3 RESIDENTIAL SECTOR

The basic equation (Eq. 2) employed for emission estimation from the residential sector is:

$$[Ep]R = \sum_{(S=1)}^{35} \sum_{(D=1)}^{n} \sum_{(f=1)}^{n} Pop_{(D,f)} \times C_{(f,S)} \times EF_{(f,p)} \quad (2)$$

where, $[E_p]_R$ is the emission of a particular pollutant (p) from the residential sector; $Pop_{(D)}$ is the population of a district using a particular fuel; $C_{(f'S)}$ = State specific per capita consumption of a particular fuel; and $EF_{(f,p)}$ = Emission factor of the particular pollutant (p) of the particular fuel type (f). We define rural areas following the 2011 India Census. Under the census, a rural area is any area that does not belong to a municipality, corporation, cantonment board or notified area and meets all of the following criteria: more than 75% of people are engaged in agricultural activities, area is not contiguous to a statutory town, area does not possess urban infrastructures (e.g., pucca road, streetlight, water tap, drainage, educational institution), and area is within the revenue limit of a village. All other areas were considered as urban areas in the present study.

The district-level population and household data (rural and urban area) were collected from the India census (2001, 2011) for the years 2001 and 2011. The population data of India census has an error of 2.3% (India Census, 2011). These data were used to derive the district-level annual population growth rate and growth rate of number of people living in one household. These growth rates were then used to project the population and number of households in 2016 based on the district-level respective data of 2011 following Eq. 3 and Eq. 4

$$Pop_{(2016)} = Pop_{(2011)} (1 + POP_{GR})^5 \quad (3)$$

$$HH_{(2016)} = \frac{Pop_{(2016)}}{HHPOP_{(2011)} \left\{1 + \frac{HHPOP_{(2011)} - HHPOP_{(2001)}}{10 \times HHPOP_{(2001)}}\right\}^5} \quad (4)$$

where, $Pop_{(2016)}$ is the projected population of 2016; $Pop_{(2011)}$ is the district-level (rural and urban) population in 2011 (Census, 2011); POP_{GR} is the annual population growth rate (Census, 2011); $HH_{(2016)}$ is the projected household number in a district (rural and urban) in 2016; $HH_{POP(2011)}$ is the average number of people in each district (rural and urban) living in each household during 2011; and $HH_{POP(2001)}$ is the average number of people in each district (rural and urban) living in each household during 2001. The annual population estimation using the method above can have an error as high as 16% based on the earlier available data from India Census (1991, 2001 and 2011). Thus, $Pop_{(2016)}$ and $HH_{(2016)}$ estimation using Eq. 4 has an error of estimation of 18.3%.

The number of households in a particular district (rural and urban area) that use a particular fuel for cooking and lighting energy during 2016 was calculated using the household amenity dataset of India census (2011). This was used to calculate the number of people using a particular fuel by considering the average household population in each district.

However, there is a significant annual growth in household electricity and liquefied petroleum gas (LPG) usages after 2011. State-level annual unelectrified village data for the years 2013 to 2016 were collected from the Central Electricity Authority (CEA, 2013 to 2016). State-wise annual electricity surplus data were also collected from the CEA (2011 and 2017). The number of unelectrified households in each district (rural and urban) during 2011 was calculated based on the household amenity data (Census, 2011). State-level annual rural electrification growth rate was calculated using the village electrification data of CEA. This was used to estimate the number of electrified households during 2016. The state- wise power surplus data (CEA, 2011 to 2016) were used to adjust the household kerosene use in both urban and rural areas using Eq. 5 and Eq. 6

$$Adj\mathrm{HH}_{\mathrm{unelc}} = \mathrm{HH}_{\mathrm{unelc}} - (\mathrm{HH}_{\mathrm{elec}} \times \mathrm{E}_{\mathrm{GR}} \times \mathrm{P}_{\mathrm{Sur}}) \quad (5)$$

$$Adj\mathrm{HH}_{\mathrm{K\_L}} = (\mathrm{HH}_{\mathrm{K\_L}} \times Adj\mathrm{HH}_{\mathrm{unelec}}) / \mathrm{HH}_{\mathrm{unelec}} \quad (6)$$

where, $Adj\mathrm{HH}_{\mathrm{unelc}}$ is the estimated number of households un-electrified during 2016; $\mathrm{HH}_{\mathrm{unelec}}$ and $\mathrm{HH}_{\mathrm{elect}}$ is the number of households unelectrified and electrified respectively in 2016 based on Census (2011); E_{GR} is the annual village electrification growth rate in a state; $\mathrm{P}_{\mathrm{Sur}}$ is the state-level change (%) in power surplus situation between 2011 and 2016 (CEA, 2011; 2017); $Adj\mathrm{HH}_{\mathrm{K\_L}}$ and $\mathrm{HH}_{\mathrm{K\_L}}$ are estimated number of households using kerosene for lighting purpose during 2016 and calculated number of households using kerosene for lighting during 2016 based on census (2011). The $\mathrm{HH}_{\mathrm{unelec}}$ and $\mathrm{HH}_{\mathrm{elect}}$ were calculated from the India census (2011), which is having an error of 2.3%; thus there is an error of 2.3% in the estimation of $Adj\mathrm{HH}_{\mathrm{K\_L}}$ in Eq. 6.

Similarly, the number of households using LPG for cooking fuel in 2016 was also estimated. State-level annual registered LPG consumers' data for the year 2013–2016 were collected from the database of Petroleum Planning & Analysis Cell, Ministry of Petroleum and Natural Gas, Government of India (PPAC, 2013; 2014; 2015; 2016). State- level rural and urban area-wise annual data of LPG distributors for the same years were also collected from the above source. These data were used to calculate the state-level annual growth of LPG consumers in rural and urban areas. The number of the LPG using households ($Adj\mathrm{HH}_{\mathrm{LPG}}$) in rural and urban areas during 2016 was adjusted using Eq. 7

$$Adj\mathrm{HH}_{\mathrm{LPG}} = \mathrm{HH}_{\mathrm{LPG(2016)}} + (\mathrm{HH}_{\mathrm{LPG(2011)}} \times \mathrm{GR}_{\mathrm{LPG}}) \quad (7)$$

where, $\mathrm{HH}_{\mathrm{LPG(2016)}}$ is the number of LPG using households in either rural or urban area of a district during 2016 using the household amenity data of the India census (2011) and the number of households in 2016 using the *eq. 4*; $\mathrm{GR}_{\mathrm{LPG}}$ is the district-specific calculated annual growth rate of LPG consumers' in rural and urban areas. The increase of numbers of households using LPG ($Adj\mathrm{HH}_{\mathrm{LPG}}$ - $\mathrm{HH}_{\mathrm{LPG(2016)}}$) was then uniformly distributed to adjust the number of FW, CR and CDC using households during 2016. Thus, the estimation of consumption of different fuels in the residential sector during the year 2016 has an error as high as: 19% for FW, 19% for CR, 19% for CDC, 20% for kerosene, 19% for coal, and 20% for LPG.

The data related to the state-level per capita consumption of different fuel ($C_{(f,S)}$) used in the residential sector was collected from the National Sample Survey Office report (NSSO, 2014).

Apart from cooking, Fuelwood (FW) is also used in the residential sector for the purpose of water heating, space heating during the winter season and also for preparing animal fodder in several parts of India. The FW use for the residential water heating was separately accounted in this study. First, it was assumed that the households in the rural areas of districts with morning temperature below 18°C during the morning hours (6 AM to 11 AM) mostly use the FW for water heating. District-wise hourly ambient temperature data were collected from the Indian Meteorological Department (IMD). The ambient temperature in the rural areas of the districts was below 18°C for three months during the year (December to February). In these districts, the total FW use (kg/annum) was adjusted ($AdjPP_{FW}$) by including the FW use for water heating using Eq. 8

$$(AdjPP_{FW})_{Ru} = (PP_{FW})_{Ru} + (PP_{FW\_H})_{Ru} \times (C_{FW})_{Ru} \quad (9)$$

where, $(PP_{FW})_{Ru}$ is the district-specific FW use (kg) in the rural area; $(PP_{FW\_H})_{Ru}$ is the district-specific number of people using FW for residential water heating and $(C_{FW})_{Ru}$ is the per capita use of FW in the rural area (NSSO, 2014). Fuel-specific emission factors of different pollutants ($EF_{(f,p)}$) were taken from Datta et al. (2016) and Pandey et al. (2014) (Table 1).

Table 1 Emission factors (g/kg) of different pollutants from different fuel types used in the residential sector

Fuel type	PM_{10}	$PM_{2.5}$	SO_x	NO_x	CO	NMVOC
Fuelwood	6.8	4.6	0.8	1.7	66.5	15.9
Crop residue	8.6	5.7	0.7	1.8	64	8.5
Dung cake	10.5	4.4	0.6	1.0	78.6	24.1*
Coal	8.3	4.0	15.3	2.16	59.5	10.5*
Kerosene (for cooking)	3.6	3.0	0.4	1.3	43	17.0*
Kerosene (for lighting)	91. 3	91.3	NA	NA	29.3	NA
LPG	0.4	0.4	0.4	2.9	2.0	3.7*

* Pandey et al. (2014); others were adopted from Datta et al. (2016)

NA: Not available

Datta et al. (2016) have reported the error in the emission factors listed in Table 1 that may be attributed to an uncertainty of up to 25% in the estimation of individual pollutants emissions.

3.1 Estimated fuel consumption in residential sector

The annual consumption of different types of fuels in the residential sector of different states of India estimated using the methodology stated above is summarized in Table 2 and Table 3.

Table 2 State-wise annual consumption (Gg) of different fuels in the rural areas during 2016

State	FW	CR	CDC	Coal	Kerosene	LPG
Andaman & Nicobar Islands	70	9	0	0	1	3
Andhra Pradesh	7964	2785	27	3	107	268
Arunachal Pradesh	742	142	0	0	3	12
Assam	10,481	4186	12	10	149	148
Bihar	12,362	25,491	4369	211	477	209
Chandigarh	0	0	0	0	0	0
Chhattisgarh	6216	0	442	37	81	12
Dadra & Nagar Haveli	0	0	0	0	0	0
Daman & Diu	0	0	0	0	0	0
Goa	45	0	0	0	2	12
Gujarat	9089	2306	406	16	179	135
Haryana	2596	468	1214	3	28	161
Himachal Pradesh	1180	0	3	0	3	27
Jammu & Kashmir	3794	787	71	6	35	89
Jharkhand	6814	1863	499	995	134	263
Karnataka	13,137	1637	48	0	167	155
Kerala	6069	356	0	2	28	196
Lakshadweep	3	0	0	0	0	0
Madhya Pradesh	11,131	6019	2413	5	249	109
Maharashtra	13,241	5851	36	16	278	458
Manipur	479	168	1	15	5	19
Meghalaya	1016	0	0	9	8	6
Mizoram	310	0	0	0	1	7
Nagaland	620	48	0	0	1	18
NCT of Delhi	1	0	0	0	0	6
Odisha	12,825	959	324	110	157	49
Puducherry	3	0	0	0	1	8
Punjab	2754	809	1885	1	28	238
Rajasthan	20,207	609	1155	7	211	182
Sikkim	86	0	0	0	1	8
Tamil Nadu	8930	1622	8	0	153	439
Telangana	4969	1738	17	2	67	167
Tripura	1884	0	1	2	14	7
Uttar Pradesh	24,735	6035	11,161	63	652	348
Uttarakhand	3800	409	35	0	25	78
West Bengal	13,842	4328	1323	998	336	172
Total	201,395	68,625	25,452	2511	3583	4011

FW: Fuelwood; CR: Crop residue; CDC: Dung cake; LPG: Liquid petroleum gas

Table 3 State-wise annual consumption (Gg) of different fuels in the urban areas during 2016

State	FW	CR	CDC	Coal	Kerosene	LPG
Andaman & Nicobar Islands	2	2	0	0	1	4
Andhra Pradesh	599	124	4	15	32	399
Arunachal Pradesh	51	0	0	0	0	8
Assam	404	95	0	3	6	158
Bihar	833	335	248	102	9	301
Chandigarh	0	0	0	0	0	0
Chhattisgarh	672	150	71	215	6	99
Dadra & Nagar Haveli	0	0	0	0	0	0
Daman & Diu	0	0	0	0	0	0
Goa	22	0	0	0	2	40
Gujarat	1271	2012	36	153	86	622
Haryana	248	59	112	6	4	368
Himachal Pradesh	265	12	1	0	12	144
Jammu & Kashmir	241	52	2	6	9	127
Jharkhand	278	57	48	766	5	197
Karnataka	2156	0	10	5	91	622
Kerala	5860	284	0	8	10	509
Lakshadweep	17	0	0	0	1	1
Madhya Pradesh	1498	25	208	47	35	449
Maharashtra	1215	258	36	26	206	1502
Manipur	73	1	1	10	0	15
Meghalaya	53	0	0	3	1	15
Mizoram	38	0	0	1	1	19
Nagaland	179	0	0	0	0	18
NCT of Delhi	19	0	2	0	3	287
Odisha	1370	79	6	97	11	124
Puducherry	35	2	0	0	2	27
Punjab	270	42	154	4	20	340
Rajasthan	1242	24	77	23	11	416
Sikkim	1	0	0	0	1	16
Tamil Nadu	1904	310	1	1	165	1121
Telangana	601	124	4	15	37	400
Tripura	245	6	0	1	1	29
Uttar Pradesh	2623	248	924	47	29	1008
Uttarakhand	279	0	9	0	5	98

State	FW	CR	CDC	Coal	Kerosene	LPG
West Bengal	1283	151	175	875	84	718
Total	25,850	4453	2127	2428	887	10,200

FW: Fuelwood; CR: Crop residue; CDC: Dung cake; LPG: Liquid petroleum gas

The estimated fuel consumption in the residential sector (Table 2 and Table 3) was comparative with the estimated fuel consumptions in the residential sector reported in other studies (Table 4). The MARKAL model simulation is based on estimates of different energy use in the domestic sector, so there are possibilities of error in the simulation framework. The MARKAL simulation does not have any estimation of coal consumption in the residential sector of India. The reported coal consumption in the residential sector in the Ministry of Statistics and Programme Implementation (MoSPI) (2014) was of FY2012–13. In the present study, we estimated the coal consumption in the residential sector by projecting the population in Census 2011 to 2016 and also the number of households using coal based on India Census 2011 data adjusted with increase in the LPG using households during 2011 to 2016. This may attribute to estimation of higher coal consumption in the present study compared to MoSPI (2014). Pandey et al. (2014) have reported the biomass use during 2012–13, while in the present study the estimation was made for 2016. However, the fuel use in the residential sector in the present study was adjusted with increase in LPG use during 2011 to 2016 period. Thus, the estimated biomass use was lower in the present study compared to that reported in Pandey et al. (2014), although the estimated population was higher during 2016 than 2012–13. The PNGStat reports the consumption of kerosene through the Public Distribution System (PDS), India; the ~14% difference in kerosene consumption in the present study with the PNGStat may be attributed to higher estimation of LPG uses during 2016 in the residential sector or lower use of kerosene for lighting in the domestic sector. The ~24% lower estimation of LPG consumption compared to the PNGStat (Table 4), may be attributed to inclusion of commercial use of LPG in PNGStat.

Table 4 Comparison of estimated energy use in the residential sector with other reported studies

	Biomass (Gg)	Coal (Gg)	Kerosene (Gg)	LPG (Gg)
MARKAL estimates	339,409		2611	10,973
PNGStat, 2017[1]			5204	18,871
Pandey et al., 2014[2]	350,476			
MoSPI, 2014[3]		2682		
Present study	327,902	4939	4469	14,212

3.2 Emission inventory of the residential sector

The activity data of different fuels (Table 2 and Table 3) was fed into the *eq. 2* along with the fuel-specific emission factors of different pollutants ($EF_{(f,p)}$) to calculate the emission of different pollutants from the use of different fuel types in the rural and urban areas (Figure 2).

1 PNGStat Indian petroleum and natural gas statistics 2016-17. Ministry of Petroleum and Natural Gas, Government of India.
2 Pandey, A., Sadavarte, P., Rao, A.B., Venkataraman, C. 2014. Trends in multi-pollutant emissions from a technology-linked inventory for India: II. Residential, agricultural and informal industry sectors. Atmospheric Environment 99: 341-352.
3 MoSPI 2014 Energy statistics 2014. National Statistical Organization, Ministry of Statistics and Programme Implementation, Government of India.

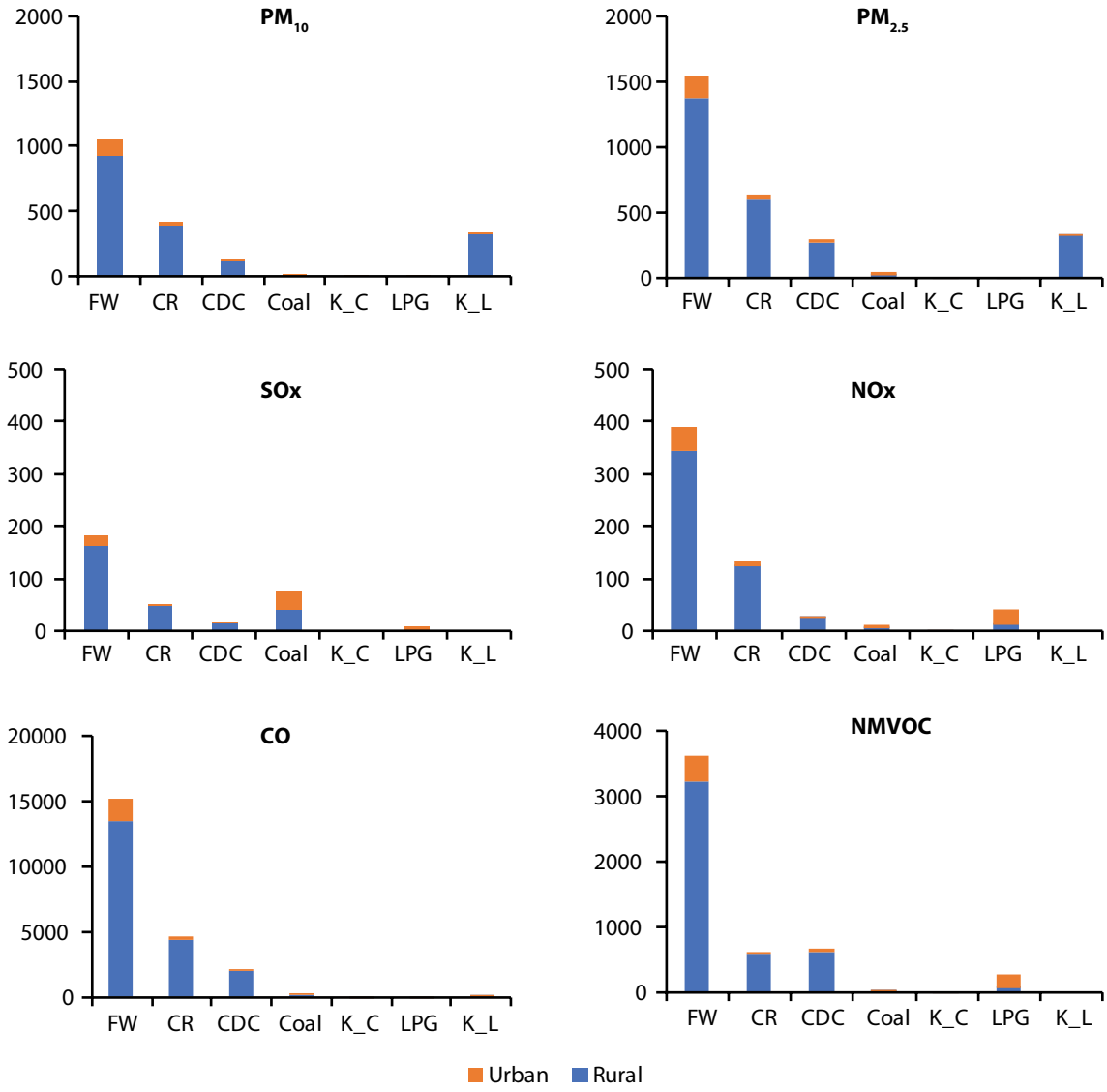

Figure 2 Fuel-wise emissions of different pollutants from the residential sector during 2016

The district-specific emissions of different pollutants were distributed spatially over 36 × 36 km2 grid (Figure 3) using the ratio of the area of each polygon and area of the respective district. However, if a polygon has higher population density in a district, it was not attributed through this method. This distribution method contains up to 5% error in spatial distribution of district-level estimated emissions of each pollutant.

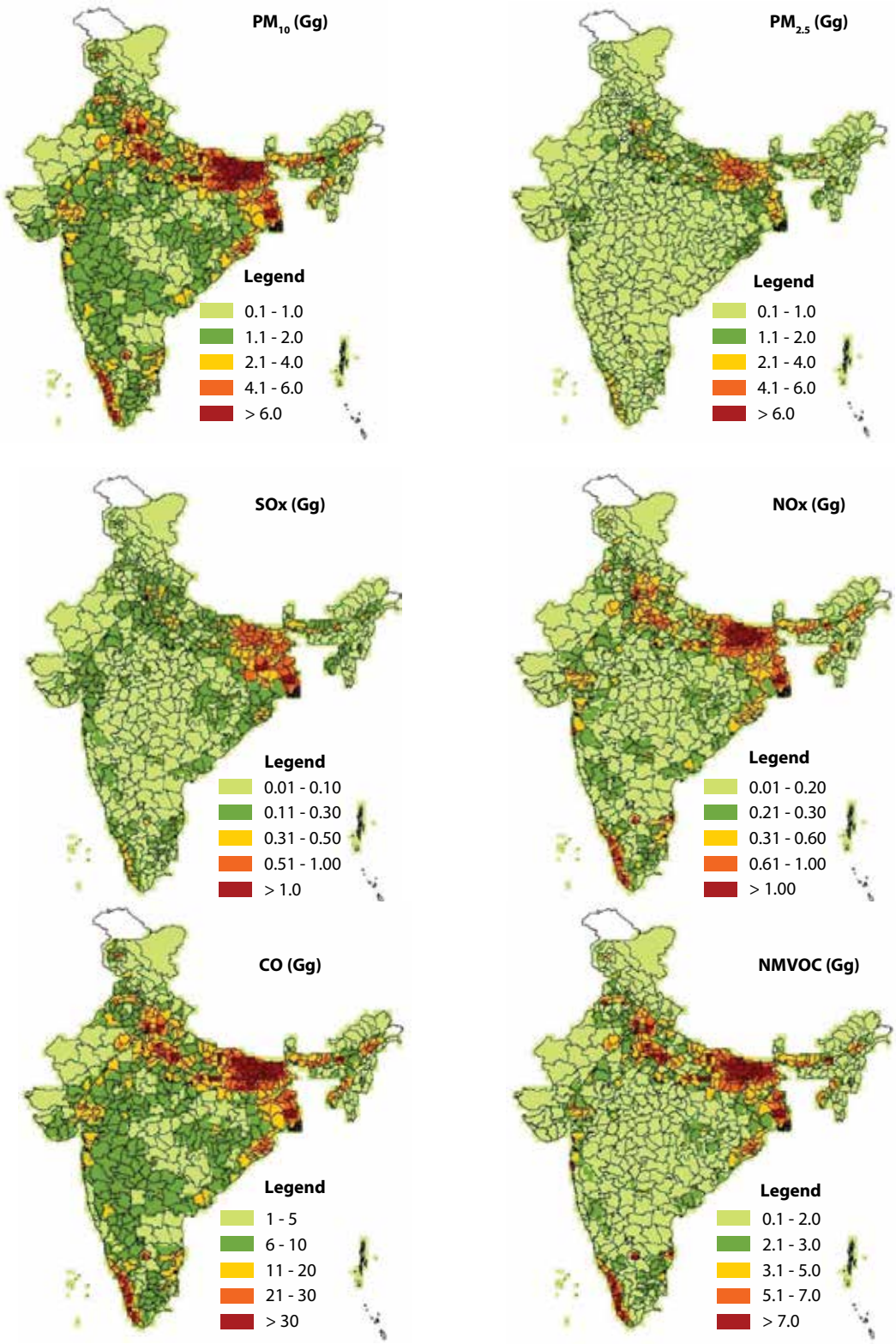

Figure 3 Spatial variations of emissions of different pollutants from the domestic sector

Total emissions of different pollutants from the residential sector are summarized in Table 5.

Table 5 Fuel-wise total emissions (Gg) of different pollutants from the residential sector during 2016

Fuel type	PM_{10}	$PM_{2.5}$	SO_x	NO_x	CO	NMVOC
Water heating						
Fuelwood	28	41	5	10	402	96
Cooking						
Fuelwood	1510	1004	177	376	14,710	3515
Crop residue	628	417	51	132	4677	621
Dung cake	290	121	17	28	2168	665
Coal	41	20	76	11	294	52
Kerosene	3	3	0	1	37	14
LPG	5	5	6	41	28	270
Lighting						
Kerosene	331	331	0	0	106	0
Total	2836	1941	331	598	22,421	5233

FW: Fuel wood; CR: Crop residue; CDC: Dung cake; K_C: Kerosene used for cooking; K_L: Kerosene used for Lighting (Wicked Lamp); LPG: Liquid Petroleum Gas

Earlier studies have estimated 3236 Gg (ECLIPSE) to 3600 Gg (IEA, 2016) of emissions of $PM_{2.5}$ and 476 Gg (ECLIPSE) to 725 Gg (IEA, 2016) of emissions of SO_2 from the residential sector during 2015. Higher estimation of emissions of $PM_{2.5}$ and SO_2 in earlier studies may be attributed to the consideration of increase of LPG uses and simultaeneous decrease in biomass uses in households for the present study. Additionally, decreases in kerosene consumption for lighting and cooking purposes have also been accounted for in the activitiy data of the present study by using the growth of electrification and LPG usage in India; this might also have contributed to decreases in $PM_{2.5}$ and SO_2 emissions from the residential sector compared to earlier studies.