Resource requirements of inclusive urban development in India: insights from ten cities

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Abstract

This paper develops a methodology to assess the resource requirements of inclusive urban development in India and compares those requirements to current community-wide material and energy flows. Methods include: (a) identifying minimum service level benchmarks for the provision of infrastructure services including housing, electricity and clean cooking fuels; (b) assessing the percentage of homes that lack access to infrastructure or that consume infrastructure services below the identified benchmarks; (c) quantifying the material requirements to provide basic infrastructure services using India-specific design data; and (d) computing material and energy requirements for inclusive development and comparing it with current community-wide material and energy flows. Applying the method to ten Indian cities, we find that: 1%–6% of households do not have electricity, 14%–71% use electricity below the benchmark of 25 kWh capita-month\(^{-1}\); 4%–16% lack structurally sound housing; 50%–75% live in floor area less than the benchmark of 8.75 m\(^2\) floor area/capita; 10%–65% lack clean cooking fuel; and 6%–60% lack connection to a sewerage system. Across the ten cities examined, to provide basic electricity (25 kWh capita-month\(^{-1}\)) to all will require an addition of only 1%–10% in current community-wide electricity use. To provide basic clean LPG fuel (1.2 kg capita-month\(^{-1}\)) to all requires an increase of 5%–40% in current community-wide LPG use. Providing permanent shelter (implemented over a ten year period) to populations living in non-permanent housing in Delhi and Chandigarh would require a 6%–14% increase over current annual community-wide cement use. Conversely, to provide permanent housing to all people living in structurally unsound housing and those living in overcrowded housing (<5 m\(^3\) cap\(^{-2}\)) would require 32%–115% of current community-wide cement flows. Except for the last scenario, these results suggest that social policies that seek to provide basic infrastructure provisioning for all residents would not dramatically increasing current community-wide resource flows.

1. Introduction

In 2015, the United Nations adopted the 2030 agenda, establishing 17 sustainable development goals (SDGs) to be achieved by the year 2030 (UN 2015). These SDGs include, achieving (1) no poverty; (2) zero hunger; (3) good health and well-being; (4) quality education; (5) gender equality; (6) clean water and sanitation; (7) affordable and clean energy; (8) decent work and economic growth; (9) industry, innovation and infrastructure; (10) reduced inequalities; (11) sustainable cities and communities; (12) responsible consumption and production; (13) climate action; (14) life below water; (15) life on land; (16) peace, justice and strong institutions; (17) partnerships for the goals. For the first time, a sustainable development goal (SDG 11) addresses cities and communities, with the goal of making cities inclusive, safe, resilient, and sustainable. Particularly target 11.1 focuses on 'access to adequate, safe and affordable housing and basic services for all' and upgrading slums. The focus of this paper is on the intersection of SDG 11.1 with the goal of
inclusive development, with housing, water-sanitation (SDG 6) and clean energy in cities (SDG 7). Fundamentally these require a focus on the provision of basic infrastructures.

Cities will be a key action arena to achieve multiple SDGs at the intersection of basic infrastructure provisioning, defined broadly as the provision of water, energy, food, shelter, transportation and communication, waste management, and public spaces (Ramaswami et al 2016). By the year 2050, more than 66% of the world’s people will be living in cities, and much of the growth in urban population will happen in Asia and Africa. About 60% of those future cities have yet to be built (UNEP 2013). At the same time, in many cities in Asia and Africa, there is a high proportion of slum populations that are underserved, as much as 28%–62% (UN Habitat 2010). Therefore, understanding the resource requirements of developing more inclusive cities is the focus of this paper and is a key aspect of achieving the SDGs. We focus on socio-spatial aspects of urban inclusive development defined by United Nations Habitat (2015) as addressing ‘the geographic marginalization of particular individuals and groups because of where they live and who they are. It is characterized by their inability to access or effectively use a whole range of facilities and resources which improve well-being and position people to take advantage of available opportunities. Particular groups and individuals often suffer a disproportionate ‘disadvantage’ because of their identity, which is physically represented in urban contexts by the presence of informal settlements.’

We study India, where rapid and large-scale urbanization is anticipated and expected to be home to some 400 million urban residents by 2050 (United Nations 2014). India and other Asian nations face several resource constraints including lack of urban land, rising construction costs and material (sand) shortages that constrain housing construction (World Bank 2017, Government of India 2006, Ramkumar et al 2015, Gavriletea and Dan 2017). For energy (electricity, LPG), rising demand and pressure on supply is the biggest resource constraint. In the face of scarcity, the poor fare the worst. The Government of India has recently initiated a social policy aimed to provide housing for all (Hindman et al 2015), which is also consistent with the goals of developing slum-free cities as noted in UN Habitat’s new urban agenda (Habitat 2016). A few studies have indicated that providing basic services to the underserved will increase community-wide resource burdens (Karekezi et al 2012, Legros et al 2009), but data and bottom-up methodologies have been lacking to quantify the anticipated increase in resource use for the underserved when compared to overall use by homes and businesses.

A recent report by the McKinsey Global Institute has estimated the cost of providing housing for all (Sankhe et al 2010) in India but does not address material requirements to be used in resource efficient cities. Several other studies have focused on assessing pathways toward more resource efficient and low-cost housing in India (The World Bank 2011, UN Habitat 2012, Chowdhury and Roy 2013, Chary Vedala et al 2012). Additional studies have evaluated deprivation (i.e. lack of access) in infrastructure sectors such as sanitation or water supply and uneven distribution of consumption in India (Walters 2014, Wankhade et al 2014, Chatterjee et al 2016, Kumar and Das 2014, Ghosal 2014, Nallari 2015, Basole et al 2015). However, the previous studies cited above do not address the physical resource/material requirements of meeting minimum service level benchmarks in multiple infrastructure sectors. This paper seeks to contribute by developing methods to quantify the material requirements of inclusive development– incorporating multiple infrastructure sectors of energy, water-sanitation/sewage, and shelter in Indian cities.

The overarching goal of this study is to describe the lack of access and deprivation in provision and consumption of key infrastructure services in Indian cities, with focus on housing, energy (electricity and cooking fuel), water, and sanitation/sewage, and assessing the material and energy implications of meeting minimum service level benchmarks for each, considering goals of achieving both more inclusive and resource efficient development. Specifically, (i) we identify India-specific benchmarks for minimum service provision of housing, electricity and cooking fuels, (ii) we quantify deprivation regarding access to basic infrastructure services in the different cities based on the benchmarks, (iii) we compute the resource requirements to meet basic service levels for electricity, sanitation, cooking fuels and housing, (iv) we compare the requirements for up-gradation of underserved communities with the current community-wide material and energy flows of a few select cities (where such data are available) to identify the percentage increase of community-wide material use required for creating a more inclusive city. The methodology, developed and tested in Indian cities, is broadly applicable to other countries provided the required data are available.

2. Methods

2.1. City selection
To understand the inequality in provision and consumption of basic infrastructure services in cities across India, we studied ten cities. Among all 495 Indian cities, these ten cities were the only subset that met all the following data availability criteria:

- Data on households with basic infrastructure deficits (i.e. no tap water, drainage, electricity, clean cooking fuel, and durable housing).
The consumption of services for those that hold that do not have toilets, treated tap water, drainage, cooking fuels, are provided at the city level in the Indian Census (Census of India 2011) identifying the percentage of households without access to electricity for lighting, clean cooking fuels, toilets in the home, and structurally unsound (kuccha, or semi-pucca) housing. Beyond the presence/absence of basic services, access also includes considerations of both minimum levels of basic service provision (when services are present) and affordability.

Affordability varies widely by nations and is beyond the scope of this paper. The level of consumption needed to meet basic needs has been defined differently across infrastructure sectors and by various national and international organizations. We conducted a review of the quantitative benchmarks that specify minimum consumption levels to meet basic needs in different sectors (summarized in table 1).

While no universal definition of minimum floor area is available across all nations, the Government of India establishes minimum house size (floor area) for different population segments based on their income. For Economically Weaker sections and Lower Income Groups, the minimum per household area is specified at 28 m² and 60 m² per household, respectively, according to the Government of India (KPMG 2011, MHUPA 2013). Therefore, we considered an intermediate living space benchmark of 35 m² per household with a household size of 4 people, as it also tracks with living area benchmarks used by The World Bank (2011), i.e. 8.75 m² per capita. Other developing nations, e.g. urban areas in Indonesia, Kenya, and South Africa are also using 36 m² per household as the minimum basic floor area in cities (Steinberg 2007, Anker and Anker 2017). The Indian Government’s bare minimum basic living area for Economically Weaker sections corresponds to 5 m²/capita for family size of five (specified by the Indian Planning Commission) and it is in line with minimum per capita floor area (5 m²/capita) noted by others to avoid overcrowding and associated health risks such as infectious disease risks (Riley et al 2007).

### Table 1. Minimum service benchmarks for floor area, electricity, and LPG requirements of households on a per household and a per capita basis.

| Service                          | Variation in defining minimum benchmarks                                                                 | Chosen benchmark                                      |
|---------------------------------|-----------------------------------------------------------------------------------------------------------|-------------------------------------------------------|
| Floor Area per household        | 25 m² to avoid overcrowding (Corburn and Sverdlik 2017)                                                 | 35 m² for family of four, or, 8.75 m² cap⁻²            |
|                                 | 28 m² to 60 m² (Govt of India 2013) for low-income groups                                               |                                                       |
|                                 | 35 m² for a family of four (The World Bank 2011)                                                        |                                                       |
|                                 | 36 m² in Indonesia, Kenya, and South Africa (Steinberg 2007, Anker and Anker 2017)                      |                                                       |
| Electricity Use per household   | 40 kWh for family of four (IEA 2016)                                                                     | 100 kWh for family of four, or, 25 kWh cap⁻¹           |
| (monthly)                       | 100 kWh for family of four (The World Bank 2011)                                                        |                                                       |
|                                 | Tier 4: 100 kWh for family of four (World Bank 2015)                                                     |                                                       |
| LPG Use per household (monthly) | 6 kg for family of five (Planning Commission of India 2006)                                              | 1.2 kg cap⁻¹                                          |
|                                 | 4.8 for family of four (HEDON the Household Energy Network 2011)                                        |                                                       |

- Data on household-level consumption and expenditure, with large survey sample sizes (>100 surveyed households), across different socioeconomic strata (SES) to assess the number of households consuming below the minimum basic service levels, and hence requiring service improvements.
- Data on current city-wide energy and/or material flow, in order to compare the resource requirements of upgrading underserved households, compared to existing community-wide resource use, including resource flows to support homes, businesses, and industries in each city.

The ten cities that met all three criteria are Chandigarh, Coimbatore, Delhi, Mysore, Nagpur, Puducherry, Rajkot, Surat, Thane, and Trivandrum.

#### 2.2. Data sources

For each of these cities, data on the presence/absence of basic infrastructure services, i.e. percentage of households that do not have toilets, treated tap water, drainage, cooking fuels, electricity, are provided at the city level in the Indian Census (Census of India 2011). The consumption of services for those that have access to these infrastructures is noted in the district-level household consumer expenditure survey and the housing condition survey (NSS 2010, NSS 2014), where the urban-households district data are applied to the corresponding city in that district. Third, community-wide electricity use and gas use for all homes, businesses, and industries in each of the ten cities are sourced from their respective Solar City Master Plans (Solar Cities Master Plan 2016), where such data are already gathered specifically for each city. Current community-wide material use focusing on cement as a critical construction material are available only for the cities of Delhi and Chandigarh that have a special status as Union Territories (DSHB 2013, SACH 2013). Therefore, this study assesses the energy requirements to meet basic service levels for underserved households in comparison with community-wide energy requirements in each of the ten cities. The same analysis to assess construction materials required for inclusive development is conducted only for Delhi and Chandigarh.

#### 2.3. Defining access to basic services

Basic services such as structurally-sound housing, clean water, sanitation-sewerage, electricity and clean cooking fuels are critical services to improve the lives of people. The first step to define existing access to any of these services is to determine whether they are present or absent, which is reported by the Census of India (2011) identifying the percentage of households without access to electricity for lighting, clean cooking fuels, toilets in the home, and structurally unsound (kuccha, or semi-pucca) housing. Beyond the presence/absence of basic services, access also includes considerations of both minimum levels of basic service provision (when services are present) and affordability. Affordability varies widely by nations and is beyond the scope of this paper. The level of consumption needed to meet basic needs has been defined differently across infrastructure sectors and by various national and international organizations. We conducted a review of the quantitative benchmarks that specify minimum consumption levels to meet basic needs in different sectors (summarized in table 1).
For energy, the UN Secretary General’s Advisory Group on Energy and Climate (AGECC) defines energy access as ‘access to a basic minimum threshold of modern energy services for both consumption and productive uses. Access to these modern energy services must be reliable and affordable, sustainable and where feasible, from low-GHG emitting energy sources’ (World Energy Outlook 2016). The International Energy Agency has defined the threshold for annual electricity consumption for rural area households at 250 kWh and 500 kWh for urban households (IEA 2016). Recently, the World Bank (2015) has defined a multi-tier framework for electricity access based on electricity power capacity, electricity use duration during a day and evening, the reliability of supply, affordability, legality, health, and safety measures. They have identified a five-tier matrix for providing access to electricity (see table S1 available at stacks.iop.org/ERL/13/025010/mmedia). Applying the multi-tier framework, we choose the criterion for the fourth tier which is 1250 kWh annually (see table S1), or about 100 kWh household-month⁻¹, as a benchmark (The World Bank 2011). This is enough electricity to support general lighting, the operation of medium power and high power appliances (e.g. air cooler, refrigerator, washing machine), and is applicable to urban areas studied here wherein Indian cities are trying to provide reliable electricity service, generally not exceeding maximum of 14 disruptions per week. We address the minimum provision of 100 kWh per household per month for a family of 4 modeled by The World Bank (2011), i.e. 25 kWh per capita (see table 1). Given our focus on direct average resource requirements, the study of the frequency of power outages in the cities, and legal and health safety measures associated with electricity infrastructure are beyond the scope of this paper.

For cooking fuels, India’s Central Planning Commission has defined a benchmark of 6 kg of LPG (liquefied petroleum gas)/month per family having five members (Planning Commission of India 2006), which is equivalent to 1.2 kg per capita month⁻¹. This benchmark is in line with the minimum standards (1.2 kg per capita month⁻¹) for access to clean energy for cooking to allow energy deprived households to attain a substantial improvement in living conditions specified by other groups (e.g. HEDON 2011). We apply the 1.2 kg LPG capita-month⁻¹ benchmark in the current study (table 1). Given the high levels of indoor air pollution from dirty cooking fuels in Indian cities, we have used the goal of providing clean fuels to all residents. It is consistent with the SDG 7 of providing clean energy to everyone.

2.4. Variation in consumption by socioeconomic status

The average per capita consumption of electricity and cooking fuel for all ten cities by households in different SES was assessed using household level consumer expenditure microdata provided by the National Sample Survey 2011–2012 (NSS 2014). Average per household floor area was assessed from the housing condition survey data provided by the National Sample Survey 2009–10 (NSS 2010). These household surveys cover urban and rural homes in all districts of India; district-level urban household surveys were evaluated to represent the consumption patterns of the corresponding cities. Data comparisons for electricity-use showed a fairly good match for most of the cities between the citywide residential electricity use, which was estimated by scaling up from household survey data, compared to the same reported by the electric utility for that city (see table S3 available in the supplementary data). This suggests that using household survey data is generally coherent with the community-wide utility data. Only three cities showed larger differences, likely due to differences in the reporting years versus the survey years.

The household surveys provide information on housing floor area, monthly electricity and cooking fuel consumption (by fuel type), as well as expenditures on water, food, and other services, organized into 12 fractiles, by SES. To get larger survey samples sizes across the ten cities, we combined the twelve fractiles into five: the lowest 20% SES-households, 21%–40% SES-households, 41%–60% SES-households, 61%–80% SES-households and the top 20% SES-households. The average per capita monthly electricity and LPG consumption within each fractile are shown in figure 3 and provide a visual on the inequality in consumption of basic services. We also computed the P80/P20 ratio (i.e. ratio of the consumption by top 20% households compared to the lowest 20% households) for electricity and LPG use for all ten Indian Cities. The housing condition survey 2009–10 (NSS 2010) does not classify the surveyed households by SES fractiles; thus to assess floor area inequality, we binned the household samples into five fractiles based on their level of reported floor area.

2.5. Computing household material used for building construction and sewerage

There have been very few studies quantifying the material requirements for housing construction for the urban poor, comparing material requirements for construction in (i) existing slum dwellings; (ii) single-family individual housing rehabilitation; and (iii) multi-family multi-story mid- to high-rise rehabilitation that becomes important in efforts to develop compact cities (IRP 2017). In situ slum rehabilitation, compared to conventional slum rehabilitation that moves residents to another area of the city or its outlying areas, is motivated by the need to rehabilitate slums within the urban core in multi-family, multi-story buildings to reduce urban housing costs and to provide access to job opportunities inside the city (Mahadevia et al 2014). Given the absence of data on construction materials used in construction in existing slums, and in structurally code-compliant slum-rehabilitation
housing in India, we conducted primary research interviewing and gathering relevant data from slum residents in Delhi and from builders involved with successfully completed slum rehabilitation projects in Rajkot (low-income housing constructed on the outskirts of the city in single story buildings) and Ahmedabad (multi-story, in situ slum rehabilitation in the urban core), both located in the state of Gujarat, which has shown success in such rehabilitation efforts (Mahadevia et al 2014, Das and Bhise 2016, Bhatkal et al 2015).

Material requirements for sewerage needs: Few data are available on the material needed for sewerage system installation because these requirements depend on pipe length, land gradient and housing density of the cities. To estimate the per households material and pipe length we used data from the Sewerage Master Plan for Delhi 2031 (2014). This design master plan includes a 10,000 km sewerage network that covers 12 drainage and 25 sub-drainage zones ranging in population density from 4130 km$^2$–70243 km$^2$. This plan provides technical and design details including pipe length by neighborhood area, pipe material, pipe diameters and pipe thickness. Based on data across the 25 different sub-drainage systems, we estimated the mean and maximum pipe-length per household (1.4 m household$^{-1}$ and 5.20 m household$^{-1}$, respectively) with different diameters and material types specified. Given the wide range of housing densities within Delhi, we assumed this range of sewerage pipe length requirements would reflect varying conditions also in the other nine cities studied. To estimate the material and energy requirements for constructing and operating wastewater treatment plants, we used data supplied by Dr. Leslie Miller-Robbie (personal communication) and Tare et al (2010), for different technologies, thus addressing the nexus between sanitation and energy-material requirements.

2.6. Computing resource requirements for infrastructure up-gradation of underserved homes, and comparing with community-wide material-energy flows

Upgrading housing and sewerage for underserved populations is assumed to be implemented over a 10 year plan time horizon to yield annual average added material requirement for upgrading to durable housing, along with provision of sewerage and wastewater treatment. The annual average added material requirements are compared to the current annual (2011–12) total community-wide cement flows in Delhi, and Chandigarh reported in the Statistical Abstracts (DSHB 2013, SACH 2013). The material requirements for such housing up-gradation were computed in two scenarios—Scenario 1 in which all households presently living in non-permanent structures are provided structurally sound housing at 8.75 m capita$^{-2}$; family sizes were computed specific to demographics in each city. In Scenario 2, we also added the material requirement if currently durable but overcrowded homes (<5 m$^2$ floor area/capita) were also expanded to avoid overcrowding. Both single-family and multi-story constructions were modeled. Since the cities of Delhi and Chandigarh only report community-wide cement use, material requirement comparisons are focused on cement, a key construction material. We compared the ten-year annualized cement requirements for providing structurally-sound housing and sewerage to all underserved households and compared the findings with current community-wide cement use.

To calculate the electricity and LPG requirement of the underserved populations, we estimated the number of households that are lacking electricity and LPG service and also the number of households that are consuming below the minimum benchmark for LPG (1.2 kg capita-month$^{-1}$) and electricity (25 kWh capita-month$^{-1}$). We then estimated the amount of electricity and LPG needed to meet minimum service benchmarks for those residents lacking access or consuming below the benchmark. To provide a context for the amounts of energy (electricity & LPG) needed for inclusive development, we compared the added electricity and LPG requirements of serving the underserved households with the total annual community electricity and LPG flows for all 10 cities for the year 2011 provided by DSHB (2013), SACH (2013) and Solar Cities Master Plan (2016). Community-wide flows refer to the annual direct energy used (gas and electricity) by all household, businesses, and industries in each of the cities.

3. Results

3.1. Field data on material needs for durable housing and sewerage

We first report on the field work on construction material requirements in slum households, in single story new construction, and in multi-family multi-story new buildings offered for slum rehabilitation in India. Our surveys found that typical slum houses are very small (floor area average was 16 m$^2$ among the nine households who provided permission to measure their living area), compared to the new construction for low-income and slum rehabilitation homes (average floor area per home varied from 25–40 m$^2$ across four building projects for which data were provided by the builders). Normalizing on a per square meter basis; the average slum household requires only 656 kg m$^{-2}$ of material mass (typically, mud, bricks, sand, tarp, etc.). This level of material-use is low, as expected, compared to the single-storey single-family code-compliant low-income housing that required 3140 kg m$^{-2}$ of material mass (i.e. steel, bricks, cement, sand, stones, and aluminum) per square meter of a house (CEMS/ISB 2011). In contrast, builder-provided data for multi-storey apartment style multi-family slum rehabilitation units required 1607–2420 kg m$^{-2}$ of
material mass in two different units constructed by the builder. Both single-storey and multi-storey multi-family housing were constructed to be code compliant for structural strength per Indian standards. On average the total construction material use in the multi-story construction was 2000 kg m$^{-2}$ requiring about 30% less material than the single story buildings. With our study providing India specific data, figure 1 shows the housing material by mass for slum houses, single story up-gradation, and multi-family/multi-story slum up-gradation. After sand, the most used materials for building construction are bricks, cement, and coarse aggregate. Cement is a key construction material and constitutes 8.5% of the total mass of a concrete structure, based on the average composition of the concrete mix, which yields cement use in the multi-family mid-rise construction of approximately 136–200 kg m$^{-2}$. These intensities are in the range of those reported by Fernandez (2007) for multi-story residential construction in China (112–115 kg m$^{-2}$ cement, estimated from reported concrete data), indicating that the India specific construction data provided by the builders are reasonable in representing local construction practices.

The materials required for housing drainage systems (material for pipe and concrete for the corresponding water treatment plant) derived from the 25 sub-drainage systems planned within Delhi, are found to constitute only 0.1%–5% of total material required for the multi-storey building construction, indicating material requirements for sewerage are relatively small compared to those for housing construction; the housing construction data included the provision of toilets within the newly constructed homes.

3.2. Inequality in Access and Inequality in consumption of basic infrastructure services

Figure 2 shows the percentage of homes across the ten cities that lack physical access to the different infrastructure sectors (i.e. no durable housing, no latrine and sewerage, no electricity for lighting, no LPG for cooking). Most of these cities report better electricity coverage as compared to access to other infrastructure services. For example, overall in the ten cities studied, only 1%–5% of the population is living in homes without an electricity connection, while 6%–60% of households are lacking closed drainage and 10%–65% lack LPG.

Across the ten cities, 14%–71% of households that have electricity, are consuming below the 25 kWh capita-month$^{-1}$ minimum service benchmark (see figure 3). Among households that use LPG, we found that very few households (1%–6%) are using less than the 1.2 kg/capita-month benchmark, but overall, high percentages of households still lack access to LPG. In terms of per capita floor area, 50%–75% of households have floor areas below the benchmark (8.75 m$^2$/capita) in the ten cities examined, including both permanent and non-permanent housing types. When considering the absolute benchmark of 5 m$^2$/capita of living area, 22%–54% of households fall below that minimum benchmark for overcrowding, across the ten cities. These data, while surprising, have been reported in the Indian newspapers (Thakur 2008) and represent the severe overcrowding conditions in Indian cities. As can be seen from figure 3, floor area, electricity, and cooking fuel consumption levels increase with increasing socioeconomic status.

Figure 4(a) shows the fraction of homes consuming below the minimum benchmarks in the different sectors, in the ten cities. To further understand infrastructure consumption inequality, the P80/P20 ratio demonstrates the level of consumption of the highest 20% relative to the lowest 20% (figure 4(b)). LPG consumption by LPG-user households shows the least inequality, while housing floor area shows the most. In Delhi, for example, the highest 20% has a per capita floor area more than ten times that of the lowest SES level (i.e. the P80/P20 ratio for floor area exceeds 10), while the ratio representing inequality in electricity consumption shows the highest consumers consuming more than five times that of the lowest SES households (i.e. P80/P20 for electricity use is $>5$).
Figure 2. Percentage of households (HHs) having: (a) No tap water from a treated source, (b) No electricity for lighting, (c) No toilet in home, (d) no drainage, (e) No LPG for cooking and (f) non-permanent house in 10 Indian cities.

Figure 3. Variation in average consumption within different fractiles for (a) LPG, (b) Electricity by different socioeconomic structure represented by monthly per capita expenditure (MPCE) for consumption; and (c) Floor area Not by MPCE but by housing samples from lower to higher consumption. In all graphs, the red dotted line represents the minimum service benchmarks used in India. For housing floor area a lower benchmark (black dotted line) is shown that represents the minimum floor to avoid poor health outcomes of overcrowding.
3.3. Direct energy and material requirements to serve under-served homes, compared to community-wide flows

Energy: We computed electricity required for the houses currently lacking electricity, as well as the houses using electricity below the minimum benchmark (25 kWh capita-month⁻¹). The analysis finds that, across the ten cities, bringing all underserved residents to the level of the minimum benchmark in the cities studied would only increase current community-wide electricity use by 1%–10%. Similarly, to bring all underserved residents to the minimum benchmark for LPG consumption, community-wide LPG use would need to increase by 3%–40% over current levels across the ten cities studied (table S2 and figure 5).

Relative to total community-wide cement use (only available for Delhi and Chandigarh) an increase of only 6%–14% of current annual cement use would be required to provide housing (single story and multi-story) to all underserved populations (4%–16%) living in structurally unsound housing, averaged over a 10 year implementation plan (figure 5, table 2 Scenario 1). Scenario 1 is a likely scenario because populations living in structurally unsound housing are typically prioritized for rehabilitation to structurally sound housing. To additionally address the overcrowding situation in current durable homes, we model Scenario 2, such that extremely overcrowded durable homes (<5 m² area per capita) also undergo expansion. In scenario 2, the added cement needed is 32%–115% of the current annual community-wide cement use in Delhi and Chandigarh (figure 5, Scenario 2). It is important to note that these computed material requirements represent the impact of social policies specifically aimed at providing housing to the underserved, and not on the impact of increasing the average or the overall wealth of a society as may be represented in macro-models. The latter models do not always address the distribution of wealth and the conditions of the most vulnerable, which are modeled in this paper.

Electricity needs for sewage treatment: We also estimated the electricity requirements for new wastewater treatment facilities needed for all ten cities in an inclusive development scenario in which all resident have access to wastewater treatment services, considering currently viable wastewater treatment technologies in Indian cities including waste stabilization ponds, conventional activated sludge processes, extended aeration activated sludge processes, up-flow anaerobic sludge blanket digestion, moving bed biofilm reactors, sequencing batch reactors, and membrane bioreactors. Our analysis indicates that to treat all untreated water; these cities would only need to increase electricity use 0%–4% over their current community-wide levels of use when considering the least to most energy-intensive technologies. These results are not surprising, given that energy use for water and sewage treatment are generally a very small percentage of community-wide energy use, as has been seen for Indian cities (Miller et al 2012) and US cities (e.g. Hillman and Ramaswami 2010).

Overall, our results show that the percentage increase in current community-wide electricity and LPG use is much smaller than the percentage of homes requiring upgrading, including those that have no physical access and those consuming below the basic level (see figure 6). For many cities such as Delhi and Chandigarh (see figures 5(b) and (c) the percentage increase in LPG and electricity to serve the underserved households is such a small percentage of the community-wide flows, that the expected increases in resources for inclusive development can barely be seen in figures 5(b) and (c). This is because high-income households are consuming many times the energy that poorer households consume, and commercial/industrial energy use is even greater than all residential use. Even accounting for the differences in aligning survey data to city-wide electricity use (see table S13), our conclusion does not change. This has important implications for inclusive and
resource-efficient development as it suggests that with modest resource efficiency strategies applied across the board, and by promoting sustainable consumption behaviors among high-consuming households, basic services for all can be provided with relatively little change to current material-energy requirements for most of the inclusive development scenarios.

4. Discussion

This paper has developed a methodology to conduct a first order analysis of resources (materials and energy) required to support inclusive infrastructure provision in Indian cities. The methodology has provided quantitative measures that represent access to basic services covering electricity supply, cooking fuel supply, and housing. This methodology was tested across ten Indian cities and can be applied in other world cities using location-specific data.

The methodology involves assessing household consumer surveys and census data to identify both the percentage of houses that do not have services as well as the percentage of houses that are consuming less than basic service levels benchmarks. We have also developed a set of India specific material...
Table 2. Minimum benchmarks, material intensity, and total material and cement needed for inclusive development in Delhi and Chandigarh computed based on Census of India (2011) and annualized over ten years, compared with annual community wide cement flow in the year 2011.

| Minimum service benchmark for family of four |  |
|---------------------------------------------|--|
| Minimum floor area required                 | 35 m² |
| Minimum electricity                         | 100 kWh month⁻¹ |
| LPG                                         | 4.8 kg Month |

| Material requirement intensity from field work and author calculation (housing construction includes toilets, Sewerage) |
|------------------------------------------------------------------------------------------------------------------|
| Single story building (material)                                                                            | 3140 kg m⁻² |
| Multi story building (material)                                                                             | 2000 kg m⁻² |
| Single story building (cement)                                                                             | 267 kg m⁻²  |
| Multi story building (cement)                                                                              | 170 kg m⁻²  |
| Sewerage per household                                                                                    | 1.42–5.2 m pipe length |

Total material and cement needed for inclusive development in Delhi and Chandigarh (Giga-grams (Gg) required over a one year period)

| Delhi                             | Chandigarh |
|-----------------------------------|------------|
| City community wide annual cement flow in 2011–12 (Baseline from Delhi and Chandigarh statistical Abstract (SAD 2014, SACH 2013)) | 1132 Gg    |
| Additional material needed for upgrading only structurally unsound house to single story building for      | 18007 Gg   |
| Additional material needed for upgrading only structurally unsound house to multi-story building            | 11469 Gg   |
| Total cement need to provide for single-story building for non-perm. house only                             | 1529 Gg    |
| Total cement need to provide for multi-story building for non-permanent only                                 | 974 Gg     |
| Total material need for sewerage pipe and waste water treatment plant                                       | 183–522 Gg |

Electricity

(a) Correlation of percentage of (a) houses not having electricity and houses using electricity below the 25 kWh capita-month⁻¹ and electricity needed as percentage of current community wide electricity use; (b) houses not having LPG and houses using LPG below the 1.2 kg capita-month⁻¹ and electricity needed as percentage of current community wide LPG use.

This can be viewed as a positive result because it implies that energy efficiency strategies applied across the board in the construction and energy sectors may be able to reduce the overall resource requirements, resulting in both sustainable consumption and inclusive development. Additional specific policies that focus on efficiency among the high-consuming households, business, and industries will further support goals of minimizing community-wide resource while simultaneously pursuing inclusive development policies. These results indicate that inclusive development may be achieved without substantially exceeding current resource requirement to provide infrastructure to the people currently lacking access, providing that these efforts are accompanied by investments in new infrastructure such that resource efficiency strategies are applied across the board and that sustainable consumption behaviors are increased among the higher consuming households.

use intensity factors for providing structurally sound housing (2000–3140 kg material m⁻²), sewerage piping (1.42–5.2 m pipe length household⁻¹), electricity use (25 kWh capita-month⁻¹) and LPG use (1.2 kg capita-month⁻¹). Using these intensity factors along with the percentage of the population lacking these services, we are able to calculate the additional requirements to support households below these service level benchmarks. However, we also find that the wealthier households consume many times more than the lowest consuming households, and further community-wide material energy flows also significantly provide for businesses and industries. Therefore, as a result, the increase in community-wide resource flow for socially inclusive development policies as a percentage of overall community-wide resource flow is much less than the percentage of homes that are underserved or that must be upgraded.
socioeconomic levels. Overall, this paper indicates that the goals of sustainable resource use and the goals of social policies aimed at more inclusive development are synergistic, and can be achieved simultaneously with relatively low added resource requirements. In future work, other social policies such as providing school access to all children, and increasing access to hospitals may also be assessed using standards published by the Government of India such as 1.2–2 m² of floor space per student for schools (Indian Standard 1978).

As the current study suggests, inclusive development in Indian cities may require only a small fraction of the current community-wide material and resource use. The manner in which these resources are provided has potential to further improve environmental outcomes. For example, compact multi-story construction within the city core offers benefits of reducing material use (36 percent less than single story construction) for all households (not only slums), in addition to reducing motorized travel demand and associated air pollution while improving access to employment (UN Environment 2017, Ramaswami 2017). Distributed and renewable energy infrastructure such as solar-powered microgrids can be particularly useful in slums and pockets of deprivation in urban and rural areas (Graber et al 2018, Kammen and Sunter 2016), providing both clean and reliable energy access. Similarly, distributed community scale wastewater systems are also being explored in many Indian slum rehabilitation as a resource efficient strategy for infrastructure and service provision (Massoud et al 2009, Larsen et al 2016).

While the situation in India may seem bleak from the figures presented here, many world cities have faced, and continue to face, similar issues of inequality and lack of access to basic infrastructure services for large segments of their population. Chinese cities exhibited similar statistics in the 1990s, but are now seeing vast improvements in access to infrastructure and services for their populations. Indian cities and cities in other countries can achieve similar gains in basic service levels by informing their plans to upgrade basic infrastructures with analysis of resource use requirements, consumption patterns and efficiency strategies. Furthermore, through compact urban design, sustainable construction programs, and investments in novel renewable and distributed infrastructures, cities have the potential to achieve the multiple goals of inclusive, resource-efficient and environment-friendly urban development.

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