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Supplement of

Nepal emission inventory – Part I: Technologies and combustion sources (NEEMI-Tech) for 2001–2016

Pankaj Sadavarte et al.

Correspondence to: Pankaj Sadavarte (p.sadavarte@sron.nl) and Maheswar Rupakheti (maheswar.rupakheti@iass-potsdam.de)

Supplementary Information

Section S1: Activity rates and fuel consumption for each sector

Residential sector

Cooking: In residential sector, *National Population and Housing Census 2011* provides primary data on the number of households using different types of cooking fuel and sources of lighting for 3915 Village Development Committees (VDCs) and 58 municipalities, i.e., administrative units in rural and urban regions, respectively (CBS, 2012). The amounts and types of fuel consumed for cooking are based on previous studies reporting the 'useful energy' required for preparing daily food in various utensil-stove-fuel combinations in different seasons (Pokharel, 2004; Kandel et al., 2016). This useful energy is quantified using the efficiency of the respective cookstove and heat content of the fuel (CES, 2001; Johnson et al., 2013).

Lighting: For lighting, the amount of kerosene used is calculated using the average burn rate, hours of daily usage and number of lamps per household (Lam et al., 2012; DECP, 2014). During hours of power cuts, the fraction of electricity users switching to kerosene lamps was determined by presuming equal weighting assigned to alternate sources such as kerosene lamps, solar lamps, batteries and inverters, and candles and also by constraining the kerosene estimate reported by the Water and Emission Commission Secretariat (WECS) for lighting (WECS, 2014).

Water heating and boiling: For water heating and boiling, the specific energy required to raise the temperature from ambient (t < 20º C) to 43º C was calculated assuming 15 l per capita per day amount of bathing water (average capacity of commonly used buckets in Nepal). The monthly mean minimum temperature maps are used to identify the districts where the morning temperature falls below 20º C (MoSTE, 2013). Table S1 provides details on the assumptions for estimating amount of specific energy required to heat water for bathing.

Table S1. Parameters used for energy required in water heating and boiling source category

Parameters	Value	Units
density of water	997	g/l
Sp. Heat capacity	4.1	J/g-K
Average water temperature	20	ºC
Desired water temperature	43	ºC
Bathing water requirement	15	l/capita-day

<u>*Space heating:*</u> Similar temperature threshold (t < 20º C) was adopted to estimate the amount of fuel used for space heating that takes place indoor and outdoor. For space heating indoors, the excess amount of fuel required to warm the space after cooking (i.e. the cooking fire is continued for the purpose of space heating) during winter season was attributed to this activity (Kandel et al., 2016) (Fig. S1). Space heating outdoors means, where people gather around an open fire to keep themselves and the immediate vicinity warm from cold by burning firewood, agricultural residue and dungcakes. Two different groups of population were identified, the first category that works during night shifts hours, i.e., during 11 PM–7 AM and the second category is the resident population who uses space heating after sunset in the evening, i.e., during 7–11 PM. Based on routine observation and expert judgement, number of hours, fraction households engaged and number of days in each month considered are shown in Table S2.

Table S2. Parameters used for space heating source category

	No. of hours (hr)		**Fraction household**		**Burn rate (kg/hr)**		**Days per month**	
	low	**high**	**low**	**high**	**low**	**high**	**low**	**high**
Regular	3.0	5.0	0.50	0.75	0.50	1.00	15	20
At night	6.0	8.0	0.10	0.20	0.50	1.00	15	20

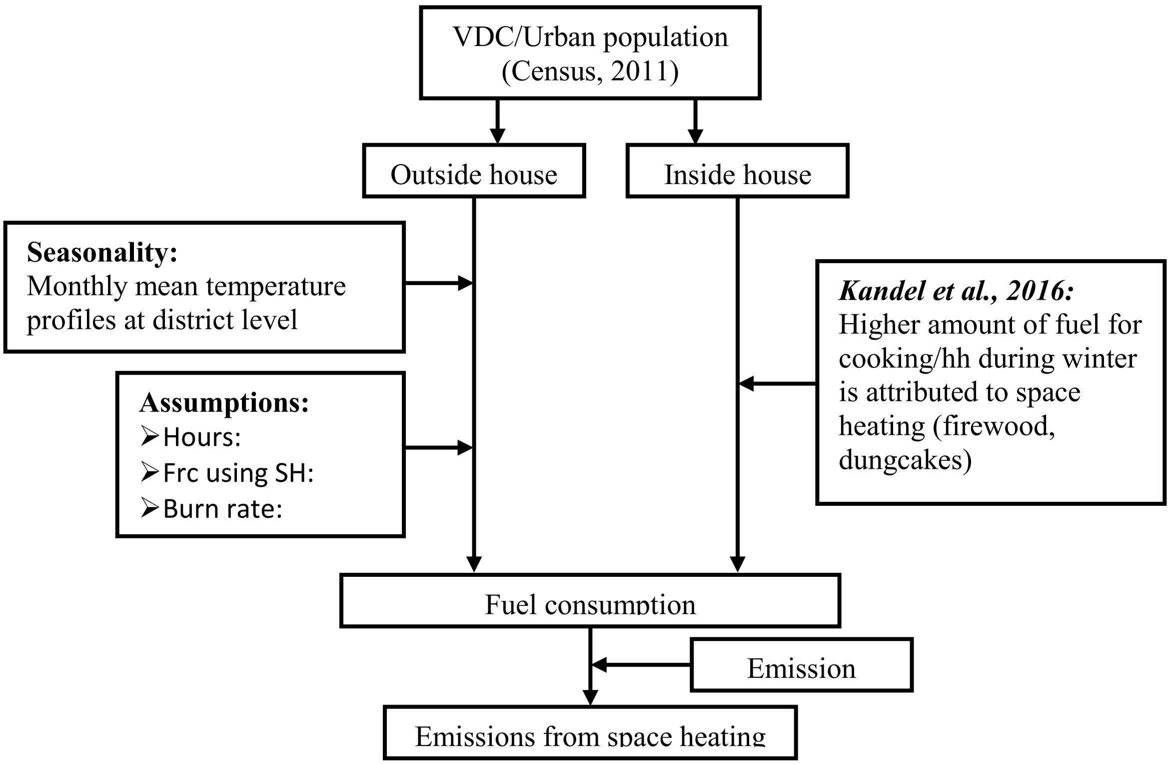

Figure S1. Flowsheet for estimating emissions from space heating

Industry sector

In the industry sector, the information available in the *National Census of Manufacturing Establishment* (CME) *2011* report was used for fuel estimation. CME 2011 has surveyed a total of 4,076 industrial units nationwide covering small, medium and large industries (CBS, 2014). The CME questionnaire survey focused on collating the annual details on proprietorship, organizational structure, production, sales figure, fuel, electricity consumption and details on pollution control equipment. The Department of Industry (DoI), Nepal categorizes these industries into small, medium and large industries based on the economic output (GoN, 1992), whereas this study has categorized industries based on the reported energy use. A total of 1,512 industrial units including cement manufacturing, basic iron, structural metal, brick production, grain mill, noodles, tea and coffee, and pharmaceuticals in this study are considered as large point sources or heavy industries (LPI); whereas rest 2,564 industrial units are considered as small and medium industries (SMI). The fuels in the above LPI and SMI of paper, sugar, beverage, dairy and soap were corrected using specific energy consumption (SEC) from a survey conducted for selected industries and the production data (PACE Nepal, 2012; CBS, 2014). The industrial census is conducted every five years, hence the reports are available so far for 2001/02 and 2006/07. The methodology described above is followed to estimate fuel consumption for these respective years, and interpolated for intermediate years.

Commercial sector

The commercial sector includes all service providing institutions that are largely dispersed over the whole country. These institutional units mainly require energy in the form of electricity while few sub-sectors like hotels, restaurants and barrack canteens also consume energy for cooking and other utilities such as water boiling and space heating. The country heavily relies on captive power generator sets using diesel (Gensets) for electricity supply during the main power outages, especially during dry and long non-monsoon season. The amount of diesel use in generators was estimated based on the demand-supply of electricity by the Nepal Electricity Authority (NEA) and the electricity sales in each sector for year 2011 (Fig. S2). For rest of the years, the diesel consumption was estimated proportionally using respective actual hours of load shedding for each year provided by NEA. For tourism-grade hotels, the total energy use was estimated based on the energy consumed per room in tourism hotels (PACE Nepal, 2012) and their availability during the study period (MoCTCA, 2013). A past study on the restaurants in India (FHRAI, 2004) have provided how frequently the urban population goes to dine out in the restaurants; which is assumed for the population in urban locations. This frequency along with the energy per capita per day required for cooking is used for estimating the amount of fuel use in restaurants. For barrack canteens the energy requirement is compiled from the WECS report since no sufficient information is available for their population and activities.

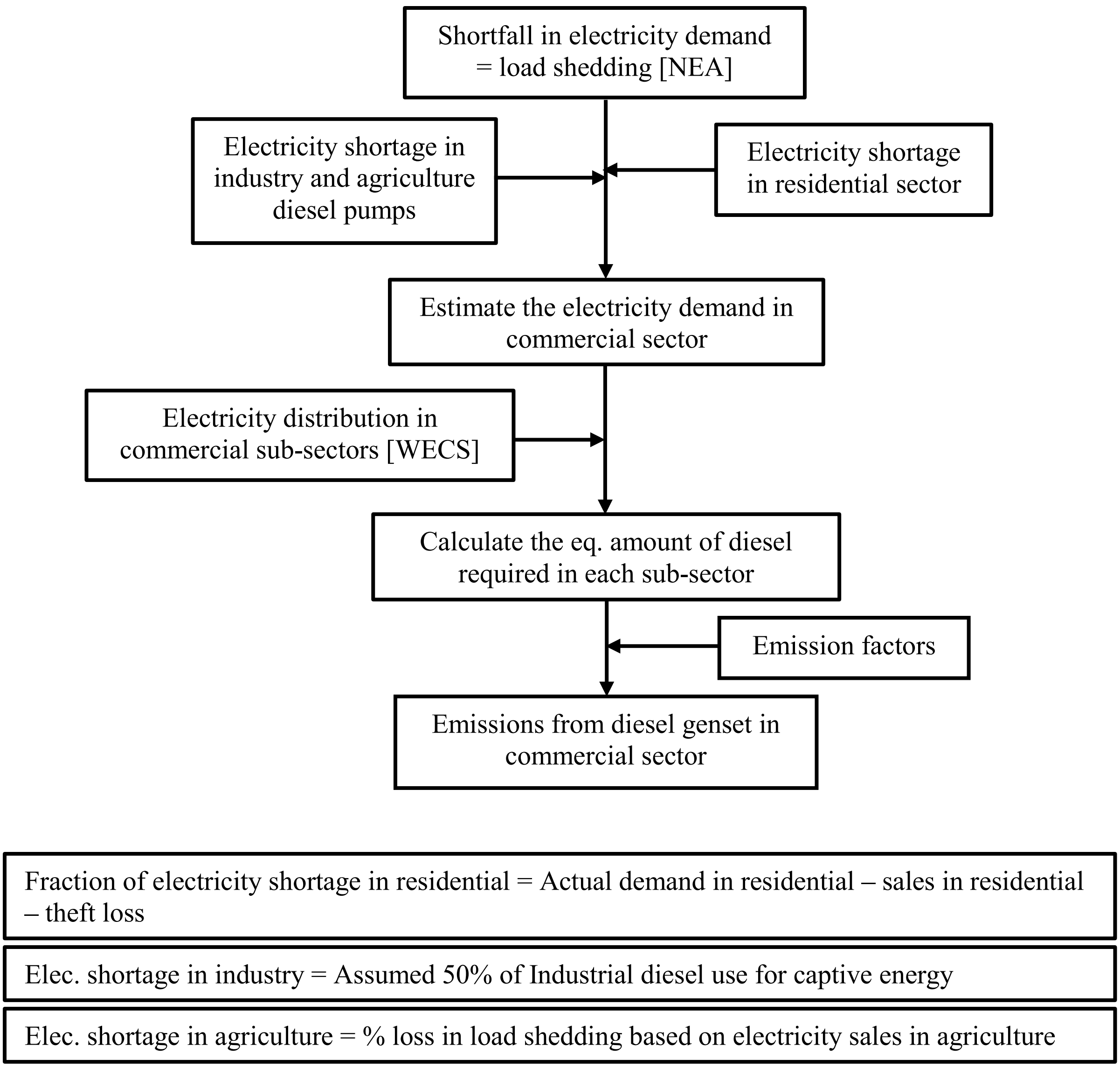

Figure S2. Flowsheet for estimating emissions from diesel generator sets

Agriculture sector

The agriculture sector in this study includes combustion activities of diesel use in pumps, tractors, power tillers and engines for threshing. The energy required for pumping water was estimated using the amount of water used for irrigation in Nepal, reported by the Food and Agriculture Organization (FAO), and the fraction of people relying on surface water (SW), shallow tubewell (STW) and deep tubewell (DTW) for irrigation (Frenken and Gillet, 2012). The fraction of diesel irrigation pump users relying on surface water, shallow tubewell and deep tubewell is well established in Nepal, where each consumes different amounts of energy depending on varying pressure head (ADB, 2012).

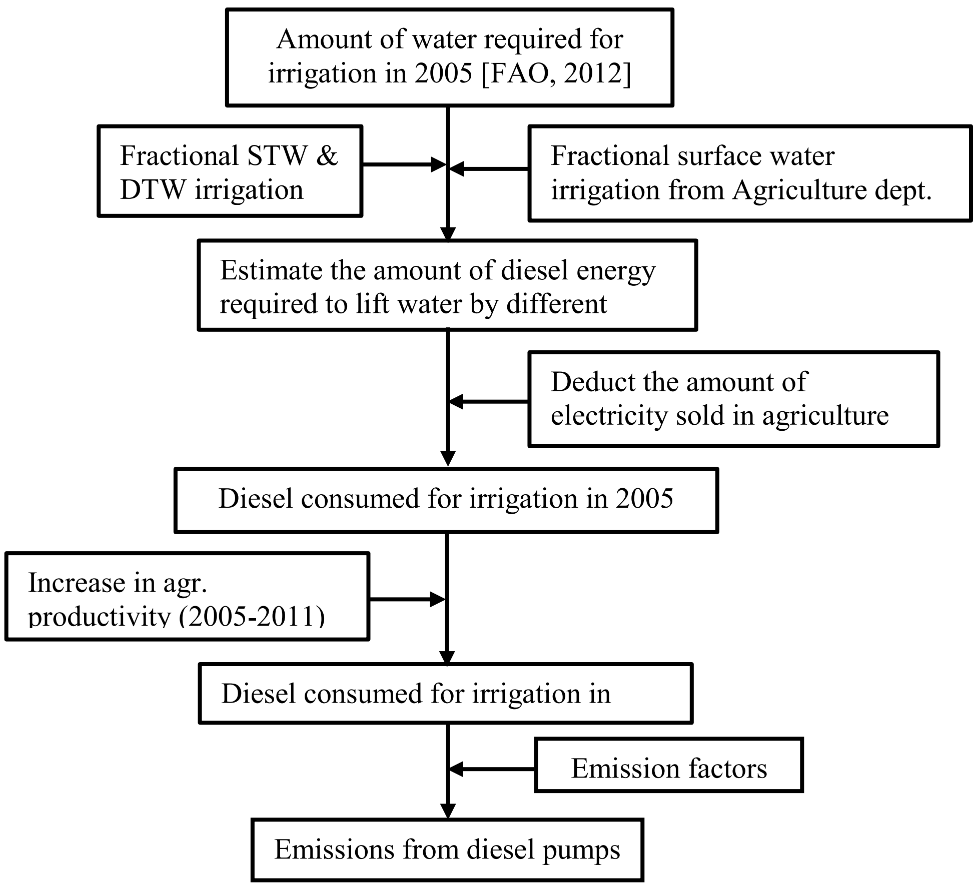

Figure S3. Flowsheet for estimating emissions from diesel irrigation pumps

These primary data was used to estimate equivalent amount of energy required to pump the water from varying depth (Fig. S3). For mechanized farming, the *Ministry of Agricultural Department* reported the number of land holdings using tractors, tillers and threshers in 2011 (MoAD, 2011). The total amount of fuel used for land preparation was estimated using area cultivated by tractors/tillers and diesel consumed per hectare (Baruah and Bora, 2008; Bohra and Kumar, 2015; Erenstein et al., 2008; Kumar et al., 2013) (Fig. S4). In this study, conventional tillage practice is assumed for land preparation that involves four tillage and two planking operations. Similarly, the agriculture statistics reports the use of threshers in each district (MoAD, 2011). The amount of fuel for threshing is estimated using the diesel consumption rate for threshing achieved through power tiller and small engines (Kumar et al., 2013).

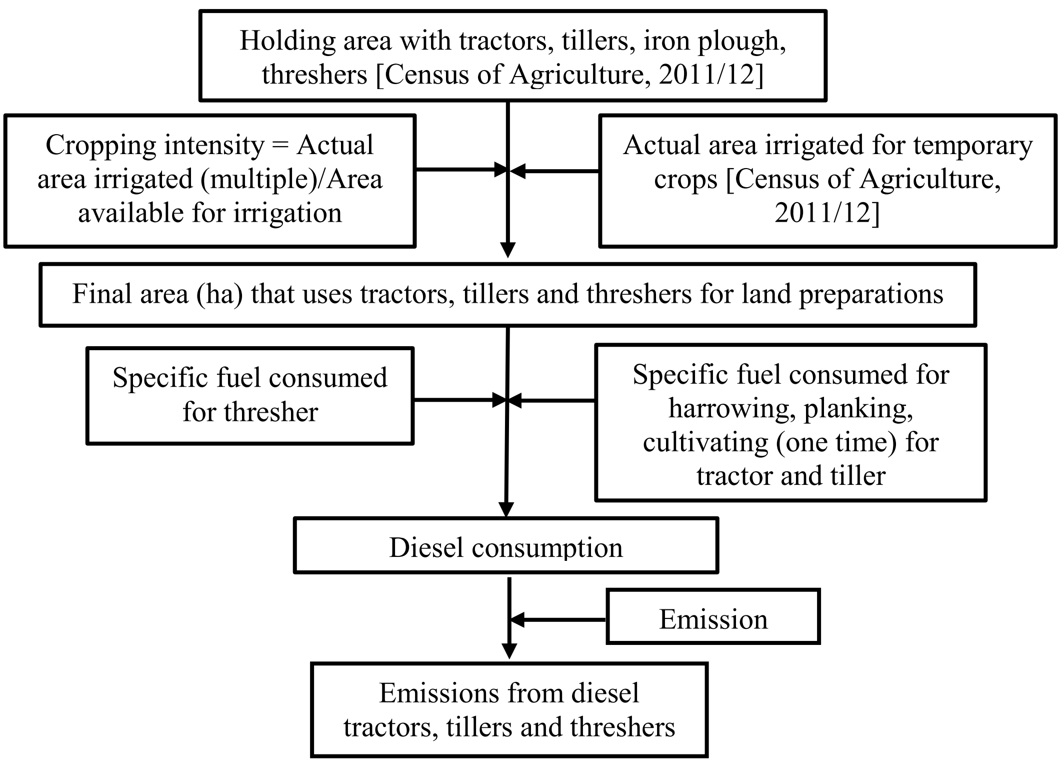

Figure S4. Flowsheet for estimating emissions from diesel tractors, tillers and threshers

Transport sector

The activity rates for transport sector includes age-distributed vehicle population, fuel efficiency (FE) and vehicle kilometer travelled (VKT) for total eight categories of on-road and off-road vehicles (Shrestha et al., 2013; DoTM, 2013). The actual number of on-road vehicles is modeled using the long-term vehicle registration data (from ca. 1989 till 2016) and the survival fraction of vehicles in each category for every year (DoTM, 2016; Baidya and Borken-Kleefeld, 2009; Yan et al., 2011). The survival fraction was modeled using a logistic function to estimate the survival function parameters 'α' and 'L_{50}' which describes the onset of retirement and the age when 50 % of the vehicles have retired (Yan et al., 2011; Pandey and Venkataraman, 2014). Essentially, the age distribution required for survival parameters was available for two-wheelers and buses for Nepal (for year 2010) from Shrestha et al., (2013) while for the remaining categories they were considered similar to vehicles in India (Pandey and Venkataraman, 2014). The fuel efficiency for each vehicle category was compiled from the survey-based studies conducted in Nepal (Dhital and Shakya, 2014; Dhakal 2003; Bajracharya and Bhattarai, 2016; Pradhan et al., 2006). The VKT was modeled using the survey study in the Kathmandu Valley for two-wheelers, buses, vans and taxis by Shrestha et al., (2013). For the remaining categories these were considered from other literature (Dhital and Shakya, 2014; Dhakal, 2003; Bajracharya and Bhattarai 2016).

Section S2: Combustion technologies

In residential cooking, the type of cookstove used is mostly governed by the fuel burned. A large fraction of rural households in Nepal still relies on traditional mud cookstoves (TCS) that use firewood, animal dung cake and agricultural residue as fuel. Apart from traditional cookstoves, 1.26 million improved cookstoves (ICS) are disseminated and 0.3 million biogas plants were installed until 2011 under various renewable energy technology (RET) programmes by the Alternative Energy and Promotion Centre (AEPC) of the government and the Centre for Rural Technology, Nepal (CRT/N) (AEPC, 2012). For water heating and boiling, population in urban areas uses LPG stoves and kerosene stoves, whereas in rural areas they rely on firewood in traditional cookstoves (WECS, 2014; CBS, 2012).

In the industry sector, energy is required for thermal purposes and utilities. Industries like tea, coffee, pharmaceuticals, noodles and other small scale industries consume solid fuel such as coal, wood and rice husk, only to be used in furnaces and boilers for thermal energy and for steam generation. The iron and steel industry in Nepal converts the imported billets into elongated rods using rolling mills that heavily consume furnace oil (FO) in reheating furnace. The cement industries in Nepal are mostly grinding units with 14 mine based units equipped with rotary kilns (Pandey and Banskota, 2008). The grinding units feed on electricity either from the grid supplied by NEA or generated in-house using diesel generators. The mine-based units consume coal and other raw material in horizontal/vertical rotary kilns. The combustion technologies in industries like sugar, paper, beverages and dairy farms are identified based on an extensive survey that reports the process and the energy consumption patterns for those industries (PACE Nepal, 2012). The brick kilns are mostly fixed chimney Bull's trench kilns (FCBTK) either with straight firing or zig-zag firing technology and a small fraction of clamp kilns (CK) and the vertical shaft brick kilns (VSBK). A total of 609 brick kilns, whose geolocations were identified, are considered in this study out of which 557 are FCBTK and 52 clamp kilns during 2011. The zig-zag firing technique is a relatively new development in Nepal. It has only been used in the brick kilns in the Kathmandu Valley, which were rebuilt after 2015 Earthquake in Nepal. Kilns outside the Kathmandu Valley are slowly adopting the zig-zag technique. An in-house survey of 82 brick factories in 2014 in the Kathmandu Valley showed that only 22 FCBTK (~25%) had zig-zag firing compared to straight ones. This fraction may be extrapolated at a national level to understand the number of zig-zag firing brick kilns in Nepal, although a thorough study is indeed required to furnish the actual numbers.

In the commercial sector, since the activity involves energy use for electricity purposes, diesel generators are considered to be the prominent combustion technology in this sector. In the case of restaurants, a technology division similar to residential sectors is followed, with additional boilers required in tourism hotels for hot water generation. The combustion technologies in the agriculture sector include diesel use in irrigation pumps, tractors, power tillers and threshers. Since insufficient information is available in terms of size for diesel pumps, tractors, power tillers and threshers, the fuel consumption estimates do not account for any additional factors that would have led to more accurate (new) fuel estimates in this study.

In the transport sector, a total of eight vehicle categories are considered including an off-road category for tractors and power tillers. The tractors and tillers append trailers for transportation during non-farming days. Since more than 80 % of the vehicles are imported from India, we have assumed all the vehicles comply with Bharat Standard (BS) norms for emissions estimation. Diesel vehicles like jeeps/taxis, mini-bus, microbus and bus are treated as public passenger vehicles, while mini trucks, pick-ups and trucks are treated as public freight vehicles. Around 40 % of the diesel vehicles in Nepal are categorized as super-emitters or high emitters due to poor maintenance of vehicles, old vintages, and a large fraction of shoddy roads (Bond et al., 2004; Yan et al., 2011; personal communication).

Section S3: Emission factors

In residential cooking, the emission factors (EFs) for biogas stoves, traditional cookstoves (TCS) and improved cookstoves (ICS) using firewood and dung cakes are taken from the NAMaSTE campaign (Nepal Ambient Monitoring and Source Testing Experiment) in Nepal (Stockwell et al., 2016; Jayarathane et al., 2018) except for the ICS $PM_{2.5}$ and OC which are taken from Jaiprakash et al., (2016) and biogas stove $PM_{2.5}$ from Smith et al., (2000) (Table S3). The OC EFs for TCS using firewood and dung cakes were averaged with other studies reducing the overall uncertainties in estimates. In NAMaSTE campaign, CO_2, CH_4, NOx, CO, NMVOC, $PM_{2.5}$, BC and OC EFs were measured explicitly from TCS and ICS reflecting the regional practice and emission factors. For kerosene and LPG stoves, the EFs are compiled from lab-simulated measurements by Smith et al., (2000) for CO_2, CH_4, N_2O, NOx, CO and NMVOC, and averaged with Habib et al., (2008) and Smith et al., (2000) for $PM_{2.5}$, whereas the fractions of BC and OC were taken from Habib et al., (2008). The GHGs and NMVOC EFs for agricultural residue burned in TCS were compiled from Smith et al., (2000); for aerosols and CO, they were taken from on-site measured Indian EFs reported by Pandey et al., (2017), and the EF for NOx was assumed similar to the saw dust from NAMaSTE campaign (Stockwell et al., 2016). SO_2 EFs for burning TCS and ICS were considered from Habib et al., (2004), for the LPG and biogas stoves based on the sulphur content; for kerosene stoves from Zhang et al., (2000), who reported values for the Chinese wick and pressure stove.

For kerosene lamps, the measured EFs from Lam et al., (2012) were available for all pollutants except CH_4, NMVOC and N_2O, which were considered to be similar to the kerosene stoves (Smith et al., 2000). Due to lack of studies on the definite number of types of lamps, it is assumed that 50 % of the population relies on kerosene wick lamps and the rest on kerosene lanterns. For biogas lamps, all EFs were considered similar to biogas stoves (Table S3).

In space heating, the EFs for open burning of firewood were assumed similar to three-pot cookstoves, whereas the EFs for dung cakes were measured during NAMaSTE campaign (Stockwell et al., 2016; Jayarathane et al., 2018).

For industrial sector, technology-linked EFs were used from the EPA AP42 repository that has identified the combustion and process activities for different sources and industries (Table S4). The measured EFs for brick production were compiled from Weyant et al., (2014), Stockwell, et al., (2016), Jayarathne et al., (2018) and Nepal et al., (2019) for zig-zag and straight firing in FCBTK and clamp kilns (Table S5).

Commercial sector activities closely resemble those in residential cooking and hence the EFs are quite similar. For diesel generators, the recently measured EFs from the NAMaSTE campaign were considered for all pollutants except CO and SO_2 (Table S6). The EF for CO was averaged from data provided in Shah et al., (2006), since among the two diesel generators measured during the NAMaSTE campaign, one apparently reflected steady-state conditions and was regularly maintained, while the other one appeared to be improperly regulated as it provided extremely high values. The SO_2 is estimated using the sulphur content of the fuel with no retention.

The recently measured EFs from the irrigation pump (Adhikari et al., 2019) were also considered and averaged with NAMaSTE campaign EFs (Table S6). For mechanized tractors, power tillers and threshers, the EFs were compiled from a study that reports the EFs for off-road vehicles measured across different power capacity (Notter and Schmied, 2015).

In the transport sector the EFs for two-wheelers were compiled from the NAMaSTE campaign for $PM_{2.5}$, BC, OC, CO, NO_X, CH_4 and CO_2 (Stockwell et al., 2016; Jayarathane et al., 2018) (Table S7). For categories other than two-wheelers, the emission factors of N_2O, NO_X, CO, NMVOC were considered from Shrestha et al., (2013), who studied the emissions from on-road traffic fleet in the Kathmandu Valley using vehicle survey data and the International Vehicle Emissions (IVE) model (Table S7). The NOx emission factors for heavy diesel vehicles were considered from Sadavarte and Venkataraman, (2014), the EFs for Indian vehicles modelled using the MOBILEv6.2 model, which were found to be consistent with EFs from Zhang et al., (2009) for Chinese vehicles. The $PM_{2.5}$ emissions for rest of the categories were averaged from Shrestha et al., (2013), Kim Oanh et al., (2010) and Jaiprakash et al., (2016). The NMVOC emissions from Shrestha et al., (2013) also include running evaporatives, and reflect the real world emissions under increasing ambient temperature. The CO_2 emission factors for all categories of vehicles, other than two-wheelers, were considered from a chassis dynamometer study that measured values for different vintages using an Indian driving cycle (ARAI, 2007).

The fractions of BC and OC were obtained by averaging respective fractions from chassis dynamometer test results by Kim Oanh et al. (2010), Wu et al. (2015), Zhang et al. (2015), Yang et al. (2019) and Jaiprakash et al. (2016). These studies reflect the regional characteristics of driving cycles and the road infrastructure, which plays an important role in tail pipe exhaust. Kim Oanh et al., (2010) made a vintage based measurements showing the degradation of emissions and resultant high fractions of EC and OC in the oldest category of vehicles. However, Wu et al., (2015) and Jaiprakash et al., (2016) emphasized the importance of driving speed (on non-highways, highways and in cities) on the EC and OC fraction from diesel vehicles. SO_2 emissions were calculated using the sulfur content of BS-II/III/IV fuel imported from India, with no retention assumed. Non-exhaust emissions such as brake wear and tire wear are not included in this study.

Section S4: Non-Renewability fraction for biomass

Non-renewability fraction for biomass (NRB) can be defined as the imbalance between demand and supply which contributes to net-CO_2 emissions. Ghilardi et al., (2007) explains it as *"when the amount extracted and burned exceeds the growth rate of the living biomass sources"*, it contributes to net-CO_2 emissions. In simple terms, Venkataraman et al., (2010) defines NRB as *"the percent of woodfuel that is harvested on a non-renewable basis"*. The NRB factor plays a crucial role in global studies that involves CO_2 or carbon budgets. The net-CO_2 emissions from harvested fuelwood or biomass products can help identify actual carbon offsets achieved through Clean Development Mechanism (CDM) projects, although it's not the only criteria. The NRB fraction used over Nepal is 10% similar to Venkataraman et al., (2010) over India based on residential sector fuelwood supply and demand. In Nepal, residential sector consumes 79 % of the national energy during 2011 and biomass is the single largest source of energy attributing to 88 % of the national energy. Therefore, we have used 10 % NRB in our study to calculate CO_2 emissions. In principle the % NRB is calculated as *% NRB = (fuelwood demand – fuelwood supply)/fuelwood supply* (Venkataraman et al., 2010, Ghilardi et al., 2007, 2009). Studies like Ghilardi et al., (2009) have estimated non-renewable fuelwood fraction ranging from 0 to 96 % based on demand and supply at local level in Central Mexico using GIS method. These NRB fractions can then be used to allocate the percentage of fuelwood that can be treated as non-renewable fuel and their emissions can be accounted as the net-CO_2 estimate. In our study, we have considered for 10 % NRB which means out of total fuelwood consumed, combustion of 10 % would give net-CO_2 emissions while the rest 90 % can be treated as sustainable fuelwood and doesn't contribute directly to the net-CO_2 emissions.

Table S3. Emission factors for residential sector (g/kg fuel)

Activities	Fuel	CO_2	CH_4	N_2O	NO_x	CO	NMVOC	$PM_{2.5}$	BC	OC	SO_2
Cooking/W.heating											
Traditional cookstove[k]	Wood	1462.42[a]	5.16[a]	0.09[i]	1.53[a]	77.24[a]	22.86[a]	7.97[b]	1.11[b]	3.16[b,m,g,n]	0.28[p]
Improved cookstove	Wood	1608.67[a]	0.54[a]		1.69[a]	20.03[a]	2.03[a]	1.97[l]	0.32[a]	1.08[l]	0.28[p]
Kerosene stove[k]	Kerosene	2985.00[h]	0.68[h]	0.09[h]		39.88[h]	17.03[h]	0.61[g,h]	0.17[g]	0.33[g]	0.02[d]
LPG stove[k]	LPG	3085.00[h]	0.05[h]	0.15[h]		14.90[h]	18.80[h]	0.32[g,h]	0.01[g]	0.05[g]	0.01[j]
Traditional cookstove	Dungcake	1129.30[a]	6.65[a]	0.31[h]	2.17[a]	80.87[a]	33.20[a]	15.93[b,m]	0.75[b]	6.15[b,m,g,h,i,o]	0.88[f]
Biogas stove	Biogas	2736.49[a]	2.54[a]	0.10[h]	1.70[a]	2.54[a]	1.12[a]	0.53[h]	0.02[e]	0.09[e]	0.01[j]
Traditional cookstove	Ag.residue	1302.00[h]	7.58[h]	0.05[h]	2.43[a]	133.56 [m]	8.49[h]	13.99[m]	1.20[m]	6.85[m]	0.16[f]
Lighting											
Kerosene lamps*	Kerosene	2863.00[c]	0.68[h]	0.09[h]		8.60[c]	17.03[h]	69.00[c]	65.70[c]	0.43[c]	0.022[d]
Biogas lamps	Biogas	2736.49[a]	2.54[a]	0.10[h]	1.70[a]	2.54[a]	1.12[a]	0.53[h]	0.02[e]	0.09[e]	0.01[j]
Space heating											
Burning fuel	Wood	1462.42[a]	5.16[a]	0.09[i]	1.53[a]	77.24[a]	22.86[a]	7.97[b]	1.11[b]	3.16[b,m,g,n]	0.28[p]
(indoor & outdoor)	Dungcake	1073.63[a]	6.55[a]	0.31[h]	2.34[a]	96.58[a]	33.20[a]	20.00[b]	0.09[b]	12.98[b]	0.88[f]

[a]Stockwell et al., 2016; [b]Jayarathne et al., 2018; [c]Lam et al., 2012; [d]Zhang et al, 2000; [e]For biogas, BC/PM and OC/PM assumed same as LPG; [f]Habib et al., 2004; [g]Habib et al., 2008; [h]Smith et al, 2000; [i]MacCarty et al, 2008; [j]SO_2 based on sulfur content of the fuel; [k]Combustion technologies also considered for water heating stove-fuel; [l]Jaiprakash et al., 2016; [m]Pandey et al., 2017,[n]Saud et al., 2012,[O]Roden et al., 2009; [p]Habib et al., 2004, Saud et al., 2011, Stockwell et al., 2015; *Assumed 50 % kerosene wick lamps and 50 % kerosene lanterns

Table S4. Emission factors for industrial combustion technologies (g/kg fuel)

Combustion technology	Fuel	CO_2	CH_4	N_2O	NO_X	CO	NMVOC	$PM_{2.5}$	BC	OC	SO_2
FBC boiler	Coal	2376[h]	0.03[a]	1.75[a]	2.50[a]	9.00[a]	0.03[a]	1.90[a]	0.38[d]	0.08[d]	8.89[a]
Cement kiln	Clinker	900[j]			2.10[j]	1.80[j]	0.059[j]	0.04[j]			0.54[j]
Hand fed Furnace	Coal	2376[h]	2.50[a]	0.02[a]	4.55[a]	137.50[a]	5.00[a]	1.90[a]	0.95[d]	0.76[d]	8.89[a]
Furnace	Wood	1404.33[b]	0.15[b]	0.09[b]	3.53[b]	4.32[b]	0.12[b]	2.23[b]	0.11[d]	0.45[d]	0.18[b]
Furnace	Ricehusk	1404.33[b]	0.15[b]	0.09[b]	3.53[b]	4.32[b]	0.12[b]	2.23[b]	0.11[d]	0.45[d]	0.18[b]
Oil boiler	Diesel	3186.30[h]	0.031[c]	0.03[i]	2.89[c]	0.72[c]	0.05[c]	0.12[c]	0.03[d]	0.02[d]	0.68[e]
Oil boiler	Furnace oil	3126.96[h]	0.129[c]	0.06[i]	7.10[c]	0.65[c]	0.04[c]	1.88	0.55[d]	0.25[d]	80.00[e]
Furnace	Furnace oil	3126.96[h]	0.129[c]	0.06[i]	7.10[c]	0.65[c]	0.04[c]	1.88	0.55[d]	0.25[d]	80.00[e]
Gas furnace	LPG	3085.00[f]	0.05[f]	0.15[f]		14.90[f]	18.80[f]	0.32[g]	0.01[g]	0.05[g]	0.01[e]
Oil boiler	Gasoline	3186.30[h]	0.031[c]	0.03[i]	2.89[c]	0.72[c]	0.05[c]	0.12[c]	0.03[d]	0.02[d]	0.68[e]

[a]Coal Combustion emission factors, from USEPA's AP42, Table 1.1-3, Table 1.1-11, Table 1.1-19. SO_2 based on sulfur content of the fuel. For coal 5% sulfur retention is assumed from AP42 document, Table 1.1-3

[b]Wood Combustion emission factors USEPA's AP42, Table 1.6-1, Table 1.6-2, Table 1.6-3 from AP42

[c]Fuel Oil Combustion emission factors USEPA's AP42, Table 1.3-7 from AP42

[d]Fraction of BC and OC from Bond et al., 2004

[e]SO_2 based on sulfur content of the fuel. For liquid and gases fuel, there is no sulfur retention in the ash.

[f]Smith et al, 2000

[g]Habib et al, 2008; Smith et al, 2000

[h]Default based on carbon content, IPCC 2006

[i]Default based on net calorific value (NCV), IPCC 2006

[j]Process based emission factors from USEPA's AP42

Table S5. Emission factors for brick production (g/kg fuel)

	Kiln technologies	CO_2	CH_4	N_2O[g]	NO_X	CO	NMVOC	$PM_{2.5}$	BC	OC	SO_2
Coal+FW	Fixed BTK	1930[a]	2.34[e]	0.017	0.64[e]	36.50[d]	1.83[e]	3.98[a]	1.68[a]	0.15[d]	28.00[i]
	Zig-zag kiln	2105[b]	2.34[f]	0.017	0.64[f]	10.68[c]	1.83[f]	2.73[a]	0.30[b]	0.33[h]	22.64[j]
	Clamps	1858[c]	19.50[f]	0.017	0.30[f]	74.75[c]	31.21[f]	3.00[d]	0.56[c]	3.57[h]	13.00[f]

[a]Average emission factor from Weyant et al., 2014 and Nepal et al., 2019

[b]Average emission factor from Weyant et al., 2014, Nepal et al., 2019 and Stockwell et al., 2016

[c]EFs averaged from Weyant et al., 2014 and Stockwell et al., 2016

[d]Weyant et al., 2014

[e]Assumed similar to zig-zag kiln

[f]Stockwell et al., 2016

[g]Assumed similar to coal stokers from USEPA AP42 document

[h]Weyant et al., 2014 and Jayarathne et al., 2018

[i]Nepal et al., 2019

[j]Average emission factor from Nepal et al., 2019 and Stockwell et al., 2016

Table S6. Emission factors for power station and irrigation pump (g/kg fuel)

	CO_2	CH_4	N_2O	NO_X	CO	NMVOC	$PM_{2.5}$	BC	OC	SO_2
Genset (Diesel & FO)	3102[b]	0.27[b]	0.03[e]	23.60[b]	28.31[f]	2.62[b]	9.17[g]	0.58[g]	6.46[g]	0.10[d]
Irrigation Pumps (Diesel)	2491[a]	3.55[b]	0.03[e]	12.10[b]	56.37[a]	8.86[b]	9.23[c]	3.02[a]	6.84[c]	0.10[d]

[a]Average emission factor from Adhikari et al., 2019 and Stockwell et al., 2016

[b]Stockwell et al., 2016

[c] Average emission factor from Adhikari et al., 2019 and Jayarathne et al., 2018

[d]SO_2 based on sulfur content of the fuel with no retention

[e]IPCC 2006

[f]Average Stockwell 2016 and Shah 2006

[g]Jayarathne et al., 2018

Table S7. Emission factors for transport sector (g/kg fuel)

Vehicle type	Fuel	CO_2	CH_4	N_2O	NO_X	CO	NMVOC	$PM_{2.5}$	BC	OC	SO_2[d]
2-Wheeler	Gasoline	1831[a]	7.17[a]	0.15[e]	2.42[a]	735.5[a]	111.13[b]	4.76[a]	0.21[a]	3.89[a]	0.10
Cars	Gasoline	1820[g]	15.03[b]	0.14[b]	27.62[b]	623.92[b]	73.57[b]	0.29[b]	0.07[c]	0.15[c]	0.10
Cars/Jeeps/Van	Diesel	1746[g]	0.13[f]	0.02[b]	43.00[e]	38.00[e]	9.00[e]	1.60[h]	3.55[c]	1.13[c]	0.10
Micro/Minibus	Diesel	1875[g]	0.59[f]	0.02[b]	15.94[b]	14.14[b]	2.01[b]	6.94[h]	2.97[c]	2.42[c]	0.10
Bus	Diesel	3467[g]	0.02[f]	0.23[b]	55.00[e]	56.66[b]	14.25[b]	5.58[h]	0.98[c]	0.31[c]	0.10
MiniTruck/PickUp	Diesel	2045[g]	0.65[f]	0.02[b]	17.39[b]	15.42[b]	2.20[b]	1.65[h]	0.69[c]	0.50[c]	0.10
Truck	Diesel	3291 [g]	0.12[f]	0.21[b]	43.00[e]	50.57[b]	12.71[b]	6.56[h]	3.99[c]	1.26[c]	0.10
Tractor/Tiller	Diesel	2045[g]	0.65[f]	0.02[b]	17.39[b]	15.42[b]	2.20[b]	7.60[h]	2.67[c]	2.41[c]	0.10
Superemitter	Gasoline							2[c]	0.68[c]	0.72[c]	
	Diesel							10[c]	6.6[c]	2.1[c]	

[a]Stockwell et al., 2016 and Jayarathane et al., 2018

[b]Shrestha et al., 2013

[c]BC and OC fractions from Kim-Oanh et al., 2010, Bobo Wu et al., 2015 and Yang et al., 2019

[d]SO_2 based on sulfur content of the fuel and zero retention

[e]Sadavarte and Venkataraman, 2014, MOBILE based emission factors modelled for Indian vehicles

[f]Using CH_4:CO_2 emission factor ratio from Sadavarte and Venkataraman, 2014 and Automotive Research Association of India (ARAI), 2007

[g]Automotive Research Association of India (ARAI), 2007

[h] EF averaged from Shrestha et al., 2013, Jaiprakash, et al., 2016, Kim-Oanh et al., 2010

Table S8. Energy consumption across different sectors (TJ/yr)

Fuel type (2001)	Residential	Industry	Transport	Commercial	Agriculture	Total
Biomass						
Fuelwood	174064	2544		1934		178542
Dungcake	15458					15458
Agr.res/ricehusk	42109	6276				48385
Biogas	556					556
Fossil fuel						
Coal		14478		47		14525
Diesel		1244	7817	315	1932	11308
Petrol		68	2150			2218
Kerosene	8384	390		989		9763
LPG	1978	17		308		2303
Furnace oil		580				580
Aviation fuel			1718			1718
Total	**242550**	**25598**	**11685**	**3593**	**1932**	**285357**

Fuel type (2005)	Residential	Industry	Transport	Commercial	Agriculture	Total
Biomass						
Fuelwood	193394	2532		2164		198090
Dungcake	17271					17271
Agr.res/ricehusk	45532	6055				51587
Biogas	703					703
Fossil fuel						
Coal		14067		80		14147
Diesel		1162	9489	316	2061	13027
Petrol		49	2986			3035
Kerosene	3922	92		568		4582
LPG	3205	33		509		3747
Furnace oil		785				785
Aviation fuel			2403			2403
Total	**264028**	**24775**	**14877**	**3637**	**2061**	**309378**

Fuel type (2011)	**Residential**	**Industry**	**Transport**	**Commercial**	**Agriculture**	**Total**
Biomass						
Fuelwood	223885	8018		1983		233886
Dungcake	20642					20642
Agr.res/ricehusk	46036	8650				54686
Biogas	913					913
Fossil fuel						
Coal		20643		152		20795
Diesel		2264	14374	4887	3738	25262
Petrol		85	6630			6715
Kerosene	1193	34		115		1342
LPG	6982	212		1271		8465
Furnace oil		937				937
Aviation fuel			3995			3995
Total	**299651**	**40843**	**24998**	**8408**	**3738**	**377638**

Fuel type (2016)	**Residential**	**Industry**	**Transport**	**Commercial**	**Agriculture**	**Total**
Biomass						
Fuelwood	244690	27481		1881		274052
Dungcake	20232					20232
Agr.res/ricehusk	44239	12431				56670
Biogas	1329					1329
Fossil fuel						
Coal		30505		167		30673
Diesel		4641	31906	2493	5258	44298
Petrol		166	13192			13358
Kerosene	514	35		44		594
LPG	10624	2407		1792		14823
Furnace oil		1052				1052
Aviation fuel			5991			5991
Total	**321628**	**78719**	**51089**	**6378**	**5258**	**463072**

Table S9. Comparing sectoral emissions from NEEMI-Tech and REAS for 2008 (All units in Gg/yr). Parenthesis shows sectoral contribution in % to national emissions

REAS 2008	CO_2	CH_4	N_2O	NO_X	CO	NMVOC	$PM_{2.5}$	BC	OC	SO_2
Industry	1598 (4.8)	0.96 (1)	0.03 (2.1)	3.65 (4.5)	73.7 (3.5)	2.78 (0.7)	5.98 (4.4)	0.35 (1.3)	1.03 (1)	6.13 (20.6)
Transport	938 (2.8)	0.14 (0.1)	0.05 (3.2)	12.08 (15.2)	29.29 (1.4)	13.09 (3.5)	1.49 (1.1)	0.36 (1.4)	0.37 (0.3)	3.45 (11.6)
Residential	29776 (90.2)	85.69 (97.9)	1.39 (93.7)	62.72 (78.8)	1957.93 (94.1)	347.26 (94.8)	126.38 (93.7)	24.94 (96.5)	100.27 (97.9)	18.8 (63.3)
Commercial	473 (1.4)	0.66 (0.7)	0.01 (0.7)	0.83 (1)	17.79 (0.8)	2.54 (0.6)	0.94 (0.7)	0.17 (0.6)	0.7 (0.6)	0.24 (0.8)
Agriculture	221 (0.6)	0.03 (0)	0 (0.1)	0.2 (0.2)	1.45 (0)	0.59 (0.1)	0.06 (0)	0 (0)	0 (0)	1.03 (3.5)

NEEMI 2008	CO_2	CH_4	N_2O	NO_X	CO	NMVOC	$PM_{2.5}$	BC	OC	SO_2
Industry	3766 (12.1)	1.57 (1.4)	0.07 (3.8)	7.76 (14.6)	30.27 (1.8)	1.8 (0.4)	4.07 (2.1)	1.83 (7.9)	0.65 (0.8)	15 (71.7)
Transport	782 (2.5)	1.01 (0.9)	0.04 (2.4)	9.92 (18.7)	69.37 (4.3)	10.98 (2.8)	1.8 (0.9)	0.89 (3.8)	0.49 (0.6)	0.17 (0.8)
Residential	25677 (83.0)	102.22 (96.9)	1.82 (92.7)	32.02 (60.3)	1501.15 (93.0)	367.79 (95.8)	178.39 (95.8)	20.08 (86.9)	76.57 (97.2)	5.58 (26.6)
Commercial	520 (1.6)	0.51 (0.4)	0.01 (0.9)	2.06 (3.9)	10.31 (0.6)	2.76 (0.7)	1.54 (0.8)	0.15 (0.6)	0.79 (1.0)	0.1 (0.5)
Agriculture	166 (0.5)	0.12 (0.1)	0.00 (0.0)	1.25 (2.3)	2.01 (0.1)	0.17 (0.0)	0.38 (0.2)	0.13 (0.6)	0.23 (0.3)	0.04 (0.1)

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Table S10. Comparing Kathmandu Valley emissions for 2011 and 2016 (All units in Gg/yr)

	CO_2	CH_4	N_2O	NOx	CO	NMVOC	$PM_{2.5}$	BC	OC	SO_2
2011	2162.552	4.005	0.117	8.088	103.639	21.719	6.981	1.260	2.695	1.539
2016	3438.891	4.430	0.247	16.379	155.234	28.881	8.299	1.762	2.865	3.247
2016/2011	1.59	1.11	2.10	2.03	1.50	1.33	1.19	1.40	1.06	2.11

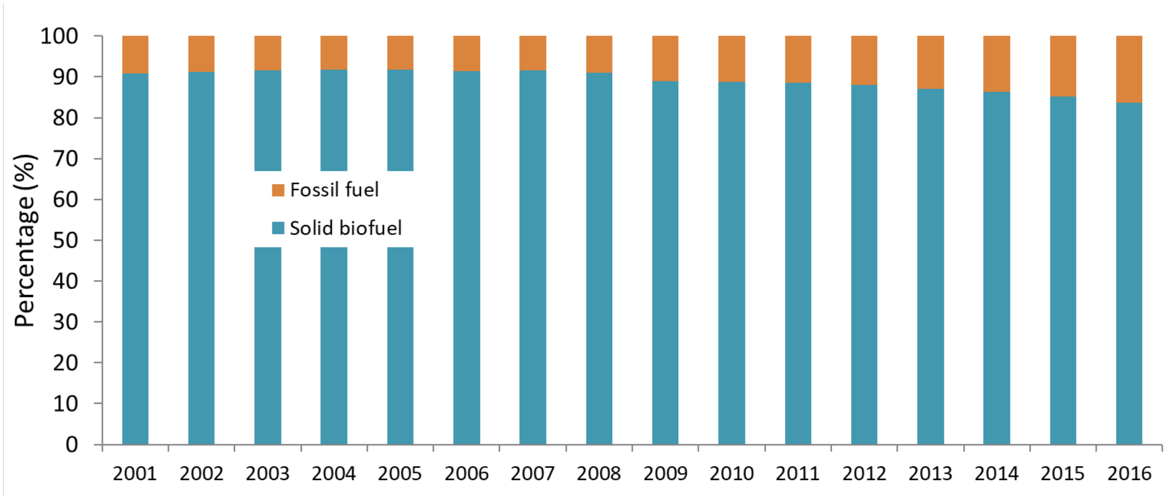

Figure S5. Fraction of national energy consumption contributed by fossil fuel and solid biofuel.

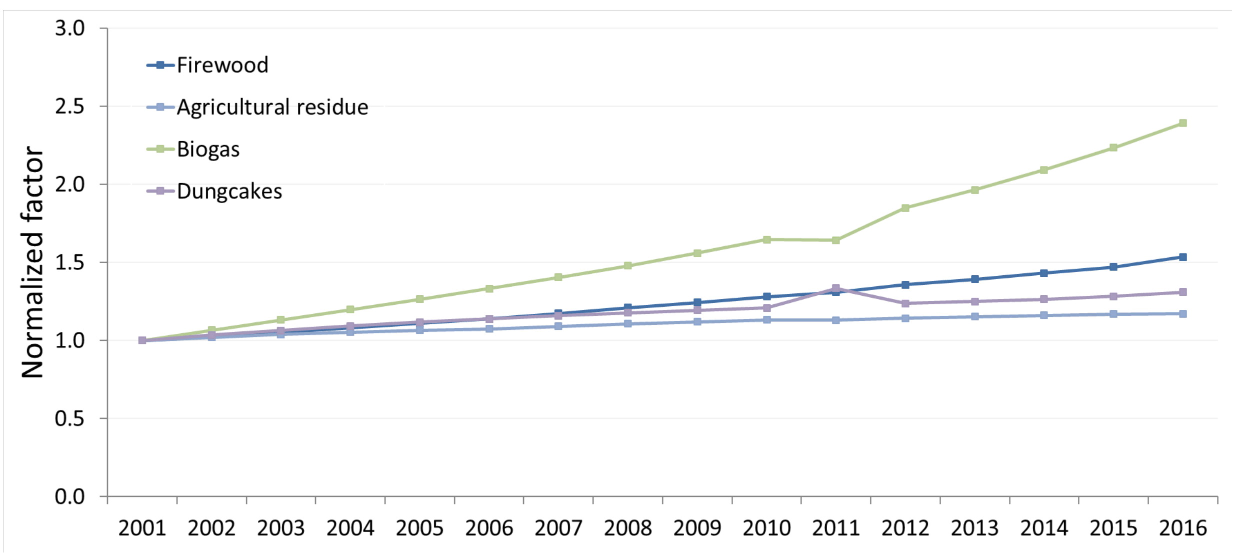

Figure S6. National biomass energy consumption normalized with respect to year 2001

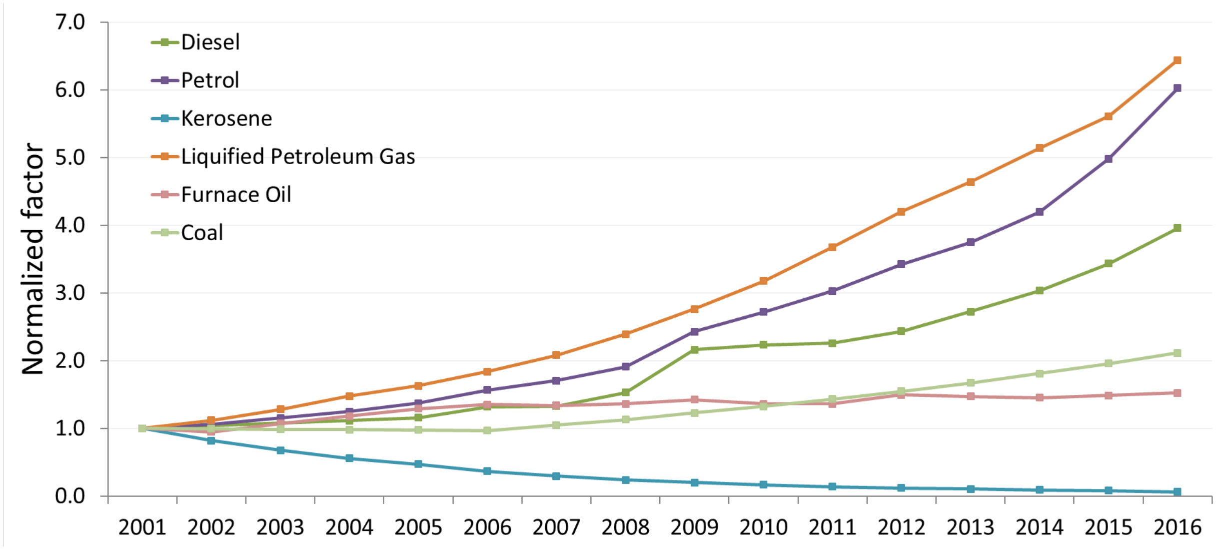

Figure S7. National fossil fuel energy consumption normalized with respect to year 2001

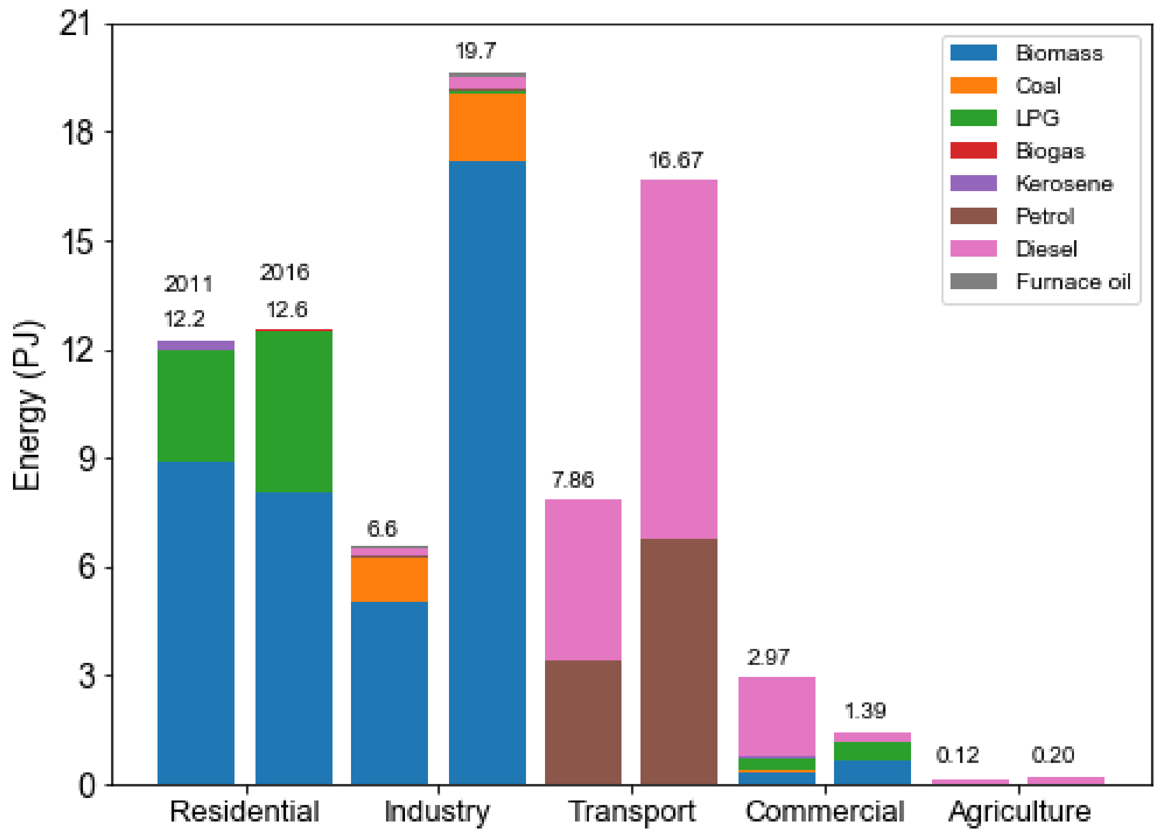

Figure S8. Sectoral energy comparison for 2011 and 2016 for Kathmandu Valley

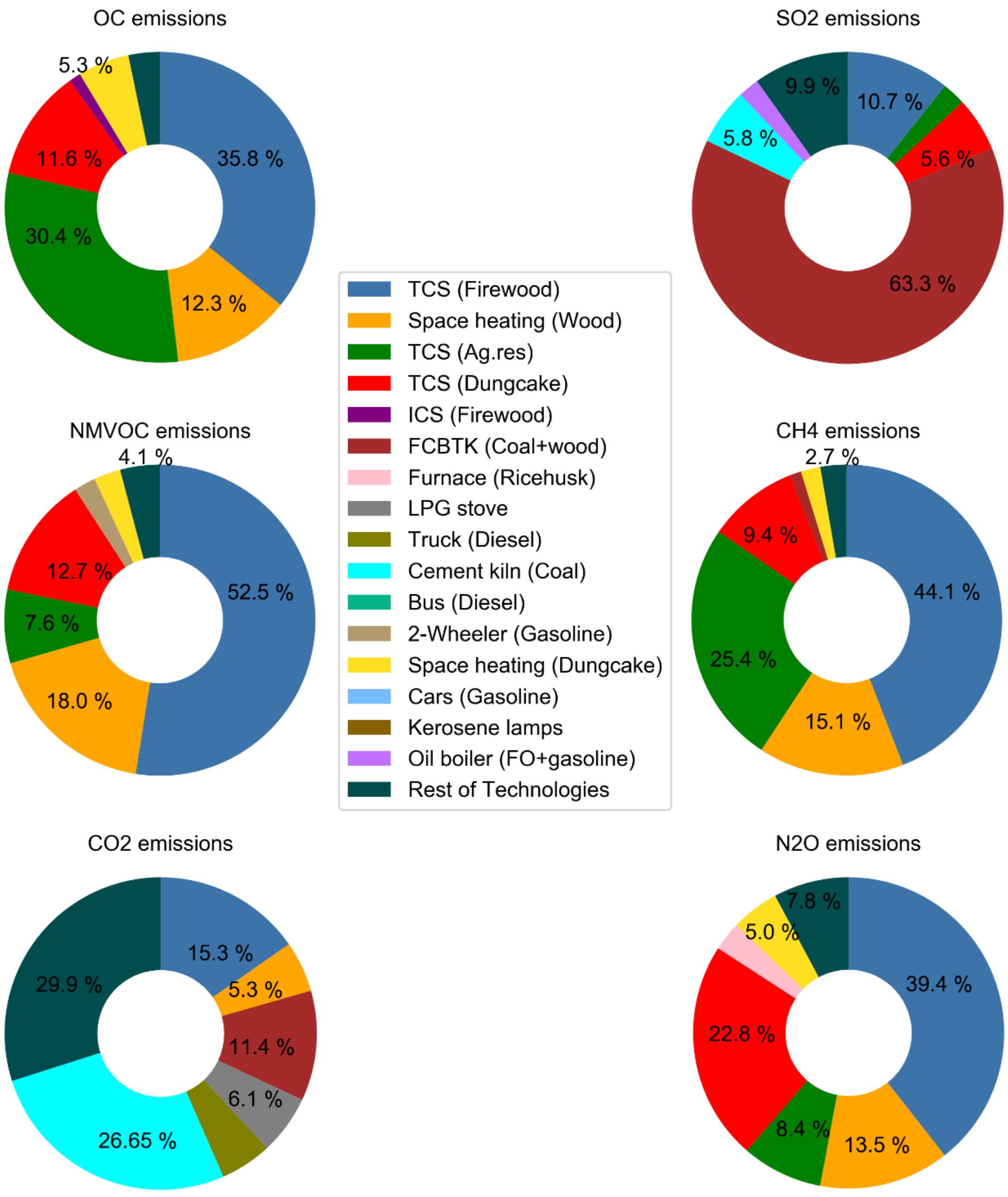

Figure S9. Top six polluting technologies contributing to OC, SO_2, NMVOC, CH_4, CO_2 and N_2O emissions

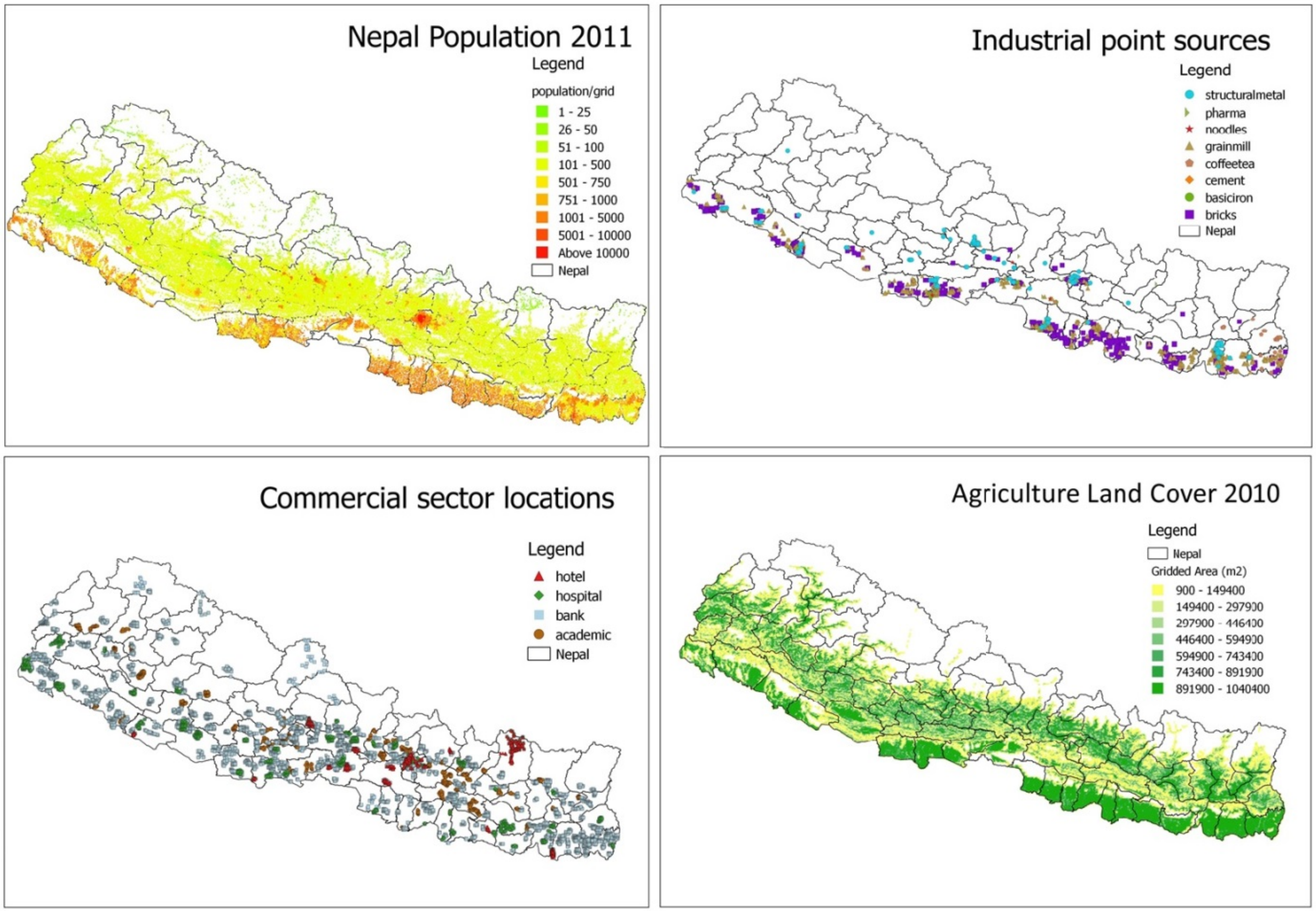

Figure S10. Proxies used in this study for (a) Residential (b) Commercial (c) Industries (d) Agriculture sector

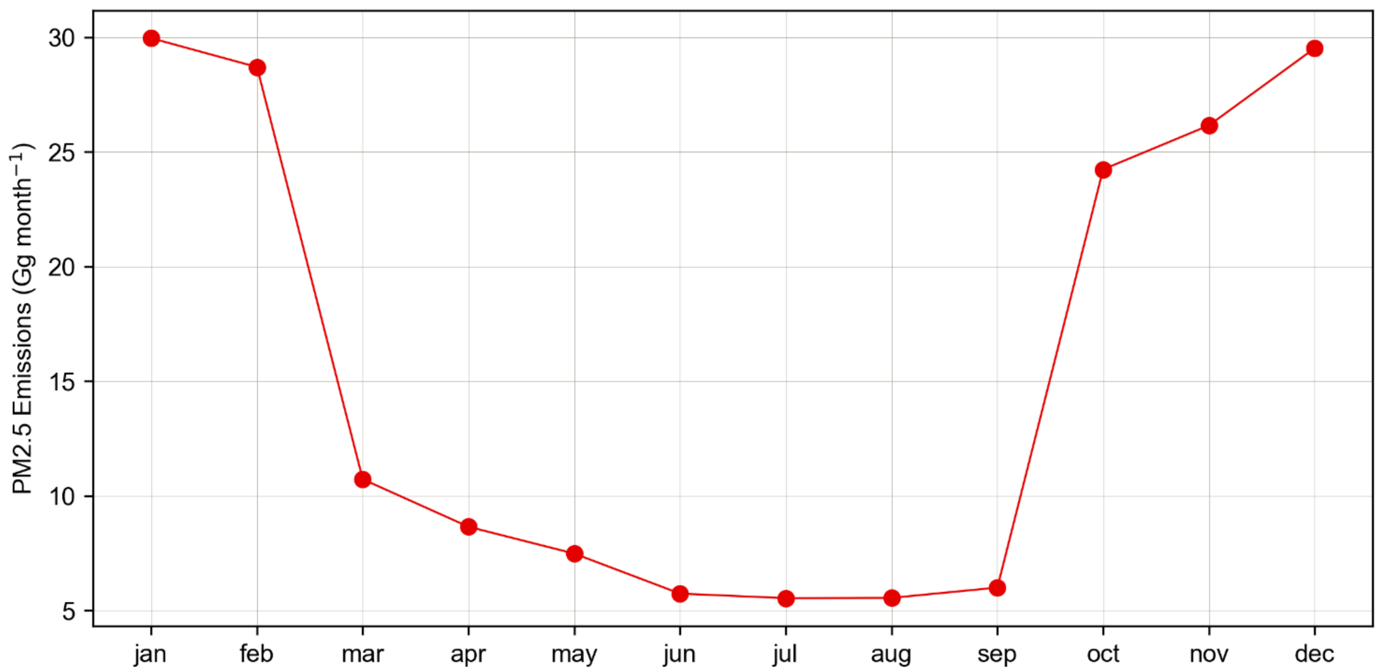

Figure S11. Seasonality in national $PM_{2.5}$ emissions

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