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Article

Impact of Circular, Waste-Heat Reuse Pathways on $PM_{2.5}$-Air Quality, CO_2 Emissions, and Human Health in India: Comparison with Material Exchange Potential

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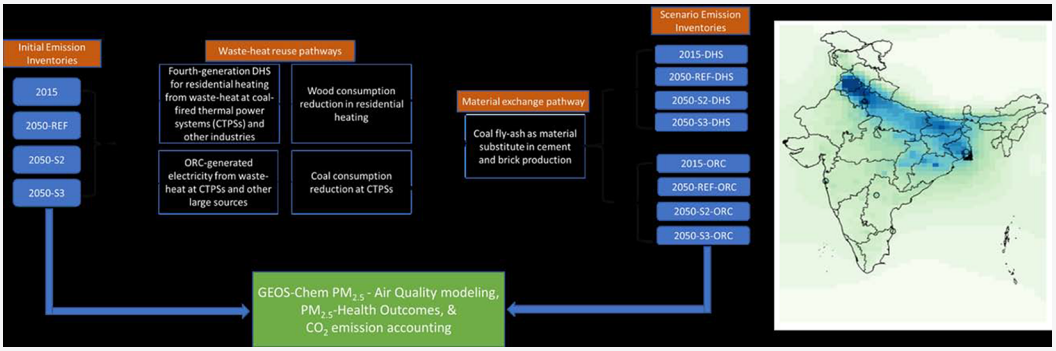

ABSTRACT: India is home to 1.3 billion people who are exposed to some of the highest levels of ambient air pollution in the world. In addition, India is one of the fastest-growing carbon-emitting countries. Here, we assess how two strategies to reuse waste-heat from coal-fired power plants and other large sources would impact $PM_{2.5}$-air quality, human health, and CO_2 emissions in 2015 and a future year, 2050, using varying levels of policy adoption (current regulations, proposed single-sector policies, and ambitious single-sector strategies). We find that power plant and industrial waste-heat reuse as input to district heating systems (DHSs), a novel, multisector strategy to reduce local biomass burning for heating emissions, can offset 71.3−85.2% of residential heating demand in communities near a power plant (9.3−12.4% of the nationwide heating demand) with the highest benefits observed during winter months in areas with collocated industrial activity and higher residential heating demands (e.g., New Delhi). Utilizing waste-heat to generate electricity via organic Rankine cycles (ORCs) can generate an additional 22 (11% of total coal-fired generating capacity), 41 (8%), 32 (13%), and 6 (5%) GW of electricity capacity in the 2015, 2050-current regulations, 2050-single-sector, and 2050-ambitious-single-sector scenarios, respectively. Emission estimates utilizing these strategies were input to the GEOS-Chem model, and population-weighted, simulated $PM_{2.5}$ showed small improvements in the DHS (0.2−0.4%) and ORC (0.3−3.4%) scenarios, where the minimal DHS $PM_{2.5}$-benefit is attributed to the small contribution of biomass burning for heating to nationwide $PM_{2.5}$ emissions (much of the biomass burning activity is for cooking). The $PM_{2.5}$ reductions lead to ∼130−36,000 mortalities per year avoided among the scenarios, with the largest health benefits observed in the ORC scenarios. Nationwide CO_2 emissions reduced <0.04% by DHSs but showed larger reductions using ORCs (1.9−7.4%). Coal fly-ash as material exchange in cement and brick production was assessed, and capacity exists to completely reutilize unused fly-ash toward cement and brick production in each of the scenarios.

KEYWORDS: *waste-heat reuse, circular economy, material exchange, $PM_{2.5}$-air quality, CO_2 emissions*

INTRODUCTION

Exposure to elevated levels of ambient air pollution, particularly fine particulate matter ($PM_{2.5}$), is associated with adverse health outcomes and is estimated to contribute to ∼500,000−2,200,000 premature mortalities each year in India.[1−5] In addition, India is the third-highest carbon (CO_2 and CH_4)-emitting country in the world at 3100 Mt. (million tons) of CO_2-equivalent greenhouse gas (GHG) emissions as of 2017, which is approximately 7% of the global total. Carbon emissions from India are growing at approximately 6% yr^{-1}, while emission rates in China and the United States, the only two countries that emit

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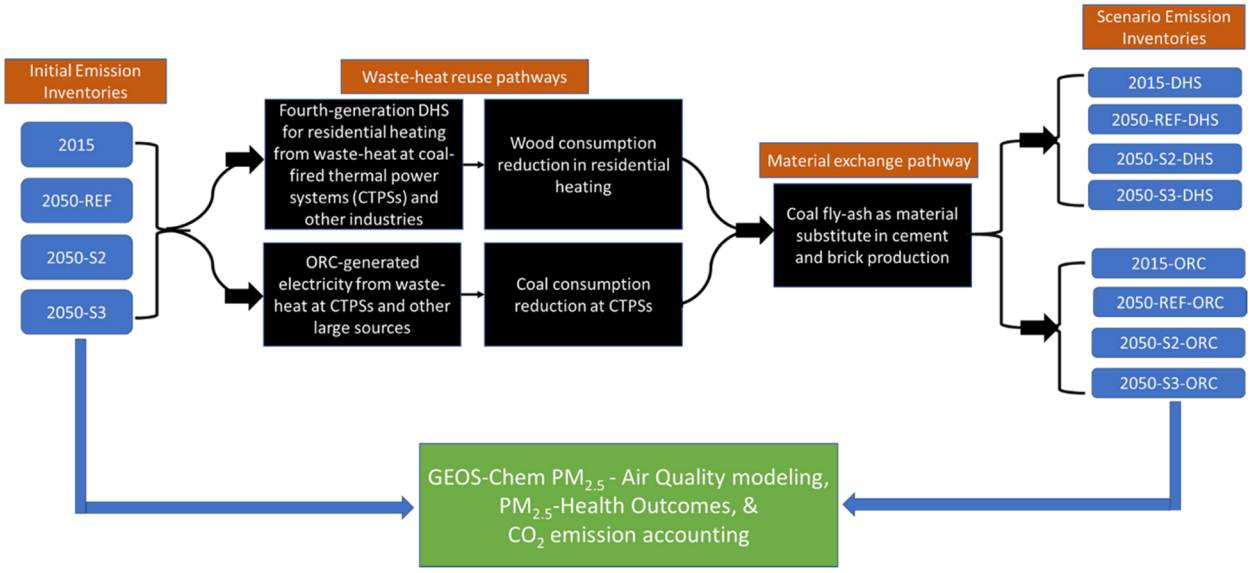

Figure 1. Overview of the two waste-heat reuse (District Heating Systems (DHSs) and Organic Rankine Cycles (ORCs)) and material exchange pathways for four base-case inventories (2015, 2050-REF: business as usual; 2050-S2: effective achievement of currently proposed targets under the Perform, Achieve, and Trade (PAT) scheme; 2050-S3: ambitious regulatory achievement). The 12 inventories are input to the GEOS-Chem model to simulate surface-level $PM_{2.5}$ concentrations from which a health impact assessment is performed. CO_2 emission reductions from these pathways are also quantified.

more carbon than India, have remained steady and decreased, respectively, over the last few years.[6] Recent studies have characterized poor air quality and carbon emissions throughout India and have identified various strategies for emission mitigation.[7−12] Despite these efforts, carbon emissions have continued to increase,[6] and there has been no noticeable improvement in nationwide, ambient air quality over the last few decades,[13,14] except during the COVID-19 pandemic.[15] Furthermore, forecasts of both carbon and $PM_{2.5}$ emission rates project large emission increases throughout India over the coming decades.[9,16]

Currently, residential biomass burning (including wood, crop, and dung cake) related to cooking, heating, lighting, and waste reduction is the largest contributor to annual ambient $PM_{2.5}$ pollution throughout India, despite being a largely indoor activity.[9,17] Although the continued introduction of cleaner fuel sources in households is yet to tackle major challenges of infrastructure and consumer drop out,[18,19] total emissions from residential biomass burning are expected to decrease in magnitude in the future.[20] GHG emissions in India, on the other hand, are dominated by emissions from the power sector, which contributes to roughly half of the present-day GHG emissions,[21,22] and that fraction is expected to grow with increased energy demand, largely being met from coal-fired plants, anticipated. The projected growth in industrial sources and coal-fired thermal power systems (CTPSs), which currently only control for PM emissions but are not required to for other pollutants (i.e., SO_2, NO_x, Hg, etc.; see Supporting Information Section 1 for further discussion on regulations/controls at power generating units), will result in future (2050) primary $PM_{2.5}$ source contributions in India dominated by power plant and industrial coal combustion emissions (33%) (followed by dust (20%) and residential biomass burning (13%)),[9] so strategies aimed to reduce carbon emissions from power plants will also improve ambient air quality.

Both previous research and implemented policies to reduce air pollutant and carbon emissions throughout India have predominantly targeted conventional, single-sector strategies (e.g., using cleaner fuels,[23] requiring traditional emission control technologies,[24] banning emitting activities,[25] etc.). Complimentary to conventional approaches, circular economy strategies, e.g., reusing waste-heat and materials, can also be an important pathway for carbon and air pollutant emission reductions.[26] There is high interest in circular economy strategies in India[27]—including offsetting residential and commercial heating and cooling emissions, but their impact is yet to be quantified. New, fourth-generation district energy systems (DESs), which have been demonstrated to be both economically and technically feasible,[28] directly utilize low-grade waste-heat ($T < 100$ °C) for reapplication toward heating (through district heating systems (DHSs)) and cooling (by evaporative processes).[29,30] Such novel, multisector strategies have been less studied to date but may offer additional benefits to conventional, single-sector strategies.[26,31,32] Organic Rankine cycles (ORCs) that utilize low- and medium-grade (100−400 °C) waste-heat to generate electricity also offer waste-heat reuse potential. ORCs operate similarly to a traditional steam Rankine cycle except that they use an organic working fluid instead of steam. ORC technology has been implemented in a cement (4 MW recovery) and iron and steel plant (125 kW recovery) in India, and recent studies have suggested that ORCs can also be implemented in CTPSs and with large-scale agricultural waste burning.[33−37]

Another circular economy strategy is via material exchanges, where byproduct materials from one industry can be used as an input to a different industry.[38] Coal combustion generates coal fly-ash that can be reutilized in several sectors as material exchange, including in cement and brick production. Globally, only 30% of coal fly-ash is reutilized,[39] and although India reportedly reuses 61% of its generated coal fly-ash,[40] the current reutilization rate in cement and brick industries is considerably lower than Indian industry standards.

This paper contributes with two main objectives. First, we build off existing modeling frameworks to assess the impact of

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two waste-heat reuse strategies (multisector DHSs and ORCs) on air pollution, health, and CO_2 emissions. We apply the framework to India using an all-India 2015 base year inventory that was further projected to 2050 under three, single-sector policy adoption strategies. Second, we assess material exchange pathways that reutilize coal fly-ash as material substitution in cement and brick production (Figure 1). We then estimate the annual number of premature mortalities that can be avoided from $PM_{2.5}$ improvements (including estimates using the new Global Exposure Mortality Model[5]) by adopting these waste-heat reuse strategies and compare them to previously published estimates that considered both government-proposed and ambitious regulatory achievement of traditional, single-sector policies.[2]

METHODS

Activity and Emission Inventory Overview. The India-specific activity and emission inventory used in this analysis was developed by Venkataraman and colleagues[9,21,41,42] and is briefly described here. The inventory includes monthly, spatially resolved (25 km × 25 km) $PM_{2.5}$, CO_2, black carbon, organic carbon, SO_2, NO_x, and total nonmethane volatile organic compound emissions from major sources including power plants (coal-fired and natural gas-fired), industries (e.g., cement, brick kilns, steel, etc.), residential biomass (e.g., cooking, heating, and lighting), transportation, distributed diesel, and open burning. The inventory includes a base year 2015 and three scenarios projected to 2050. The 2015 inventory is based on an engineering, technology-linked, energy emission modeling approach that includes technology parameters for process and emissions control technologies, including technology type, efficiency, or specific fuel consumption and technology-linked emission factors (g pollutant kg^{-1} fuel) to estimate emissions.[9] The 2050 projected emissions are defined in three pathways: (1) 2050 Reference Scenario (2050-REF); (2) 2050 Aspirational Scenario (2050-S2); and (3) 2050 Ambitious Scenario (2050-S3) (see previous papers from Venkataraman and colleagues[9,21,41,42] and Supporting Information Section 2.1 for additional details on the inventories and projection methods and assumptions).

Estimating Waste-Heat Availability from CTPSs and Other Large Sources for Reuse in DHSs or to Generate Electricity via ORCs. Waste-heat is generated at many large-scale activities, including CTPSs, cement plants, iron and steel plants, and open agricultural waste burning. Coal combustion at CTPSs in India is currently ∼34% efficient for producing electricity[24,26] (see Supporting Information Table 1 for efficiencies and properties of coal types included in the scenarios). The amount of waste-heat generated from an industrial process, i, for each temperature grade of waste-heat (high-grade >400 °C, medium-grade 100∼400 °C, and low-grade <100 °C; Supporting Information Table 2 for each sector's distribution), j, is calculated as[26]

$$\text{Waste Heat}_{i,j} = E_i \times P_i \times \text{Ratio}_{i,j} \times (1 - U_i) \quad (1)$$

where E_i is the total direct primary energy input to each industry, P_i is the waste-heat generated in each industry as a percent of E_i, $\text{Ratio}_{i,j}$ is the proportion of each grade waste-heat for each industrial process, and U_i is the current utilization rate (see Supporting Information Table 2 for values). Waste-heat can be transported up to 30 km from industry to residential application;[43] here, we consider waste-heat transfer from an industry to its emission grid (25 km × 25 km) and four tangent grids to best conserve area (Supporting Information Figure 1; see Supporting Information Section 2.2 for a sensitivity analysis of the area available for waste-heat transfer on DHS viability).

Reusing this waste-heat as input to DHSs or as input to generate electricity via ORCs can reduce air pollutant and CO_2 emissions. In this work, we only consider application in third- and fourth-generation DHSs (as opposed to DESs), in part because the emission inventory used here only estimates emissions associated with residential heating and not cooling (see Supporting Information Section 2.3 for the method of generating an activity inventory from the provided emission data). Cooling demands are expected to intensify under climate change and deep urbanization in India, so assessments of DESs may also have policy relevance. We consider boiler (30%) and pipeline (medium grade = 30%; low grade = 5%) losses, consistent with previous waste-heat reuse studies,[44,45] although pipeline losses will be less in newly installed systems. We further assess the DHS potential for each of the scenarios (2015-DHS, 2050-REF-DHS, 2050-S2-DHS, and 2050-S3-DHS) specifically in the New Delhi-National Capital Region (NCR) (Supporting Information Figure 2) as this region, which is notorious for its poor air quality, has large volumes of industrial activity collocated with high rates of residential biomass burning for heating.

In the ORC scenario set (2015-ORC, 2050-REF-ORC, 2050-S2-ORC, and 2050-S3-ORC), ORC-generated electricity from CTPSs, cement plants, agricultural burning, and iron and steel plants (rolling mills and EAFs only) are simulated to offset the equivalent coal consumption (and associated air pollution and CO_2 emissions) at CTPSs (Figure 1; specific details and assumptions about the ORC applicability in these sectors can be found in Supporting Information Section 2.4). The ORC-electricity generated at CTPSs should be interpreted as a first-order approximation; the coal needs to be combusted for the available waste-heat to generate electricity from the ORC, but some of that same coal consumption will subsequently be offset from the ORC generation.

Material Exchange of Coal Fly-Ash from CTPSs to Cement and Brick Production. Coal fly-ash is a byproduct of coal combustion and is used in India and the rest of the world as material substitution for various applications, including cement and brick production.[46] Here, we use coal fly-ash generation rates given by the Central Electricity Authority to estimate the total available coal fly-ash from CTPSs for reutilization in cement and brick production in each of the DHS and ORC (where the material exchange estimates occur after the coal consumption offsets from the waste-heat generated electricity) scenarios (see Supporting Information Section 2.5 for detailed material exchange modeling overview and assumptions). We only consider material pathways for coal fly-ash reutilization in cement and brick production as we do not have spatially resolved activity data for other industries that may utilize fly-ash, including mine filling, road paving, reclamation of low-lying areas, etc. The material exchange pathway assessed here does not affect local air pollutant or CO_2 emissions at the cement plants or brick kilns, following the premise that the fly-ash still needs to be fired with the other materials to create the cement or brick.

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Table 1. Nationwide Waste-Heat Generation and Reuse in the District Heating System (DHS) and Organic Rankine Cycle (ORC) Scenarios

DHS Scenario	2015		2050-REF		2050-S2		2050-S3	
Total Waste-Heat Produced (MJ)	Low-grade	Med-grade	Low-grade	Med-grade	Low-grade	Med-grade	Low-grade	Med-grade
Coal-fired power plants	25.0	25.0	55.0	55.0	16.9	16.9	4.90	4.90
Cement plants	N/A	3.84	N/A	17.2	N/A	14.6	N/A	14.6
Iron and Steel plants	N/A	1.55	N/A	4.93	N/A	4.07	N/A	3.66
Total waste-heat produced at all sources (low-grade and medium-grade)	55.4		132		52.5		28.1	
Total waste-heat available for resuse following SO_2 fouling, boiler efficiencies, and pipeline losses	17.1		38.7		13.4		5.4	
Total Waste-Heat Consumed by DHS (MJ)	6.2×10^{-2}		0.12		8.7×10^{-2}		0.1×10^{-2}	
Percent of space heating demand	9.3%		11.8%		11.0%		12.4%	
Percent of total waste-heat available	0.4%		0.3%		0.6%		0.1%	
ORC Scenario	**2015**		**2050-REF**		**2050-S2**		**2050-S3**	
Traditional Energy Generation (MW)								
All power plants	270×10^3		1020×10^3		1020×10^3		1020×10^3	
Coal-fired power plants	196×10^3		490×10^3		250×10^3		125×10^3	
Sectors for ORC Waste-Heat to Electricity Generation	Amount of electricity	Percent of TPS Coal	Amount of electricity	Percent of TPS Coal	Amount of electricity	Percent of TPS Coal	Amount of electricity	Percent of TPS Coal
Thermal Power Stations	7.1×10^3	3.6%	17.3×10^3	3.5%	8.7×10^3	3.5%	4.3×10^3	3.4%
Cement plants	358	0.2%	1.6×10^3	0.3%	1.4×10^3	0.6%	1.3×10^3	1.1%
Iron and Steel plants	203	0.1%	643	0.1%	530	0.2%	470	0.4%
Open burning	14.2×10^3	7.2%	21.3×10^3	4.4%	21.3×10^3	8.5%	0	0.0%
Total	21.8×10^3	11.1%	40.9×10^3	8.4%	31.9×10^3	12.8%	6.17×10^3	4.9%

base-case inventories, four DHS inventories, and four ORC inventories were used as input to the GEOS-Chem model to simulate surface-level $PM_{2.5}$ in India. GEOS-Chem is a global, 3D model of atmospheric chemistry that uses meteorological input from the Goddard Earth Observing System (GEOS).[47] Meteorology used in these simulations was from the 2015 Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA2) reanalysis product. Here, we use GEOS-Chem v12.6.3 (DOI: 10.5281/zenodo.3552959) to simulate $PM_{2.5}$ concentrations using the Tropchem (full-chemistry in the troposphere only) chemical mechanism and the simple secondary organic aerosol scheme (details of the mechanism can be found in Pai et al.[48] and references within) at a 0.5° × 0.625° nested-grid resolution over India following a three-month 4° × 5° resolution global spin-up (see Supporting Information Table 3 for more run configuration details). In the global simulations (both spin-up and year-long runs), the Indian emission inventories described above were used over India, while regional and global inventories were used over the rest of the globe[49−57] (see Supporting Information Section 2.6 for more details on the modeling framework and inventories). We use the same meteorology (i.e., 2015 MERRA2) for 2015 and each of the 2050 simulations, even though the meteorology and atmospheric conditions over India will be different in 2015 vs 2050, due in part to both climate- and aerosol-forcing effects. Projecting future meteorology in-line with emissions or under climate-change scenarios is beyond the scope of this analysis and would add uncertainty in assessing the emission-driven changes versus the climate-driven changes in ambient $PM_{2.5}$.

The simulated results for 2015 were evaluated against two satellite-retrieved, surface-level $PM_{2.5}$ concentration estimates: the first from van Donkelaar and colleagues,[58,59] which is used by the Global Burden of Disease (GBD), and the second from Dey and colleagues,[14] which was developed using similar methods but was calibrated specifically for India, as opposed to a regional calibration in the former. The GEOS-Chem $PM_{2.5}$ simulations were also evaluated with U.S. Embassy and Consulates' monitors in Chennai, Kolkata, Hyderabad, Mumbai, and New Delhi (details on the monitoring sites can be found in Supporting Information Table 1 of Singh et al.[60]). Here, we only evaluate the GEOS-Chem simulations with U.S. Embassy and Consulates' monitors for reasons discussed elsewhere[13] and the strict quality assurance/quality control procedures used in the Embassy monitoring.[60] Negative concentrations were removed from the observational data set, and we only consider daily data where 75% of hours were recorded, broadly consistent with procedures outlined by Mukherjee et al.[61] Normalized mean bias was calculated between the simulated results and the average of the observations and satellite products. We report population-weighted concentrations and use the same population distribution data as outlined in previous work utilizing this inventory.[2] The evaluation of the 2015 results is used to demonstrate that the simulated $PM_{2.5}$ fields are representative of nationwide $PM_{2.5}$ concentrations for the scenario testing to be conducted, as the primary focus of this paper is to evaluate the impact of the two waste-heat reuse strategies on changes in $PM_{2.5}$ concentrations. In addition, we refer the readers to previous work[2,9] for month-by-month air pollutant emission and concentration trends, emission evaluations with other all-India inventories, emission uncertainty estimates, and a detailed, state-by-state analysis. CO_2 emission reductions in each scenario are calculated as the difference between estimated total CO_2 emissions in the four base inventories and the eight scenario inventories (four DHS and four ORC).

Premature Mortalities Avoided from $PM_{2.5}$-Reductions from the DHS and ORC Pathways. Integrated exposure response curves used in the GBD,[62] the new Global Exposure Mortality Model (GEMM),[5] and the same population demographic distribution in 2015 and 2050 (2015 population = 1.35 billion; 2050 population = 1.61 billion; Supporting

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Table 2. Air Pollutant and CO_2 Emission Reductions (Million Tons (Mt) $Year^{-1}$) for the District Heating System (DHS) and Organic Rankine Cycle (ORC) Scenarios in the Residential Biomass and Thermal Power System (TPS) Sectors, Respectively

	DHSME Scenario			ORCME Scenario		
	Base-Case Residential Emissions	Post-DHS Residential Emissions	Percent Reduction	Base-Case TPS Emissions	Post-ORC TPS Emissions	Percent Reduction
	2015					
BC	4.95E+05	4.91E+05	0.81%	7.84E+03	6.97E+03	11.12%
NMVOC	6.78E+06	6.73E+06	0.74%	3.15E+05	2.80E+05	11.12%
NO_x	3.24E+05	3.24E+05	0.00%	3.84E+06	3.40E+06	11.49%
OC	1.43E+06	1.41E+06	1.40%	2.61E+04	2.32E+04	11.12%
$PM_{2.5}$	3.51E+06	3.48E+06	0.85%	1.00E+06	8.71E+05	13.29%
SO_2	3.22E+05	3.21E+05	0.31%	3.70E+06	3.21E+06	13.29%
CO_2	1.71E+08	1.70E+08	0.62%	9.02E+08	7.97E+08	11.65%
	2050-REF					
BC	3.98E+05	3.94E+05	1.09%	4.21E+04	3.86E+04	8.35%
NMVOC	6.35E+06	6.26E+06	1.38%	1.37E+05	1.25E+05	8.35%
NO_x	3.75E+05	3.75E+05	0.00%	1.96E+07	1.79E+07	8.94%
OC	1.29E+06	1.26E+06	2.23%	1.31E+05	1.20E+05	8.35%
$PM_{2.5}$	3.17E+06	3.12E+06	1.64%	7.66E+06	6.89E+06	10.02%
SO_2	2.30E+05	2.28E+05	0.57%	3.02E+07	2.71E+07	10.01%
CO_2	1.94E+07	1.92E+07	1.21%	8.26E+09	7.49E+09	9.33%
	2050-S2					
BC	2.52E+05	2.48E+05	1.74%	1.58E+04	1.37E+04	12.76%
NMVOC	4.32E+06	4.27E+06	1.21%	5.71E+04	4.98E+04	12.76%
NO_x	2.73E+05	2.73E+05	0.00%	7.85E+06	6.74E+06	14.07%
OC	7.96E+05	7.76E+05	2.48%	5.13E+04	4.48E+04	12.76%
$PM_{2.5}$	1.95E+06	1.92E+06	1.95%	2.81E+06	2.28E+06	18.58%
SO_2	1.57E+05	1.57E+05	0.50%	1.10E+07	8.98E+06	18.56%
CO_2	1.68E+07	1.66E+07	0.97%	3.58E+09	3.05E+09	14.84%
	2050-S3					
BC	1.08E+04	1.06E+04	1.79%	2.55E+03	2.42E+03	4.94%
NMVOC	6.88E+05	6.86E+05	0.28%	2.03E+04	1.93E+04	4.94%
NO_x	1.29E+04	1.29E+04	0.00%	2.79E+06	2.62E+06	5.96%
OC	3.02E+04	2.88E+04	4.84%	8.47E+03	8.05E+03	4.94%
$PM_{2.5}$	7.63E+04	7.39E+04	3.22%	4.36E+05	4.02E+05	7.84%
SO_2	1.53E+04	1.53E+04	0.19%	1.96E+05	1.81E+05	7.82%
CO_2	1.78E+06	1.78E+06	0.08%	1.27E+09	1.19E+09	6.54%

Information Table 4 for detailed gender and age distribution data) as outlined in previous work using this inventory[2,9] in conjunction with model simulated, surface-level $PM_{2.5}$ concentrations were used to estimate the number of premature mortalities from ischemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and lower respiratory infections for each of the 12 scenarios (four base-case, four DHS, and four ORC). Estimated mortalities from DHS and ORC implementation are compared to the estimates for each of the four base-case scenarios, and a focus is given to the 2050 scenarios to compare the health benefits of traditional, single-sector strategies (i.e., 2050-S2 and 2050-S3) with the two sets of waste-heat reuse strategies assessed here (i.e., 2050-S2-DHS, 2050-S3-DHS, 2050-S2-ORC, and 2050-S3-ORC).

RESULTS AND DISCUSSION

Waste-Heat Generation and Reuse in DHSs and Subsequent Residential Heating Emission Reductions. The total estimated amount of low- and medium-grade waste-heat available for reuse following SO_2 fouling, boiler inefficiencies, and pipeline losses (see Supporting Information Section 2.4 for explanation of these losses) from CTPSs, cement plants, and iron and steel plants in the 2015, 2050-REF, 2050-S2, and 2050-S3 base inventories are 17.1, 38.7, 13.4, and 5.4 MJ, respectively (Table 1). For each of the four scenarios, the available waste-heat that can be reused in DHSs is mostly from CTPSs (>80% in 2015-DHS, 2050-REF-DHS, and 2050-S2-DHS) (Table 1). Nationwide, <1% of the total available waste-heat is reused in DHS application (Table 1), which is attributed to limited collocation of industrial activity and residential heating demands (Supporting Information Table 5). Waste-heat reuse potential is mostly isolated to the winter months when the residential heating demand is the highest. Following estimated pipeline losses and boiler inefficiencies, 71.3−85.2% of the residential heating demand within grids containing a large point source (i.e., CTPS), where DHS is most viable, can be offset by waste-heat reuse in DHSs (9.3−12.4% of the nationwide residential heating demand) among the four DHS scenarios, and most of these benefits will be observed in low-socio-economic status (SES) areas where biomass burning for residential heating is more prevalent. The inventory used here only quantifies residential heating emissions from wood burning; however, other biomass fuels (e.g., coal, bio-oil, trash, etc.) are also used for heating applications in India, further

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Table 3. Coal Fly-Ash Material Exchange (MT; Metric Tons) for Cement and Brick Production in the District Heating System (DHS) and Organic Rankine Cycle (ORC) Scenarios[a]

DHS Scenario	2015			2050-REF			2050-S2			2050-S3		
Total fly-ash available (MT)	83			207			54			27		
	Fly-ash re-utilized (MT)	Percent of max. sector potential	Percent of max. fly-ash re-utilized	Fly-ash re-utilized (MT)	Percent of max. sector potential	Percent of max. fly-ash re-utilized	Fly-ash re-utilized (MT)	Percent of max. sector potential	Percent of max. fly-ash re-utilized	Fly-ash re-utilized (MT)	Percent of max. sector potential	Percent of max. fly-ash re-utilized
Fly-ash for cement production	48	97%	58%	164	75%	79%	54	38%	100%	27	18%	100%
Fly-ash for brick production	35	41%	42%	43	10%	21%	N/A	N/A	N/A	N/A	N/A	N/A
Total	83	N/A	100%	207	N/A	100%	54	N/A	100%	27	N/A	100%
ORC Scenario	**2015**			**2050-REF**			**2050-S2**			**2050-S3**		
Total fly-ash available (MT)	74			190			47			26		
	Fly-ash re-utilized (MT)	Percent of max. sector potential	Percent of max. fly-ash re-utilized	Fly-ash re-utilized (MT)	Percent of max. sector potential	Percent of max. fly-ash re-utilized	Fly-ash re-utilized (MT)	Percent of max. sector potential	Percent of max. fly-ash re-utilized	Fly-ash re-utilized (MT)	Percent of max. sector potential	Percent of max. fly-ash re-utilized
Fly-ash for cement production	48	94%	63%	157	71%	83%	47	32%	100%	26	17%	100%
Fly-ash for brick production	26	32%	37%	33	8.5%	17%	N/A	N/A	N/A	N/A	N/A	N/A
Total	74	N/A	100%	190	N/A	100%	47	N/A	100%	26	N/A	100%

[a]The material exchange pathway is the same for both waste-heat reuse scenarios except that there is less fly-ash available in the ORC scenarios as there was reduction in coal-fired thermal power system (CTPS) generation.

suggesting that our modeling framework is a conservative estimate of waste-heat reuse potential via DHSs. While DHSs are used in many countries in Europe and in North America and have been projected to be effective in China, the heating demand in India (<10% of the residential sector energy demand) limits the air pollutant and CO_2 emission reduction benefits nationwide (Table 2). District cooling, on the other hand, may be another intervention for Indian cities to reduce electricity use (either generated at power plants or by local, backup diesel generators). However, we are unable to assess this intervention due to limited nationwide cooling data.

Across the New Delhi-NCR, where there is collocated industrial activity and residential heating demand, we find much larger potential for waste-heat reuse from DHSs than the national average. We estimate that at least 41.4−72.5% of the residential heating demand in this region in the four scenarios can be offset through waste-heat reuse in DHSs (Supporting Information Table 6). Successful implementation of DHSs here, still however, offers little local air pollutant and CO_2 emission reductions, again explained by the low contribution of residential heating emissions to total emissions in this region (Supporting Information Table 7).

Electricity Generated Using ORCs and Equivalent Coal and Emission Reductions at CTPSs. ORC waste-heat to electricity recovery at CTPSs, cement plants, iron and steel plants, and open agricultural burning in the 2015-ORC, 2050-REF-ORC, 2050-S2-ORC, and 2050-S3-ORC scenarios leads to an estimated 21.8, 40.9, 31.9, and 6.2 GW, respectively, of electricity recovery (Table 1). This accounts for 11.1% (8.1%), 8.4% (4.0%), 12.8% (3.1%), and 4.9% (0.6%) of the coal-fired (and total) electricity generated in the four scenarios. Subsequent pollutant emission reductions from thermal power systems (TPS) ranged between 4.9 and 19% among the four scenarios with the largest fractional reductions observed in the 2050-S2-ORC scenario (Table 2). The percent reduction varies by pollutants within the same scenario as the TPS emissions include both coal-fired and natural gas emissions, and the emission factors for each pollutant are not linearly related between those two sources. In practice, such additional electricity generation would replace generation from the least efficient and highest-emitting units, which again suggests that the emission reduction estimates here may be conservative. At CTPSs, ORC generation offers 7.1 (3.62%), 17 (3.53%), 8.7 (3.49%), and 4.3 (3.42%) GW of additional electricity (and percent of combusted coal) in the 2015-ORC, 2050-REF-ORC, 2050-S2-ORC, and 2050-S3-ORC scenarios, respectively (Table 1). The amount of total electricity produced per unit input coal decreases as the thermal properties of the combusted coal (e.g., subcritical to supercritical) become more efficient (Supporting Information Table 1); i.e., in scenarios with single-sector interventions, the percent of offset combusted coal decreases.

The total amount of electricity generated from all-sector waste-heat is the highest in the 2050-REF-ORC scenario, but the percent of combusted coal offset is lower than that in the 2015-ORC or 2050-S2-ORC scenarios (it is expected to be lower than that in the 2050-S3-ORC scenario). The largest volume of coal consumed for electricity generation occurs in the 2050-REF-ORC scenario (490 GW electricity production from CTPSs). This coupled with the same amount of ORC-generated electricity recovered from agricultural waste burning in 2050-REF-ORC and 2050-S2-ORC explains this finding (Table 1). In the scenarios where agricultural waste burning, as opposed to emission-controlled deep sow mulching, is more prevalent (e.g., all but 2050-S3-ORC), agricultural waste burning dominates the nationwide ORC generating potential and exceeds electricity generating capacity at either cement plants or iron and steel plants, the two industries where ORCs have been administered already in India. In the 2050-S3-ORC scenario, electricity is not generated from agricultural waste burning because the residue is managed with a nonemitting, deep sow mulching technology.

The estimated ORC-generated electricity has varying levels of agreement with previous estimates.[33,35] A recent report estimated that the 2015 ORC potential in the cement, iron and steel, and agricultural sectors is 514, 125, and 1430 MW, respectively.[33] While there is agreement between these estimates and ours in the cement (358 MW) and iron and steel (203 MW) sectors (the differences can be attributed to different activity rates between the inventories used to build the estimates and ORC efficiency assumptions), they found a much lower generating capacity from agricultural burning than our estimate (14,200 MW), Sarkar and Bhattacharyya's estimate of 16,880 MW,[36] or Murali and colleagues' estimate of 23,200 MW.[35] That report[33] did not detail the calculations or assumptions made in their agricultural burning calculations, so it is difficult to explain what is causing the large discrepancy between the electricity generating potential in their estimate and ours. The lower estimate from Murali and colleagues[35] is attributed to a lower amount of agricultural product burned (147 MT compared to 183 MT), a lower heating value (16 MJ/kg compared to 17 MJ/kg), and a less efficient ORC (20% compared to 25%).

Given that the DHS pathway had limited air pollutant or CO_2 emission benefits, a combined approach that would reuse waste-

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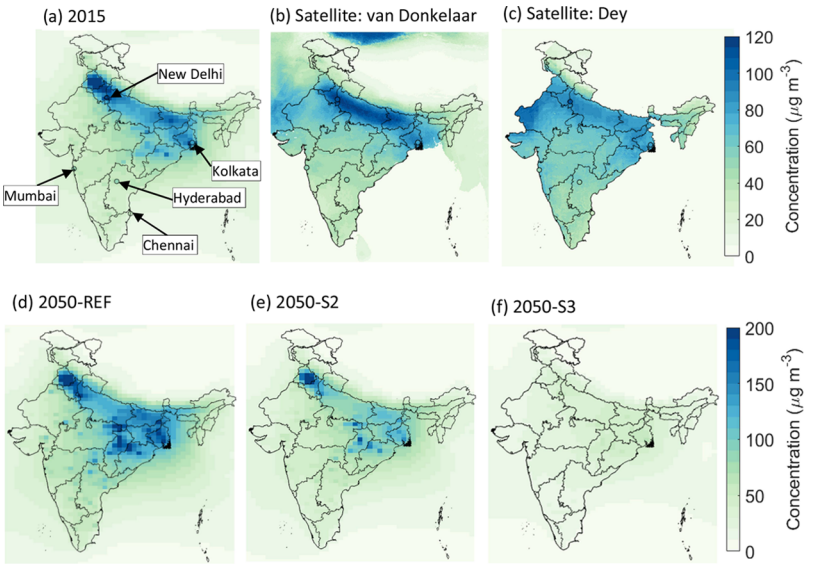

Figure 2. Simulated, annual-average $PM_{2.5}$ concentrations over India from the base-case scenarios ((a) 2015; (d) 2050-REF; (e) 2050-S2; (f) 2050-S3) and 2015 satellite-retrieved, surface-level $PM_{2.5}$ products from (b) van Donkelaar and colleagues[58,59] and (c) Dey and colleagues.[14] The five colored circles in the 2015 GEOS-Chem and satellite-retrieved products are 2015-averaged $PM_{2.5}$ measured at U.S. Embassy and Consulates' sites in Chennai, Kolkata, Hyderabad, Mumbai, and New Delhi. The 2015 figures are on a 0−120 $\mu g\ m^{-3}$ scale, and each of the 2050 results is shown on a 0−200 $\mu g\ m^{-3}$ scale. The district heating system (DHS) and organic Rankine cycle (ORC) interventions had little impact on simulated $PM_{2.5}$ (Table 5), and full-scale $PM_{2.5}$ spatial fields for all scenarios are available in Supporting Information Figure 8. Time-series evaluations at each of the five monitoring sites and bias plots between the 2015 base-case simulated results and both satellite-retrieved products are available in Supporting Information Figures 3 and 5, respectively. Monthly comparisons between our simulated results and the Dey satellite results are shown in Supporting Information Figure 4.

Table 4. Evaluation of GEOS-Chem-Simulated $PM_{2.5}$ Observations with U.S. Embassy and Consulates' Observations[a]

City	GEOS-Chem Simulated $PM_{2.5}$ (μg m-3)	Observed $PM_{2.5}$ (μg m-3)	NMB	van Donkelaar satellite $PM_{2.5}$ (μg m-3)	Dey satellite $PM_{2.5}$ (μg m-3)
Chennai	30.4	21.5 (n =289)	-13.9	39.5	44.9
Kolkata	78.1	127 (n =321)	-21.5	94.8	76.5
Hyderabad	53.0	33.3 (n =284)	16.1	44.7	58.9
Mumbai	52.8	37.9 (n =312)	2.5	47.2	69.5
Delhi	108	114 (n =346)	2.0	113	90.8

[a] n is the number of days where filtered observations existed in five Indian cities and two satellite-retrieved, surface-level $PM_{2.5}$ estimates in 2015. Normalized mean bias (NMB) between the GEOS-Chem simulations and the average of the observations and satellite-retrieved products is shown. Time-series evaluations are available in Supporting Information Figure 3.

heat in DHSs and then use the remaining waste-heat as input to ORCs was not assessed.

Material Exchange Potential of Coal Fly-Ash to Cement and Brick Production. Coal fly-ash is utilized at 60.8%[46] in the 2015 and 2050-REF scenarios, 80% in the 2050-S2 scenario, and 95% in the 2050-S3 scenarios. This leaves 83, 207, 54, and 27 MT of coal fly-ash in the four respective DHS scenarios (2015-DHS, 2015-REF-DHS, 2050-S2-DHS, and 2050-S3-DHS) and 74, 190, 47, and 26 MT in the four respective ORC scenarios (2015-ORC, 2015-REF-ORC, 2050-S2-ORC, and 2050-S3-ORC) (Table 3). The ORC scenarios have lower coal fly-ash availability due to coal combustion reductions at CTPSs following additional ORC-generated electricity. In each of the DHS and ORC scenarios, 100% of the available fly-ash can be utilized in cement and brick production. In the 2050-S2 and 2050-S3 DHS and ORC scenarios, all the available coal fly-ash is utilized in cement production alone. This is attributed to increased cement demand for construction to support the anticipated population growth and lower amounts of coal fly-ash production (higher penetration of noncarbon energy from the power supply sector).

Simulated $PM_{2.5}$ in GEOS-Chem and Evaluation with Two Satellite-Retrieved, Surface-Level Products and Observations at Five U.S. Embassy and Consulates' Sites. The 2015 GEOS-Chem simulations showed varying levels of agreement with observations at five U.S Embassy and Consulates' sites and the two satellite-retrieved $PM_{2.5}$ estimates in those cities (Figure 2, Table 4, Supporting Information Figure 3 for year-long, time-series comparisons at the five observation sites, and Supporting Information Figure 4 for monthly comparisons with the Dey product). Explanations for the inconsistent performance may be attributed to an incomplete observation data set at each monitoring site (i.e., not 365 days of observed data), uncertainties associated with the emissions, modeling framework, and observing instruments, and the coarse resolution of the GEOS-Chem output (0.5° × 0.625°) as concentration gradients will exist within these grids and may not capture local, microenvironment concentrations, including those at the monitoring sites.

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Punjab (GEOS-Chem was biased high) and just south in Rajasthan (GEOS-Chem was biased low) had the highest 2015 biases when compared against both satellite-retrieved and surface-level products (Supporting Information Figure 5). In addition, the monthly satellite-retrieved product from Dey and colleagues[14] did not find similarly elevated $PM_{2.5}$ in Rajasthan (Northwest India near Pakistan) in November 2015 (Supporting Information Figure 4). The Thar Desert extends into Rajasthan and is not explicitly accounted for in the inventory used in this study; we use the default dust emission estimates in GEOS-Chem, which has been demonstrated to be poorly constrained.[63] We found stronger agreement between the GEOS-Chem year-long simulations and the van Donkelaar product than with the Dey product across India (Supporting Information Figure 6). Of the 932 GEOS-Chem output grids ($0.5° \times 0.625°$) over India, 894 grids were biased by $< \pm 20$ $\mu g\ m^{-3}$ in the van Donkelaar product compared to only 459 such grids in the Dey product (Supporting Information Table 8 for more evaluation statistics).

Each of the four base-case scenarios found elevated $PM_{2.5}$ concentrations throughout the Indo-Gangetic Plain due to high emissions from both regional-scale (CTPSs, brick kilns, and agricultural burning) and local-scale (extensive residential biomass burning and on-road mobile sources) sources[64] as well as meteorological conditions conducive to air pollutant buildup (e.g., low planetary boundary layer heights and air basin trapping from the Himalayas to its northeast) (Figure 2). The highest $PM_{2.5}$ concentrations in the 2015, 2050-REF, and 2050-S2 scenarios are in Punjab due to open agricultural waste burning following the harvest season in November; the $PM_{2.5}$ emission rate for open burning in Punjab was ~6 times higher in November than the annual average (Supporting Information Section 3 and Figure 7). The 2050-S3 scenario showed less geographic variation and relatively low $PM_{2.5}$ levels in the area because agricultural waste is controlled by deep sow mulching technology instead of being burned.

Population-weighted, annual-average $PM_{2.5}$ concentrations showed small improvements under either waste-heat reuse strategies (DHS and ORC) (Table 5 and Supporting Information Figure 8), consistent with the small, nationwide emission reductions from these strategies. Nationwide air quality benefits were higher in the ORC scenarios, but the DHS benefits would more likely be observed in low-SES communities that use biomass burning for heating, particularly during winter in North India. Although the majority of heating activity could be offset from DHS implementation within localities that have CTPSs, these reductions resulted in low $PM_{2.5}$ benefits (Supporting Information Figure 9 and Table 9). The wintertime-average improvement in population-weighted $PM_{2.5}$ concentrations within these localized domains ranged between 0.85 and 1.8% across the scenarios, with the maximum, wintertime, local $PM_{2.5}$ improvement of 5.7 $\mu g\ m^{-3}$ (2.7%) in the New Delhi-NCR (Supporting Information Figure 9). ORCs had less of a local $PM_{2.5}$ benefit (Supporting Information Table 9) as emission reduction at such large-point sources will have more regional impacts.

Table 5. Population-Weighted $PM_{2.5}$ Concentrations in the Scenarios as Simulated in GEOS-Chem

Scenario	Population-weighted $PM_{2.5}$ ($\mu g\ m^{-3}$)
2015	**56.4 ± 28.6**
2015-DHS	56.2 ± 28.6
2015-ORC	55.5 ± 28.4
2050-REF	**96.1 ± 44.7**
2050-REF-DHS	95.9 ± 44.6
2050-REF-ORC	93.7 ± 44.4
2050-S2	**70.2 ± 34.8**
2050-S2-DHS	70.0 ± 34.8
2050-S2-ORC	67.8 ± 34.5
2050-S3	**35.7 ± 9.6**
2050-S3-DHS	35.7 ± 9.6
2050-S3-ORC	35.6 ± 96

CO_2 Emission Accounting. The total nationwide CO_2 emissions were 2120, 1190, 7180, and 4480 Mt in the 2015, 2050-REF, 2050-S2, and 2050-S3 scenarios, respectively, and these estimates have previously been demonstrated to be consistent with previously published estimates (those in ref 2 and citations within). The DHS scenario offered near-zero nationwide emission reduction benefits (<0.04%), while the ORC scenario offered larger benefits (1.9−7.4%) (Supporting Information Table 10). TPSs are the largest CO_2-emitting sector in all the scenarios except 2050-S3 (where noncarbon sources dominate the electricity supply), so reducing emissions from the energy supply sector will have larger benefits than from other sectors.

Premature Mortalities Avoided from $PM_{2.5}$-Reductions from the DHS and ORC Pathways. There were 1.05 million (95% CI: 0.67−1.37 million) and 2.01 million (95% CI: 1.85−2.16 million) premature mortalities in the 2015 base-scenario using the IER and GEMM approaches, respectively. These estimates agree with previous estimates that span 500,000−1.1 million from the IER approach[1−4] and 2.2 million from the GEMM approach[5] in India. The 2050-REF scenario had the highest annual mortality estimates among the scenarios with 1.48 million (95% CI: 1.02−1.86 million) and 2.61 million (95% CI: 2.41−2.79 million) in the IER and GEMM approaches, respectively. The ORC pathway offered higher health benefits than the DHS pathway in each of the four scenarios, which was expected considering the ORC scenarios simulated higher $PM_{2.5}$ reductions. Neither pathway offered more than 1.6% premature mortalities avoided in any of the four scenarios with either dose−response curves (Supporting Information Table 11). The highest total number of deaths avoided among the four DHS scenarios was in 2015 (IER: 790 (670−800); GEMM: 2500 (2400−2700); Supporting Information Table 11). The fewer mortalities avoided in each of the 2050 scenarios (which had 20% higher population) are attributed to reduced residential space heating activity from biomass burning, which limits the efficacy of DHSs, and an increased share of noncarbon energy supply. The highest total number of deaths avoided among the four ORC scenarios was in the 2050-S2-ORC scenario (IER: 15,000 (13,000−15,000); GEMM: 36,000 (34,000−38,000); Supporting Information Table 11). The health impact assessments were conducted at a coarse resolution ($0.5° \times 0.625°$; the GEOS-Chem output resolution), though recent work indicates that assessments done at a finer scale (e.g., 1 km resolution) will find additional benefits.[65] Further, the dose−response curves used here only consider $PM_{2.5}$, but a growing body of literature has implicated other pollutants in addition to $PM_{2.5}$ to contribute to adverse health outcomes associated with air pollution exposure.[66,67]

Recent research studies[4,9,12,68,69] and research commentaries[64,70−72] have identified the urgent need to implement

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strategies to reduce both air pollutant and climate-forcing gas emissions in India and have indicated the strong environmental, human health, and economic benefits of such actions. Traditional approaches to mitigate emissions (e.g., switch fuels for household cooking, install controls, etc.) have had success but have been largely incomplete throughout the country.[73] Here, we assessed the impacts of two, circular strategies that reuse industrial waste-heat: (1) a novel, multisector approach with DHSs and (2) the application of ORCs to convert waste-heat to electricity. These approaches, which have been proposed as intermediate interventions to reduce air pollutant and carbon emissions, offer modest nationwide air quality, CO_2 emission reduction, and human health benefits but less than those of previously assessed, ambitious regulatory achievement of cleaner fuel sources and cleaner technologies that offer larger environmental, health, and economic benefits.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c05897.

Additional modeling details, model evaluation, economic assessment, and local waste-heat reuse impacts (PDF)

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Author Contributions

R.M.L. designed the research, performed all of the analysis, and wrote the manuscript. K.T. and C.V. provided the inventory used in this study. K.T., A.F., and A.R. designed the multisector DHS strategy. Q.M., S.W., and J.K. provided GEOS-Chem data sets. All authors reviewed the manuscript before submission.

Notes

The authors declare no competing financial interest.

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