



Assessment of national emissions of air pollutants and climate forcers from thermal power plants and industrial activities in Vietnam



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ABSTRACT

This study developed a comprehensive emission inventory (EI) for thermal power plants (TPPs) and industrial activities in Vietnam for 2010. A combined top-down and bottom-up EI was conducted using fossil fuel consumption data of TPPs and industrial activities collected at the provincial level. Emission factors (EFs) were selected from literature considering the relevancy to the country emission sources. The best emission estimates, collectively from TPPs and industry activities, in Gg, was: 361 CO, 320 NO_x, 529 SO₂, 52 NMVOC, 13 NH₃, 266 PM₁₀, 79 PM_{2.5}, 2.6 BC, 4.7 OC and 105,856 CO₂, which were mainly contributed by the industrial activities. The range between low and high emission estimates were determined for each species and the largest ranges were found for BC and SO₂. Spatial emission distributions showed higher intensities over major economic zones of the country. The lowest monthly emissions were seen in February coinciding with the Lunar New Year holiday which were followed by the peaks in March when the economic activities resumed. The net GWP of the emissions in 20-yr CO₂ equivalent was 59.7 Tg with CO₂ emissions having the largest share (87%) followed by BC (6%), whereas sulfates were the main cooling agent. Fuel switching to natural gas would significantly reduce emissions from TPPs while better combustion and emission control technologies applied in small and medium industries would reduce emissions of PM species including BC. The emission database developed in this study can be used in dispersion modeling for air quality management studies in Vietnam.

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1. Introduction

High levels of air pollution observed in many places in Vietnam have raised a serious public concern due to the potential adverse effects on human health and crops (Mehta et al., 2013; Van et al., 2009; Hai and Kim Oanh, 2013; Danh et al., 2016). Similar to other developing countries in the region, rapid industrialization and urbanization in Vietnam have caused the environment deterioration. The high rates of fuel consumption, fossil and non-fossil, in Vietnam for transportation, cooking, energy production, industry and other activities, release large emissions of toxic air pollutants

and greenhouse gases (GHGs) to the atmosphere (MONRE, 2009; MONRE, 2010; MONRE, 2013a). Fuel combustion in industrial installations with backward technologies would release more pollutants that are associated with incomplete combustion such as black carbon (BC), an important short-lived climate forcing pollutant (SLCP) (Bond et al., 2013), and other toxic gases of carbon monoxide (CO), volatile organic compounds (VOCs) and semi-VOCs.

The rapid growth rate of the industrial sector in Vietnam is associated with its increased energy consumption, e.g. in 2010 the industrial sector shared 53% of the national energy consumption, as reported by the Institute of Energy (IE, 2011). Consequently, this requires more electricity generation, mainly thermal power energy that leads to high emissions of air pollution and GHGs, both directly from the industrial processes and indirectly from the increased thermal power generation. As of 2010, there were totally 293 industrial zones (IZs) which were more concentrated in the South with 65% (50% in the Southeast and 15% in Mekong River Delta), as compared to 21% in the North and 14% in the central region of the

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country (Vietnam Industrial Park and Investment Information Consulting Portal, [VIPIIP, 2010](#)). In the Northern Vietnam, as compared to other provinces, Hanoi, Bac Ninh and Hai Duong had more IZs, i.e. 14, 15 and 9 zones, respectively. In the central region of Vietnam, most of industrial activities were located in Quang Nam, Binh Dinh, Quang Ngai and Da Nang, i.e. with 8, 7, 6 and 6 IZs, respectively. In the Southern Vietnam, the highest concentrations of the industrial activities were observed in Long An, Dong Nai, Binh Duong and Ba Ria–Vung Tau provinces with 34, 31, 28 and 13 IZs, respectively. Ho Chi Minh City alone had 19 IZs while Can Tho City was the hub of industrial development in the Mekong River Delta with 10 IZs.

The Government of Vietnam approved one master plan for the industry sector development ([Decision 879/QĐ-TTg, 2014](#)) with an expectation of an annual growth rate of 6.5–7.0% until 2020 and 7.0–8.5% afterward (2021–2035). Accordingly, the increase of GHGs emission from the industrial sector was projected to increase by 4–4.5%/yr. The coal-fired thermal power generation was estimated to contribute 46.8% of the total electricity production in 2020 (with 67.3 million metric tons of coal consumption) and 56.4% in 2030 (with 171 million tons of coal consumption) ([Decision 1208/QĐ-TTg, 2011](#)). Some preliminary emission estimates showed that in 2006 the thermal power plants (TPPs) contributed 19% of nitrogen oxides (NO_x) and 30% of sulfur dioxide (SO_2) emissions, whereas the industry, service and domestic sectors collectively accounted for 15% of CO , 50% of NO_x and 66% of SO_2 in the national total emissions, respectively ([CAI–Asia, 2010](#)).

The annual average levels of the total suspended particles (TSP) at monitoring sites in many IZs exceeded the National Ambient Air Quality Standard (NAAQS) of $100 \mu\text{g}/\text{m}^3$ by 3–4 times. Normally, SO_2 and NO_2 levels in the surrounding areas of IZs were found lower than the NAAQS (both 24 h and annual average) ([MONRE, 2013a](#)). However, SO_2 levels measured at some big industrial facilities, such as the oil refinery factory (Dung Quat), large industrial plants with boilers or near TPPs, were reported exceeding the annual NAAQS of $50 \mu\text{g}/\text{m}^3$ ([MONRE, 2013a](#)).

The current environmental management status of many IZs, especially related to air pollution, in Vietnam is still not yet fully characterized. The air quality management in areas surrounding IZs therefore has recently gained increasing attention from the governmental authority ([VEA, 2015](#)) hence several policies/decisions directly or indirectly addressing the air quality management topics have been introduced, such as the issuance of the revised ambient air quality standards (QCVN 05: 2013/BTNMT) ([MONRE, 2013b](#)), the climate change mitigation and adaption decision ([Decision 9792/QĐ-BCT, 2014](#)), the waste management decree ([Decree 38/2015/NĐ-CP, 2015](#)). Specifically for air pollution control purposes, [Decision 22: 2009/BTNMT, 2009](#), has been issued to provide the national technical regulations on the emissions from the thermal power production. However, the implementation of the regulations was not progressing as required and the roles of related parties have not yet been clearly defined. According to [MONRE \(2013a\)](#), there are several existing issues of the environmental management for IZs in Vietnam, such as the lack of clear responsibilities assigned to the related management offices of the environmental protection agencies and IZ authorities at provincial level.

A comprehensive emission inventory (EI) database is required to clearly show the contributions of the industrial sources (power generation and manufacturing industries) to the national emissions so as the priority can be set for the emission control efforts. Emissions from the industrial sector in Vietnam have been reported in several regional or global EI databases, such as the Global Atmospheric Research (EDGAR) available for 2008–2010 ([EC-JRC/PBL, 2013](#)), the Center for Global and Regional Environmental Research

(CGRER) available for 2000–2006 ([Streets et al., 2003; Zhang et al., 2009](#)) and the Regional Emission Inventory in Asia (REAS) available for 2000–2008 ([Ohara et al., 2007; Kurokawa et al., 2013](#)). The top-down approach was mainly applied in producing these regional and global EI databases. Improvement of the EI databases for a more recent base year and with the use of local activity data collected at the national level is always strongly desired for the air quality management purposes.

In Vietnam, there were several efforts, mainly through the academic research, to produce EI at urban scales, but not specifically for the industry sector, e.g. for Hanoi by [An \(2005\)](#) and for Ho Chi Minh City by [Tuan \(2003\)](#). The emissions in IZs in 2009 were also estimated by [MONRE \(2013a\)](#) for four key pollutants of NO_x , SO_2 , non-methane VOC (NMVOC) and TSP. Therefore, in this study we aimed to develop a national EI of TPPs and industrial facilities for Vietnam for the base year of 2010. Multiple species were considered, including toxic gases of CO , SO_2 , NO_x , ammonia (NH_3), NMVOC, and aerosol species of PM_{10} (particulate matter with aerodynamic diameters $\leq 10 \mu\text{m}$), $\text{PM}_{2.5}$ (diameters $\leq 2.5 \mu\text{m}$), BC and organic carbon (OC). Major GHGs of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were also included in this EI work.

2. Methodology

This study considered emissions from the TPPs (fuel combustion only) and industry (fuel combustion, non-fuel combustion and manufacturing/process activities). The emission factors (EFs) used in this study were extracted from the compiled database presented in the Atmospheric Brown Cloud–Emission Inventory Manual (ABCEIM) by [Shrestha et al. \(2013\)](#). ABCEIM has included EFs from several databases including the AP-42 ([USEPA, 1995](#)), [EMEP/CORINAIR \(2006\)](#) and [IPCC \(1997\)](#), as well as available measurement data reported for various sources in Asia. For TPPs and the industrial fuel combustion, ABCEIM has extracted the relevant EFs from [IPCC \(1997, 2006\)](#), AP-42 ([USEPA, 1995](#)), [Bond et al. \(2004\)](#), [Kato and Akimoto \(1992\)](#), [Battye et al. \(1994\)](#), [Hangebrauck et al. \(1964\)](#) and [APEG \(1999\)](#), [EMEP/CORINAIR \(1992\)](#), [Streets et al. \(2001\)](#), [Reddy and Venkataraman \(2002\)](#), [Ge et al. \(2001\)](#), and [Kupiainen and Klimont \(2007\)](#). For industrial non-fuel combustion and process activities, beside the above mentioned data sources, ABCEIM also compiled the available EFs measured in Asia, e.g. brick kiln emissions in Vietnam measured by [Le and Kim Oanh \(2009\)](#). Our EI results were compared with those extracted for Vietnam from the available EI databases of EDGAR in 2008–2010, CGRER in 2006 and REAS 2.1 in 2008. The specific emissions from TPPs in Vietnam, in g/kWh, were also estimated and compared with the international emission norms.

2.1. Economic zones in Vietnam

Vietnam covers a total area of $331,690 \text{ km}^2$ (<http://www.chinhphu.vn/portal/>) and had a population of about 90.7 million in 2014, with 67% living in rural areas (General Statistics Office of Vietnam, [GSO, 2014](#)). Vietnam has 58 provinces and 5 large cities that are considered equivalent to provinces (Hanoi, Hai Phong, Da Nang, Ho Chi Minh and Can Tho). There are 8 major geographical regions and 3 key economic zones in the country (detailed in [Fig. S1](#), Supporting Material (SM)). The northern key economic zone includes Hanoi and Hai Phong cities, and 5 provinces of Quang Ninh, Hai Duong, Bac Ninh, Hung Yen and Vinh Phuc. The central Vietnam key economic zone includes Da Nang city and 4 provinces of Thua Thien Hue, Quang Nam, Quang Ngai and Binh Dinh. The southern key economic zone includes Ho Chi Minh City and 7 provinces of Dong Nai, Binh Duong, Ba Ria–Vung Tau, Binh Phuoc, Tay Ninh, Long An and Tien Giang.

The TPPs in Vietnam were mainly concentrated in the Northern and Southern regions with only 2 TPPs located in the central region, as seen by the locations in Fig. S2, SM. The TPPs located in the Northern Vietnam were mainly coal-fired while those in the Southern Vietnam used natural gas (NG) or fuel oil. Most of TPPs in the Northern Vietnam are of large scale thus consuming high amounts of fossil fuels (coal) hence resulting in high emissions. In addition, the TPPs in Vietnam are mainly located in the surrounding areas of the key economic zones thus may additionally contribute to the deterioration of air quality in these populated areas.

2.2. Emission calculation

2.2.1. Thermal power plants

This study considered only the fuel combustion emissions in TPPs hence the emissions from other power generation sources, such as hydro power or wind power were not included. The information of existing TPPs and fossil fuel types (coal, oil and NG) use was extracted from relevant documents, i.e. Decision 0152/QĐ-BCT (2011), IE (2011), Hoang (2008), and the Vietnam Electricity (personal communication; EVN, 2016) and is summarized in Table S1, SM. Totally, there were 24 TPPs in Vietnam operated in 2010 with 11, 2 and 11 facilities located in the key economic zones of Northern, Central and Southern regions, respectively, as shown in Fig. S2, SM. Totally, 12 coal-fired TPPs (with total designed capacity of 3941 MW (Megawatt-MW), 5 NG-fired TPPs (capacity of 4741 MW) and 8 oil-fired TPPs (2740 MW).

The emissions from each TPP were estimated using the fuel consumption (activity data) and EFs taking into account the emission control efficiencies (Equation S(1), Text box S1, SM). The EFs of fossil fuel combustion in TPPs, i.e. coal, oil and NG, summarized in Table S2 (SM), were extracted from those compiled in ABCEIM (Shrestha et al., 2013) as detailed above. The TPPs in Vietnam were reported to have equipped with certain control devices, mainly for the PM removal (hence also BC and OC), but some were largely out-of-date hence having low removal efficiencies (MONRE, 2013a). Detailed information on the control devices used in each TPP of Vietnam was not available; hence, the EC, OC emission control efficiencies of 80% were assigned to all TPPs, i.e. similar to the value used for an EI for Thailand (Pham et al., 2008). For PM emission control, we applied a 94% removal efficiency of scrubbers for all TPPs. For SO₂, the control efficiency of 80% was assigned for TPPs using oil, and a higher efficiency of 90% for TPPs using coal and NG assuming their generally larger sizes than oil-fired TPPs (Pham et al., 2008). However, two old coal-fired TPPs (Pha Lai 1 and Ninh Binh) were old hence we assumed no emission control for these TPPs (<http://tuoitre.vn/tin/chinh-tri-xa-hoi/20161114/siet-quan-ly-du-an-nhiem-dien-gay-o-nhiem/1219078.html>). The information on the end-of-the pipe control devices for NO_x in TPPs was not provided in any published documents, e.g. MONRE (2013a), we therefore assumed a zero degree of emission control of the pollutant. The rough assumption on the routine operation of the installed control devices along with their removal efficiencies may be a source of uncertainty of our EI results for the TPPs in Vietnam, hence future studies should collect relevant information on the control devices to improve the database.

Details on the amounts of fuel consumed by each TPP in 2010 was not readily available hence need to be estimated using available information. For coal-fired TPPs, we used the data on the unit fuel consumption (fuel consumed per kWh electricity generated) in 2010 from an unpublished report (personal communication) of the Vietnam Electricity (EVN, 2016). There were mainly two coal combustion technologies used in TPPs in Vietnam, the pulverized coal and the circulating fluidized bed (CFB), see details in Table S1a, SM. Two types of coal were used, the anthracite and the sub-

bituminous coal. The unit coal consumption appeared to vary among the TPPs depending on both the capacity and the combustion technology. The unit coal consumption was lower for CFB (618 ± 44 g coal/kWh) and higher (with more fluctuations) for the pulverized coal combustion (673 ± 232 g/kWh).

For the oil-fired TPPs, the data on fuel consumption per unit electricity generated (g/kWh) was extracted from the information available for the Hiep Phuoc and Thu Duc TPPs (Huy, 2008). Several oil-fired TPPs (Dung Quoc, Can Tho, O Mon, Bourbon, Ca Mau) had no data on the unit oil consumption, hence the average value obtained for the oil-fired TPPs in Vietnam (248 g/kWh) was used to calculate their annual oil consumption rates (http://www.noccp.org.vn/Data/vbpq/Airvariable_ldoc_vnHe%20so%20phat%20thai%202008.pdf). For the gas-fired TPPs, we also used the unit gas consumption of 172 g/kWh in Vietnam for 2010 (personal communication; EVN, 2016) to estimate the annual NG consumption of Ba Ria and Vedan gas-fired TPPs, respectively. The total annual fuel consumption in all TPPs in 2010 was 10.5 million tons of coal; 7.3 million tons of NG and 1.27 million tons of oil (Table 1).

2.2.2. Industrial facilities

A combined top-down and bottom-up approach was used in the EI for the industrial facilities to produce the emission estimates at the provincial level. Two categories of the industrial activities were considered, the fuel combustion activities (category 1) and non-fuel combustion and process activities (category 2). Table S3, SM provides the information of industrial groups in each category. In Vietnam, the industrial activities were taking place both inside IZs (mainly with large industries) and outside IZs (including factories and craft villages). In principle, to comply with the national environmental regulations, all factories located inside or outside IZs should install the emission control devices. The combustion facilities in various craft villages, e.g. for brick or pottery production, commonly were not equipped with suitable emission control technologies, hence they can generate significant emissions. There was no comprehensive record on the fuel consumption of every factory and craft village. This study therefore used the national fuel consumption along with the industrial productivity to estimate the total national emissions from the fuel combustion activities in the industry (both inside and outside IZs) and in craft villages (outside IZs).

Accordingly, under category 1, all industries having fuel combustion (used for boilers, gas turbines, stationary engines, flare stacks, furnaces, palletizing sinter plants, and so on) are listed and they are grouped into iron & steel, non-ferrous metal, cement, brick, chemicals, pulp & paper and “others” industries. Under category 2, the non-fuel combustion and process activities releasing air pollution are listed, i.e. mineral products, metal production, pulp & paper, chemicals and food & beverage. These emissions are mainly from manufacturing processes, for example, SO₂ from a copper smelting and PM from activities of materials transportation, loading and handling. In addition, there was also combustion of certain types of materials (not fuel), for example burning by-products in the pulp & paper industry, which was also included in this category (see EFs in Table S5, SM).

Note that most industries have both category 1 (fuel combustion) and category 2 (non-fuel combustion and process activities) hence they were included in both categories. For example, cement, brick or pulp & paper industries would have fuel combustion activities covered in category 1, and non-fuel combustion and process activities covered under category 2. All the activity data were scrutinized to avoid any omission and/or double counting.

2.2.2.1. Category 1: industrial fuel combustion. The fuel combustion in industries of iron & steel, non-ferrous metal, cement, brick, chemicals, pulp & paper and “others” (listed in Table S3, SM) is

Table 1

Summary of national activity data from thermal power plants and industrial sector in 2010, Kt/yr if not otherwise specified.

Thermal power plant	Combustion activity (category 1)	Non-fuel combustion and process activity (category 2)
Coal: 10,482	Coal: 18,483	Mineral product: 112,380
Natural Gas: 7323	Natural gas: 47	Metal products and pulp & paper: 4373
Oil: 1269	Liquefied Petroleum Gas: 198	Chemicals: 2102
	Kerosene: 9	Beverage: 2,974,908 (m ³ /yr)
	Diesel oil: 1290	Food: 13,360
	Heavy fuel oil: 755	
	Wood: 12	
	Unspecified primary solid biomass: 3015	

Detail activity data is given in [Tables S4 and S6](#), SM.

considered in this category. The details on fuel types and fuel consumption rates of industrial boilers and other machineries of each industrial facility were not available. Therefore, the emission was estimated based on the information of the total fuel consumption by each industry group and the capacity of every facility of the group. The information on the coal consumption by every industry group was obtained from [Can \(2007\)](#) while the consumption of other fuel types was taken from [Factfish website \(2010\)](#) which included NG, liquefied petroleum gas (LPG), diesel oil (DO), heavy fuel oil (FO), kerosene, wood and other unspecified biomass. The fuel consumption rates were converted to Terra joule (TJ/yr) to be compatible with the EFs units of ABCEIM. The provincial productivity of each industrial group and the production capacity of large factories were collected from the provincial statistical yearbooks and other available on-line data sources.

Totally, the industrial fuel combustion (category 1) in the whole country utilized 683,201 TJ/yr with the following shares: 5% by iron & steel industry, 1.3% by non-ferrous metal, 24% by cement, 36% by brick, 8.4% by chemical, 1.1% by pulp & paper, and 29.2% by “others”. The latter, i.e. “others”, consisted of several industries (listed in the group number 1.7, [Table S3](#), SM) which had no detailed fuel consumption provided in the statistical yearbooks. Therefore, [Equation S\(2\) \(Text box S1, SM\)](#) was used to segregate the country total fuel consumption by this group to each province based on the ratio between the industrial land area of a province and the national total industrial land area. The industrial fuel consumption in each province, i.e. the key activity data, is given in [Table S4](#), SM. Annually, the total fuel consumed by all industrial combustion activities in Kilotons (Kt/yr) were 18,483 of coal; 47 of NG; 198 of LPG; 9 of kerosene; 1290 of DO; 755 of FO; 12 of wood and 3015 of unspecified primary solid biomass ([Table 1](#)). Thus, the major types of fuel consumed in the industrial sector was coal, DO and FO.

The emission calculation was done using the same [Equation S\(1\) \(Text box S1, SM\)](#) as for TPPs. For the emission control efficiency, this study followed the suggestions in ABCEIM and assumed that the cement and pulp & paper industries generally had lime/limestone wet scrubbers with removal efficiencies of 90% for SO₂, and electrostatic precipitators (ESP) with a removal efficiency of 99.2% for PM, 98% for BC and 96% for OC. The EFs and sulfur content (S, %) of fuel used in the industrial combustion were also based on values provided in ABCEIM and are summarized in [Table S5](#), SM.

2.2.2.2. Category 2: non-fuel combustion industrial emission.

This category included the emission from non-fuel combustion and manufacturing process activities in the facilities under the groups of mineral products, metal, pulp & paper, chemical industry, and food & beverage industry ([Table S3](#), SM). As mentioned earlier, the emissions for this category were calculated using the annual productivity of the corresponding facilities ([Equation S\(3\), Text box S1, SM](#)). The production data of all industrial facilities in each province was taken from the respective provincial statistical yearbooks and

other related on-line sources, and are summarized in [Table S6a&b](#), SM. The EFs used for this activity category were extracted from those compiled in ABCEIM and are presented in [Table S5](#), SM. The national industrial productivity data, extracted from the published information by the Ministry of Industry and Trade ([MOIT, 2010](#)) and General Statistics Office of Vietnam ([GSO, 2010](#)), was used for cross-checking with the sum of all provincial activity data. Due to lack of the information on the installation and operation of emission control devices and also a general lack of such devices in the industrial facilities in the country we assumed a zero control efficiency for these activities.

The obtained activity data showed that, as of 2010, the total industrial production in Kt/yr was 112,380 for mineral products; 4373 for metal products and pulp & paper; 2102 for chemicals and 13,360 for food & beverage industries. Among the mineral products group, the cement production was 59,513 kt/yr, which was slightly higher (by 6.2%) than the data given by [GSO \(2010\)](#). This study also obtained higher production rates for other industries, i.e. by 10.1% for brick, 18.4% for sugar, 6.3% for animal feeds and 19.7% for coffee products as compared to [GSO \(2010\)](#). The beverage product volume was estimated to be >2.9 million cubic meter (m³) in 2010 ([Table 1](#)), which was 7.4% higher than the data given by [GSO \(2010\)](#). More details on productivity data estimated for Vietnam in 2010 are provided in [Text box S2](#), SM.

2.3. Emission estimates range

The emission results are presented as the low, best and high estimates for each species. The range of emission results was produced using the range of activity data and the range of available EFs. As the activity data used in this study (fuel consumption and productivity) was from the national and provincial statistics, we assumed an uncertainty level of 5% based on a suggestion by [IPCC \(2000\)](#) that the national statistical data would be more accurate than the international estimates (which were suggested to have an uncertainty of 10%). The ranges of EFs and the most probable EF value for each pollutant emitted from a facility were extracted from those compiled by ABCEIM. The most probable EF and the activity data level (AL) were used for the best estimate. The lowest EF was combined with the 0.95*AL for the low estimate while the highest EF was combined with 1.05*AL for the high estimate.

2.4. Temporal variation

The temporal variation of emissions is important for applications of air quality models. In this study, the monthly emissions variation from the power generation was determined based on the monthly electricity production of the power plants ([Decision 0152/QĐ-BCT, 2011](#)). The monthly emission variation from the industrial activities was calculated using the monthly industrial production rates (<http://ndh.vn/gia-tri-san-xuat-cong-nghiep-nam-2010->

tang-14-2591726p4c145.news). The hourly variations of emissions for different species would be more relevant input for air quality modeling purposes but these have to be generated using more detailed future survey data for the industrial sources in Vietnam.

2.5. Global warming potential of emission

The global warming potential (GWP) metric has been widely used to assess the relative radiative forcing effects of an emission of a species to that of CO₂, i.e. as CO₂ equivalent over a specific integration time period (20, 50 or 100 years). The GWP values of GHGs (CO₂, N₂O and CH₄), ozone precursors (CO, VOC and NO_x), and SCLPs (BC, OC and sulfate particles) over the 20-year horizon (Table S7, SM) were used in this study. The amount of sulfates, i.e. the secondary PM produced in the atmosphere from SO_x was assumed to be 2 times as much as the amount of SO₂ emitted, which was commonly used for the assessment of the potential of climate impacts (Fuglestedt et al., 2010). Note that in reality only a part of SO_x would be transformed to the atmospheric sulfate particles.

3. Results and discussion

3.1. Total national emission of power generation and industry

The national total emission of major species in Gg in 2010 (Gg/yr) was: 361 CO, 320 NO_x, 529 SO₂, 52 NMVOC, 12.9 NH₃, 266 PM₁₀, 79 PM_{2.5}, 2.6 BC, 4.7 OC, 7.2 CH₄, 1.5 N₂O and 105,856 CO₂ (Table 2). The industrial activities, collectively both categories 1 and 2, had higher contributions of all species as compared to the TPPs, i.e. from 1.1 to 127 times as much, especially for CO, NMVOC, NH₃ and aerosol species (Table 2). The GHGs emissions from the industry were also significantly above those from TPPs, i.e. about 1.4 times for CO₂, 11 times for CH₄ and 1.8 times for N₂O.

Fig. 1 presents the emissions from different regions in Vietnam which showed that the Red River Delta, Northeast (in the North) and Southeast region (in the South) contributed most of the national emissions. The Red River Delta region had most significant shares in the national emissions of NO_x, PM_{2.5}, BC, OC, CO₂, CH₄ and N₂O of 33%, 40%, 34%, 43%, 31%, 32% and 28%, respectively. The second highest shares in the national emissions were from the Southeast region with the corresponding contributions of the listed species of 21%, 14%, 20%, 19%, 24%, 22% and 28% shares, respectively. The third highest contributions were from the Northeast region, sharing respectively 20%, 15%, 13%, 14%, 18%, 12% and 14% of the national total emission of the listed species. The SO₂ emissions were largely from the Red River Delta and Northeast region with a share of 44% and 20%, respectively. The emissions of CO, NH₃,

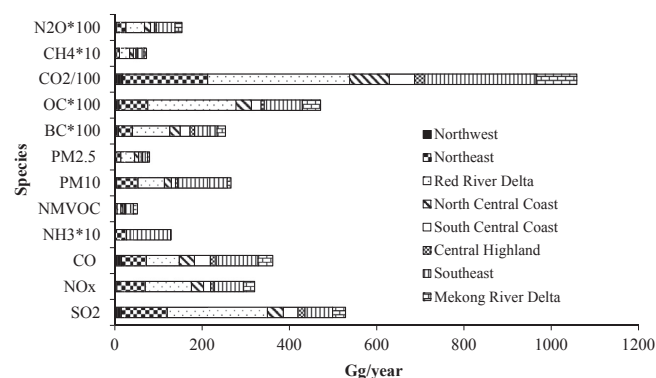


Fig. 1. Total emission from thermal power plants and industry in Vietnam (best estimates) with shares by regions (specified in Fig. S1, SM).

NMVOC and PM₁₀ were more from the Southeast region, i.e. sharing 27%, 78%, 35% and 43%, respectively. The remaining regions (Northwest, Northeast, North Central Coast, South Central Coast, Central Highland, Mekong River Delta with the locations shown in Fig. S1, SM) had only small shares in the national total emissions estimated for the TPPs and industry.

The total national emissions from TPPs and industry obtained in this study are presented in Table 3 along with the emissions from the same sectors extracted for Vietnam from available EI databases of EDGAR in 2008–2010, CGRER in 2006, REAS 2.1 in 2008 and MONRE in 2009 (MONRE, 2013a). The emission results from different databases are generally comparable but MONRE (2013a) provided the highest estimates for the four inventory species (base year of 2009) as compared to other databases. Overall, among all the databases presented in Table 3, our emission estimates for the CO, NMVOC and CH₄ were closer to EDGAR values than to other databases. Specifically, as compared to REAS2.1 values our estimates were closer for SO₂, PM₁₀ and N₂O but lower for PM_{2.5}, BC, OC and CH₄. As compared to our results, CGRER (2006) values were significantly higher for NMVOC, PM₁₀ and PM_{2.5}, but significantly lower for CO, NO_x and SO₂. The differences between the presented EI databases were expected because of the differences in the activity data, that are related closely to the EIs base years and the degrees of the incorporation of the local data, as well as the EFs used and the assumed control efficiencies. Our study used more bottom-up activity data, i.e. including the survey results, than other international databases hence is expected to produce more realistic EI results. In the following subsections, our EI results are analyzed separately for the TPPs and industrial facilities to provide further insight into their contributions.

Table 2

Annual emission (Gg/yr) from thermal power plant and industry sector in Vietnam, 2010.

Species	Thermal power plant	Industry			Total
		Fuel combustion (cat. 1)	Non-fuel combustion & process (cat. 2)	Industry total	
CO	11.3	350	—	350	361
NO _x	141	173	6.20	179.2	320
SO ₂	142	208	179	387	529
NMVOC	2.29	12.9	36.4	49.3	51.6
NH ₃	0.49	0.06	12.3	12.4	12.9
PM ₁₀	19.3	61.6	185	246.6	266
PM _{2.5}	8.01	29.1	42.2	71.3	79.3
BC	0.02	2.04	0.50	2.54	2.56
OC	0.10	1.06	3.55	4.61	4.71
CO ₂	44,776	61,080	—	61,080	105,856
CH ₄	0.60	6.63	—	6.63	7.23
N ₂ O	0.53	0.98	—	0.98	1.51

(—) EFs were zeros in literature, may be because the values are too small as compared to those from fuel combustion.

Table 3

Total emission estimates for TPP and industry of Vietnam (Gg/yr) by different EI databases with base year indicated in brackets.

Species	This study (2010)	EDGAR (2008–2010)	CGRER (2006)	REAS 2.1 (2008)	MONRE (2009) ^b
CO	361	407	128	76.8	–
NO _x	320	175	138	179	656
SO ₂	529	326	268	341	1117
NM VOC	51.6	31.0	103	15.5	268
NH ₃	12.9	0.44	–	5.89	–
TSP	–	–	–	–	673
PM ₁₀	266	145	630	262	–
PM _{2.5}	79.3	–	420	145	–
BC	2.56	–	1.90	7.40	–
OC	4.71	–	1.40	16.7	–
CO ₂	105,856	85,261 ^a	–	85,856	–
CH ₄	7.23	5.10 ^a	–	16.6	–
N ₂ O	1.51	0.90 ^a	–	1.67	–

– Not available.

^a Data in 2010.^b Emission estimate for 2009 by MONRE (2013a).

3.1.1. Emission from thermal power plants

Table 2 showed that totally, in 2010, the TPPs in Vietnam emitted significant amounts of SO₂ and NO_x, i.e. 142 and 141 Gg/yr, respectively. The PM₁₀ and CO₂ emissions amounts were more significant than other listed species, i.e. 19.3 and 44,776 Gg/yr, respectively. Detailed emission results for each TPP are presented in Fig. S3, SM. A previous EI for the TPPs in 2009 produced by the Institute of Energy (IE, 2011) showed a similar annual emission results with ours for CO₂, but about 2 times lower than ours for NO_x, SO₂ and PM₁₀ (other species were not covered in that study).

The TPPs emissions for most species were largely contributed by the coal-fired TPPs, except for CO, NH₃, N₂O and CH₄ for which the gas-fired TPPs had more contributions (Table 4). Specifically, the coal-fired TPPs were the major sources of SO₂, NO_x, PM₁₀, PM_{2.5} and OC, contributing 65–99% varying with species. The oil-fired TPPs were also considerable sources of SO₂ and BC. The EFs per unit of the energy produced (g/kWh) of three fuel types of TPPs were calculated and compared with the information extracted from the literature (Table 4). It is clearly seen that in order to produce 1 kWh of electricity, the coal- and oil-fired TPPs emitted significantly higher amounts of air pollution compared to NG-fired TPPs. For example, to produce 1 kWh of electricity, the coal- and oil-fired TPPs respectively emitted about 7.1 g and 4.7 g SO₂, 5.2 g and 3.4 g NO_x, and 1433 g and 1049 g CO₂, as compared to 0.0002 g SO₂,

0.82 g NO_x and 250 g CO₂ from the NG-fired TPPs. Hence, by a fuel switching to NG, the electricity generation would be much cleaner. If coal and oil are still used in TPPs then more effective emission control measures should be applied to reduce the emissions. The EFs per unit of electricity generation (g/kWh) obtained by this study were in similar ranges of those reported by IPCC (2012). Our average EF of SO₂ from coal-fired TPPs, for example, was in the range reported for India (Mittal, 2012). The average EFs for the TPPs in Vietnam obtained in this study were higher than the US reported values (de Gouw et al., 2014) for coal-fired TPPs but lower for gas-fired TPPs (Table 4).

3.1.2. Emission from industrial facilities

The industrial facilities in 2010 generated the total emissions in Gg/yr of 386 SO₂, 179 NO_x, 350 CO, 49 NM VOC, 12 NH₃, 246 PM₁₀, 71 PM_{2.5}, 2.5 BC, 4.6 OC and 61,080 CO₂. Fig. S4, SM presents the emission shares between the fuel combustion (category 1) and non-fuel combustion and process activities (category 2). The fuel combustion activities (category 1) contributed the absolute majority of CO and CO₂ emissions, as expected, and most of SO₂ (54%), NO_x (97%) and BC (81%). There was combustion of materials or by products (not defined as fuel), such as those in the pulp & paper industry, hence contributing some BC and OC emissions. It is expected that other emissions (CO, CO₂, VOC, etc.) should also be

Table 4

Emissions of TPPs by fuel types (Gg/yr) and by unit electricity generated (g/kWh).

Species	Vietnam TPP emission (Gg/yr) in 2010 (This study)			Emission per kWh (g/kWh)								
				Vietnam, 2010 (This study)			India ^a (2001–10)	US ^b (1995–2012)		IPCC (2012) ^c		
Fuel	Coal	Gas	Oil	Coal	Gas	Oil	Coal	Coal	Gas	Coal	Gas	Oil
SO ₂	124.4	0.01	17.9	7.083	0.0002	4.716	6.9–7.2	0.1–0.9	0.01–1.0	0.5–7.5	0–6	1.0–14.5
NO _x	91.8	36.5	12.8	5.228	0.817	3.374	4.2–4.4	0.7–2.0	0.5–1.3	1.0–4.0	0.2–2.0	1.0–4.5
CO	3.06	7.44	0.77	0.174	0.167	0.203	—	—	—	—	—	—
NM VOC	1.33	0.71	0.26	0.076	0.016	0.068	—	—	—	—	—	—
PM ₁₀	18.8	0.56	0.02	1.068	0.013	0.006	—	—	—	—	—	—
PM _{2.5}	7.94	0.06	0.01	0.452	0.001	0.003	—	—	—	—	—	—
BC	0.013	0.0001	0.010	0.0008	3.33E-06	0.003	—	—	—	—	—	—
OC	0.096	0.0014	0.004	0.005	3.17E-05	0.001	—	—	—	—	—	—
NH ₃	0.0001	0.49	0.01	4.2E-06	0.011	0.001	—	—	—	—	—	—
CO ₂	25,172	15,616	4250	1433	350	1049	910–950	900–1000	550–600	700–1700	255–900	500–1200
CH ₄	0.16	0.29	0.16	0.009	0.007	0.041	—	—	—	—	—	—
N ₂ O	0.21	0.29	0.03	0.012	0.007	0.008	—	—	—	—	—	—

^a Estimates of Emissions from Coal-fired Thermal Power Plants in India (Mittal, 2012).^b Estimated using figures given in de Gouw et al. (2014). Reduced emissions of CO₂, NO_x, and SO₂ from U.S. power plants owing to switch from coal to natural gas with combined cycle technology.^c Estimated using figures given in IPCC (2012). Renewable Energy Sources and Climate Change Mitigation Special Report of the Intergovernmental Panel on Climate Change.

released from this combustion activity but the amounts should be relatively small as compared to the fuel combustion hence were neglected (i.e. EFs of zeros were found in literature, Table S5, SM). The non-fuel combustion (category 2) significantly contributed to the emissions of NH_3 , NMVOC, $\text{PM}_{2.5}$ and OC, i.e. sharing 100%, 74%, 59% and 77%, respectively. Emissions of NH_3 were mainly from the fertilizers production and chemical industries. The PM emissions from category 2 industrial activities were higher than that from category 1. This was mainly because of several industrial activities belonging to category 2, such as mineral products and chemical industry (fertilizer production), contributed significant PM amounts, especially PM_{10} , as discussed below.

3.1.2.1. Fuel combustion (category 1). The SO_2 emission was mainly contributed by the brick manufacturing (110 Gg/yr), followed by “other” industries (56 Gg/yr). The cement industry, brick manufacturing and the “others” group collectively emitted above 147 Gg/yr of NO_x (85% of the total NO_x emission of category 1). The “others” industry group also predominantly contributed to CO and OC emissions with more than 230 and 0.7 Gg/yr, respectively (Fig. S5, SM). The fuel combustion activities in the brick manufacturing contributed 0.9 Gg/yr of BC emission, 5 Gg/yr of NMVOC, 41 Gg/yr of PM_{10} and 17 Gg/yr of $\text{PM}_{2.5}$.

Thus, the brick manufacturing and the “others” industry group were the main emission contributors of the category 1 industrial activities (Fig. S5, SM). The Government Decision 567/QĐ-TTg (2010) imposed a regulation of phasing out, by 31/12/2010, the applications of simple brick kilns technologies. However, many brick manufacturing villages in several provinces (Bac Giang, Phu Tho, Ha Noi, Ha Nam and Thai Nguyen) still continued the use of simple and polluting brick kilns after that date (MONRE, 2013a). It is expected that when the out of date brick kiln technologies are completely removed the emission from this industrial activity would be significantly reduced.

3.1.2.2. Non-fuel combustion and process (category 2). Four main groups of industries were considered in this category which included the mineral products, metal and pulp & paper industry, food & beverage and chemical industry. Major SO_2 emitters were the mineral products (92 Gg/yr) followed by the metal and pulp & paper industry (44 Gg/yr) and chemical industry (42 Gg/yr), as seen in Fig. S6, SM. The ‘mineral products’ industry was also the largest emission contributor for $\text{PM}_{2.5}$ (42 Gg/yr), BC (0.4 Gg/yr) and OC (2.7 Gg/yr). NMVOC was mainly emitted by the food & beverage industry, 27 Gg/yr or roughly 74%. The chemical industry was the only source of NH_3 (12.3 Gg/yr) and this was linked to the fertilizer production. The chemical group also contributed most of PM_{10} emission (118 Gg/yr), mainly from the urea fertilizer production, followed by the mineral products with the PM_{10} emission of 64.5 Gg/yr. NO_x emissions were mainly from the metal and pulp & paper industry (4.7 Gg/yr) followed by the chemical industry (1.5 Gg/yr).

3.2. Ranges of emission estimates

The EI results discussed above are the best estimates which are also presented in Fig. 2 along with the low and high estimates. The ranges of the emission estimates reflect the uncertainty of the EI data. In our study this range was mainly determined by the range of the available EFs of each species as the activity data was assumed to have a 5% uncertainty. The ranges of emission results were calculated for both industrial activities and TPPs. The ratio between the difference between the low and high estimates to that of the best estimate, i.e. $[(\text{High} - \text{Low})/\text{Best}]$, for each species is used to express the uncertainty. The results varied with the inventory species and

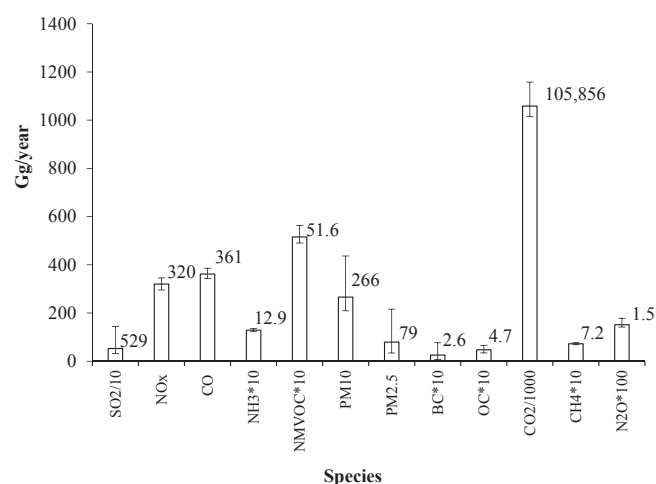


Fig. 2. Emission estimate ranges of inventory species (the best estimate values and the ranges between high and low estimates).

were from -4% to 203% . The highest emission range was found for BC, for which only a few EFs values were available but varying widely. The second largest range was for SO_2 (172%) which was mainly due to the large variation ranges of the S content of fuel. Smaller variation ranges were obtained for NO_x , CO, NH_3 , NMVOC, CO_2 , CH_4 and N_2O emission results, i.e. from -7% to 18% .

One of the major sources of the uncertainty in the EI results was the lack of the country-specific EFs for the industrial and power generation for Vietnam. The EFs values used in this study were scrutinized from the international databases for the most possible relevancy but the locally measured EFs are still much desired. Thus, future studies should focus on development of the local EFs to produce better emission estimates for the country. In addition, lack of the information on the emission control devices with their actual operation status and removal efficiencies also contributed to the uncertainty in the EI results. The assumption on the similarity of emission control efficiencies with those used for a Thailand study (Pham et al., 2008) could be partly justified due to the similarity in the industrial development and climatic conditions. In addition, large industries in Vietnam, especially those belonging to established international groups, also use international technologies for the emission control. However, future efforts should collect the relevant information on the emission control devices from the TPPs and large industrial facilities to improve the EI results.

3.3. Spatial emission distribution

The provincial distributions of the annual emissions of selected pollutants of SO_2 , PM_{10} , NO_x and $\text{PM}_{2.5}$ are given in Fig. 3, while Fig. S7a&b, SM shows the emission distributions of other species. The disaggregation of emissions was based on the administrative boundary of 63 provinces/cities in Vietnam. It is clearly seen that the spatial distributions reflected the industrial and power production activities of the province. Emissions of SO_2 and NO_x had a higher intensity over the locations of TPPs, especially coal and oil-fired TPPs, i.e. in the Red River Delta, Northeast and Southeast regions. For the industrial activities, the SO_2 emissions were mainly originated from the ‘mineral products’ industry group (copper, lead and zinc smelting) that are concentrated in the Northeast region and from the brick manufacturing (largely in the Red River Delta and Southeast regions) hence a higher emission intensity was shown over the locations accordingly. The NO_x emissions were mainly from the combustion activities in the brick manufacturing

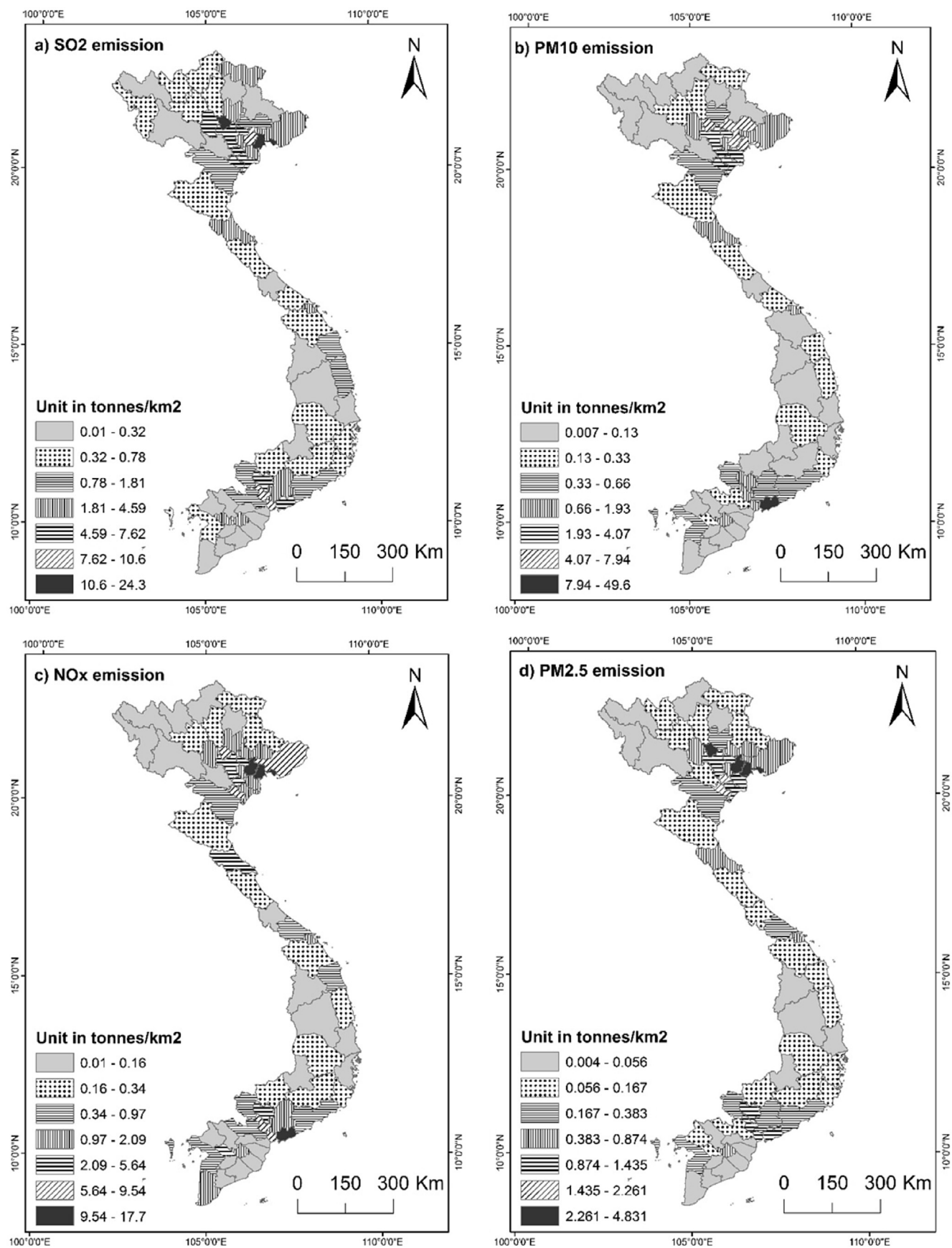


Fig. 3. Spatial emission distributions of air pollutants: a) SO₂, b) PM₁₀, c) NO_x and d) PM_{2.5}.

and cement industry hence were found higher in the areas where those industries were located, i.e. the Red River Delta, Southeast and North Central Coastal regions. Similarly, NMVOC emissions were high in the regions which had the food & beverage industry (beer and wine production), e.g. Red River Delta, Southeast, North Central Coastal and Mekong River Delta. Overall, two key economic zones of the Northern and Southern Vietnam are the regions having higher emissions from TPPs and industrial activities as compared to the Central region.

3.4. Temporal emission variation

The monthly fractions of industrial activities and thermal power generation over the country are shown in Fig. 4. The lowest monthly fractions were found in February, which may be due to the long holidays of the Lunar New Year, followed by a peak in March when all economical activities resumed. During the course of the year, more fluctuations were seen in the power generation rates while the industrial activities remained almost constant after March. The power generation was perhaps also influenced by other factors, such as weather and hydropower productivity, which would affect the monthly emission loads accordingly.

3.5. Global warming potential of emission

The GWP of the emission from the TPPs and industrial activities in the country in 2010, in CO₂ equivalent, is shown in Table 5. Both long-lived and short-lived climate forcing agents were considered, including the warming agents (i.e. CO₂, N₂O, CH₄, NO_x, NMVOC, CO, BC) and cooling agents (OC and SO₄²⁻). The net GWP of the emissions in 2010 was 59.7 Tg CO₂ equivalents (20-yr horizon). The GWP of BC was around 8.2 Tg CO₂ equivalents, i.e. 6.2% of the total positive forcing, which was the second most important warming agent after CO₂ (86%, 105.8 Tg). For the cooling agents, the secondary particulate particles (SO₄²⁻) was the most dominant species, contributing 96% of the total negative forcing (–63 Tg).

4. Conclusions

The best estimates of the emissions from the TPPs and industrial activities of Vietnam in 2010, collectively in Gg, were 361 CO, 320 NO_x, 529 SO₂, 52 NMVOC, 12.9 NH₃, 266 PM₁₀, 79.3 PM_{2.5}, 2.56 BC, 4.71 OC and 105,856 CO₂. The industrial activities, both fuel combustion and process, had significantly higher emissions of all species as compared to TPPs. The range of low and high estimates of a species was mainly determined by the variation ranges of EFs values extracted from the literature. Future efforts should focus on

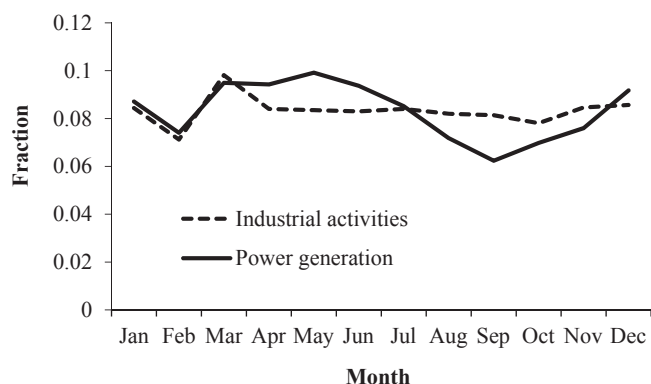


Fig. 4. Monthly emission variations of industrial activities and power generation.

Table 5

Global warming potential (20-yr CO₂ Equivalent) of emissions from industrial and power generation activities in Vietnam, 2010.

Species	Emission (Gg/yr)	GWP, CO ₂ Eq. (Gg/yr)
Warming agents		
CO ₂	105,856	105,856
CH ₄	7.23	520.6
N ₂ O	1.51	436.4
BC	2.56	8192
NO _x	320	4188
CO	361	2599
NMVOC	51.6	722.4
Sub total 1		122,514
Cooling agents		
SO ₄ ²⁻ ^a	529	–60,306
OC	4.71	–2543
Sub total 2		–62,849
Total net GWP		59,665

^a Sulfates (2 times of SO₂ emission amount) was used for GWP calculation.

the development of the EFs by measurement for local emission sources in Vietnam.

For the power generation, the highest emission loads were from the coal-fired TPPs followed by oil-fired TPPs while only small contributions from NG-fired TPPs. The results of emission factors per unit of power generation (g/kWh) obtained in this study are comparable with other published sources. The emission factors per unit of the power generation were also the highest for coal-fired TPPs and the lowest for NG-fired TPPs hence fuel switching to NG would significantly reduce emissions from the power generation in Vietnam. Among the industrial activities, the fuel combustion (category 1) had dominant contributions to most gaseous species except for NMVOC and NH₃ while higher shares of particulate species were from the non-fuel combustion and process activities (category 2).

Spatially, the emission intensity was found to distribute consistently with the locations of TPPs and industrial activities in the country. The emissions were found concentrated in three regions of the Red River Delta, Southeast (two key economic zones) and Northeast which contributed 60–99% of the national total emissions of different species. Monthly emissions were the lowest in February which coincided with the long Lunar New Year Holiday followed by the peaks in March when economical activities resumed.

The total net GWP of the emissions from industrial activities and power generation was 59.7 Tg CO₂ equivalent (20-yr horizon). CO₂ contributed the highest warming potential (87%) followed by BC (6.2%), whereas SO₄²⁻ was the main cooling agent contributing 96% of total negative forcing. Fuel switching to NG would reduce emissions of CO₂ (and other species) from TPPs significantly. The BC (and PM) emissions from industrial activities should be controlled by improving the combustion technologies and also applications of emission control technologies in small and medium industries. These measures can minimize the emission loads of both toxic air pollutants and GWP hence would bring in air quality and climate co-benefits.

This study revealed the contributions of different types of TPPs and different industrial activities to the national emissions which are useful input to the development of emission control strategies to gain co-benefits. The obtained emission database can be used in dispersion modeling studies for Vietnam. Development of a comprehensive EI for industrial activities of developing countries, such as Vietnam, remains a huge challenge, largely due to a wide range of technologies used in numerous small and medium industries. Further studies of industrial EI for Vietnam should include other types of industries, such as petroleum refining industry, solid fuel manufacturing and textile industry.

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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.apr.2016.12.007>.

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