Response to R Subramanian's comments

(original comments in black, our responses in purple, changes in manuscript in green)

The two anonymous reviewers have already raised some of my concerns, so I will focus on the new residential emissions inventory from Velamuri et al. (2024). As the authors of the current study state: "However, recent research highlights challenges in sustaining LPG usage under PMUY, including high refill costs and subsidy delays (Asharaf and Tol, 2024; Gaikwad et al., 2025), which may result in backsliding to a continued reliance on solid fuels which may not be fully captured in the updated inventory." This can be significant, leading to an overestimate of biofuel replacement by as much as half - based on studies that show LPG refills are consumed at half the rate (or even less) in PMUY households compared to non-PMUY households, e.g. https://india.mongabay.com/2023/09/lpg-subsidy-can-increase-uptake-but-interventions-needed-to-counter-myths-and-improve-access/

We are grateful for the public comment on this topic. We agree that fuel stacking (the concurrent use of solid fuels and LPG) and the financial barriers to sustained LPG refills are critical uncertainties in estimating India's residential emissions. As noted in the earlier research (Velamuri et al., 2024), the residential inventory adopted in this study explicitly recognized this challenge and was designed to mitigate this LPG overestimation.

Specifically, LPG emissions were calculated using a top-down approach based on actual district-level consumption, rather than assuming a fixed, theoretical per-capita usage for every household. This approach utilizes comprehensive survey data from the National Family Health Surveys (NFHS-3: 2005-06; NFHS-4: 2015-16; NFHS-5: 2019-21), which was projected to 2022 levels using a regression analysis. Thus, the inventory inherently accounts for the lower LPG consumption rates observed in recent years (e.g., due to limited refills captured in the 2019-2021 data), thereby reducing the overestimation of clean fuel usage or the underestimation of solid fuel reliance in 2022.

It would also be helpful to compare the new residential EI to SMoG-2015 and the newer COALESCE version. EDGAR has much lower PM2.5 and NOx numbers for this sector compared to SMoG, and the new sectoral EI numbers used in the current manuscript are even lower than EDGAR. The COALESCE SMoG (Venkataraman et al. 2024 https://doi.org/10.1029/2024JD040834) captures some of the PMUY transition (2017-2019) but including barriers to uptake, which seems a better approach:

"The SMoG-India$_{\text{COALESCE}}$ inventory captures the large fuel transition which has taken place in residential cooking and heating from the launch of the Pradhan Mantri Ujwala Yojana (PMUY, 2016) for the substitution of biomass fuels with liquefied petroleum gas (LPG), albeit with barriers which lead to significant levels of continued fuel stacking with biomass."

We have included the updated **Figure 2** below, which compares our updated 2022 emission inventory with three global inventories (CEDS: 2015–2022; EDGAR: 2015–2022; HTAP: 2015–2020) and the SMoG inventory for both 2015 and 2019. To discuss the comparison between SMoG and other inventories, we added **Supplementary Information 3**:

"Residential primary $PM_{2.5}$ emissions in other inventories are significantly lower than those in SMoG (Venkataraman et al., 2018; Venkataraman et al., 2024):

- In 2015: HTAP (2.4 Tg/yr) and EDGAR (1.6 Tg/yr) represent only 73% and 48% of the SMoG $PM_{2.5}$ emissions (3.3 Tg/yr), respectively.
- In 2019: While HTAP and EDGAR remain relatively flat (2.4 Tg/yr and 1.6 Tg/yr), SMoG reports a substantial increase to 5.4 Tg/yr. Consequently, HTAP and EDGAR represent only 44% and 30% of the SMoG 2019 $PM_{2.5}$ emission, respectively.
- Current Study: Our updated 2022 residential $PM_{2.5}$ estimate (1.1 Tg/yr) is ~21% of the SMoG 2019 value.

These discrepancies likely stem from fundamental differences in the source data and methodology used to estimate fuel consumption and resulting emissions.

The SMoG 2015 inventory calculates residential emissions based on theoretical energy demand (Pandey et al., 2014). For example, it utilizes survey-based food consumption data to derive end-use energy requirements (estimated at 12 MJ/household-day for cooking) and assumes a theoretical water heating demand (e.g., heating daily water usage to 35 °C). This 'useful energy' methodology likely overestimates actual fuel usage in low-income households subject to fuel poverty, who may 'need' that energy theoretically but cannot afford the fuel to generate it. While the SMoG 2019 publication (Venkataraman et al., 2024) incorporated recent work characterizing non-cooking residential activities based on updated survey data (Navinya et al., 2023), it did not explicitly detail methodological updates for cooking emissions, which remain the dominant source.

In contrast, the residential emission inventory adopted in this study utilized a top-down approach based on actual district-level fuel consumption, derived from comprehensive survey data including the National Family Health Surveys (NFHS-3: 2005–06; NFHS-4: 2015–16; NFHS-5: 2019–21), which were projected to 2022 levels using regression analysis. By relying on reported usage rather than theoretical demand, this approach implicitly captures the affordability constraints and actual consumption habits that define the residential sector in India.

Furthermore, both HTAP and EDGAR inventories typically rely on the International Energy Agency (IEA) World Energy Balances to estimate fuel consumption for the residential sector in India (Janssens-Maenhout et al., 2019; Kurokawa and Ohara, 2020; Guizzardi et al., 2025),

Thus, the underlying source data and methodology differ significantly among these datasets: SMoG relies on energy demand modeling (idealized consumption); Global Inventories rely on IEA statistics (international aggregates); and the inventory adopted in our study is grounded in domestic household survey datasets (actual reported consumption)."

However, we emphasize that the residential emission inventory adopted in our study was initially built using actual district-level consumption data (Velamuri et al., 2024), and its implementation in WRF-Chem yields improved agreement with surface $PM_{2.5}$ observations from the CPCB network in 2022 (**Figure 4** in the main text, not attached here). Given that SMoG $PM_{2.5}$ residential emissions are nearly 5 times higher than our inputs, adopting the SMoG residential $PM_{2.5}$ emissions (or scaling our residential inventory to similar values) would result in a very large overestimation of surface $PM_{2.5}$ concentrations compared with observations. Therefore, we maintain that our current inventory is more representative of the residential emission patterns required to reproduce observed $PM_{2.5}$ pollution level in 2022. In addition, we have explicitly addressed the uncertainty of residential emission estimates in our response to the subsequent comment.

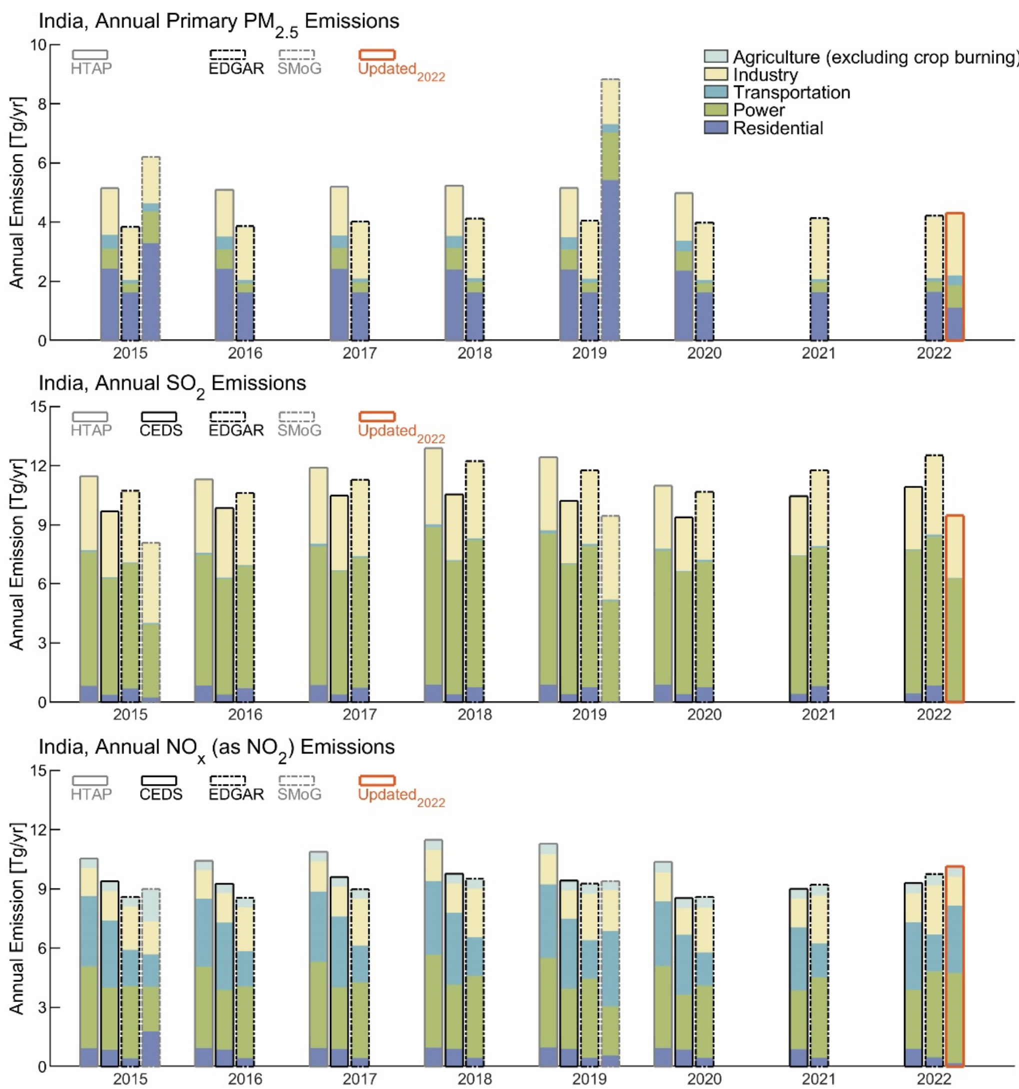

Figure 2. Comparison of annual anthropogenic sectoral total emissions over India among three global inventories, one regional 2015 inventory, and our updated 2022 inventory. For each country and species, $CEDS_{v2024-07-08}$, $EDGAR_{v8.1}$, and $HTAP_{v3.1}$ report sectoral total emission across 59, 32, and 16 detailed sectors, respectively. Those detailed sectors are aggregated into five widely used sectors: power, industry, residential, transportation, and agriculture. In this figure, because $CEDS_{v2024-07-08}$ does not include open burning of agricultural waste and wildfire, we exclude it from the agricultural sector emissions in $EDGAR_{v8.1}$ and $HTAP_{v3.1}$ to enable direct comparison among the inventories. Note that $CEDS_{v2024-07-08}$ does not provide primary $PM_{2.5}$ emissions, $HTAP_{v3.1}$ extends only until 2020, and SMoG is only available for 2015 and 2019. Details on the updated inventory are provided in **Section 2.1**.

So at the very least, I would expect an uncertainty analysis that shows the impact of this underestimated biofuel usage (e.g. increase residential emissions by 2x) - the headline finding of this study may look very different.

Regarding the potential impact of residential emission uncertainties on our conclusions, we have included a detailed discussion in **Supplementary Information 4**.

We note that the residential inventory adopted in this study (Velamuri et al., 2024) explicitly included an uncertainty analysis using 10,000 Monte Carlo simulations. This analysis estimated a total uncertainty of ±50% for residential $PM_{2.5}$ emissions, accounting for uncertainties in population, fuel penetration, and emission factors.

We then performed a simplified uncertainty propagation analysis. Assuming a near-linear relationship between sectoral emissions and resulting concentrations at the national level (a reasonable first-order approximation without additional WRF-Chem simulations), we estimate the residential sector's contribution to the annual population-weighted mean $PM_{2.5}$ to be 7.3±3.7 μg/m^3 in 2022.

We acknowledge that the upper bound of this estimate (11 μg/m^3) exceeds the baseline contribution of the industrial sector (8.6 μg/m^3). However, the industrial sector estimate is derived from global inventories (gases from CEDS, aerosols from EDGAR) which also carry significant (though unquantified in these inventories) uncertainties for India. Consequently, based on the comparison of mean estimates, we maintain our finding that the industrial sector contribution exceeds that of the residential sector in 2022, while explicitly acknowledging the limitation regarding the unquantified uncertainty of industrial emissions in our paper's **Uncertainty and limitation** Section:

"Our annual source attribution results are subject to input uncertainty from emission inventories. Focusing on the sectors with India-specific updates, we estimate annual national population-weighted mean $PM_{2.5}$ contributions of 6.1±1.1 μg/m^3 for the power sector and 7.3±3.7 μg/m^3 for the residential sector. These estimates account for uncertainties in activity data, emission factors, and residential fuel use (see **Supplementary Information 4** and **Supplementary Table 7** for detailed quantification). We do not quantify uncertainties for sectors relying on global inventories (CEDS, EDGAR, FINN) due to the lack of India-specific uncertainty estimates in these datasets. However, we note that the upper uncertainty bound of the residential sector contribution (11 μg/m^3) exceeds the baseline estimate for the industrial sector (8.6 μg/m^3). Consequently, while our central estimates identify India's industrial sector as the largest domestic $PM_{2.5}$ source in 2022, the definitive ranking of these top two sectors is sensitive to the unquantified uncertainties in the industrial emission inventory."

Reference:

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