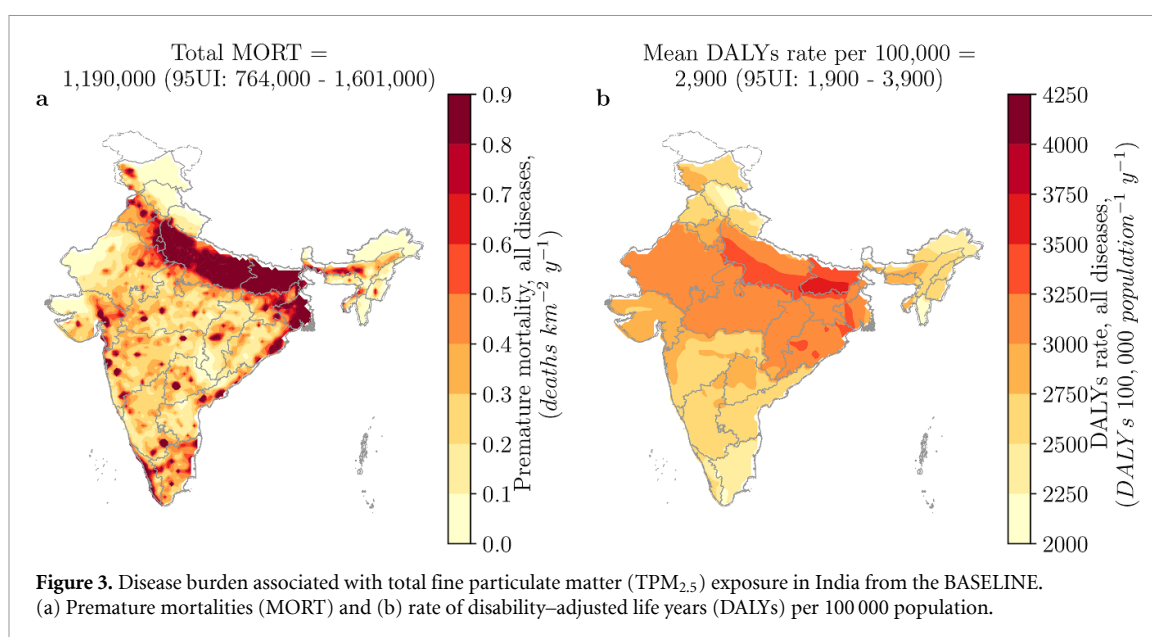
We calculated annual-mean population-weighted APM_{2.5} concentrations of 75.4 $\mu\text{g m}^{-3}$. This estimate is lower than the annual-mean measured APM_{2.5} concentrations (90 $\mu\text{g m}^{-3}$, figure 2(b)) and the latest GBD (91 $\mu\text{g m}^{-3}$, GBD 2017 Risk Factor Collaborators 2018), but higher than Chowdhury *et al* (2019b) (55 $\mu\text{g m}^{-3}$) (supplementary figure 3). We estimated annual-mean population-weighted HPM_{2.5}, based

on data from Shupler *et al* (2018), of 248.6 $\mu\text{g m}^{-3}$, 178.9 $\mu\text{g m}^{-3}$, and 216.2 $\mu\text{g m}^{-3}$ for females, males, and children, respectively.

Figure 3 shows the disease burden associated with TPM_{2.5} exposure under the BASELINE scenario. We estimated 1 190 000 (95UI: 764 000–1 601 000) premature mortalities per year associated with TPM_{2.5} exposure, with 44% from APM_{2.5} exposure and 56% from HPM_{2.5} exposure. The DALYs rate associated with TPM_{2.5} exposure was 2900 (95UI: 1900–3900) per 100 000 population, with 45% from APM_{2.5} exposure and 55% from HPM_{2.5} exposure. The individual disease burdens associated with APM_{2.5} and HPM_{2.5} exposure are shown in supplementary figures 4 and 5, respectively.

Our estimates for the disease burden associated with TPM_{2.5} exposure are slightly larger (+5% for MORT) than those from the GBD2017 (Institute for Health Metrics and Evaluation 2019). This is the result of our larger estimated disease burdens associated with HPM_{2.5} exposure (+31% for MORT), and smaller estimates of disease burdens associated with APM_{2.5} (-17% for MORT). The larger disease burden estimates associated with HPM_{2.5} exposure are due to our use of higher HPM_{2.5} exposures and the state-specific solid fuel use, both with higher estimates in the densely populated Indo-Gangetic Plain. Overall, our disease burden estimates associated with PM_{2.5} exposure in India are in general agreement with those from the GBD2017.

The health impact assessment was also estimated for ambient ozone (O₃) exposure, following the methodology of the GBD2017 (supplementary figure 6 and supplementary methods). The model underestimated O₃ concentrations (NMBF = -0.40 and NMAEF = 0.49), though the magnitude of the bias is similar to many regional modelling studies over India



(supplementary figure 7 and supplementary methods). We found no difference between the disease burden estimates across the five scenarios. Hence, we focus on the public health impacts associated with TPM_{2.5} exposure.

3.2. Public health benefits of clean household energy

A complete transition to clean household energy (i.e. ALLLPG relative to BASELINE) reduced APM_{2.5} concentrations by 25% (population-weighted from 75.4 $\mu\text{g m}^{-3}$ to 56.4 $\mu\text{g m}^{-3}$, annual-mean) as shown in figure 4(a). Improvements in air quality occur across India, with the largest reductions in pollution across the Indo-Gangetic Plain. The 25% reduction in APM_{2.5} concentrations found here is similar to the 24% reduction estimated by the GBD MAPS Working Group (2018) with similar emissions. Previous studies estimated that a complete removal of residential emissions, without any replacement fuel, would

lead to a 22–56% reduction in APM_{2.5} concentrations (Chafe *et al* 2014, Lelieveld *et al* 2015, Butt *et al* 2016, Silva *et al* 2016, Karagulian *et al* 2017, Conibear *et al* 2018, Guo *et al* 2018, GBD MAPS Working Group 2018, Gao *et al* 2018, Upadhyay *et al* 2018, Reddington *et al* 2019, Chowdhury *et al* 2019a).

We estimate that a complete transition to clean household energy would prevent 29% of the present-day disease burden associated with PM_{2.5} exposure, preventing 348 000 (95UI: 284 000–373 000) premature mortalities each year (figure 4). A complete transition to LPG reduces DALYs by 800 (95UI: 600–900) per 100 000 population.

Chowdhury *et al* (2019b) found a complete transition to household LPG in India could reduce the number of premature mortalities associated with APM_{2.5} exposure by 13%, where the population-weighted APM_{2.5} concentrations reduced by 31% to 38 $\mu\text{g m}^{-3}$. We find that a complete transition to clean household energy can reduce the disease burden associated with TPM_{2.5} by 29%, when the

Table 2. The impacts of clean household energy on air quality and public health in India. Total primary fine particulate matter (PM_{2.5}) emissions per year (Mt yr⁻¹). Annual-mean, population-weighted, concentrations from ambient fine particulate matter (APM_{2.5}) and household fine particulate matter (HPM_{2.5}). Disease burden estimates for premature mortalities (MORT, annual-sum) and rate of disability-adjusted life years (DALYs, annual-mean) per 100 000 population for PM_{2.5} pollution (APM_{2.5}, HPM_{2.5}, and TPM_{2.5}). Results per scenario of BASELINE, ALLLPG, URB15, STATE50, and EMIS50. Values in parentheses represent the 95% uncertainty intervals.

Scenario		BASELINE	ALLLPG	URB15	STATE50	EMIS50
Total primary PM _{2.5} emissions (Mt yr ⁻¹)		8.8	4.9	6.9	6.9	6.9
APM _{2.5} (μg m ⁻³)		75.4	56.4	66.3	66.4	65.9
HPM _{2.5} (μg m ⁻³)	Female	248.6	0.0	129.6	140.8	136.3
	Male	178.9	0.0	93.3	101.3	98.1
	Child	216.2	0.0	112.8	122.5	118.5
APM _{2.5}	MORT	522 000 (327 000–716 000)	842 000 (481 000–1 228 000)	686 000 (408 000–974 000)	584 000 (356 000–813 000)	570 000 (349 000–790 000)
	DALYs rate per 100 000	1300 (800–1800)	2100 (1200–3100)	1600 (1000–2200)	1500 (900–2100)	1400 (900–2000)
	MORT	668 000 (438 000–885 000)	0 (0–0)	352 000 (232 000–465 000)	510 000 (325 000–689 000)	527 000 (332 000–716 000)
HPM _{2.5}	DALYs rate per 100 000	1600 (1000–2100)	0 (0–0)	1100 (700–1500)	1200 (800–1700)	1200 (800–1700)
	MORT	1 190 000 (764 000–1 601 000)	842 000 (481 000–1 228 000)	1 038 000 (640 000–1 440 000)	1 094 000 (681 000–1 502 000)	1 097 000 (681 000–1 506 000)
	DALYs rate per 100 000	2900 (1900–3900)	2100 (1200–3100)	2600 (1700–3700)	2700 (1700–3700)	2700 (1700–3700)

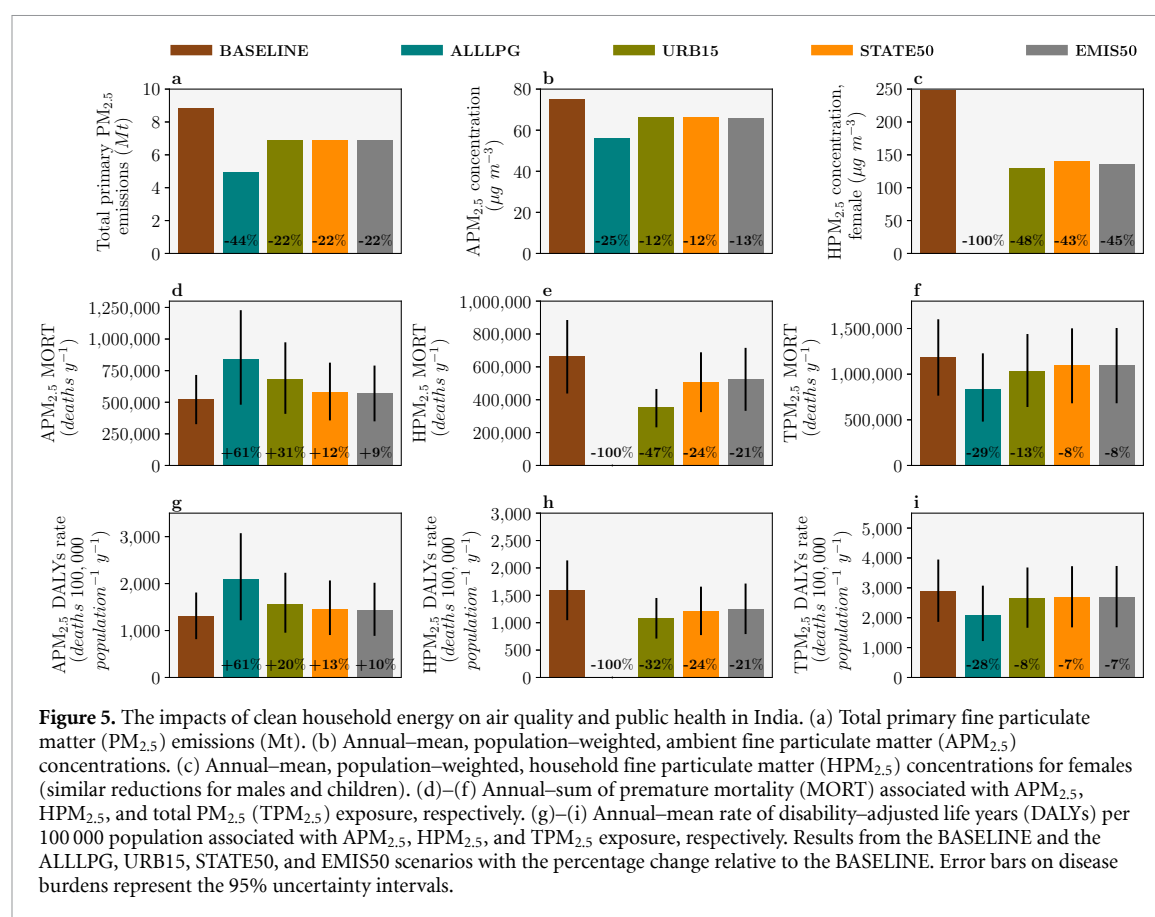
population-weighted APM_{2.5} concentrations reduce by 25% to 56.4 μg m⁻³. A key finding of Chowdhury *et al* (2019b) is that a transition to clean household energy would allow India to meet the National Ambient Air Quality Standard of 40 μg m⁻³. While we found a similar percentage reduction in APM_{2.5} concentrations, annual-mean APM_{2.5} concentrations in India remained above the National Ambient Air Quality Standard due to higher baseline population-weighted APM_{2.5} concentrations (75.4 μg m⁻³ relative to 55 μg m⁻³). The key novelties of our study are the consideration of TPM_{2.5} exposure to account for the joint risks between APM_{2.5} and HPM_{2.5} exposure, and the use of a high spatial resolution (1 km) residential emission inventory based on village surveys of energy services required. As we account for TPM_{2.5} exposure, the disease burden estimates associated with APM_{2.5} exposure are not directly comparable to those from Chowdhury *et al* (2019b). Despite these differences, our study confirms the major findings of Chowdhury *et al* (2019b), namely that a complete transition to clean household energy can substantially improve public health in India.

3.3. Incomplete transition to clean household energy

Table 2 and figure 5 summarise the impacts of different household energy scenarios on air quality and public health at the national scale in India. Detailed data per state are provided in the Supplementary Data.

An incomplete transition to clean household energy might be limited by spatial access to LPG distribution (i.e. URB15 relative to ALLLPG). This transition, which reaches 80% of the population, nevertheless reduces the potential health benefits of a clean fuel transition by about 50%. Under this scenario, APM_{2.5} concentrations are reduced by 12%, in contrast to the 25% reduction in the complete transition. This incomplete transition to clean household fuels results in a 13% reduction in total premature mortality, compared to a 29% reduction in the complete transition to clean fuels. Spatial constraints on access to LPG, falling under the category of ‘distribution potential’ (Lam and Bond 2020), therefore reduce the avoided premature mortalities by 197 000 (95UI: 160 000–211 000) per year. This scenario also reduces the avoided DALYs by 600 (95UI: 400–600) per 100 000 population (supplementary figure 9).

If emission reductions are spread evenly among remote rural areas compared with urban centres (i.e. STATE50 relative to URB15), the national-mean APM_{2.5} concentrations are also reduced by 12%. The spatial distribution of emission reductions means that APM_{2.5} concentrations under STATE50 are larger in urban areas (up to + 15 μg m⁻³ in Delhi) and smaller in rural areas (up to – 15 μg m⁻³ in Uttar Pradesh and Bihar) relative to URB15 (supplementary figure 10(a)). The disease burden from TPM_{2.5} exposure under STATE50 increases by 5% relative to URB15, and the number of premature mortalities increases by 55 000 (95UI: 41 000–62 000) per year (supplementary figure 10(b)). This increase is the net of two opposing changes: a 45% increase in the disease



burden from $HPM_{2.5}$ exposure under STATE50 relative to URB15, because all households using solid fuels under the BASELINE retain some solid fuel use in STATE50, and a 15% decrease in the disease burden from $APM_{2.5}$ exposure caused by reduced emissions in high-population urban areas. The dominating role of $HPM_{2.5}$ is due to the proportional PAF and the non-linear IER, where large $HPM_{2.5}$ exposures under STATE50 drive large disease burdens from $TPM_{2.5}$ exposure. Comparing STATE50 to ALLLPG, where remote rural areas have relatively small emission reductions, the health benefits of the clean fuel transition are reduced by approximately 75%. The implication here is that in addition to reaching remote rural areas, the reductions in $HPM_{2.5}$ exposure need to be substantial.

Stove stacking with solid fuels (i.e. EMIS50 relative to ALLLPG) reduces the public health benefits of a clean fuel transition by approximately 75%. Under the stove stacking scenario, $APM_{2.5}$ concentrations are reduced by 13%, compared to 25% in the complete transition. Stove stacking reduces the number of avoided premature mortalities by 255 000 (95UI: 201 000–278 000), and reduces the avoided DALYs by 600 (95UI: 500–700) per 100 000 population (supplementary figure 11). The implication of these constraints, coupled to the non-linear IER where risk decreases substantially at the lowest $TPM_{2.5}$ concentrations, suggests that large public health benefits are

possible, but only if there is a nearly complete and exclusive transition to clean household energy.

A key implication of these results is that it is critical for air pollution studies of residential emissions to consider the disease burden attributed to $TPM_{2.5}$ exposure, and not only the portion of $TPM_{2.5}$ attributed to either $APM_{2.5}$ or $HPM_{2.5}$ exposure. This is important because the exposure–outcome associations are non-linear and the joint effects of $APM_{2.5}$ and $HPM_{2.5}$ are proportional. This means that as the disease burden attributed to $HPM_{2.5}$ exposure decreases, the disease burden attributed to $APM_{2.5}$ exposure can increase, and vice versa. For example, under the BASELINE scenario 522 000 (95UI: 327 000–716 000) premature mortalities were attributed to $APM_{2.5}$ exposure, while under the ALLLPG scenario this attribution increased to 842 000 (95UI: 481 000–1 228 000) premature mortalities, despite a 25% reduction in $APM_{2.5}$ exposure. This increased attribution to $APM_{2.5}$ exposure when $HPM_{2.5}$ exposure is removed is due to the non-linear exposure–outcome association, where both $APM_{2.5}$ and $HPM_{2.5}$ exposures are individually high enough so that the relative risk is in the flatter section of the response (supplementary figure 2). Hence, a slightly lower total risk from $TPM_{2.5}$ exposure is now entirely attributed to $APM_{2.5}$ exposure, rather than being attributed approximately evenly between $APM_{2.5}$ and $HPM_{2.5}$ exposures. The importance of these joint

effects are also demonstrated by the variation in frequency distributions between the URB15, STATE50, and EMIS50 scenarios (supplementary figure 8). All three scenarios have similar frequency distributions of $APM_{2.5}$ exposure (supplementary figure 8(a)), however, they vary in $HPM_{2.5}$ exposures (supplementary figure 8(b)) which drives variations in the overall disease burden associated with $TPM_{2.5}$ exposure (supplementary figure 8(f)), and the corresponding attribution between $APM_{2.5}$ and $HPM_{2.5}$ exposure (supplementary figure 8(d) and 8(e)). The importance of integrating $APM_{2.5}$ and $HPM_{2.5}$ exposures in India and other areas of high residential solid fuel use has been emphasised in previous studies (Balakrishnan *et al* 2014, Aunan *et al* 2018). High residential solid fuel use leads to large $HPM_{2.5}$ exposures and substantial source contributions to $APM_{2.5}$ exposures, whereby the reduction of residential emissions is an important equity issue in India (Kathuria and Khan 2007, Cowling *et al* 2014).

3.4. The importance of a complete transition to clean household energy

We showed that the transition to clean household energy has the potential to reduce the disease burden associated with $PM_{2.5}$ exposure by 29%, preventing 348 000 (95UI: 284 000–373 000) premature mortalities every year. These potential public health benefits are dependent on the complete transition to clean fuels. Limited spatial access to LPG reduced health benefits by 50%, and stove stacking with solid fuels reduced health benefits by 75%. This dependency of public health benefits on a complete transition to clean fuels has been seen in India (Pillarisetti *et al* 2014, 2018, Hanna *et al* 2016, Smith 2017a, Aung *et al* 2018).

To complete the transition to clean household energy and provide these substantial public health benefits, remaining access and usage issues need to be overcome (Gould and Urpelainen 2018, Tripathi and Sagar 2019, Kar *et al* 2019, Pattanayak *et al* 2019, Harish and Smith 2019). These include extending access to all, especially the most remote, poor, and vulnerable (Harish and Smith 2019), increasing refill rates (Jain *et al* 2018, Pillarisetti *et al* 2019), improving continual affordability (Harish and Smith 2019, Tripathi and Sagar 2019), and improving awareness of the need for continual use of clean fuels (Smith 2018, Harish and Smith 2019). The complete transition to clean household energy may also provide multiple benefits to sustainable development, human wellbeing, the climate, ecosystems, and the economy (Smith and Haigler 2008, Wilkinson *et al* 2009, Venkataraman *et al* 2010, Smith *et al* 2014, Bailis *et al* 2015, World Health Organization 2016, Rosenthal *et al* 2018).

We explored how hypothetical transitions to clean household energy could change air pollution exposure and the consequent change in associated health

outcomes. We did not attempt to evaluate the impact of specific clean energy programmes. The isolated impacts of exposure change were quantified by holding demographics and background mortality rates constant. To directly assess effectiveness of specific air quality policies to improve human health, causal epidemiology study designs will be required once the policies are complete and the appropriate data is available (van Erp *et al* 2012, Zigler and Dominici 2014, Zigler *et al* 2016, Boogaard *et al* 2017, Burns *et al* 2019). Exposure–outcome differentials and effect modification among equity groups are important future research topics for air pollution studies in India.

4. Conclusion

We quantified the impacts of a nationwide transition from household solid fuel to LPG in India on the total loss of healthy life. We used WRF–Chem simulations to estimate that the transition to clean household energy would reduce ambient $PM_{2.5}$ concentrations by 25%. Reduced total $PM_{2.5}$ (ambient and household) exposure results in an estimated 29% reduction in the loss of healthy life, preventing 348 000 (95UI: 284 000–373 000) premature mortalities every year. These health benefits are contingent on a complete transition to LPG. If access to LPG is restricted to within 15 km of urban centres, corresponding to 80% of the national population, then the health benefits of the clean fuel transition are reduced by 50%. If half of original solid fuel users continue to use solid fuels in addition to LPG, health benefits of the clean fuel transition are reduced by 75%. As the exposure–outcome associations are non-linear, it is critical for air pollution studies of residential emissions to consider both ambient and household $PM_{2.5}$ exposures. Our work shows that a transition to clean household energy can substantially improve public health in India, but the large public health benefits are dependent on reaching a complete transition to clean household fuels.

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Contributions

LC, DVS, SRA, EWB, and TCB designed the research. KT and CV provided disaggregated emissions from the Global Burden of Disease from Major Air Pollution Sources project and the shapefile for India. TCB and NL provided residential emissions. CK provided WRFotron, a tool to automatize WRF–Chem runs with re-initialised meteorology. LC pre-processed model inputs, setup the model, performed the model simulations, performed the model evaluation, derived the exposure–outcome functions, conducted the data analysis and interpretation, created the figures, and wrote the manuscript. All authors commented on the manuscript.

Data availability

Air pollution and health impact assessment data per Indian state that support the findings of this study are included in the Supplementary Data for this article. Code to setup and run WRF–Chem (using WRFotron version 2.0) is available through Conibear and Knot (2020). Further data that support the findings of this study are available upon request from the authors.

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