Decoding urban India's carbon footprint: spatial–numerical mapping of thermal energy emissions

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Greenhouse gases (GHGs) are the prime cause of climate change, to which India is a significant party. International Energy Agency, in its World Energy Outlook report estimates that 70% of the GHGs are produced within the cities. But there is limited empirical evidence to substantiate such claims in the Indian context. India being a developing country with a large rural population base, the general perception is that cities hardly have any carbon footprint. This article is an empirical study of urban contribution of carbon dioxide emissions. In the absence of any international protocol or a standard methodology to estimate urban footprint of a nation, this article deals with theoretical issues evident while allocating city emissions like methodological differences, defining 'urban' and its boundary and the need to consider downscaling of nationally reported emissions using spatial analysis based on production or location perspective of the most significantly contributing sector namely electricity generation. The information has been assessed on the urban–rural gradient, using population-based Census definition for class/hierarchy of towns and their location with respect to the urban boundary. The results present an array of emissions, across the urban hierarchy and location in space, underpinning how substantial emissions are attributable to urban and urbanizing areas. The findings bear significance to influence research, policy and action in urban energy and ensure greater climate co-benefits at the local level.

Keywords: Carbon footprint, spatial–numerical analysis, thermal power plants, urban areas.

URBAN areas – which serve as residence to over half of the world's population – have an important role to play in regulating climate change; yet the contribution of urban areas to emissions is often unclear[1–3]. There is increasing interest in the carbon footprint (note 1) of geo-political regions, particularly cities[4,5]. The International Energy Agency, in its World Energy Outlook report estimates that 70% of the greenhouse gases (GHGs) are produced within the cities, while some back-of-the-envelope calculations suggest that contribution of urban areas to GHG emissions is to the tune of 40–70% depending upon how they are attributed[6]. Similar estimates for India, based on spatial location of where the emissions are being generated, indicate that urban areas contribute to almost two-thirds of the national GHG burdens[7]. They assume that according to a broad definition of urban areas prevalent in India, thermal plants should qualify to be located in census towns, cities and urban agglomerations and practically the entire emissions emanate from urban areas. This situation is very different from the world scenario, where large fossil-fuel power stations are located outside urban areas and estimated to contribute 8.6–13% of global emissions[6]. The present study intends to address this research gap with empirical evidence from 454 thermal units from over 100 power plants in India, by mapping them on an urban–rural gradient. It presents a literature study for a comprehensive understanding of existing knowledge and research gaps in this area, followed by a description of adopted methodology to address these gaps. This is followed by a section on discussion of results and finally a conclusion of research findings for policy application and further research avenues.

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Literature study

One of the prime concerns for difficulties in emission footprinting at the urban scale is because inventories prepared for cities vary substantially from the national ones. National inventories are prepared according to a detailed set of criteria developed by the Intergovernmental

Panel on Climate Change (IPCC): the IPCC Guidelines for National Greenhouse Gas Inventories. The accounts are estimated based on activity data for different sectors and their emission factors. The reporting does not disaggregate emissions based on spatial regions or units (like state, urban, rural, etc.) from where they emanate. There is no universally accepted protocol to estimate emission from a city[3] or entire urban areas within a nation as a whole. Thus, there are several protocols, tools or methodologies being used, with high degree of variations ranging from research methods, application and evidence from cities – some pushed by international, multilateral or non-government urban or environmental organizations having individual cities as their members[8–10], many computer-based tools (like Bilane Carbone, The Greenhouse Gas Regional Inventory Protocol, CO_2 calculator, Project2 Degrees, CO_2 Grobblianz, etc.) formulated by scientific or voluntary institutions, whereas several methodologies prepared and tested by researchers or academicians are noteworthy publications in peer-reviewed literature[11–20].

Methodological differences and inconsistencies are highlighted in research for city emissions[5,21,22] and specifically in tools and methodologies[16,23]. Amongst various factors like gases measured, sector definitions and emission sources covered, global warming potential IPCC tiers considered, methodical difference in these inventories in general, and for emissions from electricity in particularly, is how one allocates these emissions; where it is produced or where its products and services are being used. Though many protocols and methodologies[8–10,15,16] claim themselves to be within UNFCCC/IPCC framework for their allocation of emissions from electricity generation, they actually follow a hybrid categorization whereby out-of-boundary emissions from electricity purchased by a city from a power plant located outside the city boundaries are allocated to the city (also termed as ‘Scope 2’ emissions). To sound pragmatic, many insist cities to follow IPCC 2006 guidelines for identifying and reporting on key categories of emissions[8,9].

The other major factors responsible for methodological differences and incomparability amongst cities are urban-related. First, the ‘urban’ definition itself needs to be addressed[3]. Is it the town council/municipal corporation or the city itself or the larger city-region? UN Habitat in a study across countries concluded that there are numerous definitions being used for urban, based on administrative criteria, population size or density, economic characteristics and urban infrastructure, or any of their combinations[24]. Secondly, a related methodical gap what only a few studies conceptualize is on account of the spatial boundary or physical extent of a city and how it changes over time[3,13]. In many countries, including India, while local government is mandated for provision of basic urban services, there is a development authority to plan the city. Accordingly, there is a municipal boundary and a planning area boundary. Since the plan is prepared for a long-term horizon, say 20–25 years, lands under planning area generally extend extensively beyond the municipal limits. As more and more urban areas are continuing to expand horizontally in their physical extent around the world[25] and in India[26], any research that considers an urban entity as static in time and space and excludes what happens in the interphase of a city and its rural hinterland will have serious implications on its emission profile, measures taken for climate mitigation and potential co-benefits while reducing local air pollution.

In the recent past, there has been a growing research in carbon footprinting or emission mapping by considering disaggregation of overall GHG emissions for urban areas[6,7,20]. According to Sethi and Mohapatra[7], it is imperative to further research on how urban emissions vary with size, structure and form of the urban centre and the corresponding activity/land-use mix. There is also keen interest in studying emission distribution according to various scales of cities[13,27,28], that bears merits to influence urbanization policy, infrastructure planning and investments in pursuit of achieving climate mitigation benefits. Parallel but independent to the above, there is also an evolving body of work in spatial distribution or downscaling of emissions to sub-national scale. Different studies use a variety of techniques ranging from a grid-based approach transposing, distributing or assuming national or global emissions over regional spatial units through complex geographical information software/applications[29,30], to a rather aggregation-based method where emissions from various point and mobile-based sources are reclassified for a administrative/spatial unit like a county[31]. This indicates that depending upon the research needs, there is scope for methods based on spatial analysis to be used for footprint/emission assessment. Spatial analysis includes any of the formal techniques which study entities using their topological, geometric or geographic properties. It is an effective means to allocate emissions based on principle of territoriality and also account for the opportunity to mitigate local air pollution from thermal power plants, thus generating co-benefits for a win-win situation.

Methodology

Definitions

The literature study underscores that any research into urban contributions of carbon emissions should be definite about production or consumption-related issues, the ‘urban’ definition and the ‘spatial boundary’ of the urban areas in question, which are defined or assumed as below.

In India, definition of ‘urban’ is discreetly defined and classified on administrative and numerical criteria[32].

Accordingly, constituents of urban area are either statutory towns (like municipality, corporation, notified area committee, cantonment board, etc.) as notified in the Gazette or a census town (places that satisfy all the following three conditions simultaneously): (i) a population of more than 5000; (ii) more than 75% of the male working population is engaged in non-agricultural activities; and (iii) density of population is more than 400 persons/sq. km or an outgrowth (defined as viable unit such as a village or a part of a village contiguous of a statutory town and possess the urban features in terms of infrastructure and amentities such as pucca roads, electricity, taps, drainage system, education institutions, post offices, medical facilities, banks, etc.). Any place which is beyond this definition is considered as a village or rural[32]. Based on their population size, the Census of India broadly classifies all towns and cities into various class size: Class-I (100,000 and more population), Class-II (50,000–99,999), Class-III (20,000–49,999), Class-IV (10,000–19,999), Class-V (5000–9999) and Class-VI (less than 5000). As a subset of class-I cities, megacities have been defined as places with population above 100 million and million-plus cities as places with population above 10 million.

Urban 'spatial boundary' in Indian cities is defined by various administrative units in charge of its urban affairs; it may be either the municipal limits, the city or planning area boundary (that of the development authority), or even that of the larger city-region, as in the case of New Delhi, Mumbai, Bengaluru, etc. The intermediate area, its resident population, densities, activities and GHG emission sources within may vary substantially. Conceptually, location of a thermal power plant (and its emissions thereof) against the city boundary could be defined by four distinct spatial locations, namely urban, urban-periphery, transitional and rural. In order to normalize it on a numerical scale, we classify them on the basis of their areal distance from the city limits as follows: (i) urban, if the plant is within the administrative limit (for better comparability it is the same unit for which census data is available); (ii) peripheral, if the plant is located abutting or adjoining the city boundary, defined above; (iii) rurban or transitional areas – this is an often a debatable intermediate region, an area with 10 km radius beyond the city limits has been assumed for the purpose of this study and (iv) rural (in addition to the Census of India definition of rural above[32]), it is spatially defined as a place which is beyond rurban/transitional area or above 10 km radius of city limits. The identification of any thermal power plant will invariably be against the numerical and spatial dimensions of cities, as shown in Figure 1.

In order to deal with a complex environmental system like climate, a 'systems approach' that follows IPCC national inventories and its basic tenant of a production or location-based emission attribution seems more appropriate. For India, NATCOM-II available for 2007 is a production-based emission assessment. With it being territorial or jurisdictional, cities are definitely more accountable from legal and governance point of view. In this study, since we are dealing with cities and emissions from thermal power plants, both having definite location attributes, a point-source based method to spatially classify or aggregate emissions holds potential.

Data and method

The assessment was done in October–November 2013 and verified in February 2014. Generation and capacity data as an indicator for emissions for 454 thermal units reported by Central Electricity Authority for 2011–12 from over a 100 coal, diesel, gas and liquid fuel-based gas turbine (GT) plants are available in classified form for coal, combined cycle power plant (CCPP or CCGT), diesel generation (DG) and liquid fuel-based GT[33]. The individual plants are verified for their names, capacities and their local address from the National or State Generation Corporations or Electricity Boards, as applicable. The plant is then spatially located real-time, using universally available and publically verifiable web-based mapping tool of Google Earth and Wikimapia. Few locations which were untraceable or uncertain on either of these, were referred to the spatial database available for selected power plants available on Global Energy Observatory[34]. The plants for which location either from the authorities or from geographical coordinates is untraceable were considered to be unaccounted for. Their location could be ascertained from the field using global positioning system (GPS), but the current research is limited to inform policy and scientific discourse. Locating plants and their emissions using GPS could be otherwise useful for project planning, implementation and monitoring.

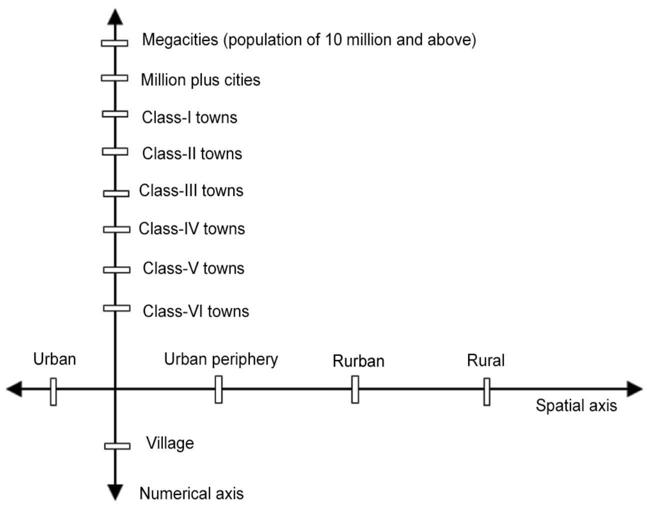

Figure 1. Spatial–numerical axis dimensions that define urbanization.

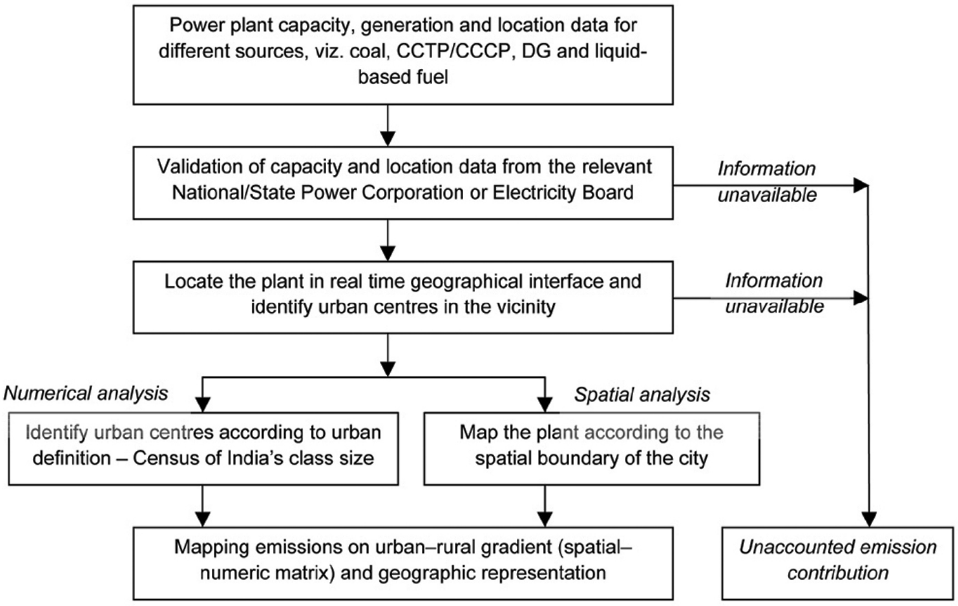

Figure 2. Methodology for spatial analysis of emissions from thermal plants within urban and urbanzing areas.

Table 1. Scheme followed in the present study

Coal/CCGT or CCPP/LGT/DG	Urban	Periphery	Up to 10 km
Megacities			
Million + cities			
Class-I cities (excluding million + or megacities)			
Class-II to class-VI census towns/cities			
Rural			

Population (numerical) data of places were obtained from Census of India 2014 for the year 2011. The procedural methodology of this spatial–numerical analysis is shown in Figure 2.

Tabulation of a thermal plant – coal, CCGT/CCPP, liquid based GT and lastly DG, against a city is based on first, the numerical definition, i.e. the population size of the city according to Census of India 2011, followed by its spatial location. If it does not fall into any of the urban definitions of numerical size or spatial categories of urban, peripheral or rurban, it is eventually classified as rural. The typical scheme followed is shown with arrows in Table 1.

Results and discussion

Result samples of mapping for all four cases – urban, periphery, rurban and rural, generated during spatial–numerical analysis to map plants in accordance to the city boundary are shown in Figure 3. All calculations for capacity, generation and emissions for each plant source and spatial area are complied in Annexure 1, with emission factors given in Annexure 2. Supplementary data are provided (online) showing detailed results for coal/lignite, CCGT/CCPP, liquid-based GT and DG plants. The results in this article account for 679.19 of the 715.82 $MtCO_2e$ reported CO_2 emissions from electricity generation in 2007 under NATCOM-II (ref. 35), thereby attaining an accuracy of 94.88% in reporting. The result of emission distribution across spatial–numerical axis is discussed next.

Based on spatial boundary, the CO_2 emission contributions from thermal power plants are graphically represented in Figure 4, showing that about 60% reported emissions could be attributed to plants located in urban areas, 7.2% from peripheral areas, 22.5% from rurban areas, while only 10% from rural areas.

Based on urban–rural hierarchy or the numerical axis, cumulative results are shown in Figure 5, indicating that megacities are associated with 5% of CO_2 emissions from thermal plants, million-plus cities with 16%, while class-I cities (excluding million-plus and megacities) are associated with a major chunk or 38% of the emissions. Large urban centres with population above 100,000 (all class-I, including megacities and million-plus cities) contribute to 59.7% of the emissions. Class-II to class-V cities are

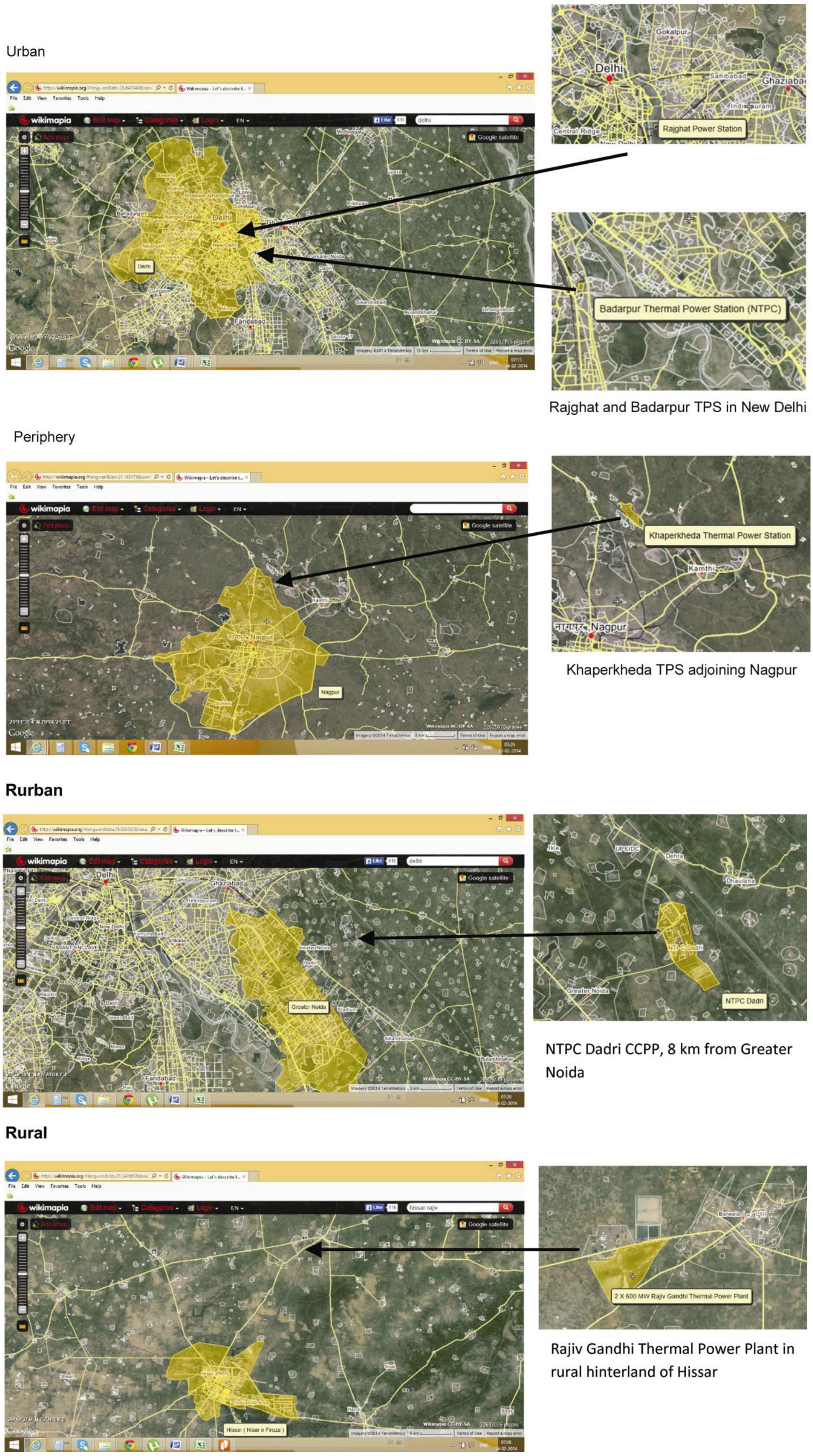

Figure 3. Mapping samples.

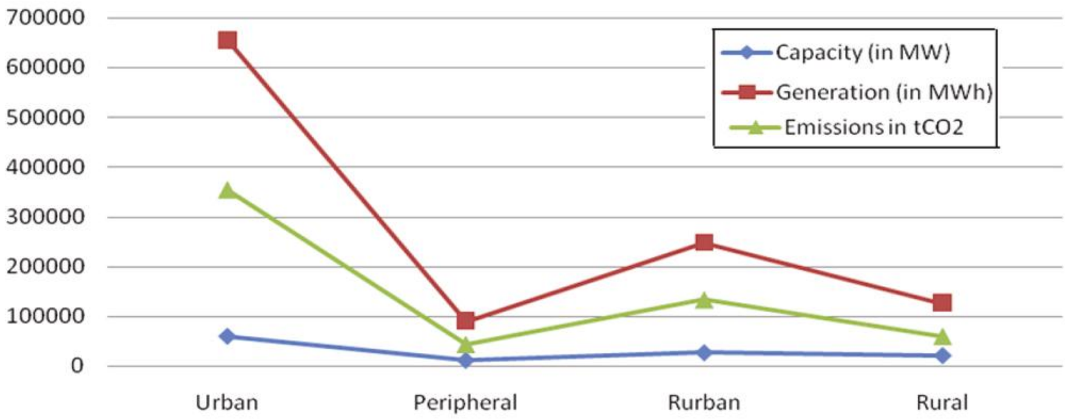

Figure 4. India's emission distribution across spatial axis. Capacity and generation data from CEA 2012, emission factors from CEA 2011; refer Annexure 2 for details.

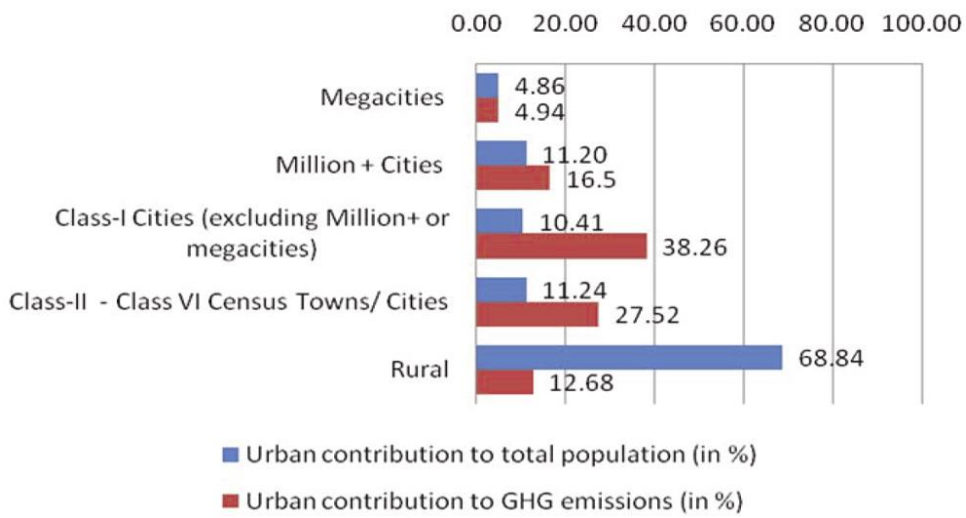

Figure 5. Contribution of Indian cities to national population and emissions (population data from Census of India[36]).

associated with about 28% of the national emissions and lastly, rural areas account for about 13% only.

The most significant result reveals how different Indian cities contribute to national population in comparison with the national emissions (CO_2 emissions from thermal power plants), as presented in Figure 5. It shows that although most of the emissions from thermal power plants (38.26%) emanate from class-I cites, excluding megacities and million-plus cities, they house only 10.41% of the national population, this is followed by emissions from class-II to class-VI towns contributing to 27.52% emissions against 11.24% to the national population. Collectively, these cities are disproportionately responsible for about two-thirds of the emissions, against their share of the one-fifth population of the country. Bigger cities, above million population, including three megacities – New Delhi, Mumbai and Kolkata, along with the rural areas are least affected by emissions from thermal plants.

Conclusion

In the national context where the general perception is that cities hardly contribute to our country's emissions, this study began with the objective to empirically recognize the role of India's urban and urbanizing areas in contributing to national emission burden, owing to growing emissions from the most significant sector – electricity generation or the thermal power plants. The study shows that urban areas are the leading carbon emitters, closely followed by the rurban or transitional areas. Coincidentally, it is predominantly from the same cities at the bottom of the pyramid, essentially class-I to class-VI in the population range of 5000–100,000 that are facing rapid population and horizontal growth. The research inferences should be interpreted carefully. Allocating responsibility on the basis of location does not allocate the entire burden to these cities, as they may not be consuming all the power being generated; but at the same time,

Annexure 1. Results for capacity, generation and emissions for different source types and spatial areas

Source type of thermal plant	Urban Capacity (MW)	Urban Generation (MWh)	Peripheral Capacity (MW)	Peripheral Generation (MWh)	Rurban Capacity (MW)	Rurban Generation (MWh)	Rural Capacity (MW)	Rural Generation (MWh)	Total Capacity (MW)	Total Generation (MWh)	Emissions in tCO_2 (%)
Coal/lignite	52,628	263,480.63	8180	26,822.92	23,790	97,950.88	15,060	35,203.57	99,658	42,3458	54,2026.2 (79.80%)
CCGT/ CCPP	5520.78	349,46.8	3085.48	19,754.99	2,689.87	166,41.3	5,442.80	30,168.89	16,738.93	10,1512	129,935.3 (19.13%)
Liquid-based GT	597.00	581.33	0.00	0.00	0.00	0.00	449.58	1,902.82	1,046.58	2484.15	3179.712 (0.46%)
DG	816.16	2785.41	0.00	0.00	125.70	377.75	36.00	0.56	977.86	3163.72	4049.562 (0.59%)
Emissions in tCO_2 (%)	354,309.40 (60.13%)		42,827.98 (7.26%)		132,755.76 (22.53%)		59,289.38 (10.06%)				

Refer emission factors in Annexure 2.

Annexure 2. Emission factors assumed for various thermal power plants

Fuel source	Emission factor for station	Source
Coal/lignite	1.04/1.28 tCO_2/MWh	CEA 2011
	0.998 kg/kW h	Chowdhry *et al.*
	0.91–0.95 kg/kW h	Mittal *et al.*
CCGT/CCPP	0.43 tCO_2/MWh	CEA 2011
Liquid-based GT	0.66 tCO_2/MWh	CEA 2011
DG	0.59 tCO_2/MWh	CEA 2011

CEA 2011, CO_2 Baseline database for the Indian Power Sector, User Guide-Version 6.0; http://www.cea.nic.in/reports/planning/cdm_co2/user_guide_ver6.pdf (accessed on 13 February 2014). p. 25, Appendix B.

Mittal, M. L., Sharma, C. and Singh, R., 2012, estimates of emissions from coal-fired thermal power plants in India. In paper presented at the International Emission Inventory Conference 'Emission Inventories – Meeting the Challenges Posed by Emerging Global, National, Regional and Local Air Quality Issues', Florida, 13–16 August 2012; at http://www.epa.gov/ttnchie1/conference/ei20/session5/mmittal.pdf (accessed on 13 February 2014). The emissions per unit of electricity are estimated to be in the range 0.91–0.95 kg/kWh for CO_2 computed during 2001–2002 to 2009–2010.

Chowdhury, S., Chakraborty, S., Bhattacharya, S., Garg, A., Mitra, A. P., Mukherjee, I. and Chakraborty, N., 2004, An emission estimation of greenhouse gas emission from thermal power plants in India during 2002–2003. In Proceedings, Workshop on Uncertainty Reduction in Greenhouse Gas Inventories (ed. Mitra, A. P. *et al.*), Ministry of Environment and Forests, Government of India, pp. 16–22.

Average emission factors for CO_2 = 0.998 kg/kWh (range 0.776–1.49 kg/kWh).

their role to mitigate emissions along with air pollution in and along their territories should not be underestimated. Any result-oriented strategy or measure oriented towards climate mitigation, power generation and consumption, local environment and sustainable urbanization has to internalize the role of the smaller, but rapidly urbanizing areas that are generally under-represented in guiding national policies. This study has achieved an accuracy of 94.88%, and it could be enhanced to 100% by ground-truthing using GPS in subsequent investigations. Further studies in this area could illuminate us on two aspects – (i) to spatially determine the role of other major sectors like industry, transport, etc. active in urban areas that contribute to national emissions and (ii) application of these findings to influence research, policy and governance at the crossroads of urban energy emissions to enhance integrated efforts for co-benefits in climate change mitigation at the local level.

Note

1. Carbon footprint has been defined differently across various studies worldwide, assessed in detail by Wiedmann, T. and Minx, J., A definition of carbon footprint. In *Ecological Economics Research Trends* (ed. Pertsova, C. C.), Nova Science Publishers, Hauppauge NY, 2008, pp. 1–11, and the most fitting definition proposed by them is, 'Carbon footprint is a measure of the exclusive total amount of carbon dioxide emission that directly and indirectly caused by an activity or is accumulated over the life stages of a product'.

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ACKNOWLEDGEMENTS. I acknowledge the UNU–IAS Ph D Fellowship under which this study was made. I also thank all the experts consulted during research and unknown peer-reviewers for their reviews and comments.

Disclaimer. Any interpretation of facts and opinions are the author's liability and not the institution he represents. The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this research.

Received 7 April 2014; revised accepted 16 December 2014