Accelerating the Health Benefits of Scaling Clean Household Energy in India

A State-wise Cost-Effectiveness Analysis

— July, 2024

Vital Strategies

Authorship

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Abbreviations

ABODE	Air Pollution Burden of Disease Explorer
ANC	Antenatal Care
COPD	Chronic Obstructive Pulmonary Disease
DALY	Disability-Adjusted Life Years
GDP	Gross Domestic Product
HAP	Household Air Pollution
HAPIN	Household Air Pollution Intervention Network
HH	Households
LPG	Liquified Petroleum Gas
PM	Particulate Matter
PMUY	Pradhan Mantri Ujjwala Yojana
WHO	World Health Organization

Executive Summary

Direct exposure to household air pollution from cooking and heating with solid fuels caused more than ten lakh (1000,000) deaths in India in 2021. In addition, household air pollution remains a leading source of ambient air pollution across the country, affecting people in rural areas and negatively affecting air quality in urban areas. Sustained, near exclusive use of clean household energy is required to substantially reduce exposures to household air pollution in order to promote public health at the population level.

Since its inception, the Pradhan Mantri Ujjwala Yojna (PMUY) program, government's flagship effort to scale clean household energy for poor people, has ushered in unprecedented liquified petroleum gas (LPG) access. At the same time, many households continue to rely on solid fuel for household energy needs. To maximize the health benefits of scaling clean household energy, we must move beyond a focus on access to identifying strategies to facilitate the near-exclusive uptake and sustained use of clean household energy, in both individual households and at the community level.

In this context, we designed and conducted a strategic set of analyses, the results of which may be used to facilitate sustained provision of clean household energy for those currently not using LPG exclusively. Using the best available health and exposure evidence, we explore various subsidy options to promote sustained LPG use. We also present state-wise health and economic impacts of each scenario.

Key findings and recommendations

- There is a public health imperative to accelerate increased uptake and sustained use of clean and safe cooking energy in India. Using the Air Pollution Burden of Disease Explorer tool (ABODE) and India-specific data inputs, we estimated the numbers of avoidable deaths expected with exclusive LPG use by PMUY households as well as households that currently have no access to LPG. **If these households use LPG exclusively, even without addressing the presence of other major sources of air pollution present in the community, over 150,000 deaths could be averted in a single year.** This includes deaths averted due to reduction in household exposure as well as improvements to ambient air quality as a result of cutting down household emissions.

- The largest health gains stem from preventing infant mortality due to low birth weight, followed by COPD deaths in people over 60 years of age.
- Nearly half of the mortality and morbidity burden from household pollution stems from four states: Uttar Pradesh, Bihar, Madhya Pradesh and West Bengal. Focusing on these states alone could save nearly 100,000 lives annually.
- **Targeted subsidies for pregnant women are not only cost-effective, but also yield substantial health and economic gains (cost-benefit ratio <1, indicating a net positive economic benefit.**

Given that household pollution is one of the major sources of ambient $PM_{2.5}$[1], exclusive LPG use has the potential of lowering ambient concentrations considerably, making both national guidelines as well as World Health Organization's health-based standards more achievable for individual states.

[1] Particles that are 2.5 microns or less in diameter

Overview

Direct exposure to household air pollution from cooking and heating with solid fuels caused over ten lakh (1000,000) deaths in India in 2021 (State of Global Air, 2024). In addition, household air pollution remains a leading source of ambient air pollution across India, not only affecting people in rural areas, but also negatively affecting air quality in urban areas. Sustained, near-exclusive use of clean household energy is required to substantially reduce exposures to household air pollution to promote public health at the population level.

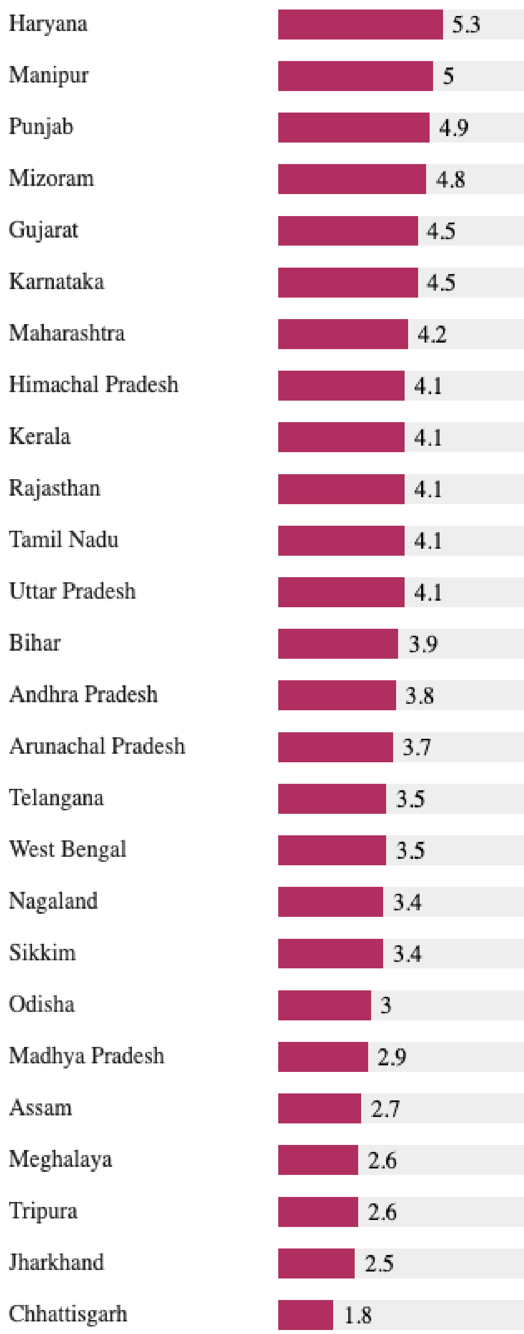


Figure 1. PMUY refill rates in 2021

As the first step toward eliminating household air pollution in India, the Pradhan Mantri Ujjwala Yojana (PMUY) program provided unprecedented access to liquefied petroleum gas (LPG) to over 10 crore (100 million) households.[2]

To date, however, in the absence of continued provision of clean fuel subsidies, clean household energy use has not increased or been sustained among poor households, likely due to a complex range of implementation, household and community factors (Kar et al., 2020). While there are substantial variations in state-level consumption patterns (Figure 1), the national average refill rate among PMUY users was just under four cylinders in 2021. It should be noted that the average annual urban consumption of LPG, representing near-exclusive use, is generally estimated to be

[2] https://www.pmuy.gov.in/about.html

somewhere between seven and eight cylinders per household, suggesting that an average PMUY household continues to rely on biomass to meet more than half of its energy needs. Financial shocks from COVID-19 and rising LPG prices further run the risk of dampening the momentum of continued access and use (Das and Biswas, 2023). In light of these factors, in the absence of a continued investment in targeted fuel subsidies, the sustained, near-exclusive use of clean household fuels such as LPG among poor people will not be a feasible goal.

To maximize the health benefits of scaling clean household energy, we must move beyond a focus on access and work toward identifying strategies to facilitate the near-exclusive uptake and sustained use of clean household energy, in both individual households and at the community level. Building on the success demonstrated through the national program, a few states have considered whether they may be able to further facilitate increased access and sustained use of LPG by providing targeted subsidies.

In this context, we designed and conducted a strategic set of analyses, the results of which may be used to devise strategies to facilitate sustained provision of clean household energy for those currently not using LPG exclusively. We selected a discrete set of potential subsidy scenarios, and conducted national and state-level analyses to estimate 1) the differential health benefits to be achieved under each scenario and 2) the cost-effectiveness expected with each subsidy scheme. Health benefits from reduced exposure to air pollution at the household level (via impact on individual exposures) as well as the community level (via impact on ambient air pollution) have been considered. We also assessed the most appropriate regions and demographics to be prioritized, with a focus on identifying groups where 1) implementation of subsidy schemes may be more practical to facilitate and 2) provision of extended clean fuel subsidy would lead to the most health gains. We present our findings and recommendations alongside a rich and growing evidence base in support of improving affordability of clean fuels to promote sustained use.

Approach

Our state-wise analysis includes PMUY households, i.e. those who already have access, but do not use it exclusively, as well as those households who still lack access to LPG (Figure 1)[3]. We excluded non-PMUY households that have some access to LPG, as these data are not available for analysis at the state level. We've excluded union territories from the analysis for simplicity and some states (Jammu and Kashmir, Uttarakhand) due to non-availability of data. As Figure 2 reveals, despite wide PMUY coverage, most Indian states have a substantial number of non-PMUY households that completely rely on biomass. This group of households likely reflects the most extreme scenario in terms of clean energy transition.

Through our analysis, we attempt to understand what it would take for all these households to use LPG exclusively, to quantify the resulting health benefits, and to estimate the cost-effectiveness of different subsidy scenarios.

Subsidy scenarios tested

We tested four subsidy scenarios representing different approaches to encouraging increased use of LPG:

1. **A_{Full}: Provision of full subsidy for eight annual refills for all households.** We assume the price for each 14.2 kg cylinder is ₹1100 (($13.18)
2. **$A_{Partial}$: Provision of partial subsidy for eight annual refills for all households.** The goal of this option is to increase the affordability of LPG refills, with cylinders available at a subsidized cost of ₹500 (cost of the subsidy would be ₹600 per refill).
3. **P_{Full}: Provision of full subsidy for eight annual refills for all households with pregnant women.**
4. **$P_{Partial}$: Targeted partial subsidy for eight annual refills for households with pregnant women.**

[3]Representative state-level data was unavailable for Chhattisgarh and North-eastern states regarding households that have no access to LPG, so we used national averages for urban and rural areas and scaled it to urban and rural proportions for each of these states.

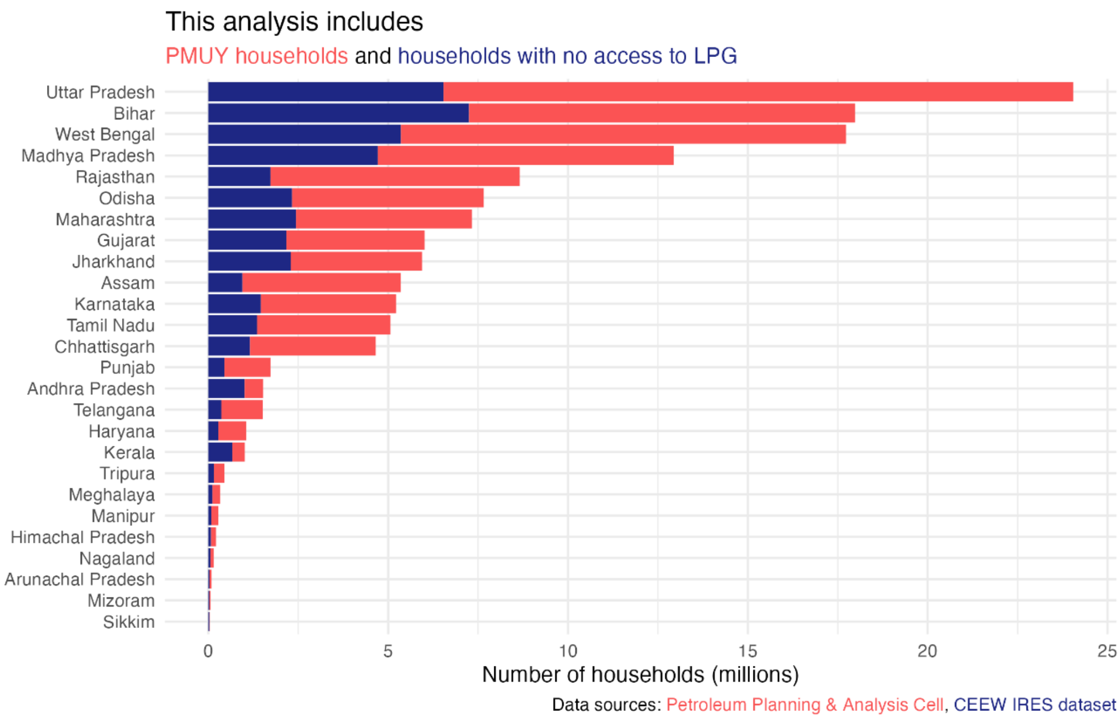


Figure 2. Households included in this analysis

Estimating changes in exposure

Pre-intervention exposures were calculated by multiplying state-wise modeled kitchen concentrations with a personal/kitchen exposure ratio (Shupler et al., 2018). Recent results from the HAPIN trial in Tamil Nadu show that exclusive LPG use brought down personal exposure by 83% (Johnson et al., 2022). We used this value to calculate the post-intervention concentrations for all states (i.e. multiply state-wise pre-intervention concentrations by 0.27). State-wise ambient exposure data were derived from Guttikunda & Nishadh, 2022.

The complete table for all data sources utilized in the analysis is provided in the Appendix.

Estimating health impacts

We used a modeling tool, ABODE version 1.0.0, to estimate direct health benefits associated with transition to exclusive LPG use. ABODE, short for Air Pollution Burden of Disease Explorer, estimates changes in morbidity and mortality due to interventions designed to lower exposures to household air pollution of members of households currently using unclean fuels. The tool incorporates background disease rates and relationships between exposure to $PM_{2.5}$ and health outcomes consistent with the Institute for Health

Metrics and Evaluation's (IHME) 2017 Global Burden of Disease and Comparative Risk Assessment efforts. We assume that the background disease rates for India apply to all the states. Background disease and mortality rates were based on national level estimates, adjusted for population size at the state level.

The health gains in form of deaths and disability-adjusted life years (DALYs) averted are estimated for lower respiratory infection in children and adults and for six diseases in adults: chronic obstructive pulmonary disease (COPD), ischemic heart disease, lower respiratory infection, lung cancer, stroke, and Type 2 diabetes mellitus. We chose estimates of illness and death from the lower end of uncertainty bounds to ensure conservative estimates of benefits.

While ABODE is designed to generate national level estimates, for state-specific estimates we used state-specific inputs, i.e., number of households, exposure estimates, etc. See the Appendix for more details.

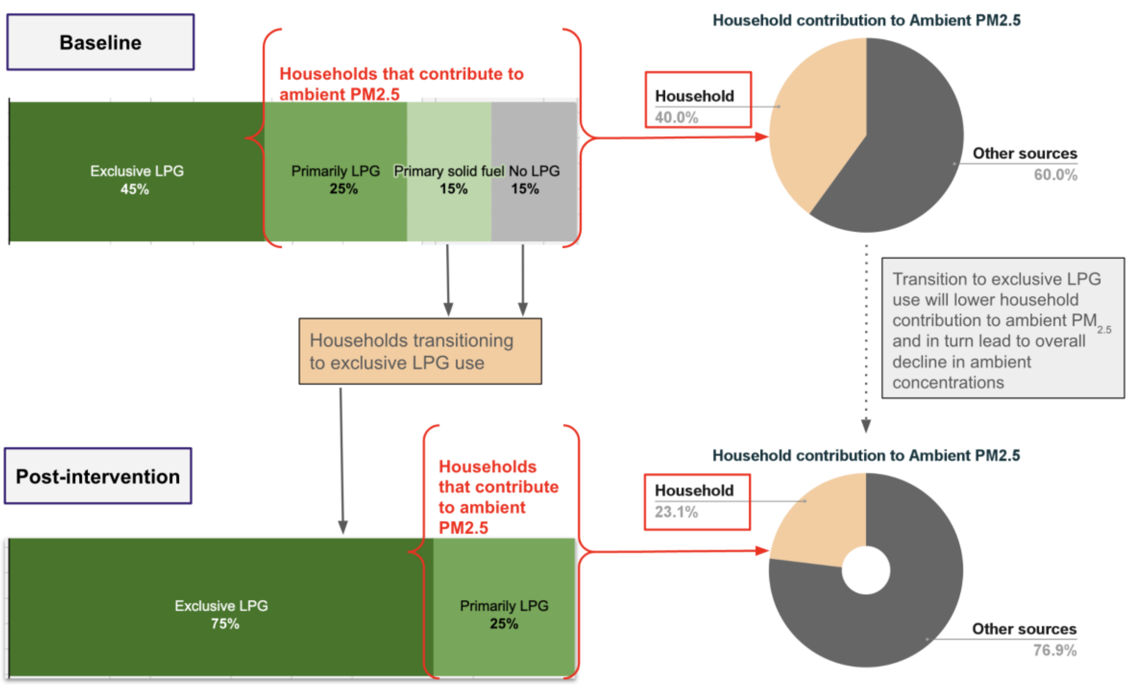
We also account for indirect impacts of reduction in household exposure on infant mortality. Modeling studies suggest that higher birth weight due to reduced household air pollution exposure would reduce infant mortality by 4 to 11 deaths per 1,000 births (Steenland, 2018). We used state-wise antenatal care (ANC) registration data and considered the number of registered pregnant women to be equivalent to the number of potential live births (a conservative estimate). To stay within uncertainty bounds, we also used a fairly conservative estimate of 5 infant deaths averted per 1,000 births in case of exclusive LPG use. We assume that each infant death averted represents 35 years of life lost, i.e., about half of the average life expectancy at birth in India, equivalent to 35 DALYs. We use a conservative approach here as well, similar to picking the infant death estimates to minimize uncertainty and to not overestimate the benefits.

We did not quantify deaths averted from other serious long-term health consequences prevented through reducing effects of household air pollution exposure, child growth and development, and burns.

Estimating ambient air pollution impacts

We estimated the changes in ambient concentration as a result of exclusive LPG use by estimating the reduction in fraction of household contribution to ambient concentrations for each state and scaled that to additional deaths averted (Chatterjee et al., 2023).

A simplified illustrative example of state-wise calculation is presented in Box 1. Here, we assume that 40% of a state's average ambient $PM_{2.5}$ results from household sources (estimates vary from 20% to 40%). Assuming that 45% of households use LPG exclusively, the remaining 55% of households would be responsible for the household contribution to ambient $PM_{2.5}$. These households either rely primarily on LPG (25%), rely primarily on solid fuels (15%), or completely rely on solid fuels (15%). Of these households, our analysis includes the latter two groups—households that primarily or completely rely on solid fuels, i.e., PMUY households, and households without LPG access. In our illustrative example, these households represent nearly half of the households that contribute to ambient concentrations. If a state's ambient $PM_{2.5}$ concentration is 50 μg/m^3, and 40% of it, i.e., 20μg/m^3 comes from household sources, exclusive LPG transition of no LPG + primary solid fuel households would lower the household contribution by ~50% and overall ambient concentrations by 22% or ~11 μg/m^3.



Box 1: Illustrated example of computing changes in household contribution to ambient $PM_{2.5}$

Estimating economic impacts

We estimated the economic benefit of the subsidies by calculating the cost per DALY averted according to Daroudi et al. (2021). Their work suggests that on average, for countries with a medium Human Development Index (HDI) (i.e. HDI ranging from 0.550 to 0.699), cost per DALY averted is 0.67 times the GDP per capita[4]. We use this estimate and state-wise GDP per capita to compute the cost-benefit ratio for each state for different subsidy scenarios. We use state-wise antenatal care (ANC) registration data for analysis of targeted subsidy scenarios.

See the Appendix for a step-by-step example of the cost-benefit analysis.

[4] According to UNDP, India's Human Development Index value in 2022 was 0.644

Findings

Exposure impacts

Transition to exclusive LPG use would dramatically decrease household exposure levels for millions of people (Figure 3). The average pre-intervention household $PM_{2.5}$ exposure concentration for all states was 180 μg/m^3 with all the states exceeding 100 μg/m^3. Applying the conversion factor from the HAPIN trial, we find that these concentrations will decline to an average of 48 μg/m^3 upon transition to exclusive LPG use. Figure 4 shows the vast disparity among the states, with Bihar having extremely high exposure levels of 460 μg/m^3. Exclusive LPG use in Bihar would bring down the concentrations to 124 μg/m^3. Except Bihar, all other states would have personal exposure concentrations lower than 100 μg/m^3 and the majority of the states would see their household exposure level decline to below 50 μg/m^3.

In the context of ambient air pollution guidelines, post-intervention exposure would fall within the national guidelines for 10 states and would be within WHO's first interim guideline of 35 μg/m^3 for seven states (nearly 43 million people).

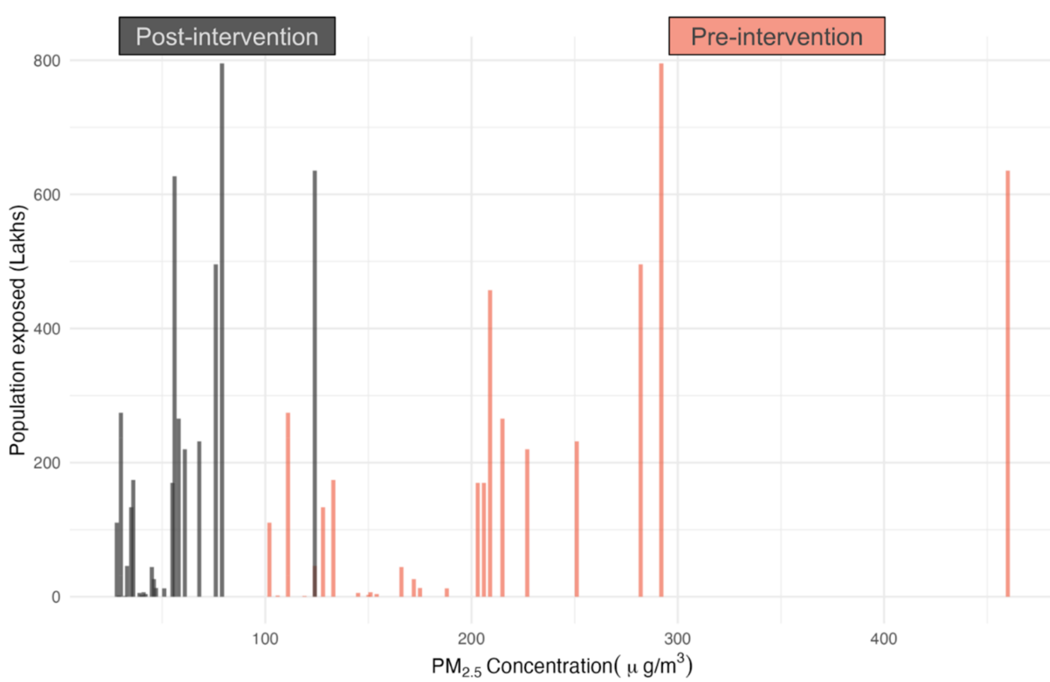


Figure 3. Changes in population distribution of household exposure

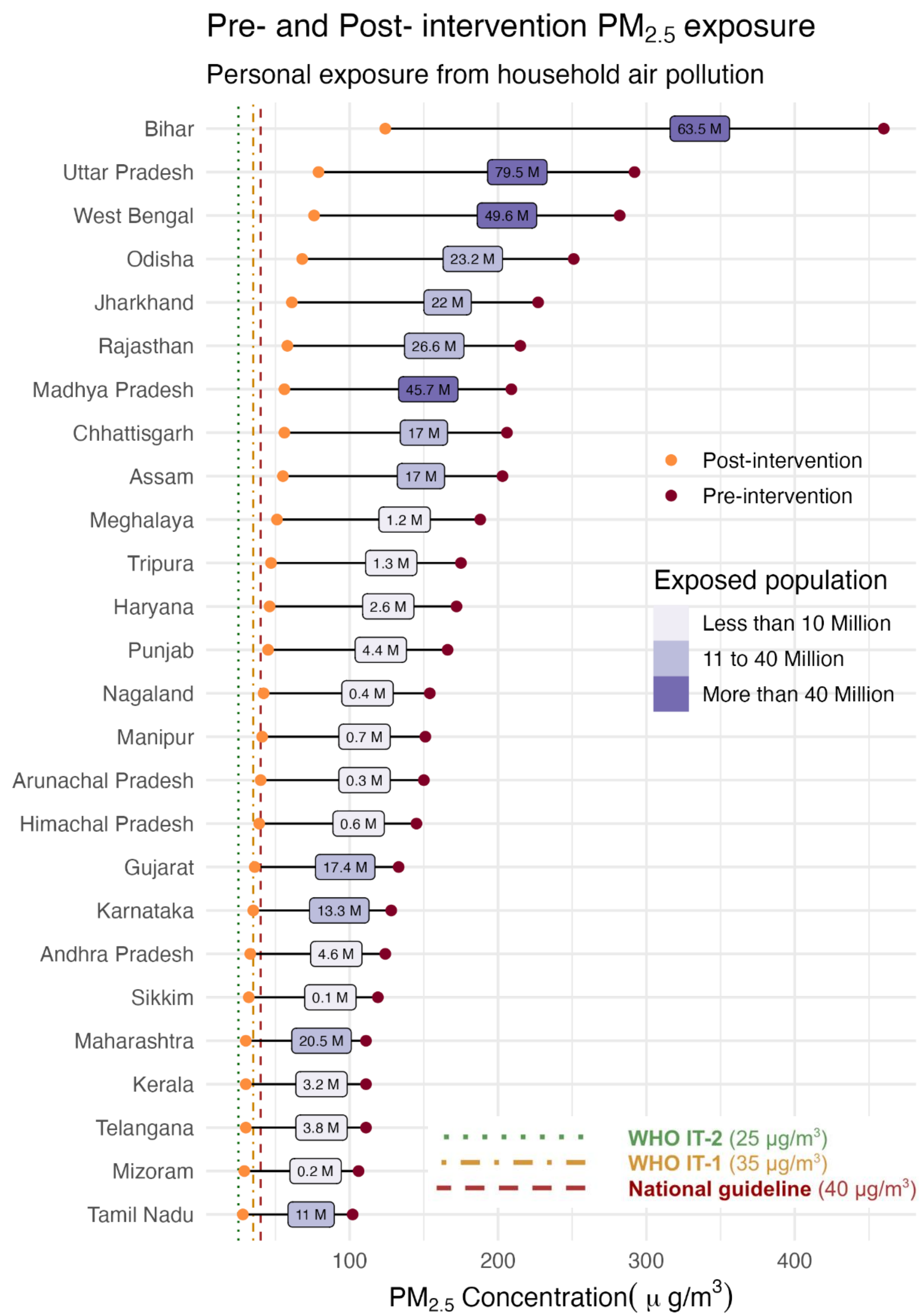


Figure 4.State-wise average personal $PM_{2.5}$ exposure from household pollution before and after transition to exclusive LPG use. Exposed population is calculated by multiplying household size by the number of households considered in this analysis.

Health Impacts

We find that complete transition to LPG for PMUY households and households with no access to LPG will result in more than 1.1 lakh (110,000) deaths averted annually (Figure 5). The grey bars represent mortality estimates derived from ABODE. The "low birth weight" deaths represent infant deaths averted due to increased birth weight associated with reduced household pollution exposure. Together, the states of Uttar Pradesh, Bihar, West Bengal and Madhya Pradesh account for more than half of the health benefits. Notably, the highest gains stem from preventing infant mortality due to low birth weight, followed by COPD deaths in people over 60 years of age (Figure 6).

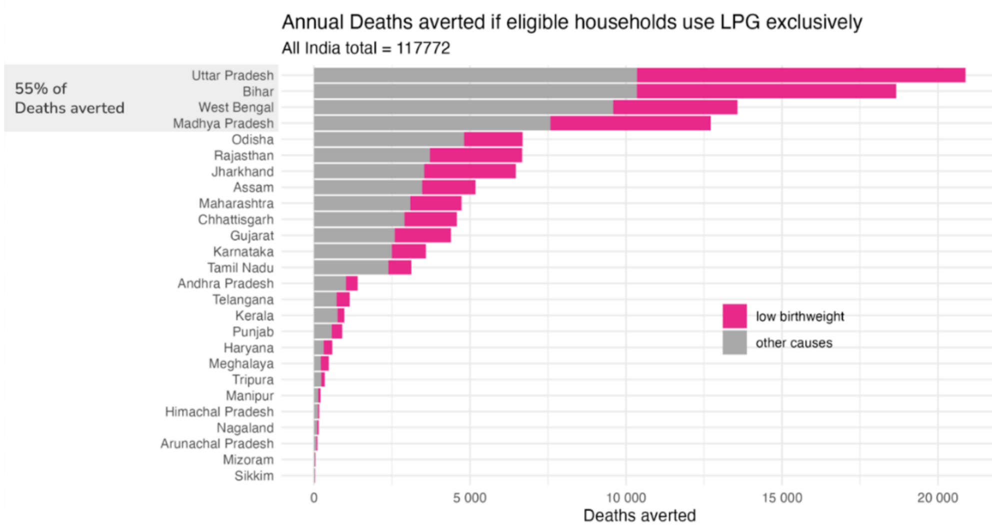


Figure 5. Annual deaths averted associated with exclusive LPG use

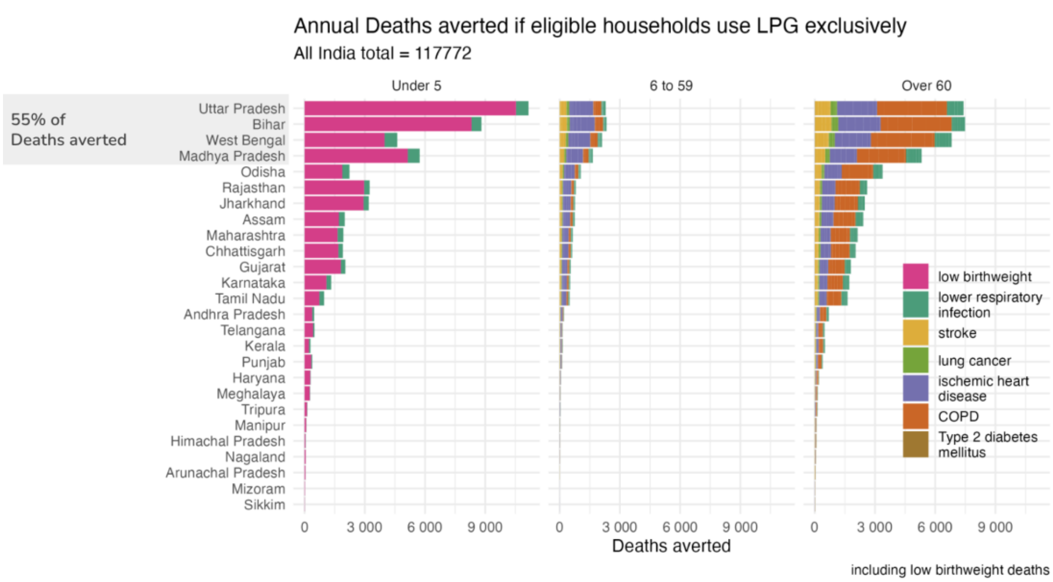


Figure 6. Annual deaths averted (by age and cause) associated with exclusive LPG use

To facilitate cost-effectiveness analysis, we also estimated DALYs averted associated with exclusive LPG use. The grey bars in Figure 6 represent DALYs derived from ABODE. The “low birth weight” DALYs represent infant deaths averted due to increased birth weight associated with reduced household pollution exposure. As seen in Figure 7, complete transition to LPG could result in an additional ~37 lakh (3.7 million) healthy person-years. Given that children have most of their life ahead of them, the highest gains in DALYs come from the under-5 age group (Figure 8).

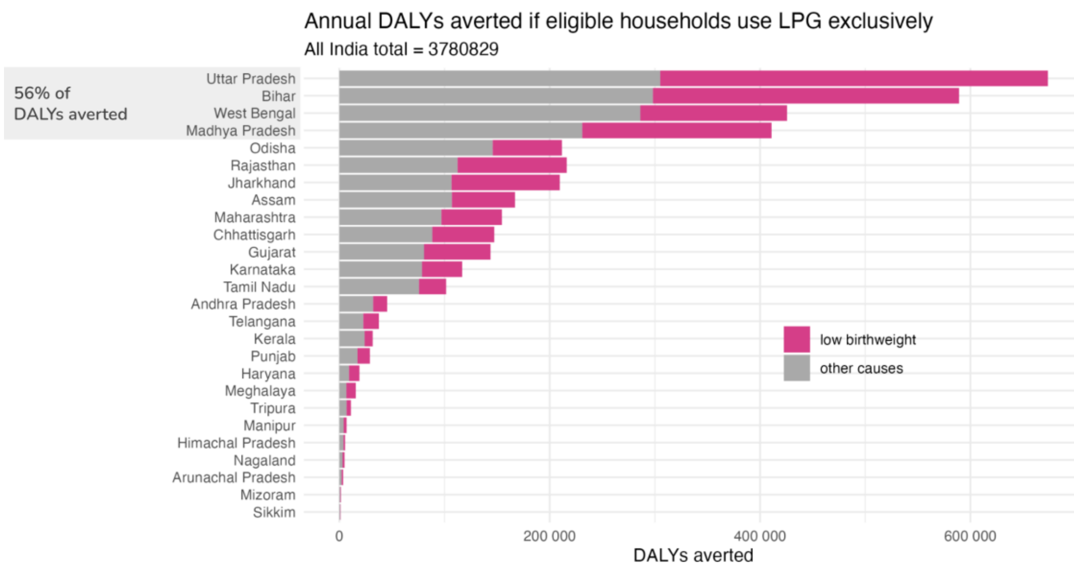


Figure 7. Annual DALYs averted associated with exclusive LPG use

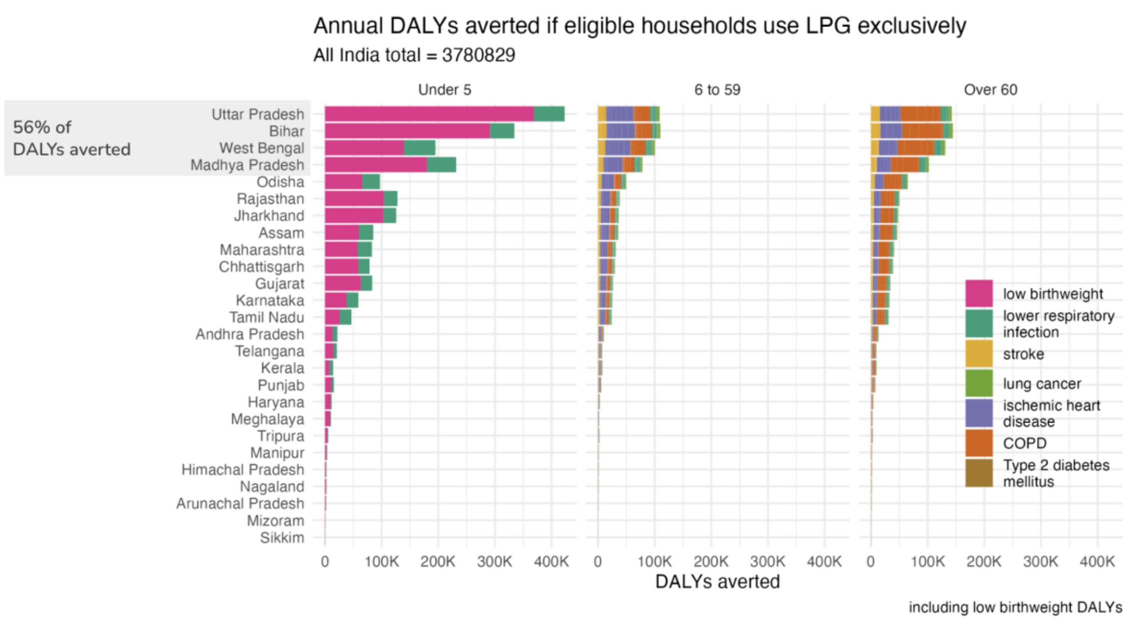


Figure 8. Annual DALYs averted (by age and cause) associated with exclusive LPG use

Cost-benefit analysis

Table 1 below presents the cost of intervention per household according to different subsidy scenarios. The intervention costs include refill costs per 14.2 kg of LPG cylinder as well as an initial connection cost for non-PMUY households. We have accounted for a one-time connection cost of ₹2000 (~24USD), which is higher than the current ₹1600 benefit covered under PMUY customers.

Subsidy scenario	PMUY Household	non-PMUY Household
A_{Full} , P_{Full} 8 cylinders x ₹1100	₹8800	₹10800 (including connection cost ~ ₹ 2000)
$A_{Partial}$, $P_{Partial}$ 8 cylinders x ₹600	₹4800	₹6800 (including connection cost ~ ₹ 2000)

Table 1: Annual cost of intervention per household

We find that all the tested scenarios are cost-effective according to the threshold set by WHO, whereby a health intervention can be considered cost-effective if the cost/DALY or cost of each additional healthy year of life falls within 1 to 3 times GDP per capita. Recent research however suggests that a much lower threshold for low- and middle-income countries of ~0.5x GDP per capita may be more suitable (Leech et al., 2018). As seen in Table 2, both the subsidy options for households with pregnant women would satisfy this stricter criterion. Notably, the cost-benefit ratio for both these scenarios also falls under 1, indicating a net positive economic benefit.

Subsidy scenario	Cost of subsidy per DALY averted	Cost-benefit ratio	Cost-effectiveness
A_{Full}	₹2,54,542 (~3000 USD)	**2.4**	**1.3x** GDP per capita
$A_{Partial}$	₹1,50,830 (~1800 USD)	**1.4**	**0.8x** GDP per capita
P_{Full}	₹49,313 (~600 USD)	**0.49**	**0.3x** GDP per capita
$P_{Partial}$	₹29,199 (~350 USD)	**0.29**	**0.2x** GDP per capita

Table 2: Cost per DALY averted

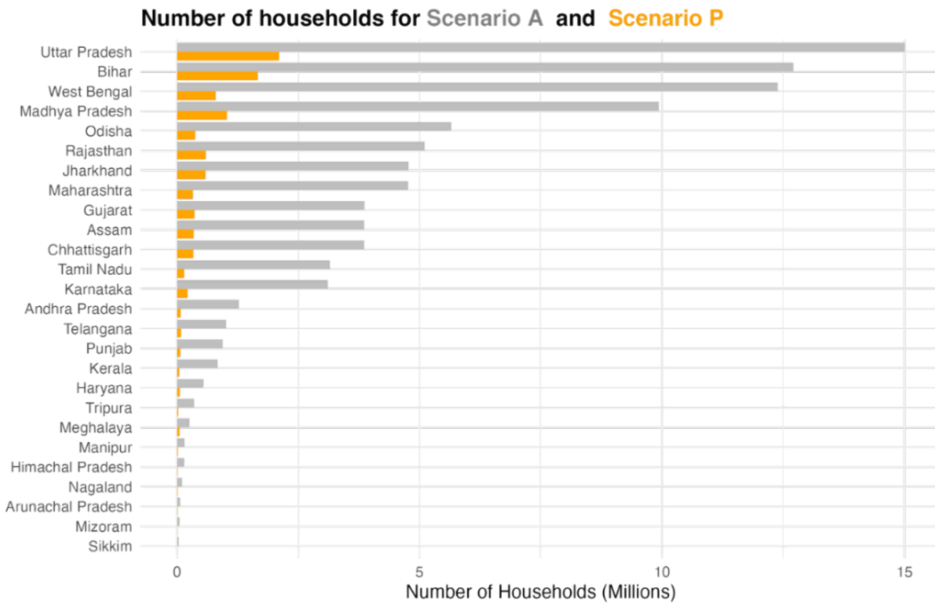


Figure 9. Number of households under each subsidy scenario. Scenario A has provisions for full or partial subsidy for all households and Scenario P has provisions for subsidies for households with pregnant women.

Figure 10 presents state-wise cost-benefit ratio estimates for partial subsidy targeted toward households with pregnant women (scenario $P_{Partial}$). While there are substantial differences among the states, all states have a ratio less than 1, indicating net positive economic benefit. In the majority of the states, the return on investment is higher than 2:1 (i.e. cost-benefit ratio < 0.5). Notably, states with highest cost-benefit ratio (Bihar and Uttar Pradesh) stand to gain the most in terms of health benefits in the form of DALYs averted.

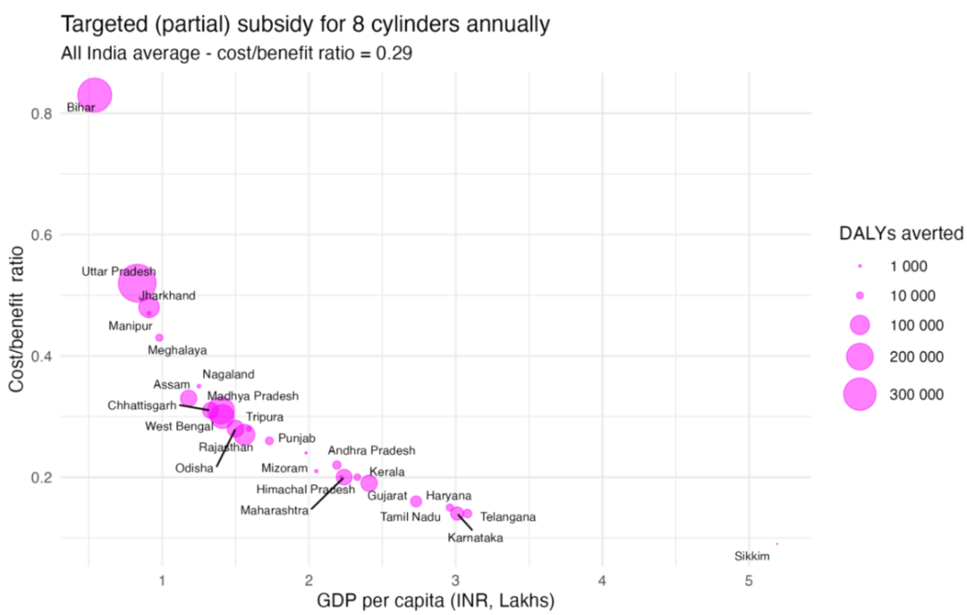


Figure 10. State-wise estimates of cost-benefit ratio for scenario $P_{Partial}$

Benefit to ambient air quality

Even though the initial motivation for programs like PMUY does not include reduction of ambient pollution, achieving complete clean household energy transition can dramatically reduce ambient PM concentrations as well. In fact, smoke from biomass burning is one of the largest sources of ambient air pollution in India, causing nearly 30% of the ambient $PM_{2.5}$ (Chowdhury et al., 2019a). Transitioning to clean household energy can help achieve progress toward meeting national ambient standards for $PM_{2.5}$ concentrations, further averting ~13% of premature mortality (Chowdhury, 2019b).

Figure 11 shows estimated decline in ambient concentrations associated with exclusive LPG use for scenario A. State-wise decline in ambient concentrations ranges from 4% (Telangana) to 28% (Bihar). Cutting down household emissions could potentially help the states of Odisha, Uttarakhand and Maharashtra achieve national ambient standards of 40 $\mu g/m^3$. For states with ambient $PM_{2.5}$ levels within the national standards, exclusive LPG use would make WHO's health-based interim target guidelines more achievable. Specifically, Mizoram, Telangana and Meghalaya could achieve WHO's interim target 1 of 35 $\mu g/m^3$ while Karnataka and Nagaland could achieve the next interim target of 25 $\mu g/m^3$. Most promisingly, Arunachal Pradesh and Kerala could achieve the interim target 3 of 15 $\mu g/m^3$.

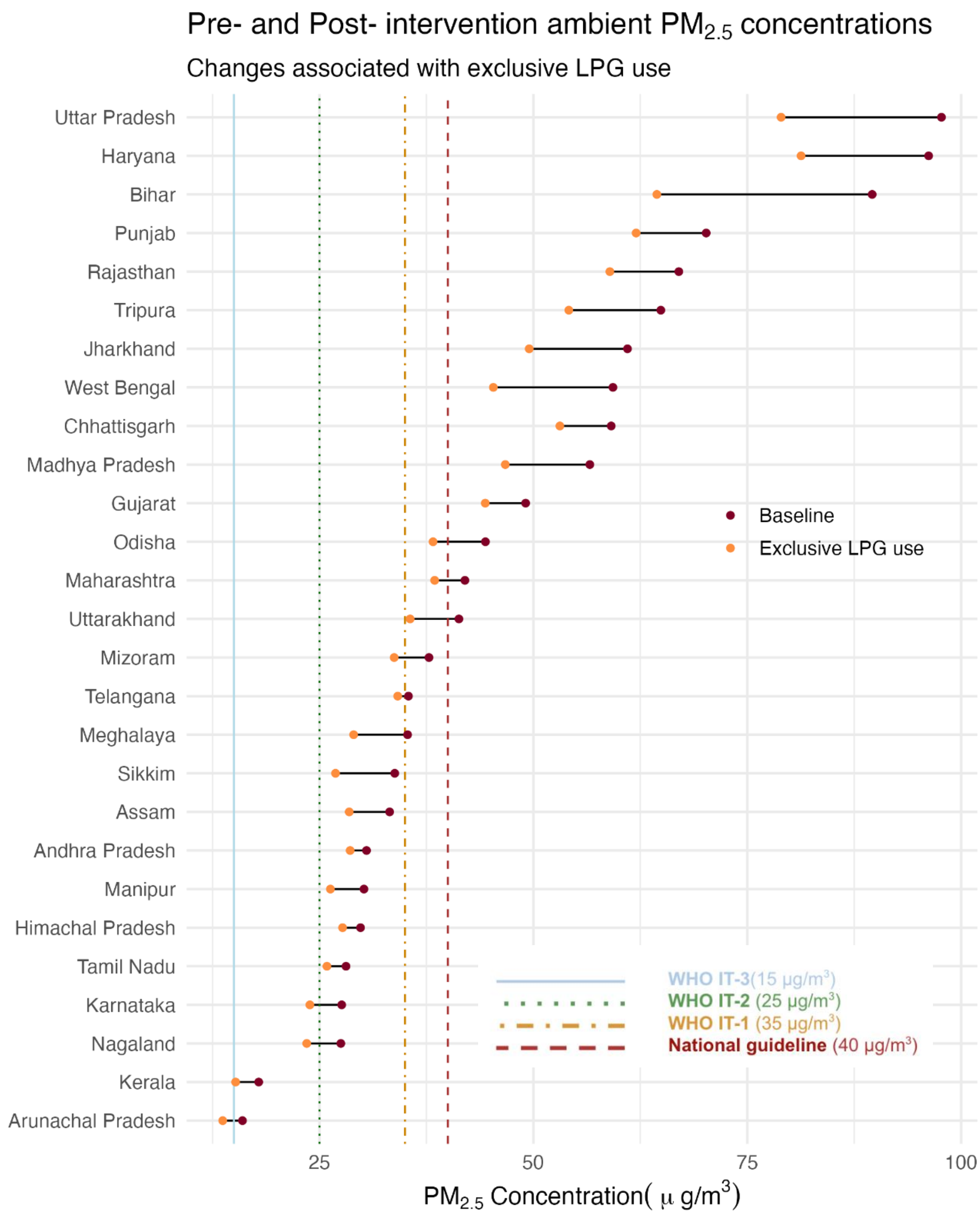


Figure 11. Impact on ambient air quality

The reduction in ambient air pollution could potentially avert additional 30% of deaths, or ~37,000 deaths, under scenario A and additional 7% of deaths averted under scenario P. Accounting for these additional deaths averted leads to lower estimates of cost per death averted. As seen in table 3, the cost under scenario A would decrease by ~25% compared to the estimates that exclude deaths averted due to reduction in ambient air pollution.

Subsidy Scenario	Cost of subsidy per death averted	
	Excluding deaths averted from ambient air pollution	**Including** deaths averted from ambient air pollution
A_{Full}	₹82,52,892 (~99,000 USD)	₹62,53,341 (~75,000 USD)
$A_{Partial}$	₹48,90,634 (~59,000 USD)	₹37,00,911 (~45,000 USD)
P_{Full}	₹17,03,880 (~20000 USD)	₹15,88,742 (~19,000 USD)
$P_{Partial}$	₹10,09,011 (~12000 USD)	₹10,11,662 (~11000 USD)

Table 3: Cost of subsidy per death averted

Since, the data on DALYs averted by reduction in ambient air pollution was not available, our DALY and cost per DALY estimates are restricted to health benefits from reduction of household exposure alone and do not include benefits associated with reduction in ambient exposure. By extension, DALY-related cost-benefit estimates represent conservative estimates of the extent of economic and health benefits that can be achieved by transition to exclusive LPG use.

Sensitivity analysis for LPG price elasticity

Assumptions about the extent of LPG use expected under different scenarios may vary depending on the amount of subsidy provided. We conducted a sensitivity analysis to explore the potential influence of different subsidy levels on LPG use, based on reference points from recently published literature.

Data from a randomized field trial in rural Tamil Nadu confirm that purchase of LPG cylinders increases significantly with the amount of subsidy (Jeuland et al., 2023). On average, the effective price elasticity value was -1 for both households without LPG and those that primarily relied on solid fuels. In other words, a decrease of 1 USD in price paid per cylinder led to an increase in purchase of about 1 kg/month of LPG. Additionally, the final cost to households of 3 USD (~₹ 240) per LPG cylinder corresponded with exclusive LPG use. Applying these findings to the final LPG price in our partial subsidy scenarios ($A_{Partial}$ and $P_{Partial}$) would translate to ~70% LPG use. See the Appendix (Table A2) for revised estimates of exposure reduction and health benefits accounting for different levels of LPG use based on the subsidy amount (or final cost of LPG cylinder to household).

While affordability is a crucial factor in LPG adoption, survey data from several energy-poor states reveal that willingness to pay is higher among households that are aware of health benefits of LPG cooking (Chindarkar et al., 2021). This highlights the critical importance of communication campaigns to supplement initiatives toward exclusive LPG use. Willingness to pay also increases with greater penetration of LPG and duration of connection. Accounting for these factors could help lower implementation costs via a graded subsidy scheme, with initial higher subsidies that taper off with time.

Key Recommendations

Subsidy for pregnant women

Our analysis reveals that targeted subsidies for pregnant women are not only cost-effective, but also yield substantial health and economic gains (cost-benefit ratio <1). These findings reinforce learnings from previous and ongoing work in Tamil Nadu and Maharashtra (Pillarisetti et al., 2019; Balakrishnan et al., 2023) where additional financial support helped households with pregnant women successfully transition to exclusive LPG use, resulting in substantial reduction in exposure and measurable health benefits.

These studies also suggest that pregnant women are a receptive population for an enhanced PMUY program. This is likely because during pregnancy, pregnant women and their families are keen to make changes for the best pregnancy outcome.

Beyond financial support, some other factors that seem to influence the successful transition to exclusive LPG use are: 1) gentle nudges, like asking, but not requiring the participating households to discontinue biomass use coupled with health messaging on why this is important; and 2) providing provisions for a second cylinder to fill the refill gap. Currently PMUY beneficiaries get just one cylinder during the connection while non-PMUY customers get two cylinders with a new connection that helps tide over the time it takes for a refill (Pillarisetti et al., 2019).

Provision of subsidy for select states

Some states stand out in our analysis as bearing most of the burden of household air pollution. Nearly half of the health benefits achieved through exclusive LPG use in terms of morbidity and mortality averted come from the states of Uttar Pradesh, Bihar, West Bengal and Madhya Pradesh. Prioritizing efforts in these states alone could save nearly 80,000 lives from reduction in household exposure and an additional 23,000 lives saved through improvements in ambient air quality.

Focusing on the benefits for ambient air quality, targeted reduction of household emissions could help Odisha, Uttarakhand and Maharashtra achieve national ambient standards of 40 $\mu g/m^3$. Targeted focus on household sources will also propel some states toward achievement of WHO's stricter health-based air quality guidelines. As discussed earlier, the majority of the north-eastern states (Mizoram, Meghalaya, Arunachal Pradesh) would fall within this category.

Implications for implementation

The most ambitious scenario described in this analysis calls for providing full subsidy for nearly 90 million households. In the short term, however, it may be more feasible to target a smaller population group, i.e., households with pregnant women (scenario P). Given that overall, there are 9 million households under scenario P, full subsidy provisions can be allocated to this group at one-tenth the cost of scenario A. The same will hold if we look at state-wise estimates. For example, in Uttar Pradesh, 15 million households fall under scenario A vs. 2 million under scenario P. Similarly, in Bihar, about 12 million households fall under scenario A compared to 1.6 million under scenario P.

One of the biggest challenges of implementing a targeted subsidy scheme is identifying eligible beneficiaries. However, PMUY's success in targeting subsidies based on economic status (households below poverty level) suggests that identification of priority beneficiary groups may be achieved through strategic planning, and could maximize the effectiveness of targeted subsidies in the future. Enrolling pregnant women during their first checkup would be critical to providing protection as early as possible during pregnancy. Ideally, women would be eligible before pregnancy to provide maximum protection to the unborn child during the earliest stages of pregnancy. This could certainly be possible if women were determined to be eligible by showing a marriage certificate, for example, given that marriage remains the key driver of childbirth in India and most women give birth within two years of marriage (Moore et al., 2009; Singh et al., 2023). At the same time, the outreach required to encourage enrollment would be logistically far more challenging.

A more feasible option, and one that aligns well with coupling enrollment with health communication emphasizing the health benefits of clean household energy, would be to work through primary health centers and frontline health workers, including Accredited Social Health Activists (ASHAs). Pregnant women could be identified and enrolled during their first antenatal care visit, or through ASHAs.

In addition, given the substantial health benefits to children (DALYs averted) it may be worth extending this subsidy to households with children using an "opt-in" mechanism. Depending on resources available at the state or district level, parents of children in childcare centers (e.g. anganwadis) or elementary schools could also be encouraged to apply for the subsidy.

Many recommendations exist for better targeting of subsidies that can be applied to the scenarios proposed here so that the provisions reach those who need them the most (Sharma et al., 2019). For example, shifting to an "opt-in" mechanism for the universal LPG subsidy, would mean that higher income households do not automatically qualify for the subsidy and will need to re-register, removing beneficiaries based on the length of time they have had the connection (~20 years), etc. These sound promising at first glance but given the historical provision of universal subsidies in India, there are likely substantial political challenges associated with these options.

An adaptation of the voluntary "Give It Up" campaign of 2016, where individuals opt out on their own, may be more acceptable to the public. Better targeting of subsidies could also be achieved by similar “opt-out” mechanisms encouraging wealthier households to give up their default LPG subsidy by establishing a social norm that subsidies are not meant for wealthy households (Harish and Smith, 2019). A revival or second push to the campaign may help states reallocate critical resources for households that need them the most. Given that the average household uses about seven to eight cylinders per year, reducing the universal subsidies to eight refills instead of currently provisioned 12 refills could further help save up to 15% of the current subsidy outlay (Mani et al., 2020). In addition, the need for the number of subsidized refills can be reduced by improving efficiency of current LPG stoves over time (Josey et al., 2019).

Future Outlook

These results clearly underscore the importance of focusing beyond connections to encourage increased uptake and sustained use of clean household energy at scale. PMUY is already targeted based on economic status (i.e., for households below the poverty line). Here, we underscore benefits of targeting based on health status. Providing targeted subsidies to pregnant women can decrease their exposure and improve health for them and their children since youngest children and infants bear the highest burden from household air pollution. Keeping LPG refills accessible **and** affordable for the most at-risk groups is critical for sustained use and maximum benefit to public health. Given that household air pollution is one of the biggest sources of ambient $PM_{2.5}$, cutting down household emissions would yield considerable health and economic benefits even in the absence of other pollution mitigation measures. Notably, half of the mortality and morbidity burden stems from just four states: Uttar Pradesh, Bihar, West Bengal and Madhya Pradesh.

For the most targeted implementation planning, intra-state patterns in household energy and critical factors affecting LPG uptake and use should also be considered. As many states exhibit widespread heterogeneity in LPG access by urbanicity, efforts may be targeted specifically for peri-urban or rural areas. Separate measures may need to be taken to serve extremely remote areas, such as in the north-eastern states, where providing a noninterrupted energy supply could require creative ways of navigating infrastructure challenges. Focused sensitization of tribal communities may be warranted to increase awareness of the health impacts of household air pollution, as well as the benefits of clean household energy. As such, district-level data on household socioeconomic characteristics may be used to further refine implementation plans in states committed to elimination of household air pollution.

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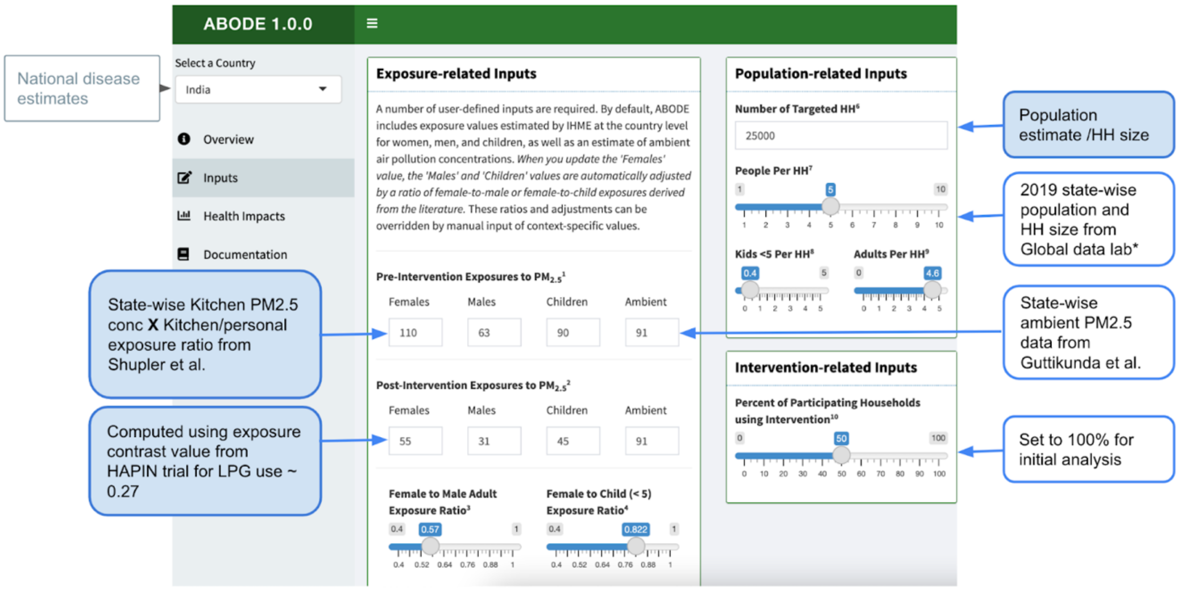
Appendix

Table A1. Sources for state-wise data

Data/metric	Source
State-wise kitchen $PM_{2.5}$ concentrations	Shupler, Matthew, William Godwin, Joseph Frostad, Paul Gustafson, Raphael E. Arku, and Michael Brauer. 2018. "Global Estimation of Exposure to Fine Particulate Matter (PM2.5) from Household Air Pollution." *Environment International* 120 (November): 354–63.
Ambient $PM_{2.5}$ concentrations	Guttikunda, Sarath, and Nishadh Ka. 2022. "Evolution of India's PM 2.5 Pollution between 1998 and 2020 Using Global Reanalysis Fields Coupled with Satellite Observations and Fuel Consumption Patterns." *Environmental Science: Atmospheres* 2 (6): 1502–15.
Household size and population	Global Data Lab https://globaldatalab.org/
PMUY refill rates	Ministry of Petroleum and Natural Gas Rajya Sabha unstarred question no. 2057 on March 21, 2022 (Annexure)
GDP per capita	Ministry of Statistics & Programme Implementation. State-wise data on per-capita income, 2023 https://www.pib.gov.in/
ANC enrollment	Health and Family Welfare Statistics (2019-20), Ministry of Health and Family Welfare
Households without LPG access	Mani, Sunil, Shalu Agrawal, Abhishek Jain and Karthik Ganesan. 2021. "State of Clean Cooking Energy Access in India: Insights from the India Residential Energy Survey (IRES) 2020". New Delhi: Council on Energy, Environment and Water.
Household contribution to ambient air pollution	Chatterjee, Deepangsu, Erin E. McDuffie, Steven J. Smith, Liam Bindle, Aaron van Donkelaar, Melanie S. Hammer, Chandra Venkataraman, Michael Brauer, and Randall V. Martin. 2023. "Source Contributions to Fine Particulate Matter and Attributable Mortality in India and the Surrounding Region." *Environmental Science & Technology* 57 (28): 10263–75.

Figure A1. Calculation of change of health outcomes using ABODE 1.0.0



*ABODE only allows integer values so values were rounded up

Box A1. Example of cost benefit computation (Using a small state as example*)

State: Sikkim
Scenario: A_{Full}

No. of households (HH) considered in the analysis
= HH with no LPG + PMUY-HH (scaled according to PMUY refill rate)
= 28606 + 7899
= 36505

Total deaths averted
= Deaths averted (calculated from ABODE) + Deaths averted due to reduction in low birth weight (calculated from ANC registrations)
= 28 + 10 = 38

Total DALYs averted = DALYs averted (calculated from ABODE) + DALYs averted due to reduction in low birth weight (1 averted death ~ 35 DALYs)
= 867 + 350 = 1217

Total cost averted (₹)
= 0.67 *DALYs averted * State GDP per capita
= 0.67 * 1217 * ₹5.19 Lakhs[5]
= ₹4,232 Lakhs

Cost of intervention (₹)
= PMUY HH * cost of 8 refills + no-LPG HH * (cost of 8 refills + one-time cost of connection)
= PMUY HH * 8* ₹1100 + no-LPG HH*(8* ₹1100 + ₹2000)
= 7899 (₹8800) + 28606 (₹10800)
= ₹3,785 Lakhs

Cost-Benefit Ratio
= Cost of intervention / cost averted
= ₹3,785 Lakhs / ₹4,232 Lakhs
= 0.89

*Calculations for all states can be found here

[5] ₹1 Lakh = ₹100,000 ~1200 USD

Table A2. Sensitivity analysis accounting for different levels of LPG use based on subsidy amount

Subsidy scenario	Final cost of LPG cylinder to household (₹)	% LPG use	Reduction in household exposure	Mean reduction in ambient PM2.5 concentration	Deaths averted
A_{Full}, P_{Full}	0	100%	73%	14%	1,54,713
--	240	100%	73%	14%	1,54713
--	320	89%	65%	12%	1,37,695
--	400	79%	58%	11%	1,22,223
$A_{Partial}$, $P_{Partial}$,	500	68%	50%	10%	1,05,205