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CO_2 Emissions from Direct Energy Use of Urban Households in India

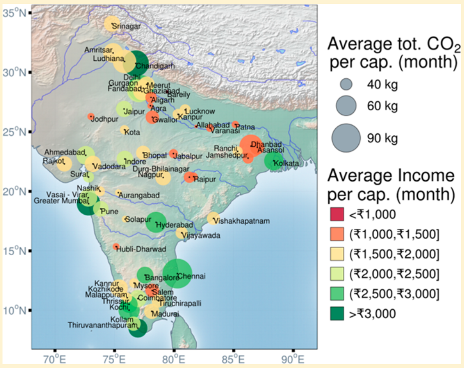
Sohail Ahmad,*[,§] Giovanni Baiocchi,[‡] and Felix Creutzig[§]

[‡]Department of Geographical Sciences, University of Maryland, 2181 Samuel J. LeFrak Hall, College Park, Maryland 20742, United States

[§]Mercator Research Institute on Global Commons and Climate Change (MCC), Torgauer Straße 12-15, 10829 Berlin, Germany

Supporting Information

ABSTRACT: India hosts the world's second largest population and offers the world's largest potential for urbanization. India's urbanization trajectory will have crucial implications on its future GHG emission levels. Using household microdata from India's 60 largest cities, this study maps GHG emissions patterns and its determinants. It also ranks the cities with respect to their household actual and "counter-factual" GHG emissions from direct energy use. We find that household GHG emissions from direct energy use correlate strongly with income and household size; population density, basic urban services (municipal water, electricity, and modern cooking-fuels access) and cultural, religious, and social factors explain more detailed emission patterns. We find that the "greenest" cities (on the basis of household GHG emissions) are Bareilly and Allahabad, while the "dirtiest" cities are Chennai and Delhi; however, when we control for socioeconomic variables, the ranking changes drastically. In the control case, we find that smaller lower-income cities emit more than expected, and larger high-income cities emit less than expected in terms of counter-factual emissions. Emissions from India's cities are similar in magnitude to China's cities but typically much lower than those of comparable U.S. cities. Our results indicate that reducing urban heat-island effects and the associated cooling degree days by greening, switching to modern nonsolid cooking fuels, and anticipatory transport infrastructure investments are key policies for the low-carbon and inclusive development of Indian cities.



I. INTRODUCTION

Cities take center stage in climate change mitigation; urban areas account for about 76% of CO_2 emissions from global final energy use and about 43% of global primary energy-related CO_2 emissions.[1] Responding to climate change by mitigating carbon dioxide emissions is placing new and complex demands on urban policy makers. This task is urgent and demands the reconfiguration of urban settings, including energy systems, urban transportation, and built environment. In this context, the aim of this paper is to understand household emissions across Indian cities and their determinants to mitigate carbon dioxide emissions through appropriate urban policy interventions.

Understanding household emission patterns in India matters for several reasons. First, urbanization is likely to become a most relevant transition effect in India in structuring future emissions. Hence, it becomes increasingly important to study the specific role of Indian cities in shaping GHG emissions profiles. Second, on a more detailed level, recent studies have emphasized the aggregate or sectoral direct energy use and GHG emissions of cities but only insufficiently analyzed the household level.[2−6] Third, these studies have also mostly focused on Europe,[3,7] the United States,[8] China,[2] and Japan[5] and at selected cities, such as Oslo.[9] However, the household level is of particular importance for finding policy solutions that respect the specific population. As India emerges as one important world region for future GHG emission growth, and because it has the second-largest urban population (after China) but, at the same time, a relatively low urbanization level, it displays the highest potential of all countries for influencing the overall urbanization trajectory toward low-carbon cities for better or worse.

Some important studies have already investigated Indian household energy consumption and emissions at city level[10−12] and the national level, with rural and urban distinction.[13−18] Notably, Pachauri has scrutinized household energy consumption in India, emphasizing its role in development and climate change mitigation.[19] These studies model fuel choices,[13,17,20] energy demand,[12,14] or both[15] using socio-economic and demographic variables as explanatory factors.

Our study is novel in focusing on the largest 60 Indian metropolises and in analytically separating the effect on emissions of idiosyncratic city-specific circumstances from the impact of relevant drivers of household emissions across cities. Moreover, this study investigates disaggregated household emissions of direct energy use (electricity, cooking fuels, and private transportation) rather than aggregated emissions, indicating stratified strategies for mitigating emissions.

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India, with an urban population of 410 million (32% urbanization level), is the second most urban populous country in the world (after China, with about 760 million) and is projected to reach 814 million (with a 50% urbanization level) in 2050.[21] The current share of India's urban population to the world urban population is 10.5%, a share that is expected to grow to 12.8% by midcentury.[21] Population distribution across urban centers also matters for climate-change mitigation.[22,23] According to the most recent census, urban India includes 7935 urban agglomerations and towns, including 468 with populations over 100 000 (8 over 5 million and 45 between 1 and 5 million).[24] The definition of India's urbanization used in this paper refers to statutory towns and census town as per the census of India.[24] Statutory towns are defined as "all places with a municipality, corporation, cantonment board or notified town area committee, etc.", whereas census towns refer to "all other places which satisfies the following three criteria: (i) A minimum population of 5000; (ii) At least 75% of the male main working population engaged in non-agricultural pursuits; and (iii) A density of population of at least 400 persons per sq. km".

We proceed as follows. First, we briefly introduce the accounting framework of household emissions in India and the underlying data (section II). We then provide a descriptive overview on household emissions among major 60 cities in India illustrating usage of electricity, cooking fuels, and private transportation fuels (section III). We then formally analyze the household emission inventories with panel regressions and investigate why some cities emit four times more than other cities (section IV). This section also presents standardized ranking, in which we controlled for socioeconomic variables to quantify the importance of structural characteristics of cities. We conclude by discussing the policy relevancy of our results.

As key findings, we obtain that income and household size are the most important determinants of household emissions. However, there are several other factors that determine emissions, such as urban and dwelling unit characteristics, education level, and gender. Our analysis indicates three possible planning interventions: reducing air conditioning needs by urban greening and design, switching to modern nonsolid cooking fuels, and anticipatory public and non-motorized transport infrastructures to prevent high-emission lock-in. These interventions would also foster much-needed inclusive development in Indian cities.

II. ESTIMATION FRAMEWORK AND DATA

This study focuses on three major household sources of direct carbon dioxide emissions: electricity, cooking fuels, and private transportation. The following equation provides an accounting framework for the empirical work.

$$\text{emissions} = f_1 * \text{electricity} + f_2 * \text{cooking-fuels} + f_3 * \text{private-transportation} \qquad (1)$$

The first term in eq 1 represents carbon dioxide emissions from residential electricity usage. The electricity usage has been converted into emissions with the emission factor f_1 (see Table S1) without considering regional differences into emissions because electricity is supplied through the national grid. The second term, cooking fuels, represents emissions mainly from cooking. The group of household cooking fuels consists of seven components (firewood and chips, liquefied petroleum gas, dung cake, kerosene, coal or coke, charcoal, and gobar gas) that were aggregated after being multiplied with specific emissions factors to compute cooking-fuels emissions. The third term in the equation represents energy use for private transportation as a vector of activities for household who own vehicles. It does not include energy use in other means of public transportation such as railway, bus or tram, taxi, and auto-rickshaw. Each source of emissions is subjected to panel regressions with several explanatory factors, including economic (consumption expenditure and employment structure), demographic, sociocultural, and settlement-related characteristics.

The data set used in this study comes from the 66th round (July 2009–June 2010) National Sample Survey on "Household Consumer Expenditure", having a stratified multistage design and consisting of over 41 736 urban households from India spread across the nation.[25] The period of survey has been a one-year duration with four subrounds of three months (July–September and October–December of 2009 and January–March and April–June of 2010). In each of these subrounds, equal numbers of blocks have been surveyed to ensure uniform spread of sample to minimize the effect of seasonal variations on several variables, such as electricity consumption. Out of these, we used about 19 000 households from 60 major cities for our analysis. Sample households are aggregated to perform analyses at city level.

III. HOUSEHOLD DIRECT CO_2 EMISSIONS IN INDIAN CITIES

We here report the GHG emissions across Indian cities. We summed the citywise mean of per-capita emissions from electricity, cooking fuels, and private vehicle fuels usage, obtaining the actual total CO_2 emissions per capita in each city.

Some lower-income cities, especially secondary cities (e.g., Dhanbad, Ludhiana, Ghaziabad, Meerut, Amritsar, and Gurgaon) but also the mega cities of Delhi and Chennai, display high emissions. In per-capita emissions ranking, households from Uttar Pradesh's cities (Bareilly and Allahabad) emit the least, whereas large cities (Chennai and Delhi) emit the most (Figure 1; see also Table S3). However, when we standardized the socioeconomic factors (income, household size, and age of the household's head), the ranking changes drastically (see the results section for discussion). At first

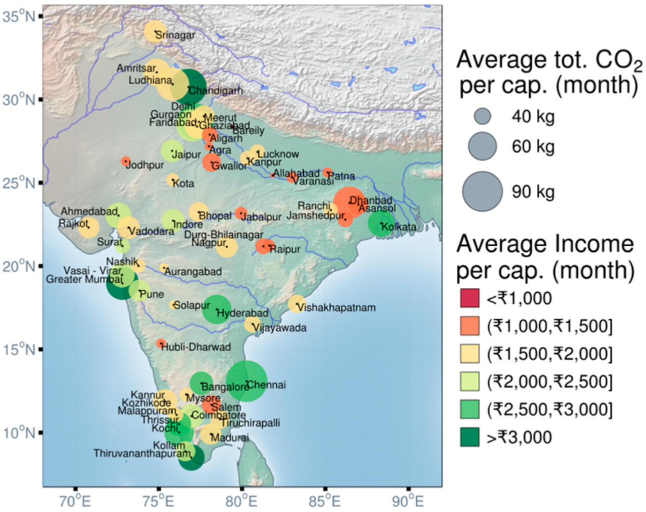
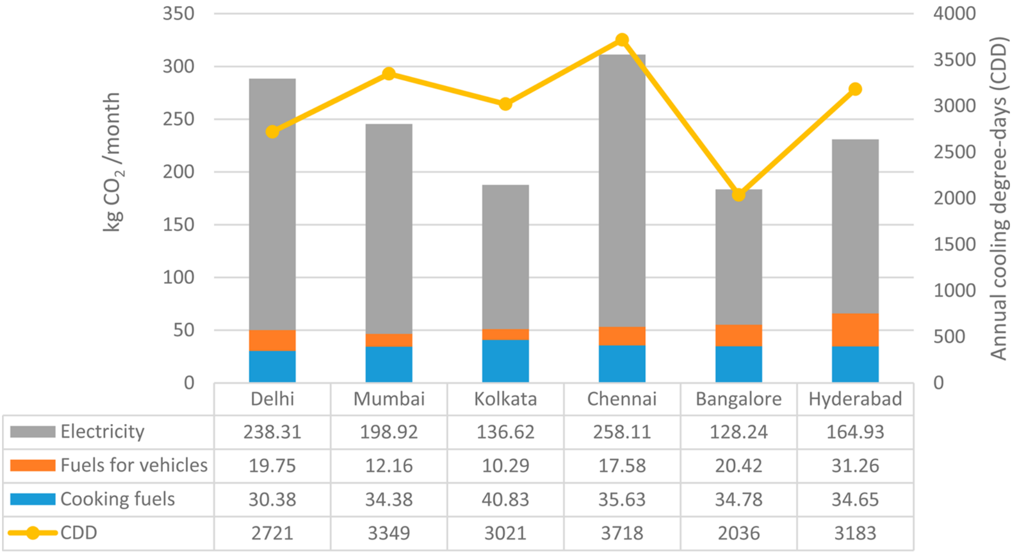


Figure 1. Total CO_2 emissions per capita in the 60 largest Indian cities, 2009–2010.



	Delhi	Mumbai	Kolkata	Chennai	Bangalore	Hyderabad
Electricity	238.31	198.92	136.62	258.11	128.24	164.93
Fuels for vehicles	19.75	12.16	10.29	17.58	20.42	31.26
Cooking fuels	30.38	34.38	40.83	35.63	34.78	34.65
CDD	2721	3349	3021	3718	2036	3183

Figure 2. Household CO_2 emissions (kg per month) in the largest six Indian metropolises, 2009−2010.

glance, it seems that secondary cities are more energy efficient. However, their low per-capita emission ratings are based on their relatively low socioeconomic household performance.

More often than not, electricity usage constitutes the highest share of household emissions in these metropolises; emissions from electricity usage take about 66%, followed by emissions from cooking fuels (27%) and private transportation (7%). Chennai is the leader of electricity consumption (81 kg CO_2 per capita per month), while residents of Allahabad consume the least electricity (12 kg CO_2 per capita per month) (see Table S3). Several factors are responsible for such a huge difference, including the availability of electricity infrastructure and income level. For cooking fuels, Dhanbad has exceptionally high monthly emissions (54 kg CO_2 per capita) because of the predominant use of coke and coal, followed by Asansol (27 kg CO_2 per capita). Emissions from cooking fuels are lowest in Vishakhapatnam and Delhi (8 kg CO_2 per capita per month). The relatively important role played by cooking fuels is mainly due to the use of predominantly traditional solid fuels, particularly coke and coal. Emissions from gasoline used for private vehicles also differ substantially among cities. The values show the fair amount of regional disparity, with monthly emissions being highest in Hyderabad (8 kg CO_2 per capita) and lowest in Bareilly (0.7 kg CO_2 per capita). These values are well reflected in the ranking.

Emission levels from Indian cities are significantly less than those of comparable U.S. cities[26] but closer to those of Chinese cities[27] in aggregate household emissions. For instance, annual household emissions from electricity usage in Indian cities is about 1.76 tons carbon dioxide, whereas corresponding values from China and the US are 2.35 tons (1.3 times) and 13 (7.4 times) tons, respectively.[26,27] Similarly, annual household emissions from gasoline used in private transportation in Indian is 0.18 tons, and corresponding values from China and the US are 0.14 tons (about the same magnitude) and 11.96 tons (about 2 orders of magnitude higher), respectively.[26,27] The World Bank[28] data show that India, China, and the United States have annual CO_2 emissions from the burning of fossil fuels and cement manufacture that are 1.7, 6.7, and 17 metric tons per capita, respectively. India emits about one-fourth the amount of CO_2 of China and one-tenth that of the United States at the per-capita level of total territorial emission.

The heterogeneity in emissions across Indian metropolises is considerable. On average, monthly household emissions vary by a factor of 3.5, and even within the six largest cities, emissions vary by a factor of 1.9 (Figure 2). These differences suggest that changing urban development patterns, improvements in the availability and accessibility of infrastructures, and urban household-specific characteristics can have potentially large impacts on total carbon emissions.

Among the six largest metropolises, on average, electricity consumption accounts for 78% of emissions, while cooking fuels account for 14%, and the remaining 7% are attributed to gasoline combustion (Figure 2). Comparing levels to those of the six largest metropolises, the six smallest metropolises emit three-fourths of their total emissions and, specifically, 6% less from electricity, 8% more from cooking fuels, and 2% less from gasoline. Interestingly, Bangalore emits the least among the largest six metropolises, followed by Kolkata, Hyderabad, Mumbai, Delhi, and Chennai. Most of these differences come from different amount of electricity consumption, possibly used for cooling: Chennai has the highest number of annual cooling degree days (CDD; about 3700), and Bangalore has the lowest number of CDD (about 2000). The emissions share of gasoline usage from private vehicle fuels is highest in Hyderabad and the lowest in Kolkata. Overall, about 90% of emissions come through the use of petrol, and the remaining 10% originate from diesel (5%), and lubricants and other fuels (5%). Our statistics on cooking fuels reveal that, on average, urban households emit 34.5 kg CO_2 per month, of which 96% is emitted through the use of modern fuels and only 4% through using traditional solid fuels. The highest share of traditional solid fuels is in Kolkata (15%), followed by Bangalore (6%); the remaining cities have less than or equal to 2%. This is also reflected in the fact that overall emissions from cooking fuels are highest in Kolkata.

To understand spatial variation of GHG emissions in Indian cities, we map average emissions per capita with the average income per capita (Figure 1). Among other trends, spatial variation of GHG emissions is clearly visible. The central Indian cities, particularly Bihar, Madhya Pradesh, Rajasthan, Odisha,

Table 1. Alternative Models of Regression Results of Emission Determinants Using 2009−2010 Microdata[a]

	electricity per capita		cooking fuel per capita		private transportation per capita		total per capita	
	FE (1)	RE (2)[b]	FE (3)	RE (4)	FE (5)	RE (6)	FE (7)	RE (8)
log monthly consumption expenditure per capita (in Rs)	0.57***[c]	0.57***	0.26***	0.26***	0.82***	0.82***	0.57***	0.57***
household size	−0.08***	−0.08***	−0.08***	−0.08***	0.07***	0.07***	−0.06***	−0.06***
log density	−0.11***	−0.02	0.06*	0.08***	−0.20***	−0.10***	−0.10***	0.02
rented DU (ref: owned)	−0.21***	−0.21***	−0.15***	−0.14***	−0.37***	−0.37***	−0.26***	−0.26***
no DU (ref: owned)	0.15	0.16	−0.18	−0.18	0.06	0.06	−0.00	0.00
others DU (ref: owned)	−0.19***	−0.20***	−0.16***	−0.15***	−0.14***	−0.14***	−0.28***	−0.27***
female-headed household	0.07***	0.07***	0.02	0.02	−0.17***	−0.17***	0.05**	0.05**
age	0.01***	0.01***	0.00***	0.00***	−0.00	−0.00	0.00***	0.00***
currently married (ref: never married)	0.06**	0.06**	0.04	0.04	0.38***	0.38***	0.21***	0.21***
widowed (ref: never married)	0.12***	0.12***	0.09**	0.08**	0.42***	0.42***	0.26***	0.26***
divorced or separated (ref: never married)	0.10	0.10	0.09	0.09	0.38***	0.38***	0.26***	0.26***
education 1−6 (ref: education 0)[d]	0.03*	0.03*	0.00	0.00	−0.02	−0.02	0.00	0.00
education: 7−10 (ref: education. 0)	0.11***	0.11***	0.01	0.01	0.04*	0.04*	0.08***	0.07***
education 12 (ref: education. 0)[d]	0.16***	0.15***	−0.05**	−0.04*	0.19***	0.19***	0.09***	0.09***
education 15+ (ref: education. 0)	0.26***	0.26***	−0.06***	−0.06***	0.45***	0.45***	0.21***	0.21***
Islam (ref: Hinduism)	0.03*	0.03*	−0.04**	−0.04**	−0.06***	−0.06***	−0.02	−0.03*
Christianity (ref: Hinduism)	−0.04	−0.04	−0.02	−0.03	0.02	0.02	−0.03	−0.04
other religion (ref: Hinduism)	0.03	0.03	0.10***	0.10***	0.09**	0.09**	0.07**	0.07***
associate professional (ref: professional/ managerial)	−0.09***	−0.09***	0.01	0.01	−0.11***	−0.11***	−0.06***	−0.07***
clerical (ref: professional or managerial)	−0.09***	−0.09***	0.07***	0.07***	−0.24***	−0.24***	−0.05*	−0.05*
sales/service workers (ref: professional or managerial)	−0.12***	−0.12***	0.07***	0.07***	−0.31***	−0.31***	−0.09***	−0.09***
elementary workers (ref: professional or managerial)	−0.05***	−0.05***	0.05**	0.05**	−0.41***	−0.41***	−0.06***	−0.06***
access to water	0.10***	0.10***	−0.03**	−0.03**	0.05***	0.05***	0.07***	0.07***
access to modern cooking fuels	0.30***	0.30***	−0.08***	−0.09***	0.12***	0.12***	0.17***	0.17***
access to electricity	0.08	0.08	−0.12***	−0.12***	−0.05*	−0.05*	0.67***	0.67***
self-employed (ref: regular salary)	−0.01	−0.01	0.07***	0.07***	0.04*	0.04*	0.05***	0.05***
labor (ref: regular salary)	−0.07***	−0.07***	−0.01	−0.01	−0.03	−0.03	−0.01	−0.02
other employment (ref: regular salary)	−0.03*	−0.03*	0.10***	0.10***	−0.12***	−0.12***	0.02	0.02
caste: SC (ref: ST)[e]	0.05*	0.05*	0.06**	0.06**	−0.10***	−0.10***	0.07**	0.07***
caste: OBC (ref: ST)	0.07**	0.07**	0.05*	0.05*	−0.09**	−0.09**	0.06**	0.06***
caste: other (ref: ST)	0.09***	0.09***	0.01	0.01	−0.02	−0.02	0.06**	0.06**
May temperature max (mean)		0.01		−0.01*		0.01		−0.00
January temperature min (mean)		0.00		−0.03***		0.00		−0.01
capital city		0.10		−0.23***		0.10		−0.05
city size 2−4 million (ref: <2 million)		−0.00		0.04		0.01		0.01
city size 4−10 million (ref: <2 million)		0.06		−0.09		0.15		0.00
city size >10 million (ref: <2 million)		0.10		−0.10		−0.31*		−0.07
constant		−4.08***		−0.16		−9.07***		−4.03
observations	17,493	17,493	18,192	18,192	19,044	19,044	18,962	18,962
R^2	0.56	0.56	0.32	0.32	0.49	0.45	0.62	0.58
adjusted R^2	0.54	0.54	0.20	0.22	0.48	0.45	0.61	0.58
F statistic	647.55***	522.46***	146.30***	129.44***	502.78***	392.44***	789.00***	646.05***

[a]Dependent variables are the logarithmic monthly CO_2 emissions per capita in kg CO_2 from the listed sources. Metropolis dummies are used as fixed effects, whereas survey rounds is used but omitted from the equations. [b]Note that the difference in coefficients between the two models is "practically" very small; therefore, it is possible that rejection of RE is driven by the large sample size used. Because of the small differences, using one or the other would not change our results. [c]*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$. [d]The education suffix represents number of years of education, for instance, education 12 represents that the household's head has attained 12 years of schooling. [e]Caste is represented by scheduled caste (SC), scheduled tribes (ST), and other backward class (OBC).

and Uttar Pradesh, reveal low emissions because of low socioeconomic bases. These states are also known as "BIMAROU" states to describe the weakness of economy and lower socioeconomic status. Some cities, despite higher income per capita, show lower emissions because of mild weather (e.g., Bengaluru) and better public transport (e.g., Greater Mumbai).

Table S2 shows the pairwise correlation between total per-capita emission and important determinants. As an example, population density is positively correlated with emissions. However, this is only a marginal relationship between variables and does not take into account the concomitant impact of other confounding factors. In fact, once we control for other determinants using a regression approach, we found population density to have a negative impact. The positive correlation might just be due to other socioeconomic variables (in particular, income, which correlates positively with density). Therefore, correlations can provide misleading information, and a proper regression analysis was deemed necessary.

The next section develops a formal regression model to identify potential statistically and, more importantly, practically significant drivers of household GHG emissions in India.

IV. MODEL SPECIFICATION AND EMISSIONS ESTIMATES

1. Model Specification. We follow the standard empirical literature based on demand for specific forms of energy that links emissions to its various types of determinants through a regression model, presented as in eq 2 (see, e.g., refs 5,7, and 29–33).

$$E_{it} = \alpha_i + \sum_{j=1}^{k} \beta_j X_{jit} + \varepsilon_{it} \tag{2}$$

with $i = 1, ..., N$ and $t = 1, ..., T_i$ representing cities and households, respectively. Here, E_{it} is a measure of direct household CO_2 emissions, and X_{jit}, for $j = 1, ..., k$, denote the control variables derived from the survey that correspond determinants of emissions. k is the total number of emission determinants, and ε_{it} is the classical error term.

Regressions that account for individual heterogeneity are typically estimated using so-called fixed and random-effect panel models (see Wooldridge,[34] for example, for more details on panel data models). The fixed-effects model (FE) treats the individual effects, α_i, as fixed and the model can be estimated by ordinary least squares (OLS) by including dummy variables for the cities and adjusting the standard errors. The random effects model (RE) considers the effect as part of the random error. To decide between the two models, one can use the Hausman statistic. If the individual city effects are correlated with the explanatory variables, then the RE estimator is biased and should not be used.

Our dependent variables are emissions distinguished by type. We use broadly four categories of explanatory variables: economic (consumption expenditure and employment structure); demographic; sociocultural; and human-settlement- and dwellings-related characteristics in agreement with theoretical expectations and previous empirical findings.[35] The models also control for seasonal variations of energy usage using a dummy of survey subrounds (not presented in the equations).

We seek a regression specification and estimation method that adequately captures the properties of the data. A pooled OLS model would be appropriate if city-specific effects were unimportant. We hence performed a Chow test to examine whether city-specific effects should be taken into account (for a methodological explanation, see Baltagi).[36] We found that city-specific effects are relevant and that panel methods are necessary to determine the impact of socioeconomic factors on the emissions.

It is important to point out that with a data set of this size, about 19 000 observations, possibly all specific null hypotheses can be rejected. Therefore, special care is needed when interpreting the statistical significance of the regression results (see, e.g., refs 37–39). As p-values tend to 0 with increasing sample sizes, undue attention might be given to practically irrelevant variables. One approach to overcoming this problem is to use a stricter criterion for significance that accounts for the sample size instead of defaulting to the conventional 5% used in statistics. Granger[38] suggests a p-value threshold of 0.001 for samples of the order of 10 000 observations. Using the rule of thumb for standardizing the p value to a sample size of a hundred as proposed by Good,[40] we confirm that for our models, only coefficients that are significant at the one per thousand level (denoted by ***) can be considered "statistically significant". Moreover, with large sample sizes, it becomes more important to look at the practical significance of the effect rather than whether it is just different from zero.

Note that using a stepwise selection approach to reduce the number of regressors, such as backward elimination as described in standard applied regression references (such as Draper and Smith[41] (pp. 339–340) or Weisberg[42] (p. 222)), is known to inflate significance by over-fitting the available sample, thus producing models that cannot be generalized (see, e.g., refs 43 and 44).

2. Understanding Differences in Carbon Emissions within Cities. We here present the main results of the regression analysis. Regression results from random and fixed effects are presented in Table 1. The Hausman statistic finds evidence of correlation between regressors and the individual effects (p value of ~0) for all emissions types; therefore, the relevant model used in the subsequent interpretations is the fixed-effect model.

Household consumption expenditure, a proxy for income (here, after income), is positively correlated with all types of emissions. Private transport emissions change most sensitively with increases in income: a doubling of income increases emissions by more than 80% on average, keeping everything else constant. Household size is negatively correlated with all types of emissions per capita except private transport. A doubling in household size reduces emissions by almost 10%. Notably, these two variables are among the most important determinants of household emissions in our study, which is consistent with other studies.[27,35] The urban density is negatively correlated with emissions except for cooking fuels emissions. The impact of population density is particularly strong on private transport emissions. A doubling of density reduces emissions of private transport by about 20%, a reduction twice as big as the reduction in emissions associated with electricity. This result agrees with theoretical and empirical literature on the negative relationship between density and gasoline consumption.[45,46]

In general, access to urban amenities increases overall emissions. A household with access to electricity is associated with per capita emission increases by more than 95%, ceteris paribus. Our results are consistent with recent findings on CO_2 emission growth for the whole of India.[47] The study reports that in the period where access to electricity improved from 25% to 74%, the change in the share of households with access contributed between 39% and 53% to the rise of CO_2 from household electricity consumption. Using the retrospective shares of access reported in this study, our coefficient estimate of 0.67 implies a change of 39%. To put these results into perspective, consider that improvements in household electricity access contributed 3–4% of national emissions growth in India (urban and rural) over the past three decades, or not more than 0.008–0.018 tons of CO_2 per person per year between 1981 and 2011.[47] One reason for this rather low increase is that access to urban amenities often is accompanied by the use of cleaner fuels for cooking (for discussion, see Heltberg)[48] that decreases cooking-fuels emissions.[49] However,

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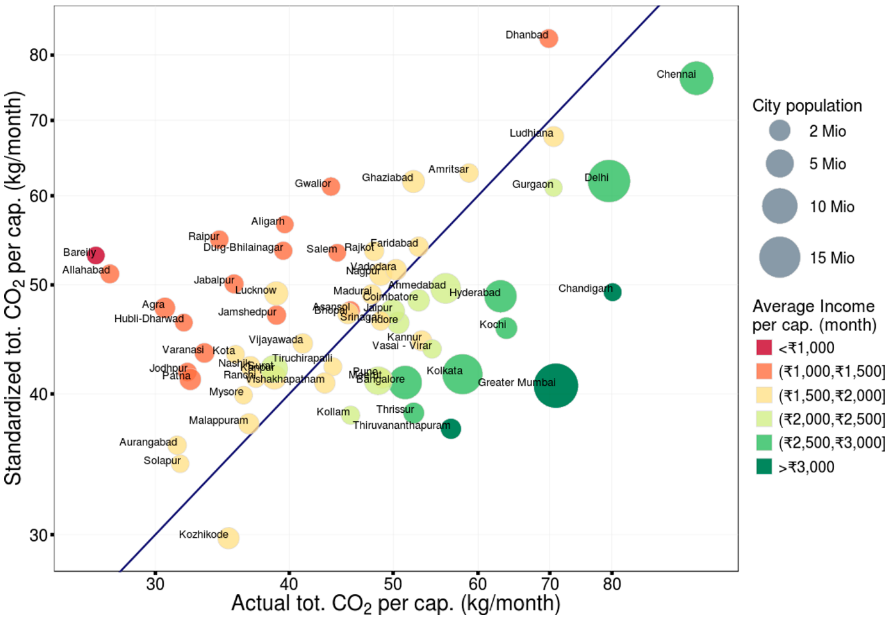

Figure 3. Actual and "standardized" total CO_2 per-capita emissions in Indian cities.

access to modern cooking fuels increases overall consumption, mirroring the codevelopment in lifestyles and consumption and pointing to the need to pre-emptively favor low-carbon energy sources for electricity generation.

The regression analysis also controls for several household's demographic and sociocultural variables. In general, highly educated households and single households (not having been married before) emit more than their counterparts. Female-headed household emits more from electricity usage but consume less gasoline. Emissions increase with the household head's age. Socially disadvantaged communities, specifically the scheduled caste, and Muslim households emit less than their counterparts, and vice versa. In the same way, households with the lower end of the occupation ladder emit less than their counterparts.

Interestingly, it also emerges that renter households emit less than the owner households by as much as 30%, provided that other variables remain constant. Renter households, unlike those in Western countries, are transitory households. Small dwelling size, a potential tendency to eat outside the home, and less traveling (due to choosing residence near to work) could be possible explanations.

3. Ranking of Indian Cities Based on Household Direct CO_2 Emissions. To understand better the importance of structural characteristics of cities, we estimate separate regressions for each of the 60 Indian cities and use them to predict emissions for a standardized household with average income, family size, and age. Using standardized household information allows us to answer the question of what would happen to net total emissions if we move individuals across cities (similar to Glaeser, Kahn,[26] and Zheng et al.[27]). By controlling only for the socioeconomic characteristics of the individuals, we attribute to the new location the emission changes resulting from types of homes and city infrastructures. Figure 3 shows actual and standardized emissions.

The figure shows that for the actual emissions, per-capita income and population are key factors in ranking emissions. However, once we standardize individuals, other factors, such as location and infrastructures, become more apparent. In particular, we find that warmer winters, with a maximum of 10 degrees higher in January, reduces standardized emissions in comparison to the actual emissions by 4 kg per month. Warmer summers have the opposite effect of increasing emissions by 1.5 kg per month for a 10 °C increase. Also, an increase of 1000 persons per square km reduces standardized emissions in comparison to actual emissions by 1 kg/month (see Table S3 for details). For example, Mumbai, one of the highest emitters among cities in the uncontrolled ranking, becomes one of the best performing cities in the standardized ranking, together with other mega cities such as Kolkata, Thiruvananthapuram, Kollam, and Bangalore. Except for the latter, which is characterized by a milder climate because of its high elevation, all of these are coastal cities with similar annual temperature ranges. Cities located on the West coast of peninsular India encounter milder average temperatures. In contrast, cities on the east coast tend to have much higher temperatures. Hence, east-coast cities such as Vijayawada, Tiruchirappalli, Vishakhapatnam, and Chennai tend to have much higher emissions. For example a standard individual moving from Chennai to Mumbai, would cut emission by half. Lower-income cities like Bareilly and Allahabad might display higher counter-factual emissions because they rely to larger amounts on dirty fuels, e.g., cooking. It seems also that cities that have poor public transportation and higher private emissions (e.g., Raipur) have also much higher standardized emissions.

V. DISCUSSION AND POLICY IMPLICATIONS

We analyzed the main factors explaining direct household GHG emissions in India and divided emissions according to their main sources: electricity use, private transport, and cooking.

We find that income, access to electricity, and education level are driving emissions, while emissions reduce with household size and population density. Access to electricity strongly drives emissions from electricity, an effect that is partially compensated for by reduced emissions from traditional cooking fuels. Cities with higher cooling degree days display higher emissions from electricity. Transport emissions grow strongest with income but are also most effectively mitigated by promoting more compact cities.

Our analysis identifies low-emitting cities, such as Bareilly and Allahabad, and high-emitting cities, such as Delhi and Chennai. Comparing actual emissions versus standardized emissions that control for socioeconomic characteristics reveals that larger cities tend to emit less per capita, possibly displaying economies in scales resulting in efficiency gains (see Bettencourt et al.[50]). In contrast, some low-emitting cities, such as Bareilly and Allahabad, display medium-high counterfactual emissions. This might be explained by low access to electricity and the use of more dirty fuels, especially for cooking. Thus, we have shown how keeping socioeconomic characteristics, such as income and population, constant, the location of the cities, the distribution of its population within it, and type of infrastructure are also key determinants of direct emissions. We found that if people moved to denser areas of cities located in areas of the India with warmer winters and cooler summers or used cleaner fuels, emissions would be lower. These results are analogous to what Glaeser and Kahn found for the United States and what Zheng et al. found for China.

Our analysis suggests three strategies for mitigating greenhouse-gas emissions. First, mitigating the growth in consumption in the electricity sector offers a few (albeit limited) opportunities. The electricity sector emissions are dominated by increasing income. Often, electricity consumption represents a welcoming shift away from inefficient and polluting traditional fuels. Nonetheless, a few options for mitigation emerge. Importantly, the number of CDDs increases electricity consumption. Hence, strategies that reduce cooling demand, e.g., urban greening that reduces the urban heat island effects, are likely to mitigate emission-increase and electricity-demand growth measurably. Specifically, efficient air conditioning[51] and city ventilation[52,53] would act as effective tools to reduce emissions from electricity usage. However, given the high magnitude of household emissions from electricity and its projected increase in the next decades, supply-side interventions, such as electricity supply from renewable sources, would be necessary to enable emission reductions.

Second, the switching of cooking fuels from coal and coke to modern nonsolid fuels is an important strategy given the relevance of cooking fuels in relative emissions, particularly in North Indian cities. Private transport emissions seem to be less important given their relatively small share. However, their share is growing most rapidly with growing affluence. Hence (and third), emission growth could be partially prevented by pre-emptively providing public and nonmotorized transport infrastructures in rapidly developing cities.[54,55] Higher taxes on gasoline and diesel would not only limit current automobile use (which is restricted to the richer parts of the population)[56] but also, most importantly, only incentivize long-term development of a sufficiently dense urban form that concurs with the high modal share of public transport.[57] Our analysis further suggests specific consideration for public and nonmotorized transportation infrastructures in smaller urban agglomerations and towns (population ≤2 million), rather than only focusing on large cities, because they emit more per capita and are also large in number.

Comparison with other countries remains a tentative enterprise because the transformation of household energy requirements is subject to idiosyncratic country-specific factors.[58] However, country-specific analysis of urban GHG emissions is relevant in feeding into national and global typologies of cities and their GHG emissions,[59,60] identifying commonalities and differences of mitigation options and helping to scale up place-specific mitigation efforts. In the context of this paper, the comparison with China is particularly interesting. Pachauri and Jiang have shown that both countries, each populated by more than 1 billion people, show similar transformations but with different fuel composition, especially in poorer households (India has a higher share of traditional biomass and kerosene but less coal consumption) and with lower overall access to electricity in India compared to that of China.[61] A main difference is that India displays a lower level of urbanization. As India urbanizes, electricity access will increase further, but emissions from the transport sector will also increase. It hence will be crucial to implement anticipatory measures in urban planning that allow for relatively low cooling demand and efficient public transportation. This would possibly offer a lower level of GHG emissions with development.

Our analyses also show that disadvantaged communities (socioculturally and spatially) have extremely low emissions in comparison to their counterparts. We do not have any acceptable standard for a minimum level of fuels emissions, but low emissions and consumptions are likely to result in deteriorated human wellbeing (see Ahmad et al.).[62] In the past few years, efforts have been made to elaborate a conceptual framework for comprehensive quantification for such an energy requirements.[63] Baer has suggested a greenhouse-development-right framework for a fair division of burdens of emissions reduction based on the assessment of capacity and responsibility on a class-based (rich and poor) rather than nation-based approach to economic justice.[64] In this context, specific programs should be deduced to enhance access (as well as availability) to fuels, through renewable sources if possible, which will advance inclusive development in Indian cities.

Our study has several limitations. First, we were limited to direct household energy use (electricity, cooking fuels, and private transportation) and not from indirect energy use or airline travel (see Chavez and Ramaswami et al.[10]). Second, we use emissions factors at the national level, which may vary at lower spatial levels. Third, electricity use is constrained by supply, given the usual blackouts. Despite these limitations, this paper explores the spatial variations of greenhouse-gas emissions fairly. Future study should be conducted to clarify and quantify the linkage between urban amenities and emissions.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/es505814g.

> Tables showing emissions factors, a pairwise Pearson's correlation matrix of total per capita emissions and associated determinants, and actual and "standardized" CO_2 emissions per capita in Indian cities (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*Phone: +49 30 33 85 537−252; e-mail: ahmad@mcc-berlin.net.

Notes

The authors declare no competing financial interest.

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