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Assessment of emissions of greenhouse gases and air pollutants in Indonesia and impacts of national policy for elimination of kerosene use in cooking

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HIGHLIGHTS

- Emissions from major anthropogenic sources in Indonesia in 2010 compared to 2007.
- Local activity data at district level were used for emission inventory.
- Spatially higher emission intensity was seen in large urban areas.
- Higher emission in dry months due to increased open burning and cooking.
- National program of kerosene to LPG conversion brought in multiple benefits.

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ABSTRACT

This study presents an emission inventory (EI) for major anthropogenic sources of Indonesia in 2007 and 2010. The EI was developed using a combination of top-down and bottom-up approaches with comprehensive activity data collected at the provincial/district level to produce spatially and temporally distributed emission of toxic pollutants and greenhouse gases (GHGs). The sources were categorized into: 1) fuel combustion in power plant, 2) industry, 3) transportation, 4) residential and commercial combustion, 5) biomass open burning, and 6) non-combustion agricultural activity and waste disposal. The best estimates of the 2010 national emissions, in Gg, of toxic pollutants were: 1014 SO_2; 3323 NO_x; 24,849 CO; 4077 NMVOC; 1276 NH_3; 2154 PM_{10}; 1728 $PM_{2.5}$; 246 BC; 718 OC; and GHGs: 540,275 CO_2; 3979 CH_4 and 180 N_2O. During the period from 2007 to 2010, the national emissions increased by 0.7–8.8% (0.23–2.8% per year), varied with species, with the most significant changes obtained for the biomass open burning emissions. For 2010 results, the low and high emission estimates for different species were ranging from −58% to +122% of the corresponding best estimates. The largest range (high uncertainty) was for BC due to the wide range of the limitedly available emission factors. Spatially, higher emission intensity was seen in large urban areas of Java and Sumatra Islands. Temporally, dry months of August–October had higher emissions. During the first 3 years (2007–2010) of implementation, the national policy of elimination of kerosene use in cooking had successfully replaced 4.9 Tg kerosene with 2.6 Tg LPG in 30 designated provinces. The net emission reductions of different species ranged from 48 Mg (SO_2) to 7.6 Tg for CO_2. The global warming potential weighted emissions from the residential cooking alone, collectively for GHGs and short-lived climate pollutants in 20-yr CO_2 eq., would reduce by 2%. More significant reductions in the residential combustion emissions are expected if the solid cooking fuel could be targeted in future fuel conversion programs. The benefits to human health resulted from the emission reduction of toxic pollutants from residential cooking could be substantial and should be assessed in future studies.

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1. Introduction

Indonesia with 250 million people is the fourth most populated in the world and the most populated country in Southeast Asia (SEA). The country has been recognized as a large emitter of air pollutants in Asia (Streets et al., 2003; Zhang et al., 2009). High rates of emissions are expected from intensive energy production activities, oil and gas extraction and refinery facilities in the country. Biomass open burning (OB) including forest fires, recorded every year, and crop residue field burning activities contribute significant emissions, which are also linked to meteorological factors and local agricultural practices. The emission results in degradation of air quality inside the country and transboundary effects to neighboring countries (Pentamwa and Kim Oanh, 2008).

Information on emission sources, and their spatial and temporal distributions is important for air quality management (AQM), especially for evaluating emission mitigation strategies. However, a comprehensive national emission database is not yet available for Indonesia. The emissions of the country reported in the existing global and regional emission inventory (EI) databases have been mainly estimated using the activity data from various international sources. For example, Streets et al. (2003) used the 2000 forecasts of the RAINS-Asia model (which used 1995 as the base year) to estimate the energy related activity data for the SEA countries, while the study of Zhang et al. (2009) was based on the extrapolation of energy trend data from the International Energy Agency (IEA). In general, temporal emission information, specifically required for air quality modeling purposes, has been only reported for a few countries in Asia, e.g. China (Zhang et al., 2009), Japan (Kannari et al., 2007), India (Reddy and Venkaraman, 2002a,b) and Thailand (Vongmahadlek et al., 2009). Such information is not yet available for Indonesia. In addition, emissions from certain important sources in the country, such as OB of crop residue or municipal solid waste (MSW), have only been roughly estimated in existing international EI works. For example, the global emissions of solid waste OB (EC-JRC/PBL, 2010; Wiedinmyer et al., 2014; Akagi et al., 2011; UNEP-WMO, 2011) could be further refined using the national specific activity data for Indonesia.

This study aimed to provide an improved EI database for Indonesia for the base year of 2010 for which sufficient activity data from the relevant departments and national statistics were available. The year of 2010 was selected for the national EI of Indonesia also because it is close to the base years of other existing international EI databases, which will conveniently facilitate the EI results comparison and eventually can contribute to the updated SEA regional EI dataset. Furthermore, to assess the impacts of the national policy on phasing out kerosene use in cooking, the EI for 2007 (Permadi, 2013), the year when the policy implementation commenced, was also presented and discussed. The available emission factors (EFs) were scrutinized to select realistic values with a consideration on the likely degrees of emission control of relevant sources in the country. The emission calculation was done following the method and the Microsoft Excel template developed for the Atmospheric Brown Cloud Emission Inventory Manual (ABC EIM) (Shrestha et al., 2012). ABC EIM compiled the EFs from various existing EI manuals (EMEP/EEA, 2013; IPCC, 2006) and AP-42 (US EPA, 2011) as well as available measurements reported for Asian sources. For the emissions from on-road traffic fleets, we relied on the composite EFs developed using the International Vehicle Emission model (IVE) for Bandung, Indonesia (Kim Oanh et al., 2015).

The EI species included the major gaseous pollutants of SO_2, NOx, NH_3, CO, non-methane volatile organic compounds (NMVOC), major greenhouse gases (GHGs) of CO_2, CH_4 and N_2O, and aerosol species or particulate matter (PM) comprising PM_{10} and $PM_{2.5}$ (particles with the size not larger than 10 and 2.5 μm, respectively), black carbon (BC) and organic carbon (OC). This study considered key anthropogenic sources of Indonesia, namely, 1) combustion of fossil fuel in power plants, 2) industrial fuel combustion, non-combustion and processes (i.e. fugitive emission from oil and gas exploration, processing and loading, solvent and other product use), 3) transportation (on-road and off-road vehicles: air traffic, shipping and inland waterway and railway), 4) residential and commercial combustion (cooking), 5) biomass OB, and 6) non-combustion agricultural activity (e.g. live-stock manure management and fertilizer application) and waste disposal. The EI results are presented as the best, low and high estimates using the ranges of the EFs and activity data, respectively. This study further presents the emissions with spatial (district) and temporal (monthly) distributions which can be used for the air pollution dispersion modeling.

The EI results for 2007 and 2010 were used as the basis to analyze the impacts of the current national policy of replacing kerosene with Liquefied Petroleum Gas (LPG) for residential cooking (Pertamina, 2012; World Bank, 2013). The potential emission reductions of toxic air pollutants and climate forcers (both GHGs and short-lived climate pollutants, SLCPs) were quantified to assess the co-benefits in air quality improvement and climate forcing mitigation resulted from the implementation of the program.

2. Methodology

2.1. Emission inventory framework

A combination of top-down and bottom-up approaches was used to develop the EI for the six considered emission source categories. A step-wise general EI framework is presented in Fig. S1, Supplementary Information (SI). Collection of the activity data at district/provincial levels was our primary focus and only when not available the national activity data was used. Both combustion and non-combustion emission sources were covered. Accordingly, fuel combustion in power plants, in manufacturing industry, in residential and commercial and transportation sectors was considered. The industrial non-fuel combustion and processes included the emission from mineral, metal, pulp and paper, chemical and beverage industries, the fugitive emission from oil and gas exploration, treatment and loading, and other non-combustion emission sources including solvent and other product use, livestock and fertilizer applications and waste disposal. The activity data collected for 2007 (Permadi, 2013) and for 2010 (this study) were used in the EI. As for the emissions from open burning of crop residues and solid waste, the EI results reported previously (Permadi and Kim Oanh, 2013) for 2007 were updated to 2010. The emissions from on-road vehicles were estimated using the vehicle population in each district for the years of 2007 and 2010, respectively, with the IVE produced composite EFs for on-road vehicle fleets mentioned above.

The emissions obtained for 2010 (annual) were disaggregated to the district level based on statistical proxy factors, e.g. fuel consumption, population etc. for more than 300 districts in 33 provinces of Indonesia, and are presented in t km^{-2} yr^{-1} using the Geographical Information System (GIS). The monthly emissions were segregated using relevant proxies that are discussed along with the considered source categories below.

The annual emission of a particular pollutant from a source/source category was estimated using a general EI Equation (1) which was taken from available EI guidebooks (Shrestha et al., 2012; EMEP/EEA, 2013; IPCC, 2006).

$$Em_{i,j} = EF_{i,j} \times AR_i \times \frac{(100 - CE_{i,j})}{100} \qquad (1)$$

where, i = Sub-sector or source$j$ = Pollutant type; $Em_{i,j}$ = Emission rate (e.g. t yr^{-1}); $EF_{i,j}$ = Emission factor (t per unit of activity); AR_i = Activity rate (with consistent unit); $CE_{i,j}$ = Emission control efficiency (%).

2.2. Emission factors

The EFs were mainly taken from the ABC EIM and other databases and are summarized Table S1, SI. The ABC EIM compiled the EFs from various sources with a special focus on the available measurements for Asian sources. For the residential sector, the ABC EIM database includes the reported EFs measured for cookstoves in China and other Asian countries (Zhang et al., 2000; Kim Oanh et al., 2005). Beside the ABC EIM database, in this study we also included additional measurements for Asia, i.e. the EFs of OB measured in Indonesia and Thailand (Permadi and Kim Oanh, 2013), EFs of BC and OC provided in Bond et al. (2004) and Kupiainen and Klimont (2007). In addition, we also used the EFs for carbonaceous aerosol provided in the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model (Klimont et al., 2009). For other sectors, e.g. non-combustion agricultural activities, EFs of NH_3 from livestock were taken from US EPA (2004) while those for fertilizer applications were taken from IPCC (2006). Note that the climate conditions and manure management practices in Asian countries are different from those in the US and Europe hence the EFs (and activity data) were carefully scrutinized to get the relevant values for Indonesia as detailed later in Section 2.3.6.

For the transportation sector, the EFs for the passenger fleets (motorcycle, taxi, bus, paratransit, and private car) were taken from the IVE results generated for Bandung, the fourth largest city of Indonesia. The IVE model considers local fleet engine and fuel technologies as well as the driving and meteorology conditions, hence the produced EFs for the Bandung city should be more appropriate than those taken from international sources. However, the IVE results were for 2015 conditions hence may not be the same as in 2010. Nevertheless, the slow rate of vehicle technology intrusion (to progressively comply with European emission standards) in the country may justify the applications of these EFs for 2010 inventory. The EFs of trucks were taken from the IVE results for Bangkok (Siangjun, 2014). The EFs of off-road transportation, such as air traffic landing and takeoff, shipping, railway, and inland waterway emissions were taken from the compiled dataset of ABC EIM.

2.3. Activity data

A summary of the type of activity data of all considered source categories and the proxies used for temporal and spatial distributions is presented in Table S2, SI. More detail of the activity data is given below.

2.3.1. Combustion of fossil fuel in power plants

Three main power generation sub-sectors were included, i.e. the National Electricity Corporate (PLN), Independent Power Producers (IPPs), and Private Power Utility (PPU). The total installed capacity was 38,000 MW and was mainly owned by PLN (68%), followed by IPPs (20%) and PPU (12%) (PLN, 2011).

In 2010, there were 14 large power plants (>300 MW) in the country, which were subsequently classified into the Large Point Sources (LPS) sub-category. For these LPS, the activity data were taken from the National Electricity Corporate Statistic (PLN, 2011). Other smaller power plants (non-LPS) were considered under the area source sub-category due to the insufficient source specific data. The national fuel consumption data were collected from the Ministry of Energy and Natural Resources Statistics (ESDM, 2011). This study considered only the combustion emissions of the power plants, i.e. other related emissions, such as coal dust from coal storage or distribution, were not included.

In term of the total fossil fuel consumption, in 2010 the power generation utilized around 27 Megatonnes (Mt) coal, 11.5 million m^3 fuel oil and 8 million m^3 NG. The oil based power plants had the largest number (in term of counts) in Indonesia (LPS and non-LPS) with the state-owned PLN company operating nearly 5000 units of small diesel-fired power plants in the country. Three types of fuel oil were used, including the industrial diesel oil (IDO) of 8.8 million m^3, high speed diesel (HSD) of 2.3 million m^3, and marine fuel oil (MFO) of 0.4 million m^3. Based on the total energy generation, the oil based power plants also contributed a larger share of around 36% than natural gas (NG) and coal based power plants which shared about 25% and 23%, respectively. The remaining part of the energy generation was from hydro power (15%) and geothermal (2%).

The coal based power plants in Indonesia were mostly equipped with electrostatic precipitators (ESP) to control PM emission while oil based power plants used cyclones. Flue Gas Desulfurization (FGD) devices were installed in some large coal based power plants to control SO_2 but no $deNO_x$ device (to remove NOx from the emission) was reported to be available in any plants (PLN, 2011). Some power plants were reported to upgrade their combustion to incorporate low-NOx burner technologies, e.g. Suralaya of West Java and Paiton of East Java, but that was done only after 2010 (Borsani et al., 2012; Abe et al., 2012) hence NOx control was not included in our EI. The specific information of power plants including capacity, latitude-longitude, and the districts where respective plants are located (http://carma.org/dig/show/country+91+plant#top), was used to disaggregate the national emission to the district level. Monthly consumption rates of each fuel type taken from ESDM (2011) were used to derive the monthly emission from the annual emission results.

2.3.2. Industrial combustion, non-fuel combustion and processes

2.3.2.1. Fuel combustion: The industrial source sector mostly used fuel oil. The national fuel consumption data was extracted from the statistics of the large and medium scale manufacturing industry (BPS, 2011a). The number of registered industries in a district was used to disaggregate the national emission to the district level. Monthly emission was derived using monthly production indices for every type of industry (ESDM, 2011; BPS, 2011b) because monthly fuel consumption data specific for each industry was not available.

2.3.2.2. Non-fuel combustion and process: This group included the process-related emissions from manufacturing industry and fugitive emissions from oil and gas industry, as well as the emissions from solvent and other industrial product use.

Emissions from both combustion of by-products or raw materials (i.e. non-fuel) and non-combustion manufacturing processes were included for five industrial categories: 1) mineral products (i.e. cement, asphalt, brick manufacturing), 2) metal production, 3) pulp and paper, 4) chemical, and 5) food and beverage industries. The production data were taken from the large and medium scale manufacturing statistics (BPS, 2011b). The number of the registered industries in each district was used for the spatial distribution. The monthly emissions were estimated using the proxy of monthly industrial indices for each industry type (BPS, 2011a). For fugitive emissions, the activity data of production of oil and gas, refinery products, national sale of gasoline and the amount of gas flared were collected from the oil and gas statistics for 2010 (ESDM, 2011). The spatial emission distributions of refinery plants, and oil and gas exploration fields were prepared using their exact locations, while for gasoline distribution emission we used the population distribution data. The monthly emissions were derived using the monthly production data (ESDM, 2011).

The VOC emissions from the solvent and other product use (paint applications, chemical products, and uses of solvent in printing, glue and adhesives applications, and household uses) were estimated based on the actual production data in the country. Due to the lack of the production data from paint manufacturers, the national consumption data was estimated using the consumption per capita data reported for Indonesia of 2.6 kg person^{-1} yr^{-1} (Jumar and Wandebori, 2012). We relied on the "simpler methodology" described in EMEP/EEA (2013) to calculate emissions, i.e. by multiplying the estimated annual paint consumption with the EFs. The EFs were selected for the specific types of paint applications in the country which are decoration (44%), industry (46%), and automotive (10%) as reported in Jumar and Wandebori (2012). More detail of the activity data for emission estimation under this category is provided in Table S3, SI. The number of registered industries (using solvent and other products) in a given district was used to disaggregate the VOC emissions into the district level while monthly industrial production indices (BPS, 2011b) were used to develop the monthly emissions.

2.3.3. *Residential and commercial fuel combustion*

For the residential and commercial sector, fuel combustions at both the household level (domestic cooking) and in the commercial sector (restaurant, hotel, etc.) were considered. The consumption rates of different fuel types were obtained from the National Statistics Bureau (BPS, 2011b). As of 2010, out of the total 62 million of households (HHs) in the country, approximately 28 million HHs used LPG for cooking (46%) and 24 million HHs used fuel wood (39%) which was burned mainly in the traditional biomass cookstoves (World Bank, 2013). Of the remaining, about 7 million of HHs used kerosene (12%) while the rest of 3 million HHs used charcoal and coal (3%) (BPS, 2011b). Thus, in 2010, LPG was the most popular fuel used in domestic cooking (mainly in urban areas). In term of the total amount fuel consumed, the following data were collected and used in the EI: fuel wood of 100 Mt, charcoal of 20 Mt, LPG of 3.6 Mt, kerosene of 1.9 Mt and coal of 0.03 Mt. Note that the energy content and the efficiency of cooking devices are important factors in the determination of amounts of fuels used in the HH combustion.

Thanks to the government policy of switching from kerosene fuel used in domestic cooking to LPG (Pertamina, 2012) which has been implemented since 2007, there was a sharp decrease in the national kerosene usage, i.e. by 70%, and a simultaneous increase in the LPG consumption, i.e. by 72%, during the period from 2007 to 2010 (Fig. S2, SI). Accordingly, the impacts of this kerosene phasing out program on air pollution and climate forcer emissions are assessed in this paper.

For the commercial sector, the fuel consumption data in 2010 was extracted from ESDM (2011) which showed an amount of fuel wood of 0.6 Mt, heavy fuel oil (HFO) of 0.8 Mt, and NG and LPG of 0.1 Mt each. The district population was used as a proxy to disaggregate the residential emission to district level while the monthly fuel sale data (BPS, 2011a) was used for monthly emission segregation.

2.3.4. *Transportation*

2.3.4.1. On-road: For the on-road vehicles, we incorporated the survey results for the Vehicle Kilometer Travelled (VKT) available for different cities of Indonesia. To represent the average usage in Java Island, the VKT (km veh^{-1} d^{-1}) obtained for the fleets of Bandung (Kim Oanh et al., 2015) were used: personal car (PC): 37, motorcycle (MC): 25, paratransit: 91, bus: 117, and taxi: 70. For other places in the country, we used the VKT data generated from the survey conducted in Padang in 2012, West Sumatera by Sukarno et al. (2016): PC: 18, MC: 18, paratransit: 100, bus: 126, and taxi: 24. As for trucks, the VKT of 27 km veh^{-1} d^{-1} from Sukarno et al. (2016) was used for the whole country. The vehicle registration number in a district, collected from the district statistics reports, was used to compute the total annual VKT of a fleet in the district. These VKT values were compiled with the composite IVE EFs (running emission, g km^{-1}) presented in Table S1, SI to calculate the annual emissions. It is noted that the VKT (and IVE EFs) values were obtained from the surveys conducted in different years and locations, e.g. 2015 for Bandung and 2012 for Padang, may not fully represent the fleet conditions for the country in 2010. The EI results for on-road vehicles for the country thus may be more readily updated to a more recent year, e.g. 2015, with the corresponding registration data, but more surveys are still required for other cities in the country. The monthly emission was derived using monthly fuel (gasoline and diesel) sale data while the spatial distribution was prepared using the number of registered vehicles in each district.

2.3.4.2. Off-road: For the air traffic, we estimated landing and take-off (LTO) emissions based on the LTO data per airport following the method reported in EMEP/EEA (2013). It is noted that aircraft cruise emissions were not included. This was partly because the emissions are released at a considerable altitude, around 10 km, hence it would be more important for the assessment of long-range transport or other large scale effects, such as regional air quality or climate modeling, than for national AQM purposes. The locations of airports (in a particular district) reported in the transportation statistics book (DEPHUB, 2011) were used for the spatial emission distribution. The monthly number of passengers given in the national transportation statistics was used as a proxy to assign the monthly LTO emission.

The national shipping emissions were only preliminarily estimated using the number of registered vessels obtained from the transportation statistics (DEPHUB, 2011). This database provided only the domestic vessels hence the international ships travelling in the territory were not included in this EI. The shipping emissions represented the emissions over the sea hence were not segregated into the district emissions (land-based emissions). Nevertheless, the total shipping emissions have been added in the national total emissions for respective species. There was no suitable proxy data available for the monthly emission estimation hence a simple arithmetic average of the annual emission was calculated.

The emission from the railway and inland waterway transportation was estimated using the fuel consumption data taken from the Ministry of Energy and Mineral Resource (ESDM, 2011). Diesel was the major fuel used for the railway and waterway transportation and collectively contributed 1% of the total fuel consumption for transportation in Indonesia. Note that, as of 2010, the electric train system was only operated in Jakarta. Other off-road vehicles of agricultural and construction machineries were not included in this EI, mainly due to the lack of the activity data. Thus, future studies should quantify the contributions of these off-road vehicles, specifically construction machineries would be important in several big urban areas, such as Jakarta, Surabaya, Bandung and Medan.

2.3.5. *Biomass open burning*

The detailed activity data of biomass OB, including crop residue and MSW OB, has been presented previously in Permadi and Kim

Oanh (2013) for the base year of 2007. The forest fire emissions in the year of 2010 for Indonesia were extracted from the Global Fire Emission Database version 4 (GFEDv4), which includes the above ground forest, savanna and grassland fires, as well as peatland (Randerson et al., 2015). Note that in our early study (Permadi and Kim Oanh, 2013) the EI for forest fires in 2007 did not include the underground peatland burning hence it was updated with GFEDv4 and presented here accordingly. The crop residue OB emissions were updated using the crop production data collected for every district in 2010 from the provincial statistics reports (BPS, 2011b). Other parameters used for the EI of crop residue OB, such as residue-to-crop ratio, dry matter-to-crop residue ratio, residue burning efficiency, as well as the fraction of biomass burned in the field, were the same as in our previous paper. For the solid waste OB, the 2007 EI was updated using the population data of 2010. Other activity data, including the municipal solid waste generation factor, collection efficiency, and fraction of solid waste subjected to OB (Enri et al., 2009), was assumed to be the same as in the 2007 EI. The methodology for estimating emissions from solid waste OB and proxy factors used for the temporal variation (dry and wet season) was similar to that presented in Permadi and Kim Oanh (2013). Monthly emissions of crop residue OB were calculated using the monthly production data while those for forest fires were directly taken from the GFEDv4 database.

2.3.6. *Non-combustion agricultural activity and final waste disposal*

This category includes other emission sources releasing NH_3, CH_4 and N_2O, such as those agriculture-related activities of livestock and fertilizer applications, as well as the CH_4 emission from solid waste final disposal site (FDS). The emissions from livestock depends on the manure management system (MMS) therefore the existing MMS in the country was used as the basis for selection of relevant EFs of NH_3. We considered 8 livestock types available in Indonesia in this EI: dairy and beef cattle, poultry, swine, horses, sheep, goat, and buffalo. The majority (70%) of the beef cattle population used the dry lot MMS while the remaining used the pasture MMS. All of dairy cattle livestock used the daily spread MMS. All buffalo, sheep, goat, horses and swine livestock used the dry lot MMS. Poultry in the country mainly used either with or without litter MMS (MoE, 2010) hence EFs were selected accordingly. Note that the MMSs mentioned above for the country reflected also the climate conditions. The climate conditions were also explicitly considered, for example using "warm" climate for "developing countries" in selecting the EFs of CH_4 for MMS and NH_3 for fertilizer applications.

In this EI, we did not include the emissions from the agricultural machineries (as mentioned in the off-road source category, Section 2.3.4), as well as those from agricultural soils, wetland and paddy, which would particularly affect the results of N_2O and CH_4 emissions.

2.4. *Range of the emission estimates*

This study presents the annual emission of a species as the low, high and best estimates to indicate the emission range. The emission range was produced based on the ranges of both the activity data and the available EFs as detailed in Fig. S3, SI.

Specifically, the uncertainty in the activity data of the fossil fuel combustion in the energy sector was assigned based on the data sources. The activity data collected from the Indonesian National Statistics Bureau (BPS) was reported to have an uncertainty range of 10% for demographic data (SUSENAS, 2011) and 5% for other activities (BPS, 2011b). The statistic data obtained from the relevant ministries, e.g. statistics of transportation of Indonesia (Ministry of Transportation) and energy statistics and outlook (Ministry of Energy and Mineral Resources), was reported to have the uncertainty of 5% (DEPHUB, 2011; ESDM, 2011). We therefore assumed that the national activity data taken from BPS and related National Agencies or Ministerial Departments had an uncertainty level of 5%. For the data collected from the international agencies, e.g. the United Nation (UN) database or other international agencies, a higher uncertainty of 10% was adopted following the suggestion of IPCC (2006).

Based on available EFs of a species emitted from a source category, the "best estimate" of a species was produced using the most appropriate EF, which was selected based on the following screening method. The first choice was the EFs developed for Indonesia. The second choice was the values generated for the Asian region, namely, for the similar combustion and fuel type in contained burning, and for similar burning practices for OB. When no such Asian regional data was available, the relevant EFs measured in other parts of the world were used. For the low and high estimates, the EFs were the lowest and highest values of the range for each species reported in literature.

The best estimates of given EI species were summed up over all source categories to obtain the sector wise and national wise EI results. A similar approach was used to produce the low and high emission estimates of given species. In this study, the ratio of the low and the high estimate, respectively, to the best estimate was used to express the uncertainty of the EI results. Hence, a negative (−) uncertainty showed magnitude of the difference (in %) between the low estimate and the best estimate while a positive (+) uncertainty showed the relative difference between the high and the best estimate. Thus, the range given in this study is not the standard deviation of the best estimates. For example, the high uncertainty of the estimated amounts of biomass burned and the large variation in the available EFs caused large ranges of the emission estimates for biomass OB (Permadi and Kim Oanh, 2013).

2.5. *Impacts of fuel switching policy for residential cooking*

The Indonesia National Program of conversion from kerosene to LPG, initiated in 2007 based on the Presidential Decree No. 104/2007, has been considered as one of the world's largest efforts to promote cleaner cooking fuels (World Bank, 2013). The considerations of both environment (i.e. emission reduction of air pollution and climate forcers) and economy are the motivation of the program implementation. Kerosene was popularly used for cooking in the country and it has been heavily subsidized by the government since 1970s when LPG was not abundantly available (Budya and Arofat, 2011). The subsidy has been implemented to ensure the access of the public to the cooking fuel with affordable price. However, there was misuse of the subsidy and a large part of the subsidized kerosene was ended up in non-household sectors, e.g. industry, hence the government decided to reduce this subsidy. In parallel, the government has increased the national LPG production to provide an adequate infrastructure to support the fuel switching from kerosene to LPG. It is noted that the government has continued providing subsidy to LPG to encourage the use of this clean fuel for cooking (Pertamina, 2012). Based on the calorific value, the National Oil and Gas Authority (Pertamina) estimated that 1 L of kerosene is equivalent to 0.39 kg of LPG and this number was used in valuation of the economic effects. The unsubsidized price of 1 L kerosene (0.66 USD) was higher than that of equivalent amount of LPG (0.31 USD per 0.39 kg) while the corresponding subsidized prices were 0.25 USD and 0.17 USD, respectively (Budya and Arofat, 2011). Even with the LPG subsidy, Pertamina estimated that, once completed, the program could save of 2.17 billion USD of the state's budget (Pertamina, 2012).

The program was officially authorized by the commencement of Presidential Decree No. 104 in 2007. At the completion of the fuel conversion program, it is expected that all kerosene use for cooking in 30 designated provinces (out of 33 provinces in the country) would be eliminated and these provinces will be named as "closed and dry". By then, approximately 58 million conversion packages (each consist of an LPG cylinder, one-burner stove and the supporting kit) would be distributed and the kerosene subsidy in the provinces would be removed (Pertamina, 2012). Only 3 provinces in the Eastern part of Indonesia (Papua, Maluku and Nusa Tenggara Timur) would not implement the kerosene switching due to a technical reason related to the LPG supply. Initially, the target year of the program completion was 2013 but it was shifted to 2014 in the revised implementation roadmap. It was reported that by 2012, the program was fully implemented in 23 provinces with 53.9 million conversion packages distributed which reached 93% of the target.

The energy consumption and social impacts of this program have been reported (Andadari et al., 2014; Budya and Arofat, 2011) but the impacts on the environment, particularly on the emissions of air pollutants and GHGs have not been analyzed. This study, therefore, filled in the data gap by analyzing the program impacts on the emissions of toxic air pollutants and climate forcers. We assumed that the reduction in kerosene and the increase in LPG fuel use (Fig. S2, SI) was solely made possible by this program. The emission difference between 2007 (beginning of the program) and 2010, was determined and attributed to the program success. Further, we also estimated the potential emission reductions when the program would be fully implemented, i.e. 100% of kerosene would be replaced by LPG in 30 provinces.

The total consumption amounts of both fuels were shown to reduce (Fig. S2, SI) because of the higher calorific value and higher efficiency of LPG stoves compared to kerosene, i.e. 1 liter (L) of kerosene is equivalent to 0.39 kg of LPG in term of useful thermal energy as suggested by the National Oil and Gas Authority (Pertamina, 2012; Budya and Arofat, 2011). In 2007, there was 6.86 Tg (Tg) of kerosene and 0.98 Tg of LPG used in the country (Fig. S2, SI) and most of that, i.e. 6.82 Tg (kerosene) and 0.96 (LPG), were used in the 30 designated provinces. As of 2010, only 1.92 Tg of kerosene was still remained in use in the 30 designated provinces (BPS, 2011a) and a small amount of 0.05 Tg was used in 3 non-designated provinces. Thus, after 3 years from the program inception in 2007, about 4.9 Tg of kerosene was replaced by 2.6 Tg of LPG. After the conversion program completion in the 30 designated provinces, it is estimated that 6.5 Tg of kerosene would be replaced by 3.3 Tg of LPG in residential cooking.

The climate impacts of the program, through the emission reductions of different climate forcing species, were quantified using the global warming potential (GWP) metric weighted against that of CO_2 over 20-yr horizon. We analyzed only 20-yr GWP in this study because the SLCPs have short atmospheric lifetime hence the impacts on climate would be more clearly seen only on this short time horizon. The CO_2 eq. values of the species vary with the geographical region and the values selected for Indonesia are presented in Table S4, SI. This study considered GWP of two groups, GHGs (CO_2, CH_4 and N_2O) and SLCPs. The later consist of toxic air pollutants which also have climate impacts, including both warming agents, e.g. BC particles and ozone precursor gases (NOx, NMVOC and CO), and cooling agents, e.g. OC particles and SO_2.

3. Results and discussion

3.1. Total national emission and comparison with existing EI databases

The EI results for 12 species are presented in Table 1 and are discussed in comparison with the Indonesia National EI data extracted from the international EI databases for the same anthropogenic source categories. Our best emission estimates for the considered species in 2010, $Gg\ yr^{-1}$, for toxic pollutants were: 1014 SO_2; 3323 NO_x; 24,849 CO; 4077 NMVOC; 1276 NH_3; 2154 PM_{10}; 1728 $PM_{2.5}$; 246 BC and 718 OC; and for GHGs were 540,275 CO_2; 3979 CH_4 and 180 N_2O. Due to the change in the activity levels during the 3 year period, the national emissions of different species

Table 1
Annual emission of Indonesia (2007 and 2010) in comparison with other works, $Gg\ yr^{-1}$.

Species	2010 (this study)		2007[a]	% change[b]	EDGAR (2008)[c]	CGRER (2006)[d]	REAS v2.1 (2008)[g]
	Range	Best estimate	Best estimate				
CO_2	471,884–686,421	540,275	508,022	6.4	1,700,450 (514,882)[g]	587,000[e]	573,207
CH_4	3276–5190	3979	3950	0.73	10,300	6,443[e]	11,398
N_2O	168–199	180	181	−0.6	329	NA	219
SO_2	745-1352	1014	997	1.7	2433	1499	1808
NO_x	2920–3930	3323	3282	1.7	2162	1896	2817
CO	16,425–34,923	24,849	24,169	2.8	32,246	26,703	22,499
NMVOC	1800–5224	4077	3840	6.2	4528	8225	7316
NH_3	1193–1733	1276	1258	1.4	1617	1,390[e]	1743
PM_{10}	1325–3712	2154	2046	5.3	3454	1,838[f]	1327
$PM_{2.5}$	996-3137	1728	1644	5.1	2023	1,609[f]	997
BC	100–545	246	226	8.9	173	229	179
OC	369-1311	718	674	6.5	711	1246	682

Note: values in parenthesis are the best estimates.
NA: not available (not estimated).

[a] EI of 2007 by Permadi (2013). EI of crop residue OB and above ground biomass forest fire for 2007 were from Permadi and Kim Oanh (2013).

[b] $\%\ _{change} = \frac{E_{2010}-E_{2007}}{E_{2007}} \times 100\%$. Based on the best estimates.

[c] Data can be downloaded at http://edgar.jrc.ec.europa.eu/datasets_list.php?v=42.

[d] Data can be downloaded at http://www.cgrer.uiowa.edu/EMISSION_DATA_new/data/intex-b_emissions/.

[e] Emission inventory base year of 2000 (Streets et al., 2003).

[f] Biomass open burning was not included.

[g] No biomass open burning emission was included. Data can be downloaded at https://www.nies.go.jp/REAS/. Value in the bracket excludes forest fire post burn decay and decay of drained peatland emission which were not covered in this study.

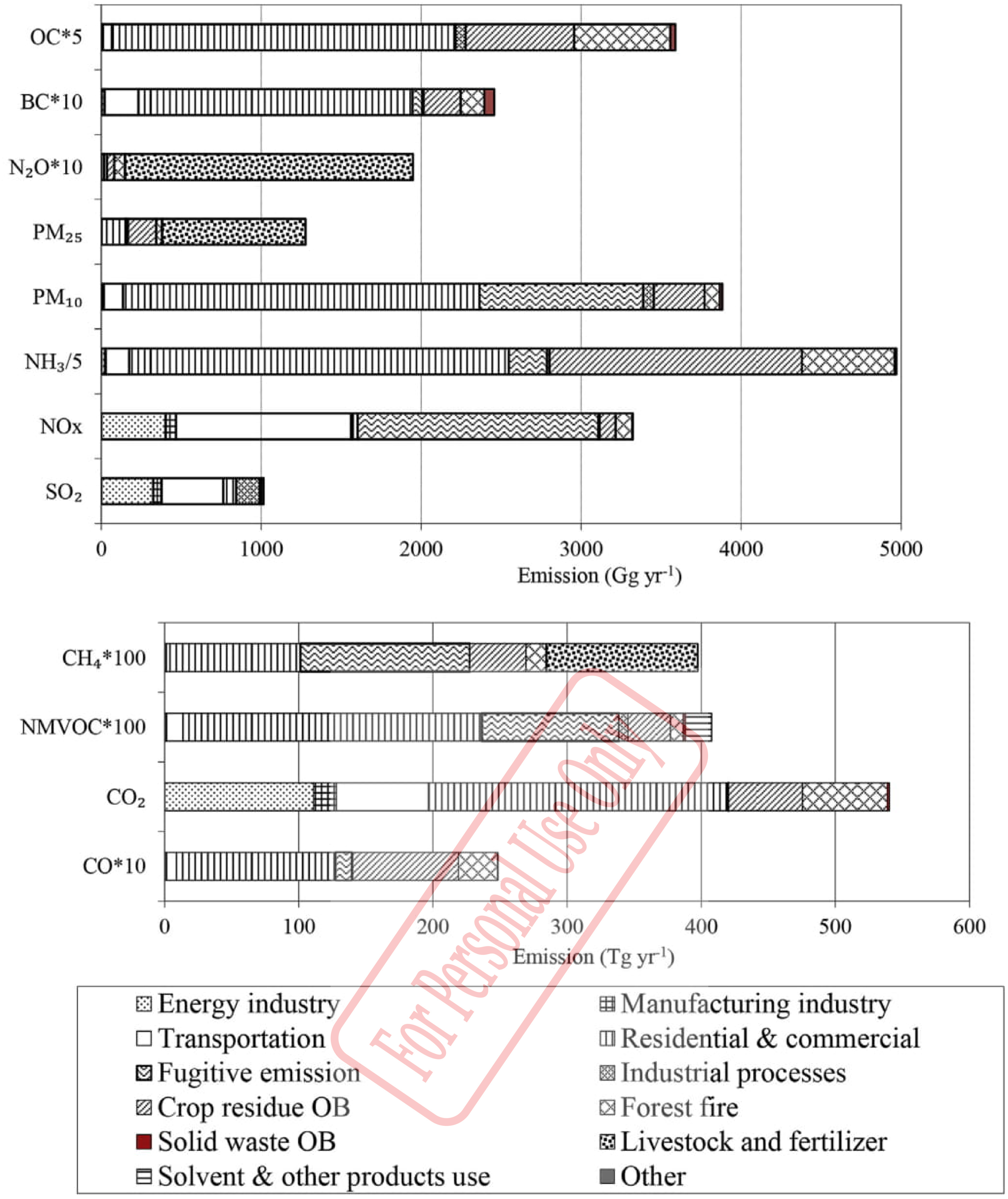

Fig. 1. Sector wise emission for different species 2010.

in 2010 were increased by 0.7–8.8% as compared to 2007 (Table 1) or equivalent to an annual increase rate of 0.23–2.8% yr^{-1}, varying with species. N_2O was an exception which featured a small reduction (0.6%) because of the reduction in the number of livestock headcounts in 2010 as compared to 2007. Note that other major sources of N_2O, such as soil and fertilizer applications, were not considered in our EI. Emissions of SO_2, NO_x, NH_3 and CH_4 did not change much between the 2 base years, 0.7–1.7%, because of small changes in the activity data in the power generation and oil & gas production. The emission changes for these species were smaller than those extracted from the Regional Emission Inventory in Asia (REAS) version 2.1 for Indonesia of 7.6–8.3% over the period of 2005–2008. More significant differences were seen for other species which were mainly due to the differences in the activity data of the residential combustion, i.e. higher amounts of LPG and fuel wood but lower amount of kerosene consumed in 2010 as compared to 2007. The resulting increases in the national emissions of CO, NMVOC, CO_2 and aerosol species over the period of 2007–2010 were 2.8–8.8% (Table 1), which are similar to that, 6–14%, obtained from the REAS database.

The most significant changes were obtained for the biomass OB emissions which in 2010 were 2.1–37% above those in 2007. The increases in emissions from crop residue (2.1–12%) and solid waste OB (4%) were mainly due to the increases in crop production and population, respectively, within the period. However, the increases in the forest fire emissions in 2010 by 9–51% above 2007 (detailed in Table S5, SI) were mainly attributed to the inter-annual variations of the burning events in Indonesia.

In 2010, the SO_2 emission was mainly dominated by the fuel combustion in transportation (38%) and energy industry (32%) followed by industrial manufacturing processes (14%), and commercial and residential combustion (7.8%) (Fig. 1 and Table S6, SI). The NOx emission was mainly contributed by the industry (45%), mainly from catalytic cracking units in petroleum refinery, and waste gas disposal through flaring that is classified as fugitive emissions in EMEP/EEA (2013), followed by transportation (33%)

and energy industry (12%). NH_3 emission was dominated by livestock and fertilizer applications (70%) followed by crop residue OB (14%), and residential and commercial combustion (12%). The residential and commercial combustions contributed dominantly to the emissions of CO (48%), NMVOC (55%), CO_2 (41%) and PM species (43–70% for PM_{10}, $PM_{2.5}$, BC and OC). Fugitive emissions from oil and gas exploration contributed significantly to the CH_4 emission (32%), while N_2O emission was mostly from the livestock manure management (92%). Note that the CH_4 and N_2O from soil, rice paddy and wetland were not included in this EI and the shares may change once those sources are included.

For comparison, we used the reference EI databases for 2008 by the Emission Database for Global Research (EDGAR), hereby referred to as EDGAR, and EI for 2006 by the Center for Global and regional Environmental research (CGRER), the university of IOWA (Zhang et al., 2009), referred to as CGRER. In addition, the EI database of the REAS for the base year of 2008 for several species were also extracted for the comparison (Kurokawa et al., 2013).

There were significant differences in the EI results reported for Indonesia by the 3 existing international databases. In general, the CGRER values available for 11 species, were higher than our best estimates for 7 species (i.e. SO_2, CO, NH_3, CH_4, NMVOC, OC and CO_2) and lower than ours for the rest 4 species (NOx, PM_{10}, $PM_{2.5}$ and BC). The EDGAR results, available for 12 species, were significantly higher than our values (also were mostly higher than the CGRER values) for 9 species (SO_2, CO, NMVOC, CH_4, NH_3, CO_2, N_2O, PM_{10} and $PM_{2.5}$). REAS emission data, available for 12 species, was higher than our best estimates for 6 species (SO_2, NH_3, NMVOC, CH_4, CO_2, N_2O) and lower for the others.

To explain the discrepancies, it is required a detail analysis on the sectoral emissions using both the activity data and EFs applied in all the quoted studies. However, not all the required details are available for the purpose. We also discussed and compared our sectoral emissions (Fig. 1 and Table S6, SI) with the international emission databases in Textbox S1, SI. Sector wise, the emission ranges were comparable for most of the species but there were certain discrepancies. For example, our estimates for SO_2 were 1.5–2.4 times lower than the international databases and it may be linked to the lower sulfur content in fuels used for transportation, i.e. 350–500 ppm in gasoline and 2100 ppm in diesel as of 2010 (Safrudin, 2016), as well as the progressive implementation of air pollution control devices, such as FGD, in major coal power plants. Our emissions results of most species for the industrial processes were lower than the international databases and this would reflect the impacts of the government program to limit production of key minerals. Overall, our estimates for other species are mostly close to or slightly higher than other EI studies which could be attributed to the economic growth of the country, i.e. increased activity data levels of dominant sources during the time gap between the base year of this study and that of other international EIs.

For PM species, the total estimates were highly affected by emissions from fuelwood combustion in the residential sector. We carefully scrutinized the available EFs and selected the most relevant to be used as detailed in Section 2.2. Our BC/OC emission ratio for fuel wood residential cooking was 0.37 that is close to the reported values in other EI works, from 0.25 to 0.35. However, the BC and OC emission results still contain high levels of uncertainty because of the inherent variability of the emissions from fuelwood residential combustion (Bond et al., 2004) along with the lack of EFs measurements for the relevant cookstoves in Indonesia. A more detail discussion of the EI results for every species is included in Textbox S1, SI.

Note that, several sources were not incorporated in our EI, such as direct and indirect emissions from agricultural soil, rice paddy, wetland, agricultural machineries, construction machineries and wastewater handling. This would introduce discrepancies for the estimates of N_2O and CH_4, for example. Future EI studies should include these emission sources using specific data for Indonesia to refine the national EI databases.

3.2. Temporal and spatial distribution

The spatial distributions of annual emissions for selected pollutants of SO_2, NMVOC, $PM_{2.5}$, and BC are shown in Fig. 2 (t km^{-2} yr^{-1}) while those for other pollutants are presented in Fig. S4, SI. The SO_2 emission load showed a higher intensity in large urban areas, which was mainly due to the transportation, and residential and commercial combustion. Besides, high SO_2 emissions were also seen outside large cities, in some districts in Java and Sumatera Island where the big power plants (LPS) were located. The highest SO_2 emission intensity of around 875 t km^{-2} yr^{-1} was shown in Jakarta and Surabaya. NMVOC emission loads were also concentrated in the large cities in Java Island (1175 t km^{-2} yr^{-1}) that were mainly due to residential and commercial combustion. The highest $PM_{2.5}$ and BC emission intensity (575 and 74 t km^{-2} yr^{-1}), respectively, was shown over the Jakarta Metropolitan Area (JMA), Padang (West Sumatera), and several cities in Eastern Java (EJ). In JMA and Padang, BC emissions were mainly from the residential and commercial combustion, and traffic emissions, while in Eastern Java it was mainly from the residential and commercial combustion, and crop residue OB. Residential combustion (solid fuel) and biomass OB (crop residue OB and forest fires) mainly contributed to high $PM_{2.5}$ and BC emissions over the western part Kalimantan. Similar patterns were also seen for OC as shown in Fig S4, SI. As mentioned earlier, the national shipping emissions, about 1–29% of the total emissions, varying with species, were not segregated into spatial distributions presented in Fig. 2 and Fig. S4, SI. Future efforts should focus on the segregation of the ship emissions into a suitable grid network for modeling studies.

Monthly emission distributions of the pollutants were dictated largely by the monthly variations of the major contributing sources (Fig. 3 and Fig. S5, SI). Emissions of SO_2 (Fig. 3) and NOx (Fig. S5, SI) had similar monthly patterns, both showed less variations during the year with only slightly higher emissions in July and August. These 2 months had higher monthly coal consumption in the power generation and higher monthly sales of fuel for transport, which were probably linked to the elevated power demand and traveling activities during the Moslem festival from July–September 2010. These months were also in the dry season hence biomass OB may have higher contributions to the emissions.

The NMVOC, BC, $PM_{2.5}$ (Fig. 3), CO and OC (Fig. S5, SI) emissions were higher during August–October period which were mainly caused by more intensive biomass OB in the dry season together with higher monthly sales of domestic cooking fuels because of more cooking activities in celebration of the big Moslem festival in July–September. The similarity in the patterns of these pollutants suggested that they were largely linked to the same emission source sectors.

3.3. Range of the emission estimates

Fig. 4 shows that for all considered species, the low and high estimates were ranged between −58% and +122% of the corresponding best estimates, respectively. The largest range (implying a high degree of uncertainty) was obtained for BC that was mainly due to the wide range of available EFs data for the considered emission sources. For example, there were large ranges of EFs reported in Asia and elsewhere for biofuels (wood and charcoal) which contributed to wider ranges of BC and OC, as well as CO emissions. The EI results of other pollutants had the ranged

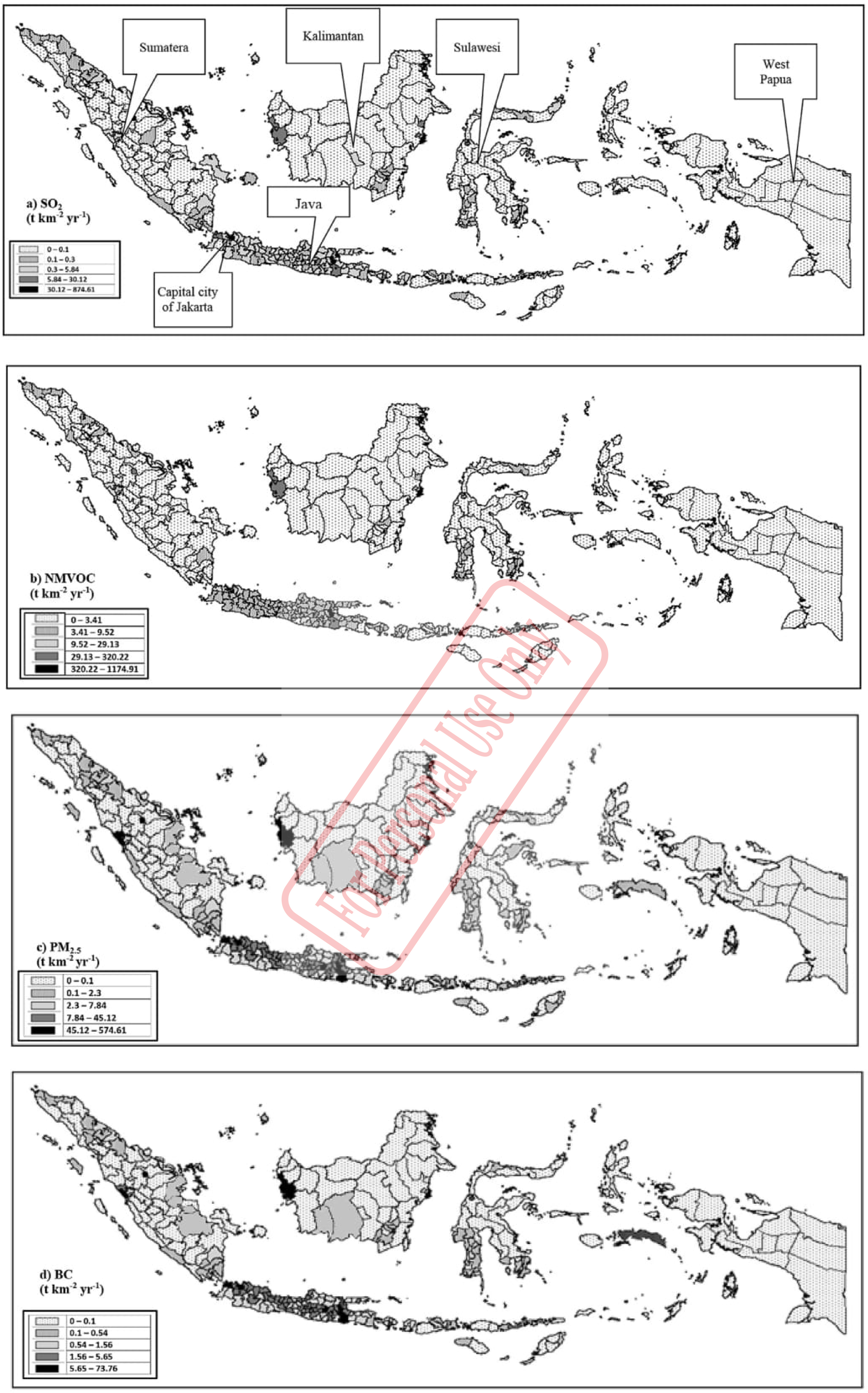

Fig. 2. Spatial distributions of annual emissions (t km^{-2} yr^{-1}), corresponding color figures are given in SI, Fig. S4.

between −42% and +82% of the corresponding best estimates. A number of sources of coarse particles, such as dust resuspension related to wind-blown and unpaved roads, and construction activities were not included in this EI and this appeared to reduce uncertainty of PM_{10} estimates, for example. Overall, the wide range of BC estimates obtained in this study is similar with other regional EI works (Zhang et al., 2009; Kurokawa et al., 2013). More measurements should be made for EFs in the country to produce better

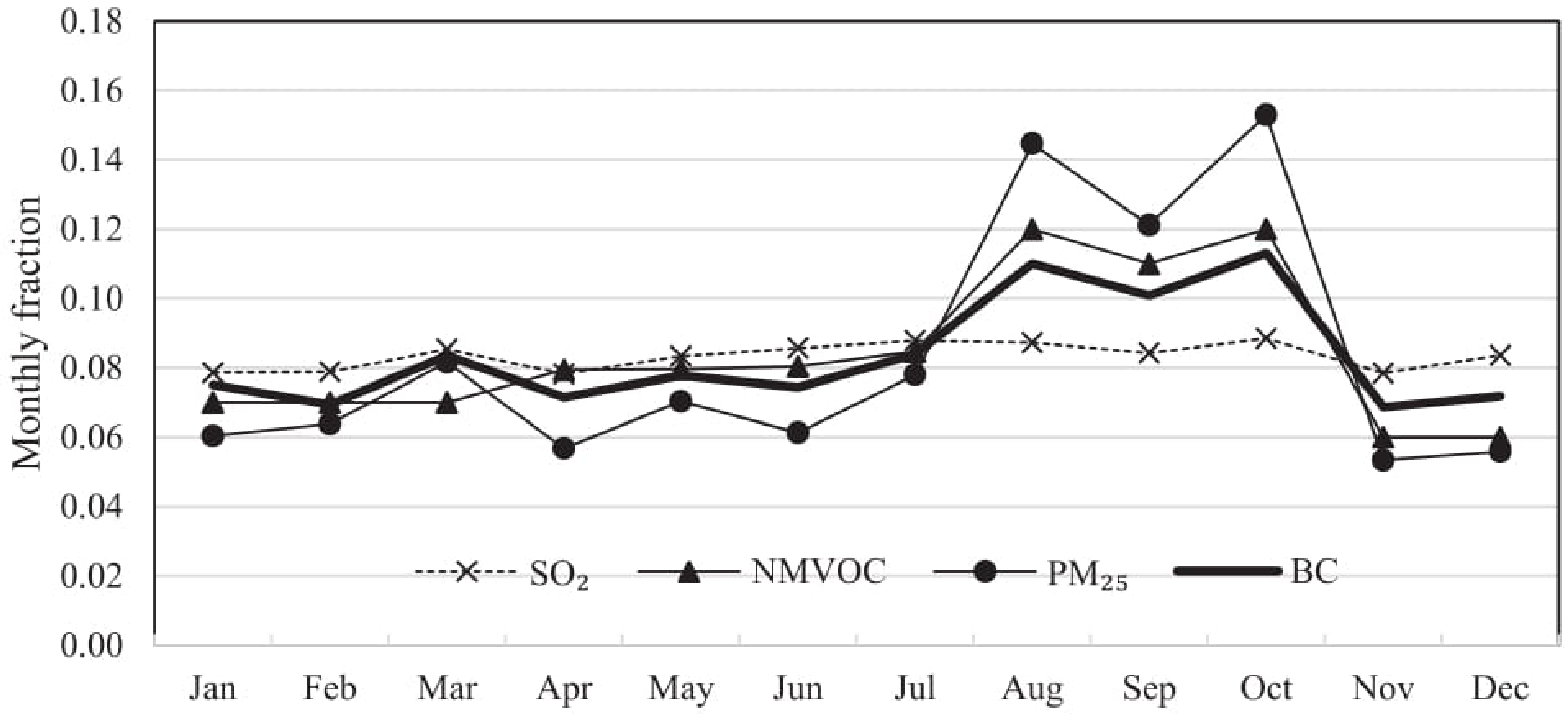

Fig. 3. Monthly variations of emission of selected pollutants.

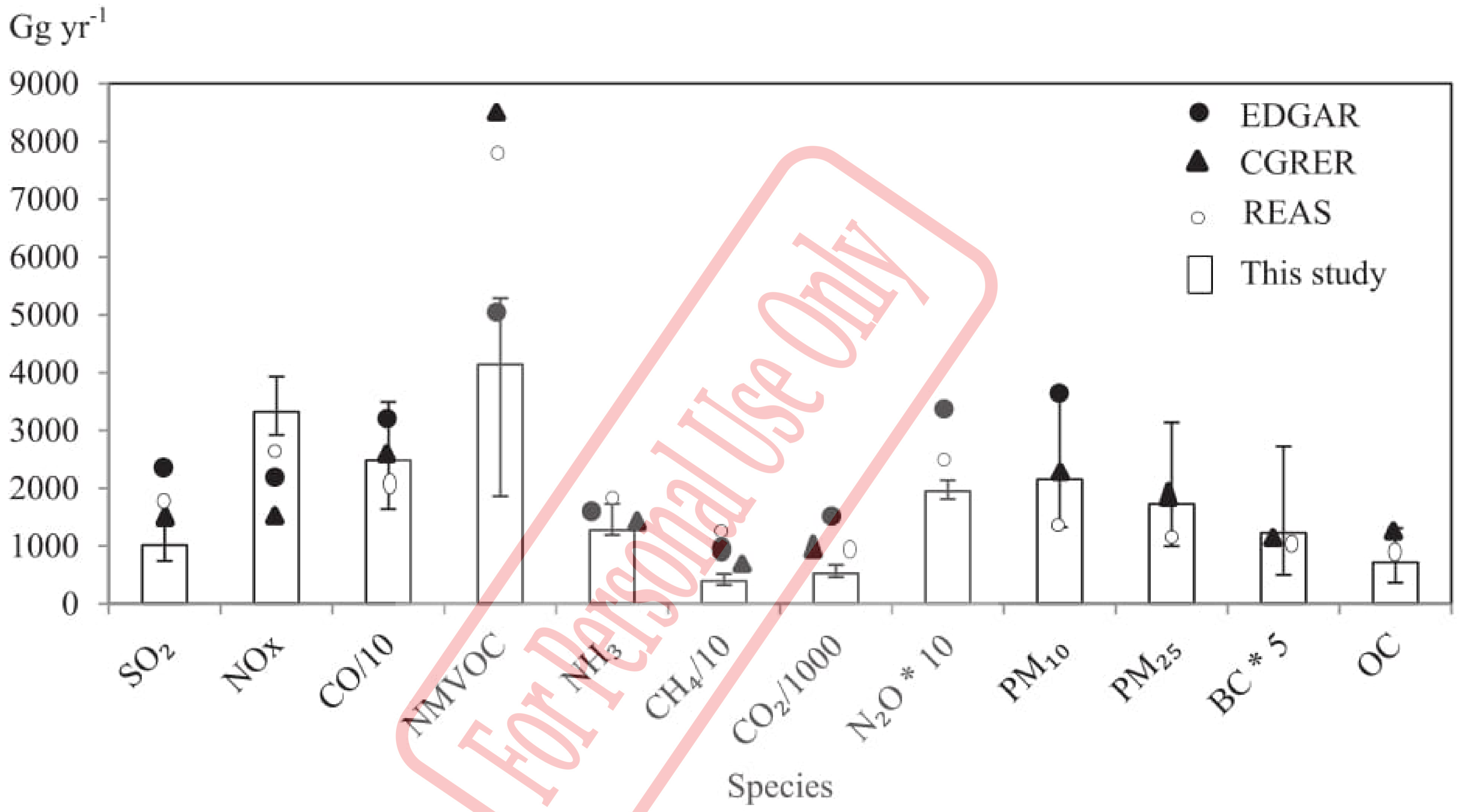

Fig. 4. EI best estimates and the range showing low and high estimates (corresponding values from the international EI data are indicated).

Table 2
Residential emissions, Gg yr^{-1}, from different types of fuel in 2010.

Fuel type	Wood	Coal	Kerosene	LPG	Charcoal	Total
Fuel consumption, Gg yr^{-1}	99,608	28	1973	3564	20,388	125,561
Greenhouse gases (GHGs)						
CO_2	154,392	64	6176	10,621	48,136	219,389
CH_4	797	1.0	1.1	2.0	171	972
N_2O	6	NE	0.10	0.30	3.5	10
Total GWP of GHGs[a]	213,510	136	6284	10,852	61,460	292,263
Short-lived climate pollutants (SLCPs)						
PM_{10}	847	0.19	0.59	1.2	80	929
$PM_{2.5}$	817	0.16	0.59	1.2	67	886
SO_2	69.7	0.07	0.02	0.001	10	80
CO	7720	1.9	15	13	4037	11,786
NOx	20	0.03	2.2	6.3	8.6	37
BC	149	0.01	0.10	0.10	20	170
OC	398	0.10	0.10	0.10	27	426
NMVOC	2032	0.3	0.40	0.80	194	2227
Total GWP of SLCPs[a]	114,728	−22	316	561	50,083	165,644
Combined GWP[a]	**328,238**	**114**	**6600**	**11,413**	**111,542**	**457,907**

Note:
Residential combustion emission only while commercial was not included.
NE – not estimated (due to non-availability of EFs). For SO_2, the GWP was based on sulfates (2*SO_2) and for NOx, the GWP was based on N (See Table S4, SI).

[a] GWP values are in Gg of 20-yr CO_2 equivalent. The combined GWP is the sum of GWP of two groups (GHGs and SLCPs).

Table 3
Impacts of kerosene to LPG conversion program.

Species	Kerosene use emission (Gg yr^{-1})					LPG use emission (Gg yr^{-1})					Net emission reduction (Kerosene + LPG)[e]	
	2007[a]	2010	Program completion	Reduction 2010[c]	Reduction after completion[d]	2007[a]	2010	Program completion	Increase 2010[c]	Increase after completion[d]	Reduction by 2010	Reduction after completion
Greenhouse gases (GHGs)												
CO_2	21,484	6176	1251	15,308	20,233	2917	10,621	12,878	7703	9961	7605 (31%)	10,272 (42%)
CH_4	3.8	1.1	0.2	0.3	0.36	0.55	1.9	2.4	1.4	1.9	1.3 (29%)	1.7 (40%)
N_2O	0.48	0.14	0.03	0.34	0.45	0.088	0.3	0.39	0.23	0.3	0.11 (19%)	0.15 (27%)
Total GWP of GHGs [f]	*21,896*	*6296*	*1274*	*15,601*	*20,622*	*2982*	*10,845*	*13,164*	*7862*	*10,181*	*7738 (31%)*	*10,441 (42%)*
Short-lived climate pollutants (SLCPs)												
PM[b]	2.1	0.59	0.12	1.5	1.9	0.32	1.18	1.4	0.85	1.1	0.61 (26%)	0.84 (35%)
SO_2	0.07	0.02	0.004	0.05	0.06	0.0003	0.001	0.001	0.0077	0.009	48 (69%)	64 (92%)
CO	51	15	2.9	36	47	3.6	13	16	9.6	12	26 (49%)	35 (65%)
NO_X	7.5	2.2	0.44	5.4	7.1	1.7	6.3	7.6	4.5	5.9	0.83 (8.9%)	1.2 (13%)
BC	0.27	0.08	0.02	0.19	0.26	0.04	0.14	0.17	0.1	0.13	0.09 (29%)	0.12 (40%)
OC	0.2	0.06	0.01	0.15	0.19	0.032	0.12	0.14	0.08	0.11	0.06 (26%)	0.08 (35%)
NMVOC	1.5	0.44	0.09	1.1	1.4	0.23	0.84	1.02	0.61	0.78	0.49 (28%)	0.67 (38%)
Total amount of SLCPs	61	18	3.6	43	57	5.9	22	26	16	20	27 (40%)	37 (55%)
Total GWP of SLCPs [f]	*1063*	*304*	*63*	*759*	*1000*	*153*	*568*	*675*	*415*	*522*	*344 (28%)*	*478(39%)*
Combined GWP [f]	**22,959**	**6600**	**1337**	**16,359 (71%)**	**21,622 (94%)**	**3135**	**11,413**	**13,839**	**8278 (268%)**	**10,704 (345%)**	**8081 (31%)**	**10,918 (42%)**

Note: values in the brackets are percentage to 2007.

[a] Data taken from Permadi (2013).

[b] Most PM emitted from cooking using kerosene or LPG belong to fine fraction ($PM_{2.5}$).

[c] Emission increase/reduction by 2010 as compared to 2007.

[d] Emission increase/reduction after the full implementation of the program as compared to 2007.

[e] Net emission reduction (kerosene + LPG) after the completion of the program as compared to 2007.

[f] Unit of GWP values are in Gg of 20-yr CO_2 equivalent.

EI results. Further, the uncertainty analysis should also consider the insufficiency of EF measurement data and should use statistical tools such as the Monte Carlo (Zhang et al., 2009).

3.4. Impacts of fuel switching in residential cooking sector and co-benefit

The sectoral shares of the emissions of different species (Fig. 1) showed that the residential and commercial sector contributed significantly to the total emissions of CO, PM_{10}, $PM_{2.5}$, BC, OC, CH_4 and CO_2, i.e. sharing from 25% to 64% of the total emissions depending on species. The residential cooking was the major contributor to the emissions with a share of 92–99% for different species as compared to commercial cooking (1–8%). Thus, cleaner residential combustion has a good potential to bring in large emission reductions in the country. The emissions from the residential cooking by different fuel type (Table 2) showed that the total emissions for all species were dominated by fuelwood use (60–93%). Note that the GHGs group contributed the majority (64%) of the total combined GWP weighted emissions in term of 20-yr CO_2 eq. from the residential cooking.

Impacts of the kerosene to LPG switching program were assessed for the period from the beginning of the program (2007) until 2010, when 72% of the target in the designated 30 provinces was achieved, and at the end of the program when 100% of the target achieved. The co-benefits were quantified based on the associated emission reductions of both toxic air pollutants (SLCPs) and GWP (combined for GHGs and SLCPs). The total net emission reduction was calculated as the sum of the emission reductions (+) associated with the declining kerosene use and the emission increase (−) due to the rising of LPG use. The results (Table 3) showed that by 2010, the program had achieved the net emission reductions ranged from 7.6 Mt for CO_2, 26 kt for CO to a few hundred tonnes for PM, NOx, N_2O and NMVOC, and some lower amounts for other species (Table 3). Upon the completion of the program, the total emission reductions would range from 10.3 Mt for CO_2, 35 kt for CO, to a few hundred tonnes for PM, NOx, N_2O and NMVOC. Note that the kerosene consumption (0.05 Tg yr^{-1}) in the 3 non-designated provinces mentioned above would be remained after the completion of the program.

The net GWP weighted emissions in 20-yr CO_2 eq. from the residential combustion are presented separately for two groups of GHGs and SLCPs, and were added to produce the combined GWP in Table 3. The total combined GWP emissions from the kerosene use in 2007 was 23 Tg yr^{-1} which were reduced by about 71% in 2010 and would be by 94% at the completion of the program. The total GWP emission from the LPG fuel use in 2007 was 3 Tg of CO_2 eq. which would increase by about 2.6 times in 2010 and 3.5 times at the completion of the program. Thus, due to the fuel switching, a net emission reduction of 8 Tg of CO_2 eq. (31%) would be achieved in 2010 and of 11 Tg (42%) at the completion of the program, from the program inception in 2007. Note that, the net changes in the combined GWP (20-yr CO_2-eq.) brought about by the fuel switching, were mainly attributed to the changes in GHGs emissions (96%) while the SLCPs group contributed only 4%, both in 2010 and at the completion of the program.

Despite of lower contributions of the SLCPs group to the net changes in GWP, emission reductions of these toxic pollutants were significant. Individually, the SLCP species reduced by 9–69% (2010) and 13–92% (at the completion of the program) from the 2007 levels (Table 3). The sum of all toxic pollutants (SLCPs) emissions would have the net reduction from the 2007 levels, by 40% in 2010 and 55% at the completion of the program, which should bring in substantial health benefits.

The residential cooking sector had predominant contributions to the national emissions, from 1% to 69% of different species (Fig. 1), hence it was among the most important source sectors in the country. Within the residential cooking, the major emission contributions were from solid fuel combustion, i.e. 54–90%, while kerosene and LPG collectively shared 0.1–23% of the emissions of different species (Table 2). At the completion of the kerosene conversion program, the total emission reductions would be from 0.1% to 5% considering the emissions from the residential cooking alone and about 0.01%–2% of the total national emissions (from all source categories).

This study showed that the kerosene conversion program could contribute considerable emission reductions of both toxic air pollutants and climate forcers. Especially, this would lead to less exposure to toxic pollutants emitted indoor hence would bring in substantial health benefits. These co-benefits are a proven win-win success of the program. Nevertheless, to bring in greater impacts on the emission reductions in the residential sector, future fuel switching should primarily focus on solid fuels, i.e. fuelwood and charcoal, and on promoting cleaner cookstoves, especially for the fuelwood.

4. Conclusions

This study quantified emissions of major air pollutants and GHGs from key anthropogenic sources in Indonesia in the year 2007 and 2010. The EI was developed using the activity data available at national and provincial/district levels, and EFs selected to be relevant to the country context. As compared to 2007, the national emissions in 2010 increased by 0.7–8.8% that is equivalent to an annual increase rate of 0.23–2.8% yr^{-1}, varying with species. Sector-wise, the most significant changes were obtained for the biomass open burning emissions that is attributable to the increase in crop production, population growth (solid waste OB) and inter-annual variations of forest fires.

Our best emission estimates for toxic air pollutants and GHGs in 2010, Gg yr^{-1}, were: 1014 SO_2; 3323 NO_x; 24,849 CO; 4077 NMVOC; 1276 NH_3; 2154 PM_{10}; 1728 $PM_{2.5}$; 246 BC; 718 OC; 540,275 CO_2; 3979 CH_4 and 180 N_2O. Overall, the ratios of the low and high estimates to the respective best estimates for EI species ranged from −58% to +122% with the highest range (uncertainty) found for BC.

The ranges of our best estimate EI results were largely overlapped with those reported in the existing international databases. The differences in the EI results are explained by the difference in the base years as well as the progressive emission control measures promulgated by the government, e.g. roadmap of sulfur content in fuel for on-road transport. The detail activity data used in our study is expected to produce a more relevant EI for Indonesia.

The results showed that PM, CO and CO_2 were mainly released from the residential and commercial combustion, crop residue open burning, and transportation. The 2010 emission of SO_2 was mainly from the transportation (38%) and power plants (32%) while NOx was mainly from oil and gas refinery and flaring (45%) and the transportation (33%). Residential and commercial combustion, and fugitive emissions from oil & gas operation contributed dominantly (77%) to the total NMVOC emission. The livestock-related emission was the largest contributor to NH_3 (70%) and N_2O (92%). The solid fuel use contributed the majority of the emissions from the residential cooking (60–93%) hence measures targeting these fuels, such as improved biomass cookstoves, are expected to gain significant emission reductions.

Monthly variations in emissions were largely driven by the major contributing sources that had strong seasonal variations, e.g. forest fire and crop residue open burning activities. Higher emissions were observed in the dry season (August–October) because of more intensive biomass open burning and also more intensive fuel use in residential cooking during the festival period. Spatially, higher emission intensity was shown in Java Island which had high population density hence high contributions from the residential and transportation sources.

By 2010, the government project of fuel conversion for residential cooking (initiated in 2007) had successfully replaced 4.9 Tg of kerosene by 2.6 Tg of LPG. By the completion of this program, totally 6.5 Tg of kerosene would be replaced by 3.3 Tg of LPG. The program had brought in significant emission reductions of both toxic air pollutants (SLCPs) and GHGs. The net emission reductions over the period from 2007 to 2010, resulted from the fuel switching, ranged from 48 t for SO_2 to 7.6 Tg for CO_2. The net reduction of the combined GWP weighted emissions, considering both GHG and SLCPs groups, in 2010 would be 8.1 Tg of 20-yr CO_2 eq. or by about 31% from the 2007 level. At the completion of the program, the total net GWP weighted emission reduction would be 42%. As compared to the 2007 level, the sum of all toxic pollutants (SLCPs) emissions would be reduced by 40% in 2010 and by 55% at the completion of the program, which showed potential significant health benefits.

Several important sources omitted in this EI should be incorporated in future studies, such as direct and indirect emissions from agricultural soils, wetland, rice paddy, agricultural machineries, shipping, construction machineries and wastewater handling. The EI database should be regularly updated, especially to include the locally measured EFs when available for the country. Assessment of the impacts from residential cooking emissions on human health would add more value to the national fuel conversion program.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2017.01.041.

References

Abe, N.; Matsuda, M.; Domoto, K., 2012. Latest super critical boiler technology – Paiton III 865 MW coal fired boiler. Technical Paper presented at the Power-Gen Asia. October 3–5, Bangkok, Thailand.

Akagi, S.K., Yokelson, R.J., Wiedinmyer, C., Alvarado, M.J., Reid, J.S., Karl, T., Crounse, J.D., Wennberg, P.O., 2011. Emission factors for open and domestic biomass burning for use in atmospheric models. Atmos. Chem. Phys. 11, 4039–4072.

Andadari, R.K., Mulder, P., Rietveld, P., 2014. Energy poverty reduction by fuel switching. Impact evaluation of the LPG conversion program in Indonesia. Energy Policy 66, 436–449.

Bond, T.C., Streets, D.G., Yarber, K.F., Nelson, S.M., Woo, J.H., Klimont, Z., 2004. A technology-based global inventory of black and organic carbon emissions from combustion. J. Geophys. Res. 109, D14203. http://dx.doi.org/10.1029/2003JD003697.

Borsani, S.; Nesbitt, P.; Fedak, M.; Popelmayer, M.; Numasawa, Y.; Soekono, H., 2012. Capacity Upgrade, Rehabilitation, NOx Reduction, and Efficiency Restoration (CO_2 Reduction) of Suralaya Units 1 and 2. Technical Paper presented at the Power-Gen Asia, October 3–5. Bangkok, Thailand.

BPS, 2011a. Large and Medium Scale Manufacturing Industry Statistics. Indonesian Bureau of Statistics, Jakarta, Indonesia.

BPS, 2011b. National Indonesian Statistics. Provincial Statistics. Documents can be downloaded at. http://www.bps.go.id/.

Budya, Hanung, Arofat, M.Y., 2011. Providing clean energy access in Indonesia through the Megaproject of Kerosene conversion to LPG. Energy Policy 39, 7575–7586.

DEPHUB, 2011. Transportation Statistics. Ministry of Transportation of Republic of Indonesia, Jakarta. Retrieved from. http://gis.dephub.go.id/gallery/Foto/Buku/BUKU%20STATISTIK%20PERHUBUNGAN%20I.pdf.

EC-JRC/PBL, 2010. Emission Database for Global Atmospheric Research (EDGAR), Release Version 4.1. European Commission, Joint Research Centre/Netherlands Environmental Assessment Agency. http://edgar.jrc.ec.europa.eu.

EMEP/EEA, 2013. European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) Air Pollutant Emission Inventory Guidebook, 2013. European Environment Agency (EEA). Retrieved from. http://www.eea.europa.eu/publications/emep-eea-guidebook-2013.

ESDM, 2011. Oil and Gas Statistics. 2011. Ministry of Energy and Mineral Resources (ESDM) of Indonesia. Retrieved from. http://statistik.migas.esdm.go.id/index.php?r=publikasi/buku.

Enri, D., Wahyu, I.M., Ruslan, R., Tri, Padmi, 2009. Evaluation of municipal solid waste flow in the Bandung metropolitan area, Indonesia. J. Mater Cycles Waste Manag. 11, 270–276.

IPCC, 2006. Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories. Retrieved from. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

Jumar, Wandebori, H., 2012. Proposed strategy formulation and implementation for PT. XYZ. Indones. J. Bus. Adm. 1 (2), 66–74.

Kannari, A., Tonooka, Y., Baba, T., Murano, K., 2007. Development of multiple-species 1 km×1 km resolution hourly basis emissions inventory for Japan. Atmos. Environ. 41, 3428–3439.

Kim Oanh, N.T., Albina, D.O., Ping, L., Wang, X., 2005. Emission of particulate matter and polycyclic aromatic hydrocarbons from select cookstove–fuel systems in Asia. Biomass Bioenergy 28, 579–590.

Kim Oanh, N.T., Huy, L.N., Permadi, D.A., 2015. On-road Traffic Emission Inventory Using International Vehicle Emission Model for Bandung City, Indonesia. Final report: research for development of a co-benefit action plan. Research Cooperation between AIT, IGES and ITB, Bangkok, Thailand.

Klimont, Z., Cofala, J., Xing, J., Wei, W., Zhang, C., Wang, S., Kejun, J., Bhandari, P., Mathur, R., Purohit, P., Rafaj, P., Chambers, A., Amann, M., Hao, J., 2009. Projections of SO_2, NO_x and carbonaceous aerosols emissions in Asia. Tellus 61 (4), 602–617.

Kupiainen, K., Klimont, Z., 2007. Primary emissions of fine carbonaceous particles in Europe. Atmos. Environ. 41, 2156–2170.

Kurokawa, J., Ohara, T., Morikawa, T., Hanayama, S., Maenhout, G.J., Fukui, T., et al., 2013. Emissions of air pollutants and greenhouse gases over Asian regions during 2000–2008: regional Emission inventory in ASia (REAS) version 2. Atmos. Chem. Phys. 13, 11019–11058.

MoE, 2010. Indonesia Second National Communication under the United Nations Framework Convention on Climate Change (UNFCCC). Ministry of Environment of Indonesia, Jakarta, Indonesia.

Pentamwa, P., Kim Oanh, N.T., 2008. Air quality in Southern Thailand during haze episode in relation to air mass trajectory. Songklanakarin J. Sci. Technol. 30, 539–546.

Permadi, D.A., 2013. Assessment of Efficacy of Black Carbon Emission Reduction Measures and Co-benefit on Climate Forcing Mitigation and Air Quality Improvement in Southeast Asia. Asian Institute of Technology Dissertation, Pathumthani, Thailand.

Permadi, D.A., Kim Oanh, N.T., 2013. Assessment of biomass open burning emissions in Indonesia and potential climate forcing impact. Atmos. Environ. 78, 250–258.

Pertamina, 2012. Kerosene to LP Gas Conversion Program in Indonesia: a Case Study of Domestic Energy. PT Pertamina (Persero) & the WLPGA, France. Document retrieved from. http://fr.exceptionalenergy.com/uploads/Modules/Ressources/kerosene-to-lp-gas-conversion-programme-in-indonesia.pdf.

PLN, 2011. Indonesian National Electricity Corporate: Annual Statistics 2011. Retrieved from. http://www.pln.co.id/dataweb/STAT/STAT2011IND.pdf.

Randerson, J.T., van der Werf, G.R., Giglio, L., Collatz, G.J., Kasibhatla, P.S., 2015. Global Fire Emissions Database, Version 4, (GFEDv4). ORNL DAAC, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1293.

Reddy, M.S., Venkataraman, C., 2002a. Inventory of aerosol and sulphur dioxide emissions from India. Part I – fossil Fuel Combustion. Atmos. Environ. 36, 677–697.

Reddy, M.S., Venkataraman, C., 2002b. Inventory of aerosol and sulphur dioxide emissions from India. Part II – biomass combustion. Atmos. Environ. 36, 699–712.

Safrudin, A., 2016. Status and roadmap of vehicle emission standard: Supporting implementation and advancement of vehicle emission policies in Southeast Asia. Paper presented at Asia LEDs Partnerships, Manila, Philippines.

Shrestha, R.M., Kim Oanh, N.T., Shrestha, R., Rupakheti, M., Permadi, D.A., Kanabkaew, T., Salony, R., 2012. Atmospheric Brown Cloud (ABC) Emission Inventory Manual (EIM). United Nation Environmental Program (UNEP), Nairobi, Kenya. Document can be retrieved from. http://www.unep.org/delc/Portals/119/atmospheric/ABC_EIM.pdf.

Siangjun, K., 2014. Air Quality and Climate Co-benefits of Optimistic Scenarios for Vehicle Fleets over Bangkok Metropolitan Region. Asian Institute of Technology master thesis, Pathumthani, Thailand.

Streets, D.G., Bond, T.C., Carmichael, G.R., Fernandes, S.D., Fu, Q., He, D., et al., 2003. An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. J. Geophys. Res. 108 (D21), 8809. http://dx.doi.org/10.1029/2002JD003039.

Sukarno, I., Matsumoto, H., Susanti, L., 2016. Transportation energy consumption and emissions: a view from city of Indonesia. Future cities Environ. 2 (6) http://dx.doi.org/10.1186/s40984-016-0019-x.

SUSENAS, 2011. Guidance for National Socio-economic Survey 2011 (SUSENAS 2011). Indonesian Bureau of Statistics, Jakarta, Indonesia.

UNEP-WMO, 2011. Integrated Assessment of Black Carbon and Tropospheric Ozone. United Nation Environment Programme (UNEP) and World Meteorological Organization (WMO), Nairobi, Kenya.

US EPA, 2004. National Emission Inventory—ammonia Emissions from Animal Husbandry Operations. United States Environmental Protection Agency. Report retrieved from. https://www3.epa.gov/ttnchie1/ap42/ch09/related/nh3inventorydraft_jan2004.pdf.

US EPA, 2011. Updates on the 5th Editions of AP-42 Volume 1: Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources. Retrieved from. https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emission-factors.

Vongmahadlek, C., Thao, P.B.T., Satayopas, B., Thongboonchoo, N., 2009. A compilation and development of spatial and temporal profiles of high-resolution emissions inventory over Thailand. J. Air & Waste Manag. Assoc. 59 (7), 845–856.

Wiedinmyer, C., Yokelson, R.J., Gullet, B.K., 2014. Global emissions of trace gases, particulate matter, and hazardous air pollutants from open burning of domestic waste. Environ. Sci. Technol. 48 (16), 9523–9530.

World Bank, 2013. Indonesia: toward Universal Access to Clean Cooking. The World Bank Group, Washington DC, USA.

Zhang, J., Smith, K.R., Ma, Y., Ye, S., Jiang, F., Qi, W., Liu, P., Khalil, M.A.K., Rasmussen, R.A., Thorneloe, S.A., 2000. Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors. Atmos. Environ. 34, 4537–4549.

Zhang, Q., Streets, D.G., Carmichael, G.R., He, K.B., Huo, H., Kannari, A., Klimont, Z., Park, S., Reddy, S., Fu, J.S., Chen, D.L., Duan, Y., Lei, L.T., Wang, Yao, Z.L., 2009. Asian emissions in 2006 for the NASA INTEX-B mission. Atmos. Chem. Phys. 9, 5131–5153.