A State-Level Methodology for Estimating Present-Day Emissions of Short-Lived Climate Pollutants from Fired Brick Production in India

Kushal Tibrewal, Sameer Maithel and Chandra Venkataraman

Abstract Indian brick sector is dominated by traditional kilns with inefficient combustion technology. However, it has substantial potential in mitigating SLCPs through shifts towards efficient technologies, thus highlighting the need to understand the present-day emission profile from manufacturing of fired-clay bricks. We developed a methodology to estimate the emissions of black carbon (BC), organic carbon (OC), SO_2 and ozone precursors (CO, CH_4, NO_x, NMVOC) at state level. It is used to estimate national brick demand which is distributed among states to estimate state-level production assuming production to follow demand. Fractional contribution of four major kiln technologies in India (Bull's trench kiln, clamp kiln, Zig Zag fired kiln and vertical shaft brick kiln) is estimated for each state to estimate the state-wise share of different kiln technologies in production. Emissions of $PM_{2.5,}$ BC, OC and SO_2 are estimated to be 165.9 (142.0–189.7) Gg yr^{-1}, 119.1 (97.6–140.5) Gg yr^{-1}, 9.4 (7.3–11.4) Gg yr^{-1} and 393.6 (314.1–473.1) Gg yr^{-1}. For ozone precursors, the estimates are 2.6 (2.2–3.0) Tg yr^{-1}, 248.4 (137.4–359.4) Gg yr^{-1}, 66.2 (49.2–83.1) Gg yr^{-1} and 64.0 (48.2–79.7) Gg yr^{-1} for CO, CH_4, NO_x and NMVOCs. The states with large share of BTKs contributed most to BC emissions while regions having clamp kilns emitted higher OC, CO and CH_4.

Keywords Brick kilns · Short-lived pollutants · Aerosols · Ozone precursors

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1 Realizing the Role of Brick Sector in Mitigation of Short-Lived Climate Pollutants

Anthropogenic activities induce changes in composition of atmospheric composition through emissions of long-lived greenhouse gases (LLGHGs) and short-lived climate pollutants (SLCPs) which influence global climate change (Stocker et al. 2013). Although CO_2 is considered to be the most important contributor of climate change (Stocker et al. 2013), other forcing elements, like short-lived climate pollutants (SLCPs), also contribute significantly to climate change (UNEP 2017). SLCPs comprise of black carbon (BC) and organic carbon (OC) (particulate matter constituents) and SO_2 (particulate matter precursor), tropospheric ozone (O_3) and its precursor gases (CH_4, CO, NO_x and NMVOCs) (CCAC 2014). These pollutants are characterized by short atmospheric lifetimes varying from a few days to a few decades contributing to impacts that last for several decades (10–20 years) because of their radiative effects.

Besides influencing global climate change, SLCPs also play a large role in degrading regional air quality. Rising levels of particulate matter have led to increasing mortality rates (Cohen et al. 2017). In addition to this, modelling studies have shown the potential of increasing levels of tropospheric ozone (Ghude et al. 2014) and BC emissions (Burney and Ramanathan 2014) in reducing crop yield. Thus, there is growing consensus on the potential of mitigation strategies targeting SLCPs to alleviate near-term climate change with a potential to reduce warming due to their rapid temperature response (UNEP/WMO 2011) and simultaneously improve air quality (Shindell et al. 2012). Moreover, adoption of policies for improving air quality focuses on reducing NO_x and SO_2 emissions, and reduces the masking of GHG warming by such cooling SLCPs, thus motivating the need for addressing mitigation of warming SLCPs like BC and CH_4 (UNEP 2017).

For India, energy-intensive activities involving traditional combustion practices and extensive use of biomass fuel such as residential cooking, brick manufacturing and open burning of agricultural residue are major emitters of warming SLCPs (Venkataraman et al. 2016). The brick industry in India is the second largest producer of bricks with an annual production of approximately 250 billion bricks and consuming large amount of coal and biomass fuel (Maithel et al. 2012). Use of traditional and inefficient technologies emitting particulate matter along with CO and SO_2 are major causes of degraded air quality around major urban centres of India (Guttikunda and Calori 2013; Kumbhar et al. 2014). Several studies have recognized the potential of brick industry in reducing emissions through shifts towards efficient technology (USEPA 2012; Weyant et al. 2014). Thus, careful accounting of brick production activity, dominant technologies, diversity of fuel mixes and resulting emissions over India is needed to harness the potential of brick industry in mitigating SLCPs.

There are few available emission estimates from Indian brick industries, addressing local air pollution (Guttikunda and Calori 2013; Kumbhar et al. 2014) or made at a gross national level (Pandey et al. 2014) focussing on coal as a single fuel. More recently, the carbon footprint of brick kilns in a region of North India showed an average value of 427.985 kg CO_2/1000 bricks for fixed chimney Bull's trench kilns (FCBTKs) (Maheshwari and Jain 2017). However, there are significant differences in brick-making technology among different parts of the country (Maithel et al. 2012) which include Bull's trench kilns (BTKs) and Zig Zag fired kilns dominating the Northern India while clamp kilns contributing more in the southern states. It is also known that fuel used in brick kilns varies by region and can include mixtures of coal and biomass fuels such as firewood, dry dung, rice husks and other agricultural residues (Maithel et al. 2012). Therefore, it is important to account for regionally varying technologies and the widespread use of biomass in brick kilns.

To address these gaps, the chapter provides a methodology to estimate emissions from brick kilns at a state level in India. The methodology is used to estimate a national brick demand and distribute it among all states. The existing knowledge on regional spread of prevalent technology is utilized to quantify the fractional share of different brick kiln technologies in each state. Average values of emission factors and heating values are calculated from different studies to estimate the final emissions from combustion of a fuel mix (coal and biomass) per kiln type.

2 Estimating Emissions at State Level

This section summarizes the underlying methodology followed to estimate the state-level emissions of SLCP aerosols (PM2.5, BC, OC and SO_2) and ozone precursors (CH_4, CO, NO_x and NMVOCs) from manufacturing of fired-clay bricks in India. The approach for calculating emissions (Eq. 1) begun by estimating the national brick demand 'B' (millions/year). The national demand is distributed to each state 's' using brick utilization fraction 'u_s' (%) to estimate the production at state level assuming production would follow demand. For each state, the production is apportioned into various kiln technologies 'k' using the kiln share '$t_{k,s}$' (%). The amount of brick produced is converted to mass of the bricks produced using a typical weight 'w' (kg) of one block of fired-clay brick. Subsequently for each kiln technology, corresponding specific energy consumption 'SEC_k' (MJ/kg) and fuel characteristics [assumed fuel mix and calorific value of the fuel mix, 'CV' (MJ/kg)] are used to estimate the fuel consumption. Finally, for each pollutant 'p', technology-linked emission factors '$\mathrm{EF}_{p,k}$' (g/kg) are multiplied with the fuel consumption to arrive at the emissions '$E_{p,s}$' (Gg/year). The overall methodology is represented in Fig. 1.

$$E_{p,s} = \sum_k \frac{B \times u_s \times \mathrm{SEC}_k \times t_{k,s} \times w}{\mathrm{CV}} \times \mathrm{EF}_{p,k} \quad (1)$$

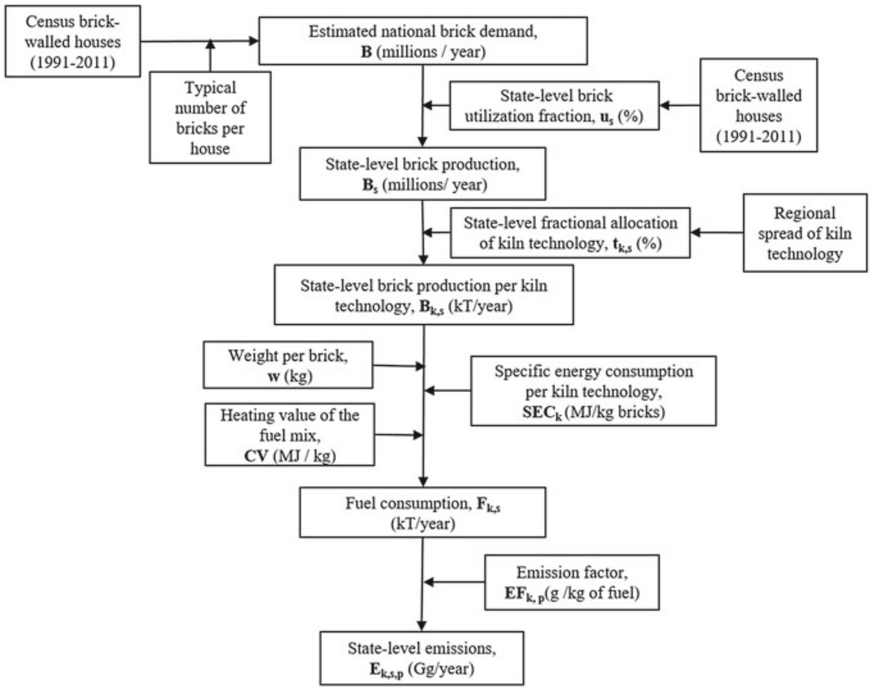

Fig. 1 Methodology to estimate state-level emissions from brick manufacturing

2.1 Activity Data

2.1.1 Estimated National Brick Demand

The brick industry in India is an unorganized sector. Unavailability of accurate data on number of kilns and their locations makes it difficult to know the exact brick production and its regional difference. Thus, an attempt is made to estimate annual demand of burnt clay bricks and distribute among states to estimate state-level production, assuming demand is equal to production because of transportation barriers in supply of raw materials and finished products. Demand in brick sector is driven by need for housing due to growth of population and urbanization and strong growth in construction sector (KASPL 2015). Since exact share of bricks for various purposes is not available, the demand in brick is distributed as 50% for new constructions, 10% for bricks used in repair works. As 40% of the brick production is in the form of damaged or low-quality bricks (GKSPL 2014), the total production of bricks to meet the demand is considered as 1.6 times the demand. Activities requiring brick under new constructions are assumed to have similar share as cement. With this assumption, out of total bricks used in new constructions, 67% is used for housing, 13% for infrastructure, 11% for commercial construction and 9% for industrial construction (KASPL 2015).

National demand per year of fired-clay brick for housing is estimated using trend in the number of brick-walled houses as reported in census of India for 1991, 2001 and 2011 (Census of India 2011). The following approach is applied to estimate the probable number of brick-walled houses constructed in 2015. Data for state-wise total number of brick-walled houses is collected from census for the years 1991, 2001 and 2011. An exponential trend-line is fitted for each state to analyse the growth in number of brick-walled houses up to 2015. The slope of the trend-line for any year gives the number of newly constructed brick-walled houses in that year. Besides covering the trend well, the use of exponential trend-line is favoured to fit the data as the slope of the trend-line at each year is representative of the fact that with increasing growth in national population, the growth in newly constructed houses must also increase to cater to the increasing housing demand. The total bricks required for newly constructed houses are calculated assuming an average built-up area of 1000 ft.[2] per house with specific brick consumption of 13 bricks per sq. ft. of built-up area (Happho 2017).

2.1.2 State-Level Brick Utilization Fraction

The aim here is to distribute the national brick demand among the states. Since majority of demand is driven by housing, therefore a proxy, in form of brick utilization fraction, is developed to distribute the estimated national brick demand among the states proportionally to number the newly constructed brick-walled houses in each state. Brick utilization fraction for each state is the ratio of number of brick-walled houses constructed in each state to the total number of brick-walled houses constructed in the country for that year. For estimating brick utilization fraction 'u_s' (Eq. 2), the number of brick-walled houses constructed in 2015 for each state 'H_s' and for the whole nation 'H' is calculated using trend from census as discussed in previous section.

$$u_s = \frac{H_s}{H} \tag{2}$$

The brick production for each state 'B_s' is calculated by multiplying the brick utilization factor for each state to the national estimated brick demand 'B' (Eq. 3).

$$B_s = u_s \times B \tag{3}$$

2.1.3 Fractional Allocation of Kiln Technology for Each State

There are mainly four types of technologies currently used in manufacturing fired-clay bricks. Maithel et al. (2012) provide an estimate of the contribution of each of the kiln technology in the national production and their regional spread. BTK contributes 66% to national production spread all over the country covering states in the Indo-Gangetic plains (IGP), north, east, south and west. Clamp kilns with its 25% share cover predominantly central, western and southern states. Zig Zag fired kilns contributes 8% to the national production with production happening mostly in West Bengal and northern states. Finally, vertical shaft brick kilns (VSBK) contributing a meagre 1% are in Central India and with few others in Odisha and Kerala. This information is used to apportion the brick production into different kiln technologies for each state.

Using the regional spread as reported, the first step is to identify the states covered by each kiln technology. The respective national contribution of number of bricks by VSBK, Zig Zag fired kilns and clamp kilns is distributed among the states covered by each of them in proportion of the brick utilization fraction for those states. This resulted in the number of brick produced by VSBK, Zig Zag fired and clamp kilns, respectively, in each state. For bricks produced by BTKs in each state, the summation of bricks produced by these three kiln types is subtracted from the total brick amount for the state. Finally, the kiln share '$t_{k,s}$' for each kiln type 'k' is calculated (Eq. 4) as the ratio of number of brick produced by a kiln type in a state '$B_{k,s}$' to the total brick produced in the state 'B_s'.

$$t_{k,s} = \frac{B_{k,s}}{B_s} \quad (4)$$

2.2 *Technology-Linked Emission Factor*

Emissions of eight pollutants are estimated by using mean emission factors for each kiln type assuming a fixed fuel mix. Emission factors vary for different kiln technologies and depend on the fuel mix used. BTK and clamp kilns are the most polluting technologies (Maithel et al. 2012). Clamp kilns have the highest emission factors for particulate matter followed by BTKs due to intermittent feeding of fuel. Zig Zag fired kilns, although similar to BTKs in structural designs, has lower BC emissions due to better firing practice and continuous feeding of fuel. Zig Zag fired kilns also have the lowest emissions for CO indicating most efficient combustion of the fuel. The estimated emission factors suggest that VSBK are the most eco-friendly technologies with the least emissions of particulate matter (PM2.5) and black carbon (BC) due to steady-state combustion conditions and use of internal fuel. Emissions of SO_2 primarily depend on the sulphur content of the fuel. Thus, kilns using large amounts of coal-based fuels emit larger SO_2 as compared to kilns using biofuels.

Mean emission factors for each kiln type are calculated from measured emission factors for various fuel mixes from several studies for each pollutant (Appendix). Measured emission factors are used for particulate matter (PM2.5, BC and OC) from 11 Indian brick kilns with varying fuel mixes (Weyant et al. 2014). Another study based on same brick kilns is used to obtain emission factors for SO_2 (Rajarathnam et al. 2014). Emission factors for CO are also based from (Weyant et al. 2014) for BTK and VSBK while for Zig Zag fired and clamp kilns, they are obtained from two studies (Weyant et al. 2014; Stockwell et al. 2016). Stockwell et al. (2016) also reported emission factors for CH_4 and NO_x Zig Zag fired kilns and clamp kilns. Since no measured emission factors are found for BTK and VSBK, values for Zig Zag fired kilns are assumed to be same for them. NMVOCs emission factors are based on values reported for biofuels burnt in brick kilns (Christian et al. 2010) which are assumed to be same for all fuel mixes and all kiln type.

2.3 Uncertainty Estimation

Uncertainties in emissions are calculated analytically, assuming the underlying uncertainties in all input quantities to be normally distributed. Key sources of uncertainties include brick production number, specific energy consumption per kiln type and emission factors which vary with kiln technology and fuel mix. Uncertainty in bricks production amount is calculated as the standard deviation in the estimate of annually built brick-walled houses. Standard deviation in the estimates of brick-walled houses is calculated using the errors obtained in the coefficients of regression for the trend in brick-walled houses from 1991 to 2011. Uncertainty in specific energy consumption is taken as reported in (Weyant et al. 2014). Mean and standard deviation in emission factors for each pollutant per kiln technology are calculated from values obtained from multiple studies, as discussed in the previous section. Final uncertainties in emissions are calculated by combining uncertainties in individual parameters using rule of quadrature. For emissions having relative uncertainties (ratio of standard deviation to arithmetic mean) greater than 30%, lognormal distribution is assumed and the emissions are reported as means with upper and lower bounds calculated using geometric standard deviation.

3 Technology-Specific Brick Production Per State

3.1 National Brick Demand

From the slope of the trend of brick-walled houses from 1991 to 2011 (Census of India 2011) for the year 2015, the total number of newly constructed brick-walled houses is estimated to be 6.2 ± 0.5 million. The regression coefficients and the slope of the exponential trend at year 2015 are presented in Appendix. Assuming an average built-up area of 1000 $ft.^2$ per house, with specific brick requirement of 13 bricks per sq. ft. of built-up area, the national brick demand for housing is estimated to be 82.2 ± 23.8 billion. Since it is 67% of the demand under new constructions, total brick demand for new constructions (including housing, infrastructure, industrial and commercial construction) is 122.7 ± 35.6 billion. Finally, with an assumption that 50% of the total national brick demand is for new constructions while the rest is used for repair work and to account for the damaged and low-quality bricks, the total national brick demand is estimated to be 245.4 ± 71.2 billion.

3.2 State-Level Brick Production

Assuming demand to be equal to production, the national brick demand is distributed among the states using the brick utilization fraction (Fig. 2). The states covering the Indo-Gangetic plains (IGP) accounted for the most brick utilization with nearly 44% of the total national demand. Uttar Pradesh, Bihar and West Bengal contribute 15%, 8% and 8%, respectively, to national demand producing approximately 37.9 ± 0.8, 20.4 ± 2.6 and 20.3 ± 3.0 billion bricks annually. Although Delhi as the national capital territory (NCT) is found to contribute only 2%, considering national capital region (NCR—includes NCT and parts of Haryana, Rajasthan and UP) the contribution is 9% highlighting the rapid urbanization that underwent in the recent years in that region. Gujarat, Rajasthan, Madhya Pradesh and Maharashtra are the major contributors in the Western and Central India contributing 6%, 5%, 3% and 8%, respectively. Southern India contributed nearly 14% with AP and Tamil Nadu being the major states producing 17.2 ± 10 and 9.4 ± 8.2 billion bricks, respectively. The brick production at the state level estimated using this methodology is presented in Appendix.

3.3 Fractional Allocation of Kiln Technology for Each State

Even though brick industry is such an energy-intensive sector with significant share in energy consumption and driven by heavy demand, there has been very few initiatives to promote energy efficiency and emission control. It is not until 1990s when the first set of emission standards were proposed for brick industry. The standards laid down the maximum limit for concentration of particulate matter (750–1000 mg/Nm^3) and minimum stack height for optimal dispersion of sulphur dioxide (12–30 m) for different kiln capacities. The introduction of emission standards in 1996 led to the shift from moving chimney BTKs to fixed chimney BTKs and encouraged adoption of newer technologies (Maithel and Uma 2000). Despite introduction of advanced technologies as early as 1970s for Zig Zag fired kilns and 1995 for VSBK, there is no large-scale implementation (Maithel et al. 2012). Recently, due to increasing pollution levels, the Central Pollution Control Board (CPCB) directed all State Pollution Control Boards to provide status on conversion of natural draft to induced draft brick kilns with rectangular shape and Zig Zag setting (CPCB 2017).

The estimated share of different kiln technologies for each state is shown in Fig. 2. The states in the IGP and north-eastern parts of the country are predominant

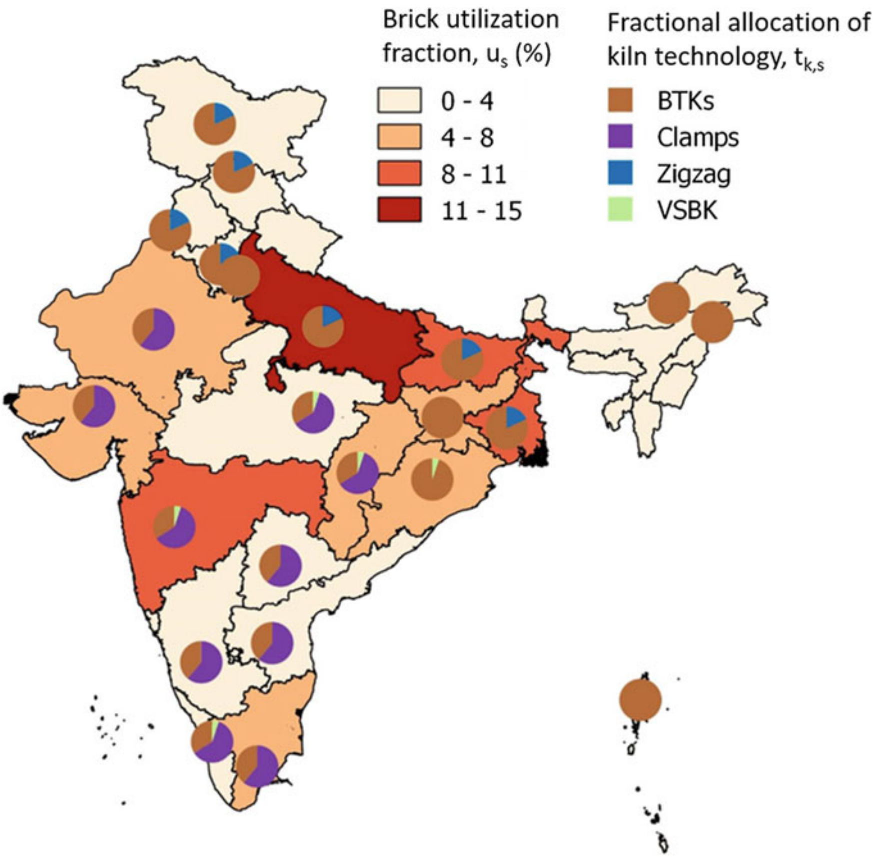

Fig. 2 State-level brick utilization fraction (u_s) and fractional allocation of kiln technology ($t_{k,s}$)

users of BTKs (greater than 80%) and Zig Zag fired kilns, while the central and the peninsular regions are dominated by clamp kilns (greater than 60%). VSBKs contributing to a meagre 1% to the national production are present mostly in Odisha, Madhya Pradesh and Kerala. However, understanding the actual prevalence of brick-making technology is highly important as it influences the energy consumption and emissions of various pollutants the most. Thus, a thorough exploration is required to extract the ground truth on the extent of various technologies under operation through field surveys, government listings or geo-spatial tagging through satellite imagery.

4 State-Level Emissions of SLCPs

The state-wise brick production distributed among different kiln type is multiplied with the mass of a typical brick, 2.9 kg/brick, to obtain the total mass of bricks produced per state. For each kiln type, specific energy consumption (Appendix) is used to estimate the total energy use per kiln type per state. Mean heating values of fuel mix (Appendix) for each kiln type are calculated from measured values (Weyant et al. 2014) to estimate the fuel mix consumed. Finally, the mean factors are used to estimate the emissions discussed in the following sections.

4.1 Aerosols: Constituents and SO_2

National emissions of $PM_{2.5}$ are estimated to be 165.9 (142.0–189.7) Gg yr^{-1} (Table 1), with 50% from clamp kilns, 47% from BTKs and rest from Zig Zag fired kilns and VSBK. The emissions of BC and OC are 119.1 (97.6–140.5) Gg yr^{-1} and 9.4 (7.3–11.4) Gg yr^{-1} (Table 1). The contribution of clamp kilns (44%) to BC emissions is lower than that of BTKs (55%) even though they have the highest emission factors for $PM_{2.5}$ as they are found to have lower black carbon-to-total carbon ratio (BC/TC) than BTKs due to batch firing process (Weyant et al. 2014). Therefore, states such as Maharashtra and Andhra Pradesh have higher $PM_{2.5}$ emissions with lower BC emissions than Uttar Pradesh even though they had lower brick production as they are dominated by clamp kilns (Fig. 3). Emissions for SO_2 are estimated to be 393.6 (314.1–473.1) Gg yr^{-1} (Table 1). Since emissions for SO_2 are primarily dependent on the sulphur content of fuel used, thus states using predominantly coal would result in greater SO_2 emissions as compared to those using biomass fuels. However, in this study emission factors are kiln specific assuming a common fuel mix for each kiln type for all states. Thus, more accurate spatial variation can be generated by collecting information of various fuel mixes used across different regions and using state-specific emission factor for each kiln type based on fuel mix.

The emission estimates are compared well with previously published study (Pandey et al. 2014) for $PM_{2.5}$, BC and OC (164, 114 and 11 Gg yr^{-1}, respectively). The SO_2 estimates (357 Gg yr^{-1}) are lower than this study due to different assumptions in emission factors and fuel used. Comparing the emissions with the total national emissions from India (Pandey et al. 2014; Sadavarte and Venkataraman 2014), brick industry contributed approximately 10% to the total BC emissions. Several studies have asserted replacing traditional brick kilns with newer technologies, particularly VSBK, will help in reducing BC emissions (Rajarathnam et al. 2014; Weyant et al. 2014). There have been limited efforts to motivate use of efficient and eco-friendly technologies in brick industry. The emission standards proposed in 1996 were revised in 2009 to include limitations by type of kiln technology (1200 mg/Nm^3 for the downdraft kiln; 750–1000 mg/Nm^3 for BTKs; and 250 mg/Nm^3 for the induced draft BTK, Hoffmann and vertical shaft kiln) (MoEFCC 2009) but were not

Table 1 State-level emissions of SLCPs from brick kilns in India (Gg yr^{-1})

States	Aerosols and SO_2				Ozone precursors			
	$PM_{2.5}$	BC	OC	SO_2	CO	CH_4	NO_x	NMVOC
Jammu and Kashmir	2.9	2.2	0.1	7.9	33.4	0.1	1.3	1.3
	(1.1–6.3)	(0.9–4.6)	(0.1–0.2)	(4.1–13.7)	(14.2–67.2)	(0.0–0.3)	(0.2–4.3)	(0.2–4.1)
Himachal Pradesh	1.3	1.0	0.1	3.6	15.2	0.0	0.6	0.6
	(0.5–2.9)	(0.4–2.2)	(0.0–0.1)	(1.8–6.6)	(6.1–31.7)	(0.0–0.1)	(0.1–2.0)	(0.1–1.9)
Punjab	2.8	2.1	0.1	7.6	32.1	0.1	1.3	1.2
	(0.8–7.5)	(0.6–5.7)	(0.0–0.3)	(2.4–18.4)	(8.9–83.2)	(0.0–0.3)	(0.2–4.5)	(0.2–4.3)
Chandigarh	0.1	0.1	0.0	0.3	1.1	0.0	0.0	0.0
	(0.0–0.3)	(0.0–0.2)	(0.0–0.0)	(0.0–0.8)	(0.2–3.5)	(0.0–0.0)	(0.0–0.2)	(0.0–0.2)
Uttarakhand	3.1	2.3	0.1	8.2	34.8	0.1	1.4	1.3
	(1.2–6.5)	(0.9–4.7)	(0.1–0.2)	(4.3–14.3)	(14.8–69.9)	(0.0–0.3)	(0.2–4.5)	(0.2–4.3)
Haryana	3.6	2.7	0.1	9.6	40.6	0.1	1.6	1.5
	(1.4–7.7)	(1.1–5.6)	(0.1–0.2)	(4.9–17.0)	(16.9–82.7)	(0.0–0.3)	(0.3–5.3)	(0.3–5.0)
Delhi	2.0	1.6	0.1	5.6	23.5	0.1	0.8	0.8
	(0.0–11.8)	(0.0–9.8)	(0.0–0.4)	(0.1–33.3)	(0.5–139.9)	(0.0–0.3)	(0.0–5.0)	(0.0–4.8)
Uttar Pradesh	17.0	12.8	0.6	45.6	192.5	0.5	7.6	7.3
	(6.6–36.1)	(5.2–26.3)	(0.3–1.2)	(23.9–79.3)	(81.7–387.3)	(0.1–1.6)	(1.3–24.9)	(1.3–23.8)
Bihar	9.1	6.9	0.3	24.5	103.5	0.3	4.1	3.9
	(3.5–19.7)	(2.7–14.4)	(0.2–0.6)	(12.3–44.0)	(42.5–212.8)	(0.0–0.9)	(0.7–13.5)	(0.7–12.9)
West Bengal	9.1	6.8	0.3	24.4	103.1	0.3	4.1	3.9
	(3.4–19.8)	(2.7–14.5)	(0.2–0.6)	(12.0–44.3)	(41.8–213.8)	(0.0–0.9)	(0.7–13.5)	(0.7–12.8)
Jharkhand	6.0	5.0	0.2	17.1	71.5	0.2	2.5	2.4
	(2.1-13.6)	(2.0-10.4)	(0.1-0.4)	(8.5-30.7)	(28.5-150.1)	(0.0-0.6)	(0.3-9.3)	(0.3-8.8)
Odisha	4.8	4.0	0.2	13.5	59.4	0.1	2.1	2.0
	(1.7–10.9)	(1.6–8.3)	(0.1–0.3)	(6.6–24.7)	(24.2–122.7)	(0.0–0.5)	(0.3–7.4)	(0.3–7.1)
Chhattisgarh	9.5	6.4	0.7	20.3	180.9	23.8	3.6	3.5
	(4.3–18.3)	(1.6–17.8)	(0.2–1.8)	(3.4–67.4)	(91.7–321.8)	(2.7–92.6)	(0.6–12.3)	(0.6–11.4)
Madhya Pradesh	8.3	5.6	0.6	17.7	157.8	20.7	3.1	3.0
	(3.8–16.0)	(1.4–15.5)	(0.1–1.6)	(3.0–58.8)	(80.0–280.9)	(2.4–80.8)	(0.5–10.7)	(0.5–10.0)
Rajasthan	12.4	8.5	0.8	26.7	231.7	30.5	4.6	4.5
	(5.5–24.2)	(2.1–23.2)	(0.2–2.4)	(4.6–87.6)	(113.7–422.1)	(3.5–119.2)	(0.7–15.9)	(0.8–14.8)
Gujarat	14.9	10.2	1.0	32.0	277.8	36.6	5.5	5.4
	(6.8–28.5)	(2.6–27.7)	(0.3–2.8)	(5.6–104.6)	(140.6–495.2)	(4.2–142.5)	(0.8–19.0)	(0.9–17.6)
Maharashtra	19.7	13.3	1.4	41.8	373.3	49.1	7.4	7.2
	(6.8–45.0)	(2.9–39.6)	(0.3–4.1)	(6.4–145.3)	(136.3–827.4)	(5.0–198.8)	(1.0–26.4)	(1.1–24.7)
Andhra Pradesh	17.2	11.8	1.2	37.0	321.1	42.3	6.3	6.2
	(4.9–44.4)	(2.3–36.7)	(0.2–3.8)	(5.3–131.7)	(91.0–825.4)	(3.9–177.5)	(0.8–23.7)	(0.9–22.3)
Karnataka	7.3	5.0	0.5	15.7	136.8	18.0	2.7	2.6
	(1.5–22.4)	(0.8–17.3)	(0.1–1.8)	(1.9–60.1)	(26.7–425.5)	(1.4–80.2)	(0.3–10.7)	(0.3–10.2)
Kerala	1.0	0.7	0.1	2.1	19.0	2.5	0.4	0.4
	(0.0–6.8)	(0.0–4.6)	(0.0–0.5)	(0.0–14.5)	(0.1–129.5)	(0.0–17.0)	(0.0–2.5)	(0.0–2.5)
Tamil Nadu	9.4	6.4	0.6	20.2	175.2	23.1	3.5	3.4
	(1.8–29.6)	(0.9–22.7)	(0.1–2.4)	(2.3–78.1)	(31.8–563.6)	(1.7–104.1)	(0.4–14.0)	(0.4–13.2)
North-east	3.7	3.1	0.1	10.5	44.1	0.1	1.5	1.5

(continued)

Table 1 (continued)

States	Aerosols and SO_2				Ozone precursors			
	$PM_{2.5}$	BC	OC	SO_2	CO	CH_4	NO_x	NMVOC
	(1.7–7.0)	(1.6–5.5)	(0.1–0.2)	(6.3–16.6)	(22.3–78.5)	(0.0–0.3)	(0.3–4.6)	(0.3–4.4)
Union territories	0.6	0.5	0.0	1.8	7.5	0.0	0.3	0.3
	(0.1–2.1)	(0.1–1.8)	(0.0–0.2)	(0.7–3.8)	(4.5–11.8)	(0.0–0.1)	(0.0–1.4)	(0.0–1.4)
Total	165.9	119.1	9.4	393.6	2635.7	248.4	66.2	64.0
	(142.0–189.7)	(97.6–140.5)	(7.3–11.4)	(314.1–473.1)	(2239.7–3031.6)	(137.4–359.4)	(49.2–83.1)	(48.2–79.7)

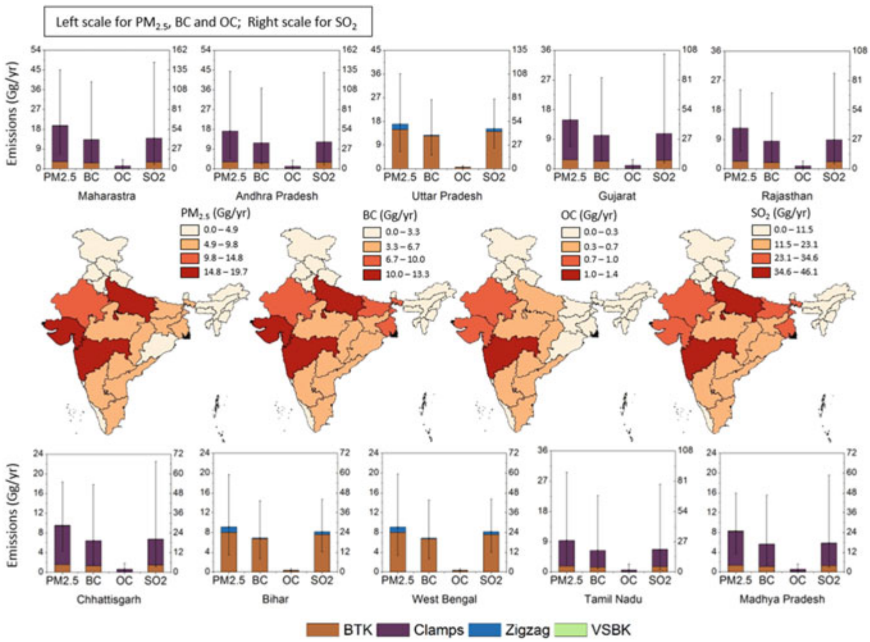

Fig. 3 Regional distribution and major emitters of aerosols ($PM_{2.5}$, BC, OC) and SO_2 emissions from brick kilns (Gg/yr)

stringent enough to induce much change (Maithel et al. 2012). Draft of new emission standards has been proposed in 2015 (MoEFCC 2015) with stricter limits for BTKs. Other than regulating stack emissions, there were initiatives to promote resource-efficient bricks, such as hollow and perforated bricks, which consume less energy and resources for their productions (UNDP 2009), fly ash bricks and non-fired bricks such as autoclaved aerated concrete (AAC) blocks.

4.2 Ozone Precursors

National emissions of CO are estimated as 2.6 (2.2–3.0) Tg yr^{-1} with 63% from clamp kilns and 35% from BTKs (Table 1). Emissions of CO are an indicator of incomplete combustion of fuel as the carbon is not allowed to fully convert into CO_2. Among the kilns, Zig Zag fired kilns are found to have the lowest CO emission factors as the firing pattern allows large amount of time for the fuel to get burnt and clamps have the highest. Even the highly efficient technology such as VSBK has greater CO emission factors than Zig Zag fired kilns due to use of internal fuel as limited supply of air is available at the surface of the fuel for complete combustion. CH_4 is primarily emitted due to use of biomass fuel. Clamp kilns are assumed to be operated mostly using larger share of biomass in the fuel mix. Thus, the national emissions of 248.4 (137.4–359.4) Gg yr^{-1} are contributed 99% by clamp kilns (Table 1). Since clamp kilns dominated emissions of both CO and CH_4, western and southern states such as Maharashtra, Andhra Pradesh, Gujarat, Rajasthan and Tamil Nadu are among the top emitters (Fig. 4). Emissions of NO_x and NMVOCs are estimated to be 66.2 (49.2–83.1) Gg yr^{-1} and 64.0 (48.2–79.7) Gg yr^{-1} (Table 1).

When compared with the emissions from previous study (Pandey et al. 2014), emissions of CO (2.6 Tg yr^{-1}) are comparable to this study while CH_4 emissions (5 Gg yr^{-1}) are 50 times lower than this study. The reason for such a significant difference can be attributed to assumption in the fuel mix. Coal was assumed to be

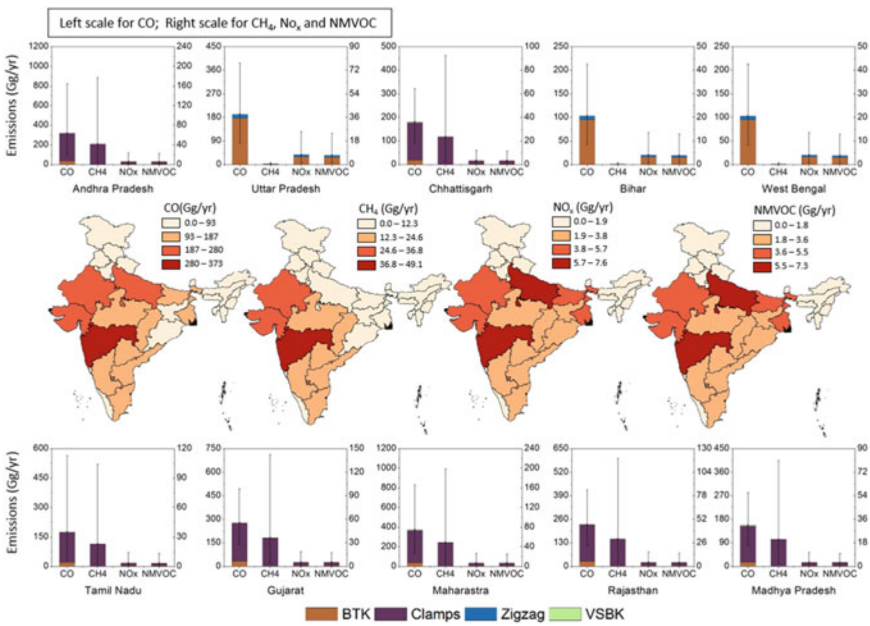

Fig. 4 Regional distribution and major emitters of CO, CH_4, NO_x and NMVOC emissions from brick kilns (Gg/yr)

the only fuel with very low emission factors in all the kilns (Pandey et al. 2014), whereas this study assumed a mean emission factor from a combination of different fuel mixes, particularly use of biomass fuel from clamp kilns. Emissions of NO_x (139 Gg yr^{-1}) are higher while of NMVOCs (8 Gg yr^{-1}) are lower than this study, which again can be attributed to different values of emission factors used.

4.3 Uncertainty in Emissions

Confidence bounds in emissions are calculated analytically from combination of uncertainties in brick production, specific energy consumption of kiln type and the respective emission factors. Uncertainties in brick production are represented as plus or minus one standard deviation. A lognormal distribution is assumed to represent uncertainties in final emissions for each state since the combined relative uncertainty (standard deviation/mean) is greater than 30% for almost all states. The standard deviation in the sum of emissions of a given pollutant from different technologies and for nation from different states is estimated as the sum of the individual uncertainties in quadrature.

Although the relative uncertainties for individual states are greater than 30%, the values for national total after combing all states are found to be 14% for $PM_{2.5}$, 18% for BC, 20% for SO_2, 15% for CO, 45% of CH_4 and 25% for NO_x and NMVOCs. Uncertainties are greater for CH_4, NO_x and NMVOCs due to large uncertainties in emission factors. Since reported emission factors had no reported uncertainty or are unavailable, 100% uncertainty is assumed in the mean emission factor. Reasons for uncertainties in other pollutants primarily arise due to lack of information on fuel mix used across different states. A single emission factor is considered for a particular kiln type averaged from measured values with different fuel mixes, thus giving rise to large standard deviations in the final emission factors. The upper and lower bounds in emissions for each state are presented in (Table 1).

5 Conclusions

A state-level emission inventory is developed to estimate the emissions of SLCPs from manufacturing of fired-clay bricks in India. A methodology is developed to estimate national brick demand, using trends in numbers of brick-walled houses, and assumptions in share of brick demand for other constructions (commercial, industrial and infrastructure), repair works and to account for damaged bricks. Brick demand is distributed to state level using trends in brick-walled houses at state level. Assuming that production would follow demand, it is found that Uttar Pradesh, Bihar, West Bengal and Maharashtra are the largest production centres for fired bricks. Using state-wise kiln technology data (with BTKs dominating in north and eastern states and clamp kilns dominating in western and southern states) and technology-linked emission factors averaged across fuel mixes (coal and biomass), emissions of different SLCPs are calculated.

Emissions of PM2.5, BC, OC and SO_2 are estimated to be 165.9 (142.0–189.7) Gg yr^{-1}, 119.1 (97.6–140.5) Gg yr^{-1}, 9.4 (7.3–11.4) Gg yr^{-1} and 393.6 (314.1–473.1) Gg yr^{-1}. For ozone precursors, the estimates are 2.6 (2.2–3.0) Tg yr^{-1}, 248.4 (137.4–359.4) Gg yr^{-1}, 66.2 (49.2–83.1) Gg yr^{-1} and 64.0 (48.2–79.7) Gg yr^{-1} for CO, CH_4, NO_x and NMVOCs. States with large share of BTKs (such as Uttar Pradesh, Bihar and West Bengal) contributed most to the BC emissions while regions having clamp kilns (Maharashtra, Gujarat and Rajasthan) emitted higher amounts of OC, CO and CH_4. Further improvements in inventory methodology will require survey-based data allowing estimation of brick production, along with better understanding of regional spread of various kiln technologies and fuel types, as well as field measurements of emission factors.

Appendix

Mean emission factors across different fuel mixes (g/kg of fuel mix)

	$PM_{2.5}$	BC	OC	SO_2	CO	CH_4	NO_x	NMVOC
BTK	3.3	2.7	0.1	9.3	38.9	0.1	1.4	1.3
Clamp kilns	3.7	2.4	0.3	7.4	74.7	11.2	1.3	1.3
Zig-Zag fired	2.0	0.3	0.1	3.1	14.3	0.1	1.4	1.3
VSBK	1.3	0.4	0.1	1.7	44.5	0.1	1.4	1.3

The values presented here are mean emission factors averaged over different fuel mixes from a particular kiln type. These are compiled from different studies Christian et al. 2010; Weyant et al. 2014; Rajarathnam et al. 2014; Stockwell et al. 2016

Regression equation and coefficients of the trend in brick-walled houses (1991–11)

$y = a \times \exp(b \times x)$

States	a	b	Slope of trend in the year 2015
Andaman and Nicobar	227.63	0.16	2124
Andhra Pradesh	5904848.59	0.03	435,651
Arunachal Pradesh	4299.61	0.08	2677
Assam	520339.8	0.06	139,315
Bihar	4550067.07	0.04	516,356
Chandigarh	166726.18	0.02	5345
Chhattisgarh	362278.92	0.08	245,034
Dadra and Nagar	10256.72	0.08	6632
Daman and Diu	12169.58	0.07	5421
Delhi	2135088.94	0.03	103,920
Goa	14795.87	−0.01	0

$y = a \times \exp(b \times x)$			
States	a	b	Slope of trend in the year 2015
Gujarat	4601356.95	0.03	376,987
Haryana	3011436.06	0.03	202,514
Himachal Pradesh	298337.37	0.06	75,914
Jammu and Kashmir	390776.35	0.07	166,838
Jharkhand	587839.55	0.08	316,568
Karnataka	3114619.37	0.03	185,559
Kerala	2261188.15	0.01	25,741
Lakshadweep	68.11	0.23	4592
Madhya Pradesh	3817165.79	0.03	213,803
Maharashtra	7148854.43	0.03	505,731
Manipur	19439.43	0.07	7176
Meghalaya	11911.74	0.09	9137
Mizoram	4496.32	0.08	2483
Nagaland	26132.27	0.05	5050
Odisha	1596779.42	0.05	261,614
Puducherry	91670.27	0.05	14,598
Punjab	3925453.5	0.02	159,985
Rajasthan	1724557.89	0.05	314,330
Sikkim	1577.46	0.16	11,867
Tamil Nadu	6408504.31	0.02	237,771
Tripura	32094.21	0.08	17,429
Uttar Pradesh	12603818.11	0.03	960,686
Uttarakhand	286329.81	0.08	173,434
West Bengal	4895899.75	0.04	514,708

State-level distribution of total brick production across different kiln types

States	BTKs	Clamp kilns	Zig-Zag fired	VSBK	State-level total production, B_s (million/year)
Andaman and Nicobar	84				84
Andhra Pradesh	6648	10,520			17,168
Arunachal Pradesh	105				105
Assam	5490				5490

States	BTKs	Clamp kilns	Zig-Zag fired	VSBK	State-level total production, B_s (million/year)
Bihar	16,696		3652		20,348
Chandigarh	173		38		211
Chhattisgarh	3259	5917		480	9656
Dadra and Nagar	261				261
Daman and Diu	214				214
Delhi	4095				4095
Goa					0
Gujarat	5753	9103			14,856
Haryana	6548		1432		7981
Himachal Pradesh	2455		537		2992
Jammu and Kashmir	5395		1180		6575
Jharkhand	12,475				12,475
Karnataka	2832	4481			7312
Kerala	342	622		50	1014
Lakshadweep	181				181
Madhya Pradesh	2844	5163		419	8425
Maharashtra	6727	12,212		991	19,930
Manipur	283				283
Meghalaya	360				360
Mizoram	98				98
Nagaland	199				199
Odisha	9797			513	10,310
Puducherry	575				575
Punjab	5173		1131		6305
Rajasthan	4797	7590			12,387
Sikkim	468				468
Tamil Nadu	3629	5741			9370
Tripura	687				687
Uttar Pradesh	31,064		6794		37,858
Uttarakhand	5608		1227		6835
West Bengal	16,643		3640		20,283
India	**161,958**	**61,348**	**19,631**	**2454**	**245,390**

Specific energy consumption per kiln type

Sp. energy consumption, SEC_k (MJ/kg brick)			
Kiln, k	Mean	SD	SD/mean
BTK	1.2	0.2	0.2
Clamp kilns	2.9	0.0	0.0
ZigZag fired	1.1	0.1	0.1
VSBK	0.7	0.3	0.4

Source Weyant (2014)

Heating value of fuel mix (MJ/kg)

Heating value of fuel mixes, CV (MJ/kg)			
Kiln	Mean	SD	SD/mean
BTK	23.8	4.9	0.2
Clamp kilns	23.3	8.4	0.4
ZigZag fired	20.4	0.3	0.0
VSBK	15.1	10.8	0.7

Source Weyant et al. (2014)

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