Development of a high-resolution gridded emission inventory of anthropogenic air pollutants for urban air quality studies in Hanoi, Vietnam[1]

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[1] Abbreviations: air quality model (AQM), The Weather Research and Forecasting (WRF), the Community Multi-scale Air Quality Model (CMAQ), the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem), Emission Database for Global Atmospheric Research (EDGAR), the Hemispheric Transport of Air Pollution (HTAP), Regional emission inventory in Asia (REAS), Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS), the International Vehicle Emission (IVE) model, the European Monitoring and Evaluation Programme/ European Environment Agency (EMEP/EEA), International Energy Agency (IEA), Hanoi Statistical Office (HSO), Atmospheric Brown Cloud Emission Inventory Manual (ABC EIM), General Statistics Office (GSO), the Japan International Cooperation Agency (JICA), Research Centre for Gender, Family and Environment in Development (CGFED), United States Environmental Protection Agency (USEPA), Norwegian Institute for Air Research (NILU), Oak Ridge National Laboratory (ORNL), Food and Agriculture Organization (FAO), National Environment Protection Council Service

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Abstract

A high-resolution (1 km × 1 km) emission inventory was developed for Hanoi for 2017 and 2018. The total emissions of $PM_{2.5}$, BC, OC, NO_x, SO_2, NMVOC, NH_3, CH_4, and CO were 14.9, 1.6, 2.9, 56.7, 19.1, 109.2, 23.0, 37.9, and 472.7 Gg, respectively. Transport, industry, and agriculture contributed 89.1%, 92.2%, and 81.3% to the total emissions of $PM_{2.5}$, BC, and OC, respectively. Transport contributed 72.4%, 52.1%, and 72.5% to the emissions of NO_x, NMVOC, and CO, respectively. Industry contributed 64.9% to the emissions of SO_2. Agriculture was a major source of NH_3 and CH_4, contributing 84.2% and 76.6%, respectively. Future emissions of selected sectors were estimated for 2030. The emissions from transport will increase in the range of 26.9% (CH_4) to 245.8% (NH_3), despite the intrusion of the EURO 5 standard. For domestic cooking, transitioning from coal to LPG will help reduce the emissions of most pollutants in the range of 3% (NH_3) to 52.6% (OC), except NO_x and NMVOC. The crop residue burning (CRB) ban will reduce emissions in the range of 0.27 Gg (SO_2) to 138.4 Gg (CO) in 2030, respectively. The study will help policy-makers to develop strategies for air pollution in Hanoi.

Keywords:

High-resolution emission inventory; Urban air quality; NMVOC speciation; Spatial distribution; Temporal profiles; Future prediction

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Corporation (NEPCSC).

List of abbreviations and chemical formulas

Abbreviation	Meaning	Abbreviation	Meaning
Air quality model	AQM	National Environment Protection Council Service Corporation	NEPCSC
The Weather Research and Forecasting	WRF	Research Centre for Gender, Family and Environment in Development	CGFED
The Community Multi-Scale Air Quality Model	CMAQ	General Statistics Office	GSO
The Weather Research and Forecasting model coupled with Chemistry	WRF-Chem	Hanoi Statistical Office	HSO
Emission Database for Global Atmospheric Research	EDGAR	Atmospheric Brown Cloud Emission Inventory Manual	ABC EIM
The Hemispheric Transport of Air Pollution	HTAP	PM	Particulate matter
Regional emission inventory in Asia	REAS	BC	Black carbon
Greenhouse Gas and Air Pollution Interactions and Synergies	GAINS	OC	Organic carbon
The International Vehicle Emission model	IVE model	NO_x	Nitrous oxides
The European Monitoring and Evaluation Programme/ European Environment Agency	EMEP/EEA	SO_2	Sulfur dioxide
International Energy Agency	IEA	NMVOC	Non-methane volatile organic compounds
The Japan International Cooperation Agency	JICA	NH_3	Ammonia
United States Environmental Protection Agency	USEPA	CH_4	Methane
Norwegian Institute for Air Research	NILU	CO	Carbon monoxide
Oak Ridge National Laboratory	ORNL	HC	Hydrocarbons
Food and Agriculture Organization	FAQ		

1. Introduction

Air pollution is a challenging problem in developing countries. In countries like India or China, particulate air pollution is exceptionally serious in big cities due to fast-paced economic growth and urbanization. Particulate matter generated from anthropogenic sources such as on-road transport and industrial activities have worsen the air quality in those cities and caused an unhealthy urban environment for people to live in. As the results, Indian and Chinese cities are the most polluted regional cities in South Asia and East Asia, respectively (IQAir, 2020). Delhi and Beijing were ranked among the most polluted capital cities in the world (IQAir, 2020). Researchers have tried to study the long-term variations of this species, including spatial and seasonal variations (Gautam and Jayanarayanan, 2020). Other attempts have been made by researchers to understand the characterization, distributions and the health impact of black carbon in urban regions (Ambade et al., 2021, Sun et al., 2022). Heavy metals, which are typically emitted from the transport and industrial sectors, have also been closely investigated to reveal the level and the spatial distribution of these species in Uttarakhand, India (Bisht et al., 2022). Regarding China, the status and the chemical characteristics of air pollution, especially $PM_{2.5}$ were closely examined to understand the distribution and the components of this species in highly polluted Chinese cities (Gautam et al., 2019).

In Southeast Asia, Vietnam is experiencing rapid socio-economic development. Currently, Hanoi, the capital city of Vietnam, is experiencing deteriorating air quality due to this development. According to the 2020 World Air Quality Report, Hanoi is among the most polluted capital cities in the world, with an annual mean concentration of 37.9 μg/m^3 during 2020 (IQAir, 2020), with 69.4% of the days with daily $PM_{2.5}$ concentrations ≥ 25 μg/m^3 (IQAir, 2020). In addition, the air pollution in Hanoi was found to be more serious in winter than in summer (IQAir, 2020; Ly et al., 2018).

Air pollution has been harming the people living in Hanoi. According to Luong et al. (2017), an increase in 10 μg/m^3 of $PM_{2.5}$ concentrations could lead to a 2.2% rise in hospital admissions among children in Hanoi, regardless their gender. Another study has discovered that outdoor emission sources such as transport, residential coal combustion, or the industries were the main contributors to indoor $PM_{2.5}$ in Hanoi and exposure to this indoor $PM_{2.5}$ increases the risk of getting diseases among elderly people (Vo et al., 2022). Connection between the level of air pollution and the number of hospital visit has also been established (Trinh et al., 2019). As stated in the study, the number of patients who have acute respiratory diseases and cardiovascular diseases increases as the air pollution level rises.

This has increased the urgency for research on air quality in Hanoi. In Southeast Asia, air quality models (AQM) such as the Weather Research and Forecasting-the Community Multi-scale Air Quality Model (WRF-CMAQ) system have been used for studies on air quality (Nguyen et al., 2019a, 2019b; Vongruang et al., 2017; Vongruang and Pimonsree, 2020). Technically, an AQM system requires meteorological fields such as temperature, wind, precipitation, and emission data to simulate the concentrations of pollutants in the atmosphere. Thus, emission data are one of the essential factors that determine the quality of the model simulation. However, due to lack of a national emission inventory, modelling studies in developing countries like Vietnam mostly rely on international emission databases, such as the Emission Database for Global Atmospheric Research (EDGAR; EC-JRC/PBL, 2019), Regional Emission inventory in Asia (REAS; Kurokawa and Ohara, 2020), Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS; IIASA, 2017), or the Hemispheric Transport of Air Pollution (HTAP; Janssens-Maenhout et al., 2015). Although these emission inventories include many countries and sectors, the activity data used to create them are mostly from international sources, or the same input data are used for different countries; this is especially observed in developing countries where local data are inaccessible for developers (Kurokawa et al., 2013). In addition, due to the rough spatial resolutions (e.g. 0.25°, 0.1°, and 0.5°) and a lack of detailed temporal variations (e.g. diurnal variations), these emission inventories are not suitable for urban air quality modelling.

City-scale emission inventories are crucial for the development of air pollution control policies and for air quality modelling purposes (Zhao et al., 2015). In addition, a high-resolution emission inventory can help to reliably identify the contribution of emission sources or be used as inputs for AQMs; such as WRF-CMAQ or

WRF-Chem (H. Liu et al., 2018; S. Liu et al., 2018; Tan et al., 2017). Therefore, a comprehensive and accurate high-resolution emission inventory of air pollutants for Hanoi is essential to conduct studies on air quality at the city scale using AQMs, especially for revealing the contributions of various emission sectors to air pollution and the trends. Previous studies have also demonstrated that air quality models tend to produce more consistent results when using local emission data as input (Timmermans et al., 2013).

Several EIs for individual sector have been developed for Vietnam and Hanoi; such as transport (Kim Oanh et al., 2012; Trang et al., 2015; Roy et al., 2021), industry (Huy and Kim Oanh, 2017), and livestock (Truong et al., 2018). However, these Eis either lack information on the spatial distributions or temporal variations of emissions or include only one sector, making them not suitable for modelling purposes. To date, the most comprehensive study on the EI for Hanoi have been conducted for the transport, industrial, and residential sectors (Hung, 2010). However, the study was conducted for 2008, making it outdated.

To date, there have been no studies that investigated the contribution of the anthropogenic emission sources to the total emission of air pollutants in Hanoi. Existing studies on emission inventories for Hanoi only considered a single sector and overlooked the contributions of other sectors. For that reason, the actual contributions of major emission sectors could not be evaluated altogether. In addition, the existing emission inventories either lack information on the spatial distributions of emissions or only have a relatively rough spatial resolution, making these emission inventories not suitable for urban-scale simulations using AQMs. Additionally, most of the existing emission inventories do not include information on temporal variations of emissions (e.g., monthly or diurnal profiles) and this makes the emission data not suitable for air quality modelling purposes.

This study aims to overcome the limitations of the previous studies by developing a comprehensive high-resolution emission inventory at a horizontal resolution of 1 km × 1 km for 2017 and 2018 as the base emissions and projecting the emissions for selected sectors in Hanoi for 2025 and 2030. We focused on agriculture, residential activities, transport, commercial activities, the industrial sector, and other sources (solvent use and gas stations) in Hanoi. In addition, various temporal variations (monthly, day-of-week, and diurnal) of emissions were considered. These spatial distributions and temporal variations will enable the emission data developed in this study to be used for air quality modelling studies.

This study was conducted to achieve the following objectives: a) To estimate a comprehensive emission inventory of atmospheric pollutants for Hanoi to reveal the main sources of air pollution in the city; b) To provide scientists with a model-ready emission database that can further be used as input for AQMs for urban-scale simulations; c) To project the future emissions of selected sectors taking into consideration the pollution mitigating policies proposed by both the Vietnamese and local governments.

This study aims to provide policymakers and researchers with new knowledge regarding the emission sources in Hanoi. This study is the first to indicate the primary emission sources of air pollutants in Hanoi. This information will help policymakers to adopt the most effective policies to reduce emissions and mitigate air pollution in Hanoi. The high spatial resolutions of the emissions reveal the pollution hotspots within the city, helping policymakers to design proper strategies to mitigate air pollution at these hotspots. More importantly, this study is the first attempt to project future emissions of some major sources, taking into consideration the action plans and projections proposed by the Vietnamese and local governments. This information is valuable for researchers and policymakers to reduce the emissions of air pollutants from these specific sectors, partly helping to improve the air quality in Hanoi.

Compared with the existing emission inventories for Hanoi and Vietnam, our newly developed emission inventory is more recent and more complete in terms of sector coverage. Moreover, our emission inventory includes high spatial resolution (1 km × 1 km) and detailed temporal variations (up to diurnal), as well as NMVOC species. To our knowledge, almost none of the existing emission inventories for Hanoi or Vietnam have all the prementioned information all together.

2. Methodology

2.1. Study area

The location of our study area, Hanoi, is shown in **Figure 1**. Hanoi covers an area of 3358.59 km^2 and the population of the city in 2017 and 2018 was 7.661 and 7.853 million, respectively. The city comprises 31 districts, of which 11 are urban districts, and 19 are rural districts. The numbers of people living in the urban and rural districts were 3770 and 3891 million people in 2017, and 3874.3 million and 3978.3 million in 2018, respectively (HSO, 2019). The average temperatures in Hanoi in 2017 and 2018 were 24.7°C and 24.8°C, respectively. The hottest month was June, with the monthly average temperatures reaching 29.7°C and 30.2°C in 2017 and 2018, respectively. The coldest month in 2017 was December with an average temperature of 17.6°C, while the coldest month in 2018 was February with an average temperature of 17.3°C. In winter the northeast monsoon could bring air pollutants from the surrounding provinces and countries to Hanoi.

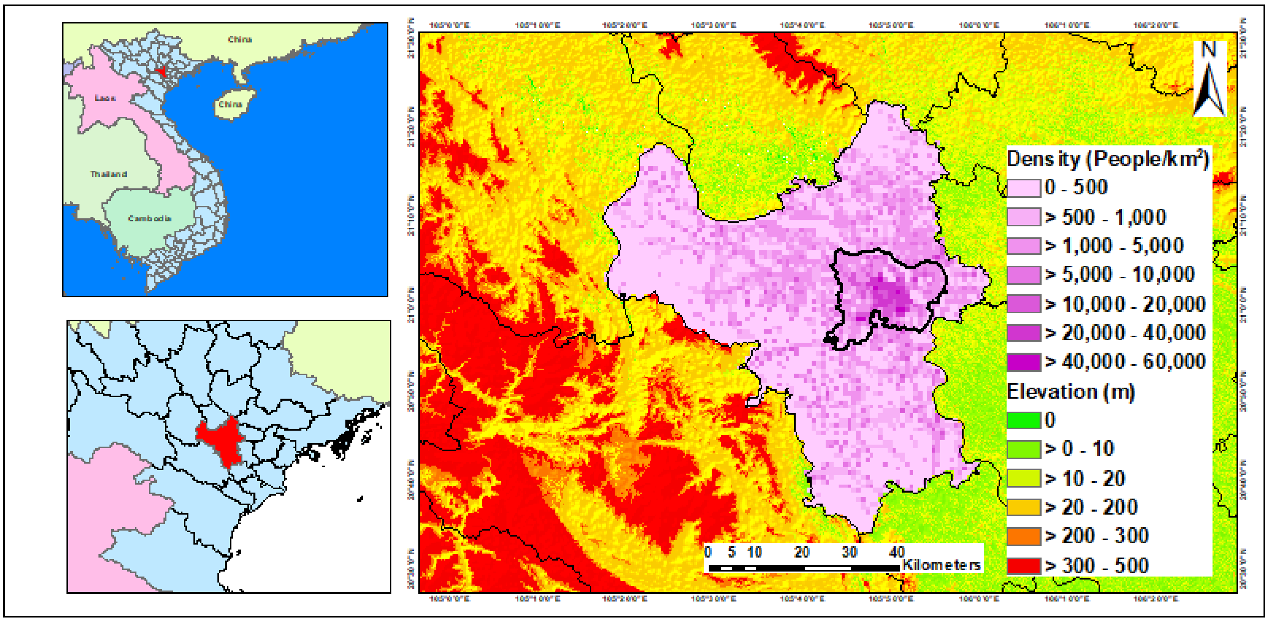


Figure 1. Location of Hanoi in Vietnam (Left). Administrative map of Hanoi, the elevation of Hanoi and the surrounding provinces and the population density in Hanoi in 2017 were also shown in the map (Right). The area within the black line represents the urban districts of Hanoi.

2.2. Covered sectors

Detailed information about the emission inventory is provided in **Table 1**. For some subsectors, we only estimated the emissions for specific species (NH_3, CH_4, and NMVOC). In those cases, the estimated species are listed next to the subsector. To minimise the uncertainty in the activity data used for estimating the emissions, we attempted to collect the local activity data for Hanoi from local sources, such as the Statistical Yearbook of Hanoi, Hanoi People's Committee, or Hanoi Statistics Office. Only when the local data were not available did we use the national or international data collected from international sources such as the International Energy Agency (IEA).

Sectors	Agriculture	Livestock (enteric fermentation (CH_4), manure management (NH_3, CH_4)), fertiliser application (NH_3), and crop residue burning (CRB)
	Residential	Cooking, water heating for bathing (hereafter referred to as water heating), and municipal solid waste (MSW) burning
	Commercial	Hotels and restaurants
	Transport	On-road vehicles (Motorbikes, cars, trucks, buses (intercity and transit buses), taxis)
	Industry	Iron and steel, chemicals, non-metallic minerals, machinery and transport equipment, mining and quarrying, food and tobacco, paper and pulp, wood and wood products, construction, textile and leather, chemical fertiliser, beverage, and other subsectors.
	Others (NMVOC)	'Solvents and other products use' (printing, paint application and manufacturing, glue, adhesive tape, application of glues and adhesives), and gas stations.
Temporal coverage	Yearly (2017, 2018, 2025, and 2030), monthly, day-of-week, diurnal	
Species	SO_2, CO, $PM_{2.5}$, BC, OC, NO_x, NH_3, CH_4, Total NMVOC and its speciation	
Spatial resolution	1 km × 1 km	

Table 1: Details regarding the coverage of the emission inventory developed in this study.

2.3. The general equation for emission estimation and activity data.

Different techniques can be applied to measure the amount of air pollutants discharged into the atmosphere. The most straightforward method is the direct measurement from the emission source. Although the data obtained through this method are highly reliable since it was measured directly from emission source, this method is only suitable for point sources like power plants and industrial facilities. This method, however, are not suitable for estimating area sources or line sources. Another method, which are considered to be the most common approach to estimate emissions (Shrestha et al., 2012), is the emission factor method. In this method, the emissions of a pollutant can be estimated by multiplying activity data by an EF. This method is simple and can be used to estimate emissions for any sectors. A disadvantage of this method is that, unlike the direct measurement approach, the accuracy of this approach relies on the input data (e.g., activity data or EF). Therefore, using unsuitable input data could greatly overestimate or underestimate the actual emissions. To our knowledge, some global and regional emission inventories such as REAS or EDGAR and most of the existing Eis for Vietnam or Hanoi, including the EI developed in this study, were estimated using this approach.

2.3.1. The general equation for emission estimation

The general equation used for estimating emissions is presented in Equation 1 (Shrestha et al., 2012). More details about the equations used for estimating the emissions from each sector and sub-sector are provided in **Table S1**.

$$Em_{i,j} = A_{i,j} \times E_i \times \frac{(100 - R_{i,j})}{100} \quad (1)$$

where *Em* is the emission load of pollutant i and emission source j; *A* is the Activity data; E_i is the emission factor of pollutant i and emission source j; and R is the Emission control efficiency (If applicable).

2.3.2. Activity data

Transport:

On-road transport has been a major emission source of air pollutants in Hanoi (Kim Oanh et al., 2012; Trang et al., 2015; Truc and Kim Oanh, 2007). A dominant number of motorcycles along with buses and trucks, which are usually not well maintained, make up a large share of emission load in Hanoi. This study estimated the hot emissions, cold emissions, tire wear, brake wear, road wear, and evaporative emissions from on-road vehicles, namely: motorbikes, cars, transit and intercity buses, trucks and taxis. Emissions from rails, domestic shipping, and aviation were not considered in this study. Also, resuspended emissions from paved and non-paved roads were not considered. Motorbikes, cars, and taxis use gasoline while buses and trucks use diesel oil. Hot emissions of a vehicle type were estimated using equation S4. The number of active vehicles, which are actually in operation, was estimated based on the number of registered vehicles in Hanoi (Chung, 2017; Hanoi Police Department, personal communication, 2019; Vietnam Register, 2018). The actual number of buses in operation was 90% of the registered buses while the actual number of other vehicles in operation was 80% of registered vehicles. The vehicle kilometers travelled (VKT) (km/vehicle/day) were obtained from previous studies in Hanoi (Roy et al. 2021, Chung (2017), Trang et al. 2015) for on-road vehicles. Unlike transit buses, intercity buses also travel to the territories of other provinces. Thus, using the same VKT for transit buses would greatly overestimate the actual emissions in Hanoi. To estimate the VKT of intercity buses, ArcGIS version 10.4.1 was used to measure the distance between the intercity bus stations and the borders between Hanoi and the surrounding provinces, based on the operative schedule at each intercity bus station. The number of vehicles and VKTs used in this study are summarised in **Tables S2 and S3**, respectively. In addition, the intrusion of the EURO standards was also considered (**Table S3**).

Cold emissions from cars, taxis, and buses were estimated for NO_x, CO, and NMVOC. Cold emissions from cars and taxis were calculated using equation S5. The equations for calculating the fraction of distance traveled driven with a cold engine (β_i) and the cold/hot emission quotient (E_{COLD}/E_{HOT}) were obtained from the European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) emission inventory guidebook 2019 (EEA, 2019). Because β_i and E_{COLD}/E_{HOT} are temperature-dependent parameters, the monthly mean temperatures, which were collected from the statistical yearbook of Hanoi in 2017 and 2018, were adopted (HSO, 2019, 2018a). E_{COLD}/E_{HOT} was calculated for non-compliant vehicles, and for those that complied with the EURO-1 standard. For post-EURO-1 vehicles, the E_{COLD}/E_{HOT} values of EURO-1 vehicles were used without further reductions (EEA, 2019). EURO-1 relative B-reduction factors were obtained from the EMEP/EEA emission inventory guidebook for calculating the cold emissions from post-

EURO-1 vehicles. For buses, the cold emissions for NO_x, CO, and NMVOC were calculated using the number of daily starts and cold EFs per start, obtained from the study conducted by Trang et al. (2015).

For tyre wear, brake wear, road wear, and evaporation emissions, we used the Tier 1 method in the EMEP/EEA emission inventory guidebook (Equation S6 and S7, respectively). The pollutants emitted from tyre wear, brake wear, and road wear included in this study are $PM_{2.5}$, BC, and OC while the pollutant emitted from evaporation is NMVOC. The monthly temperatures were used to estimate the evaporative emissions. *Agriculture:*

The emissions from enteric fermentation were estimated for livestock and the emissions from manure management were estimated for all the livestock and poultry. The number of animals were obtained from the Statistical Yearbooks of Hanoi (HSO, 2019, 2018a) and from the Statistical Office of Hanoi (HSO, 2018b, 2017). The Statistical Yearbooks report the number of animals for all 30 districts of Hanoi. This study estimated the emissions for each district and added them up to yield the total emissions from livestock and poultry.

For fertiliser application, the amount of fertiliser used (kg) per area of cropland calculated in a study that investigated the production efficiency of farms in Hanoi in 2018, was used to estimate the emissions (Dang et al., 2019).

CRB is common in Hanoi to remove crop residues and to prepare for the next crop planting. The amount of dry biomass burned on the field (kg/year) was calculated using **Equation S11**. The data for the crop production (kg/year) were collected from the Statistical Yearbooks of Hanoi (HSO, 2019, 2018a), while the data for other factors (crop-specific residue-to-production ratio (fraction), dry matter-to-drop residue ratio (fraction), fraction of dry matter residue burned in the field, and crop-specific burn efficiency ratio (fraction)) were collected from the Atmospheric Brown Cloud Emission Inventory Manual (ABC EIM) (Shrestha et al., 2012) and previous studies on emissions from CRB in Southeast Asia and Hanoi (Dong et al., 2014; Kim Oanh et al., 2018).

Industrial sector:

Pollutants from industrial facilities come from combustion and non-combustion processes. While the combustion process usually generates gaseous species such as NO_x, SO_2, or CO through burning fuel such as coal, oil, or gas, the pollutants emitted from the non-combustion process depend on the type of industry. To estimate the emissions from these two processes, fuel consumption and output production rate of each industry are necessary. The fuel consumption of an industrial facility in Hanoi belonging to a subsector was estimated by first taking the ratio between the output production of that facility and the total output production of the same subsector of Vietnam. The same ratio was then applied to the total fuel consumption of the same subsector for Vietnam (IEA, 2019a) to derive the fuel consumption of that specific facility in Hanoi. Emissions from non-combustion processes were calculated for the chemical industry, metal production, non-metallic minerals, paper and pulp, food, and beverage industries. The output production rate that is needed for emission estimation was collected for each industrial facility in Hanoi from the Hanoi Statistics Office as unpublished data (HSO, 2019, unpublished data). In addition, emission control efficiencies were applied to the pulp and paper industry. Details about the emission control efficiencies are provided in **Section 2.5**.

Residential sector:

Fuel combustion for domestic cooking, especially coal or wood combustion, is a major source of fine-particulate matter. Type and amount of fuel consumption for domestic cooking in Hanoi's urban areas are often different from those in Hanoi's rural areas. Therefore, a face-to-face survey was conducted in October 2019 to obtain information on the total number of people in each household surveyed, type and amount of fuel consumption, and the period of cooking. In total, 273 households (136 households in urban areas and 137 households in rural areas) across Hanoi were investigated. The result of the survey shows that people in Hanoi use LPG, coal, wood, and oil for domestic cooking. However, the type and amount of fuel used in urban areas are distinct from those used in rural areas. In Hanoi's urban areas, people used LPG and coal for cooking while wood and oil are still being used by a number of rural populations along with LPG and coal. In total, the total amount of LPG used by urban and rural population was 141 Gg and 63.8 Gg, respectively. The amount of coal used for the same purpose was 16.2 Gg and 20.5 Gg for urban and rural population, respectively. Rural population consumed 41.7 Gg of firewood and oil each for cooking while no firewood and oil were used by urban population.

Although a part of Hanoi's population is still relying on combustion fuel for water heating, the emissions from this source are generally not considered in previous emission inventories for Hanoi. In this study, the energy needed to heat 30 L of tap water (the capacity of a typical water heater used in Hanoi) from its monthly temperatures to 36°C, the desired water temperature for bathing in Hanoi (Otani et al., 2015), was used to estimate the emissions (Sadavarte et al., 2019). The number of households with water heaters (GSO, 2020) was used to estimate the percentage of people using combustion fuel for water heating, which was 11.2% and 21.1% for Hanoi's urban and rural areas, respectively. The same types of fuel used for domestic cooking were used to estimate the emissions from water heating. The parameters used to estimate the energy consumption and fuel consumption for water heating are listed in **Table S5**.

For MSW burning, the MSW_{GR} values in Hanoi's urban and Hanoi's rural areas were 1.25 and 0.82 kg in 2016 and 1.31 kg and 0.86 kg in 2018, respectively (Hoang and Fogarassy, 2020). The values for 2017 were estimated as 1.28 and 0.84 kg, respectively, by averaging the 2016 and 2018 values. E was 95% and 60% for the urban and rural areas, respectively (Thanh et al., 2015). Δ was estimated as 60.5% (van den Berg et al., 2018). Λ was 5.4% per day (Thanh et al., 2015), and η was selected to be 58% (Shrestha et al., 2012).

Commercial sector:

In this study, the emissions were calculated for 726 and 733 hotels in 2017 and 2018, respectively, and 1,536 restaurants (for both 2017 and 2018) were calculated in this study. The data on fuel consumption by hotels and restaurants were selected based on the results of the survey of the Japan International Cooperation Agency (JICA, 2016) which showed an amount of 0.02 Gg LPG, 15.4 Gg coal, 1 Gg diesel oil, and 0.01 Gg heavy oil each.

Other sectors:

The NMVOC emissions from the printing industry, paint application, paint manufacturing, adhesive tape and glue manufacturing, rubber processing, and gas stations were estimated. We separated the data of printing industry from that of other industrial sectors to estimate the NMVOC emissions from this specific sector, although the emissions from fuel combustion of the printing industry were included in the industrial sector. **Equation S16** was used to estimate the NMVOC emissions.

For paint manufacturing, a total of 64,308 and 64,516 t of paint were produced in 2017 and 2018, respectively (HSO, 2018, 2017). For paint application, 3.7 L of paint was used per capita in Vietnam (equivalent to 4.81 kg, based on the density of paint of 1.3 kg/L (NEPCSC, 2014)) (CGFED, 2016).

For sources other than gas stations, the activity data were collected at the facility level from the Hanoi Statistics Office as unpublished data (HSO, 2019, unpublished data).

Regarding gas stations, the method proposed by the United States Environmental Protection Agency (USEPA, 2008) with the annual amount of gasoline consumed by on-road vehicles obtained from the World Energy Statistic 2019 (IEA, 2019a) was used to estimate the emissions from 471 gas stations across Hanoi. To estimate the amount of gasoline sold out in Hanoi in 2017, the ratio between the amount of gasoline sold out in Hanoi and the total gasoline sold in Vietnam from the study by Huy and Kim Oanh (2020), which was 17.1%, was applied to the total amount of gasoline consumed by the on-road transport sector, which was obtained from the World Energy Statistics 2019 (IEA, 2019a). Accordingly, the amount of gasoline consumed by the gas stations in Hanoi was 841.32 kt in 2017.

2.4. NMVOC speciation

NMVOC speciation is important to AQMs because it plays an essential role in the formation of secondary $PM_{2.5}$ and ozone. To the best of our knowledge, there have been no NMVOC speciation profiles specifically developed for Hanoi or Vietnam. Thus, we relied on the profiles developed for China to conduct NMVOC speciation for Hanoi. Since China has been recognised as the most significant contributor to NMVOC in Asia, it is considered that the NMVOC speciation profiles developed for China are also suitable for conducting NMVOC speciation for other Asian countries, including Vietnam (Huang et al., 2017). In this work, we used the NMVOC speciation profiles which were developed from ambient measurements and emission ratios against CO (Li et al., 2019). The study developed an emission inventory for NMVOC for five sectors: transportation, CRB, stationary combustion of fossil fuel, solvent utilisation, and industrial processes. Each of the five sectors was then classified into subsectors such as off-road transport, on-road transport, crop residue, firewood, power sector, residential consumption, etc. The study classified NMVOC into 152 species and built up a speciation profile for each subsector according to these 152 species. In our study, we used the same profiles for 152 species to conduct NMVOC speciation for Hanoi.

2.5. Emission factors

The EFs for livestock were obtained from previous studies conducted in Vietnam (Le et al., 2017; Truong et al., 2018). The EFs for CRB and fertiliser application were obtained from the ABC EIM. For the transport sector, the EFs for the conventional vehicles were collected from different sources (NILU et al., 2015; Permadi et al., 2017; Trang et al., 2015). In this study, we also considered the EURO standards by assuming that all newly registered vehicles of a certain year complied with the EURO standard set for that year (**Table S3**). The EFs for OC and BC for the vehicles complying with the EURO standards were estimated based on the OC/$PM_{2.5}$ and BC/$PM_{2.5}$ ratios of the non-compliant counterparts. The same method was used to estimate the EFs for OC and BC for other types of vehicles complying with the EURO standards. The EFs for NMVOC for all the vehicles were considered as the difference between VOC and CH_4. We applied the ratio VOC/HC (HC = hydrocarbons) = 0.933 for motorbikes, cars, and taxis and VOC/HC = 1.053 for buses and trucks to convert the EFs of HC to VOC (EPA, 2005) because the HUTEI project and the EURO standards only report the EFs for HC (Ngo and Pham, 2014).

The EFs for the industrial subsectors except for that of SO_2 were obtained from the ABC EIM and the EMEP/EEA emission inventory guidebooks. These guidelines provide an emission rate per unit of energy generated. Therefore, we converted the fuel consumption rates into energy units (KJ) using the calorific values of burned fuel collected from different research articles and reports (International Energy Agency, 2019b, 2009; Luo et al., 2017; Natarajan et al., 2008; Piaskowska-silarska et al., 2017; Zhenning and Qinfeng, 2012). The EFs for SO_2 were calculated using the following equation (Shrestha et al., 2012):

$$EF_{SO2} = 2 \times \left(\frac{CS_{fuel}}{100}\right) \times \left(\frac{100 - \alpha_S}{100}\right) \times \frac{1}{H_u} \times 10^6 \times \left(\frac{100 - \eta_{cd}}{100}\right) \quad (2)$$

where EF_{SO2} is the EF for SO_2 (Kg/TJ), CS_{fuel} is the sulfur content in the fuel (% wt), α_S is the sulfur retention in the ash (%), H_u is the lower heating value of the fuel (TJ/kt), and η_{cd} is the reduction efficiency of the control device (%).

The EFs for the NMVOC emissions from paint application, paint manufacturing, ink manufacturing, and glue manufacturing were obtained from the ABC EIM, which reports the emissions in kilogram per tonne of the product consumed or produced. Regarding paint applications, the EFs introduced in ABC EIM are classified according to their purposes, including automobile manufacturing, industry, and decorative purposes. Because there was no available information on the percentage of paint used for each sub-activity source, we used the average EF to estimate the emissions from these sources.

For gas station EFs, the method proposed by the EPA was applied for the calculation (USEPA, 2008). In detail, equation 3 and 4 were used to estimate the EFs for UST filling and vehicle refuelling.

$$E_L = \frac{12.46 \times SPM}{T} \quad (3)$$

$$E_R = 264.2 \times [-5.909 - 0.0949 \times \Delta T + 0.0884 \times T_D + 0.485 \times RVP] \quad (4)$$

where E_L and E_R are the EFs for UST filling and vehicle refuelling, respectively; S is a saturation factor; P is the true vapor pressure of liquid loaded; M is the molecular weight of vapor; T is the temperature of bulk liquid loaded; ΔT is the difference between the temperature of fuel in vehicle tank and the temperature of dispensed fuel; T_D is the temperature of dispensed fuel; and RVP is the Reid vapor pressure.

To estimate the EFs for UST filling and vehicle refueling, T was assumed to be 27°C or 80.6°F based on the average temperature of Hanoi and ΔT was assumed to be 2°C or 3.5°F. The values of the other parameters were as follow: S=1; M=67; P=6.3 psia (estimated using equation S19); and RVP = 8.4 psia (Huy and Kim

Oanh, 2021).

Information on the emission control technologies for the industrial sector in Hanoi is limited. For the paper and pulp industry, we used the removal efficiency from the study conducted by Huy and Kim Oanh (2017), assuming that the paper and pulp manufacturing facilities were equipped with lime/lime-stone wet scrubbers, which remove 90% of the SO_2 emission, and electrostatic precipitators (ESP), which remove 91.9% of the $PM_{2.5}$ emissions, 91.1% BC emissions, and 96% OC emissions from the fuel combustion processes (Shrestha et al., 2012). For the emissions from fuel combustion of other industrial subsectors (other than the industries mentioned above) and emissions from non-fuel combustion of all the industrial subsectors, 0% removal efficiency was assumed (Huy and Kim Oanh, 2017).

2.6. Emissions projection for Hanoi for 2025 and 2030

Knowing how the emissions of air pollution could change in the future is critical for air quality management. In this study, in addition to the emissions of air pollutants for 2017 and 2018, we also developed a projected emission inventory for selected sectors based on several scenarios proposed by both the Vietnamese and Hanoi governments. The projected emissions were compared with the base emissions in 2017 to evaluate how the emissions will change in the future. Based on the availability of the action plans proposed by the Vietnamese and Hanoi governments, we projected the future emissions for the transport, residential (domestic cooking and MSW burning), commercial buidldings (hotels and restaurants), and agricutural sectors **(Table 2)**. Future predictions for other sectors were not considered in this study because there is a lack of information about the governmental action plans and future predictions for those sectors. Future studies should also consider including these sectors.

Sector	Sub-sector	Scenario description	Reference
Transport	On-road transport	The number of active vehicles (all types) will increase to 6.7 million vehicles by 2025 and 7.5 million vehicles by 2030 (The number of each type of active vehicles from 2021 to 2030 are listed in **table S3**)[a].	Hanoi People's Committee, (2017)[a]
		Engined vehicles other than motorcycles are to meet EURO 5 standard as of 2022[b].	Decision 49/2011/QD-TTg[b]
Residential	Residential cooking MSW burning	The use of coal is to be banned in Hanoi as of 2021[a]. Hanoi's population is to increase to 9.0 million people by 2025 (urban population accounts for 58% total population of Hanoi) and 9.8 million people by 2030 (urban population accounts for 65% of total population of Hanoi)[b]. MSW collection efficiency in Hanoi's rural area will increase from 60% to 85%. MSW collection efficiency in Hanoi's urban area remains at 95% (80% – 100%)[c]. The amount of MSW generated per capita in Hanoi's urban and Hanoi's rural areas will be 1.51 and 0.99 in 2025 and 1.72 and 1.13 in 2030, respectively[d].	Directive 15/CT-UBND[a] Plan 237/KH-UBND[b] Decision 1259/QD-TTG[c] van den Berg et al., (2018)[d]
Commercial	Hotels and	The use of coal is to be banned in Hanoi as of 2021.	Directive

	restaurants		15/CT-UBND
Agriculture	CRB	CRB is to be banned in Hanoi as of 2021[a].	Directive 15/CT-UBND[a]
		The growth rate of agricultural production will be 4.1% (4.0 – 4.3%) per year from 2021 to 2030[b].	Decision 124/QĐ-TTg[b]

Table 2: List of sectors and scenarios used for future prediction of emissions in Hanoi in 2025 and 2030

Note: the values of MSW generated per capita in 2025 were estimated by taking the average values of MSW_{GR} of 2018 and 2030.

2.7. Spatial and temporal distribution of emissions

2.7.1. Spatial distribution

Emissions from livestock and CRB were allocated based on 1 km × 1 km grassland and cropland cover from the Global Land Cover-SHARE (GLC-SHARE) provided by the Food and Agriculture Organization (FAO). Emissions from swine and poultry were distributed based on the 1 km × 1 km urban-rural population, created by combining the population distribution derived from the LandScan dataset for 2017 and 2018 (ORNL, 2018, 2017) and the urban land use fraction of Vietnam for 2017 derived from the JAXA dataset (JAXA, 2019).

Regarding the residential sectors, the spatial distributions of the emissions from domestic cooking and water heating were based on the urban-rural population distribution. The emissions from MSW burning were allocated based on the location of the two main MSW incinerators in Hanoi. For the emissions from the commercial sector, Google Maps (https://www.google.com/maps) and OpenStreetMap (ArcGIS Editor, https://www.openstreetmap.org) were used to allocate the emissions, using the corresponding coordinates of each emission source.

For the emissions from the road transport sector, we used OpenStreetMap to create the road network and classify it into highways, national, main, secondary, tertiary, and residential roads. Each road was then converted into grid cells with a resolution of 1 km × 1 km for the emission distribution. The emissions were distributed on each road based on the traffic count data in Hanoi (NILU et al., 2015).

For the industrial sector, the locations of the registered industrial facilities in Hanoi provided by the HSO were used to distribute the emissions. The emissions for construction were treated as an area source and distributed using the population density. Regarding the NMVOC emissions from solvent use, the location of each industrial facility and the population distribution were used for the spatial allocations. Similarly, the emissions from gas stations were distributed using the location of each gas station in Hanoi. The locations of individual emission sources were investigated using Google Maps and OpenStreetMap. The spatial distributions of all the emission sectors were allocated to the map at a 1 km × 1 km spatial resolution.

The proxies used for allocating the emissions of the transport and industrial sectors are shown in **Figure 2**.

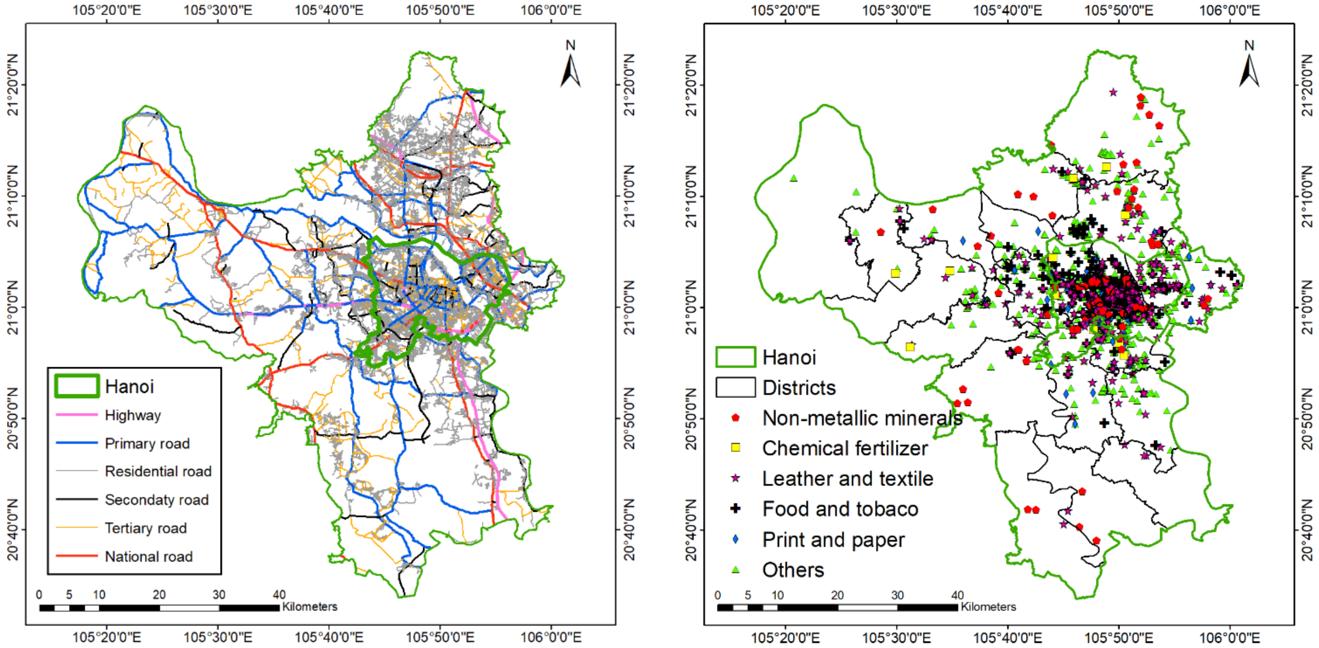


Figure 2: The road network (Left) and locations of industrial facilities (Right) used for spatial distribution of emissions of the transport and industrial sector, respectively.

2.7.2. Temporal distributions

For the transport sector, the monthly profiles were created based on the profile of cold, evaporative emissions, and the monthly VKT of each vehicle type. The day-of-week profile was created using the traffic count data from a previous study on transport emissions in Hanoi (Truc and Kim Oanh, 2007), while the diurnal variations were obtained from the HUTEI project (NILU et al., 2015).

For livestock and fertiliser application, the number of livestock, the areas of planted crops, air temperature (T_2), and windspeed (WS) were used to allocate the monthly and diurnal emissions **(Equation S2 and S3)**. For CRB, the seasonal harvested crop production was used to create a monthly emission profile while the diurnal profile was adopted from the study by Kanabkaew and Kim Oanh (2011).

For domestic cooking, the monthly profile was kept flat, while the diurnal variation was calculated based on the survey conducted in 2019. For water heating, the monthly diurnal variations were allocated based on the monthly combustion fuel consumption. The diurnal variations were allocated based on the hot water usage profile of Hanoi (Toyosada et al., 2018). For MSW burning, the monthly and day-of-week profiles were created based on the precipitation data for Hanoi in 2017 and 2018 by assuming that no burning activity occurred on rainy days.

For the commercial sector, the monthly variation profiles were created based on the monthly number of domestic and international tourists visiting Hanoi. These tourists tend to stay in hotels and have meals at restaurants during their visit. The day-of-week variations were assumed to be evenly distributed among seven days of the week due to a lack of information. Commercial cooking activities occur from at 4:00 until late at night with the highest activity from 18:00 to 22:00 (Hai and Kim Oanh, 2013).

For the industrial sector, the monthly emissions of each industrial subsector were estimated using the monthly industrial production index (IPI) for 2017 and 2018 (GSO, 2019b; HSO, 2018b, 2017), while the diurnal variations were estimated based on the typical working time, or operating hours of industrial facilities (Pham et al., 2008).

3. Uncertainty analysis

3.1. Uncertainty analysis

As with all of the existing emission inventories, the emission inventory developed in this study is subject to uncertainties due to the choices of the activity data, EFs, and removal technologies (Kurokawa and Ohara, 2020; Nguyen et al., 2021; Permadi et al., 2017; Roy et al., 2020). In our study, we prioritised the data specifically developed for Hanoi or Vietnam to minimise these uncertainties. When these data were not available, the data for countries with a comparable socio-economic status as Vietnam were used instead. We used the Monte Carlo method to estimate the uncertainty for each sector and the entire emission inventory. We applied the normal probability distribution to the activity data and the lognormal distribution to the EFs and ran 10,000 Monte Carlo simulations for each subsector with a 95% confidence interval. Details about the Monte Carlo simulation have been described in Nguyen et al. (2021) and McMurray et al. (2017).

3.2. Uncertainty ranges of input data

The uncertainty range of emissions from each sector was evaluated based on the uncertainty range of each activity and the EFs used. The activity data collected from national and provincial statistics were assumed to have a 2% uncertainty as suggested by EMEP/EEA emission inventory guidebook (EEA, 2019). This uncertainty range was applied to the agricultural, on-road transport, domestic cooking, non-combustion industrial sectors, and solvent use. For the sectors in which the activity data were collected from international sources (JICA, FAO, or IEA) and previous studies, an uncertainty of 10% was selected (EEA, 2019). For the other sources, an uncertainty of 30% was selected (EEA, 2019). The uncertainties of the EFs were selected from the EMEP/EEA emission inventory guideline (EEA, 2019) as well.

4. Results and discussion

The results of the year 2017 are presented in this section. The results of 2018 are included in the supplementary materials.

4.1. Emissions in Hanoi

Figure 3 shows the relative contributions (%) of each emission sector to the emission inventory for Hanoi. The total emissions of pollutants in Hanoi were estimated as 14.9 Gg $PM_{2.5}$, 1.6 Gg BC, 2.9 Gg OC, 56.7 Gg NO_x, 19.1 Gg SO_2, 109.2 Gg NMVOC, 23.0 Gg NH_3, 37.9 Gg CH_4, and 472.7 Gg CO.

Industry, transport, and agriculture (CRB) were the predominant emission sources of $PM_{2.5}$ emissions, contributing 35.2%, 32.0%, and 21.8%, respectively. Transport, agriculture (CRB), and industry were the main sources of BC emissions, contributing 46.6%, 30%, and 15.6%, respectively. Transport and agriculture were the key sources of OC, contributing 42.4% and 23.9%, respectively. Transport and industry were the two leading sources of NO_x, contributing 72.4% and 25.4%, respectively. Similarly, SO_2 was mainly emitted by the industrial (65.0%) and transport (32.6%) sectors. In contrast, the NMVOC emissions were predominantly contributed by transport (52.1%) and solvent use (35.2%). Agriculture was the main source of NH_3 and CH_4 emissions, contributing 84.2% and 76.6%, respectively. CRB, livestock, and fertiliser application contributed to the emissions of NH_3 and CH_4 and CRB was the only agricultural subsector that contributed to the emissions of the other species. As expected, transport was the highest emitter of CO, contributing 72.5%, followed by CRB (20.0%).

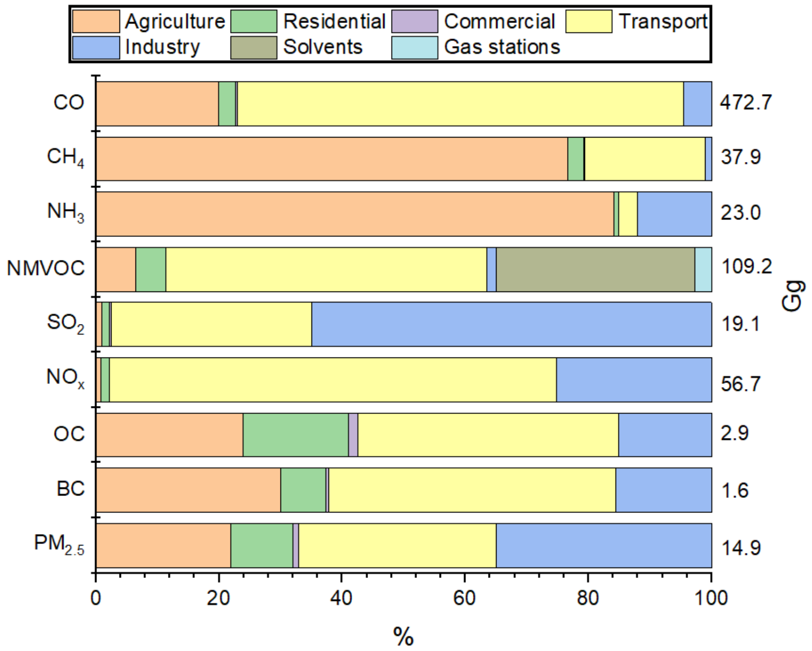


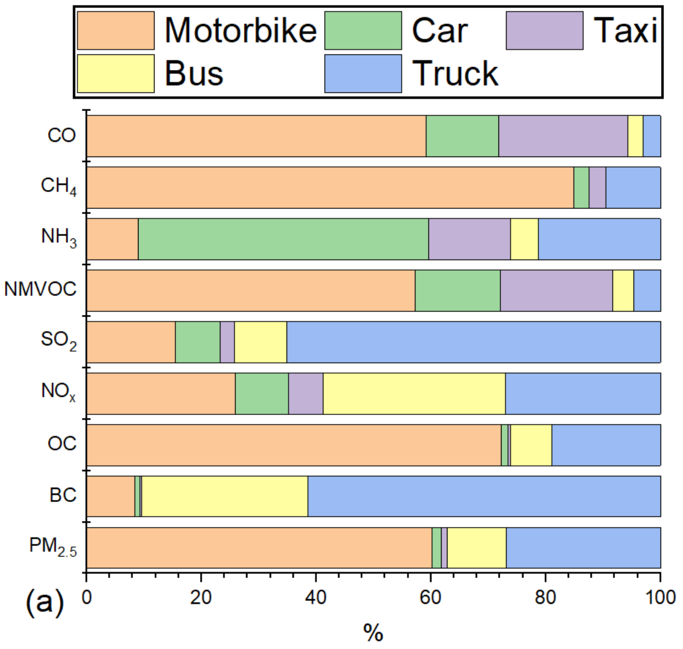
Figure 3. Contribution of each emission sector in Hanoi (in percentage) to the total emission of air pollutants in 2017.

Figure 4.a illustrates the relative contributions of each vehicle type to the total emissions of the transport sector. Overall, due to a large number of active vehicles, motorbikes were a major source of $PM_{2.5}$, OC, NMVOC, CH_4, and CO. The contributions of motorbikes to the emissions of these species came from exhausted emissions rather than non-exhaust emissions. In contrast, BC came mainly from the exhaust emissions of buses and trucks. In terms of NO_x, buses and trucks contributed more than half of the total emission of this species (58.8%). A fleet of non-compliant buses and trucks in Hanoi was found to have very high NO_x emission factors (NILU et al., 2015; Trang et al., 2015), which led to the high emissions of this species. For the same reason, motorbikes and taxis were the main emission sources of CO, which contributed 81.6% to the total emissions of CO from the transport sector. SO_2 was mainly emitted from trucks, because of a relatively high EF and lack of emission control for this species. As shown in **Figure 3**, despite the intrusion of the EURO standards, on-road transport was still a major source of air pollutants in Hanoi in 2017. Therefore, unless the government discourages using private vehicles and start building an environmentally friendly public transport network, the emissions from this source will continue to increase in the near future **(Section 4.5)**.

Figure 4.b presents the relative contributions of each industrial subsector to the total emissions of the

industrial sector. Non-metallic minerals, paper and pulp, and textile and leather were the leading emission sources of the primary $PM_{2.5}$ species, with 95.8%, 88.9%, and 97.5% of the emissions of primary $PM_{2.5}$, BC, and OC, respectively. Unlike the leather and textile subsectors, where combustion was the main source of primary $PM_{2.5}$, the non-combustion processes of the non-metallic minerals and paper and pulp subsectors were the predominant contributors of primary $PM_{2.5}$. In contrast, combustion processes were the key source of NO_x emissions from the non-metallic minerals and the textile and leather subsectors. For SO_2, the combustion processes of the textile and leather and non-combustion processes of the non-metallic minerals subsector (the kiln process of brick manufacturing) were the leading emission sources of this species. Additionally, the food, tobacco, and beverage subsectors were the main sources of the NMVOC emissions, primarily because of the processing requirements of these industries. The combustion processes of the non-metallic minerals subsector were also a substantial source of CH_4 and CO due to the high amount of fuel used. Chemical fertiliser manufacturing dominated the emissions of NH_3 from the industrial sector by contributing 99.9%.

Although, the government has been taking actions to reduce the emissions from some sectors, including transport, residential and commercial activities, and CRB; the emissions from the indutrial sector have not been well considered. Therefore, it is suggested that the government should apply emission control devices to the highly polluting industries or transition to cleaner combustion fuels.



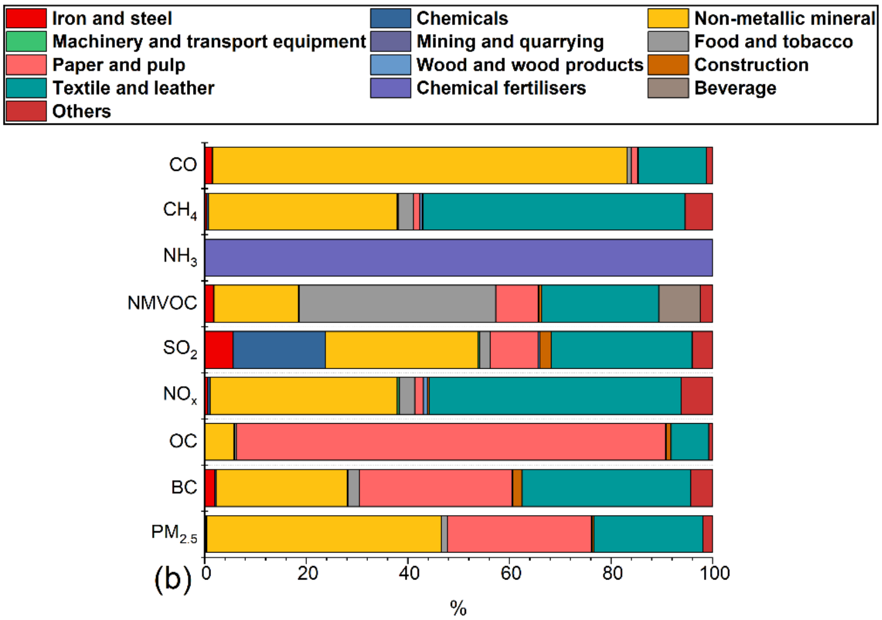


Figure 4. (a) Contributions by vehicle types to the emissions of the tranport sector and (b) contributions by industrial subsectors to the emissions of the industrial sector in Hanoi in 2017.

4.2. Comparison of emissions in Hanoi with REAS, EDGAR, and GAINS

We compared the results of our work with those from the existing global or regional emission inventories, which are REASv3.2, EDGARv5.0, and GAINS (hereafter referred to as REAS, EDGAR, and GAINS, respectively). The emissions for Hanoi in REAS and EDGAR were calculated as the sum of the emissions within Hanoi's provincial boundary. The emissions for Hanoi in GAINS, however, were obtained from the study conducted by Amann et al. (2018). **Table 3** compares the emissions of different species from each dataset. Additionally, a sector-wise comparison between the results of this study and those of other emission inventories is included in the supplementary materials (**Table S11**). To explain the differences in the results of our studies and those of the other EIs, detailed information about the activity data and EFs used for estimating emissions in each EI is needed. However, not all the required data are available for this purpose. Therefore, we attempted to explain the reasons behind these differences using the information available from published literatures.

Pollutant	This study (2017)	REAS 3.2[1] (2015)	EDGAR 5.0[2] (2015)	GAINS[3] (2015)
$PM_{2.5}$	14.9	18.2	26.5	23.5
BC	1.6	3.7	3.6	-
OC	2.9	9.1	11.7	-
NO_x	56.7	16.6	44.7	66.6
SO_2	19.1	18.8	37.9	17.8
NMVOC	109.2	97.7	79.2	-
NH_3	23.0	20.4	14.6	23.3
CH_4	37.9	-	46.3	-
CO	472.7	359.8	459.8	-

Table 3: Emissions in Hanoi in 2017 in comparison with other emission inventories (in Gg/year)

Note: "-" Estimated but not available in the referenced documents (or not estimated)

[1] Data are available at https://www.nies.go.jp/REAS/

[2] Data are available at https://edgar.jrc.ec.europa.eu/

[3] Amann et al. (2018)

Our estimates of $PM_{2.5}$, BC, and OC emissions were smallest among the studies considered. These differences were because the emissions of the residential and industrial sectors estimated in our study were smaller than those estimated in REAS and EDGAR **(Table S11)**. All the prementioned studies used fuel consumption as activity data. But our study used the local data and the other two studies used the international data provided by IEA. The total emissions of the primary $PM_{2.5}$ species of the residential and industrial sectors in our study were exceeded by those in REAS in the range from 7.3 ($PM_{2.5}$) to 15.8 (BC) times and from 1.2 ($PM_{2.5}$) to 4.9 (BC) times, respectively. For the residential sector, the EFs for $PM_{2.5}$ applied in REAS were smaller than those used in our study (Kurokawa et al., 2020). Therefore, the fuel consumption was the factor that made the emission of $PM_{2.5}$ in REAS greater than that in our study. The EFs applied to estimate the emissions of BC in REAS were greater than those used in our study. Therefore, both EFs and fuel consumption were the factors leading to higher emission of this species in REAS than that in our study. In addition, the EFs of OC used in our study were also different from those used in REAS, making it a joint cause of the discrepancies between the emission of OC in our study and that in REAS, together with fuel consumption. Differences in the fuel consumption and EFs could also have been the reason for the discrepanices between the emissions of primary $PM_{2.5}$ species in our study and those in EDGAR. For the industrial sector, all three studies collected the fuel consumption from IEA documents such as World Energy Statistics or World Energy Balances. Therefore, the EFs and non-combustion emissions could have been the cause of the dicrespancies between the studies. For example, the amount of output products used in this study was collected at the facility level while those in REAS and EDGAR were collected at either national or international level. The NO_x emissions estimated in our study were higher than those estimated in REAS and EDGAR, but smaller than those estimated in GAINS. The main factor leading to this disagreement was the differences between vehicular emissions. Our emissions of this sector were 6 and 2.8 times larger than those estimated in REAS and EDGAR, respectively. Our selections of EFs for diesel vehicles such as trucks or buses were relatively high compared with those used in REAS and EDGAR, leading to the differences in the emissions of this sector as well as the total emissions in Hanoi. For example, the NO_x EFs for conventional buses and trucks used in our study were 30.3 g/km and 10.8 g/km, respectively, and those for REAS ranged from 13.1 to 14.8 g/km for buses and from 2.36 to 11.7 for light-duty and heavy-duty trucks (Kurokawa et al., 2020). In terms of the SO_2 emissions, our estimate was close to the values estimated in REAS and GAINS but smaller than the value estimated in EDGAR because the emissions of this species from the residential and industrial sectors in EDGAR were higher than those in our study. The total NMVOC emissions estimated in our study were close to that estimated in REAS but 1.4 times greater than that estimated in EDGAR. One of the reasons for this discrepancy was because the NMVOC emission for the transport sector estimated in our study was higher than the value estimated by EDGAR. This difference could have been because of the differences in the selection of activity data and EFs. The emisisons of CH_4 in EDGAR were found to be higher than that in our study by 1.2 times. Regading the CO emissisions, Our estimate is similar to that estimated in EDGAR but 1.3 times greater than that estimated in REAS. This was because, our estimate of this species for transport was higher than that estimated in REAS. The CO EFs for gasoline vehicles used in our study were higher than those used in REAS, leading to higher vehicular CO emissions in our study than those in REAS. For example, the EFs of CO used in this study for cars were 76.05 g/km and that used in REAS ranged from 2.56 – 3.3 g/km. In addition, the exclusion of the emissions of CRB from REAS also led to the differences in CO emissions in the two studies.

In terms of the proxies used for the spatial distributions, in REAS, the urban, rural, and total population were mostly used to allocate the emissions for all the sources, except power plants, large industrial plants, and on-road transport. Some point sources, such as small and medium industrial plants, were treated as area sources. Using the population distribution as the main proxy for distributing emissions could not properly reflect the actual location of the emissions, especially in industrial zones with a high density of industrial facilities and a low population density. Our study used the locations of the point sources, such as industrial plants, hotels, restaurants, or gas stations, to allocate the emissions. Therefore, our approach could better reflect the exact locations of the emissions. Another improvement of this study is the finer spatial resolution. At 1 km × 1 km, the emission data developed in this study will be more suitable for urban-scale simulations than existing emission databases, such as REAS, EDGAR, or GAINS, which only provide coarsely gridded emission data. The spatial distributions of primary $PM_{2.5}$ in Hanoi created in REAS and EDGAR are included in the supplementary materials to illustrate the differences between the spatial distributions of our study and those of REAS and EDGAR (Figure A1). Due to the low resolutions, the differences between the spatial distributions of primary $PM_{2.5}$ emissions in the urban and rural areas of Hanoi cannot be seen clearly.

4.3. NMVOC speciation

The total NMVOC emissions in Hanoi were estimated to be 109.2 Gg. Using the NMVOC speciation profile developed by Li et al. (2019), we estimated the contribution of the components to the total NMVOC. **Figure 5** represents the 25 most abundant NMVOC species. It can be seen in **Figure 5** that transport and solvent use were the dominant contributors to these NMVOC species. Transport was the primary source of some NMVOC species, such as ethyne (5.86 Gg), toluene (3.24 Gg), m/p-xylene (2.31 Gg), ethene (2.2 Gg), and benzene (1.9 Gg). These species were predominantly emitted from gasoline vehicles such as motorbikes, cars, and taxis. Motorbikes and taxis together constituted 84% of the total emission of toluene and 85.8% of the total emission of m/p-xylene. In this study, we used the NMVOC speciation profile of passenger cars for taxis because specific profiles for taxis were not available in the study conducted by Li et al. (2019). In Hanoi, the printing industry and the application of solvent-containing products such as paint or adhesive tapes were also major sources of NMVOC species. For example, the printing industry dominated the emissions of ethyl acetate (1.97 Gg) and isopropanol (1.77 Gg). Similarly, paint application was a major source of mp-xylene (5.9 Gg), ethylbenzene (4.2 Gg), and toluene (1.3 Gg).

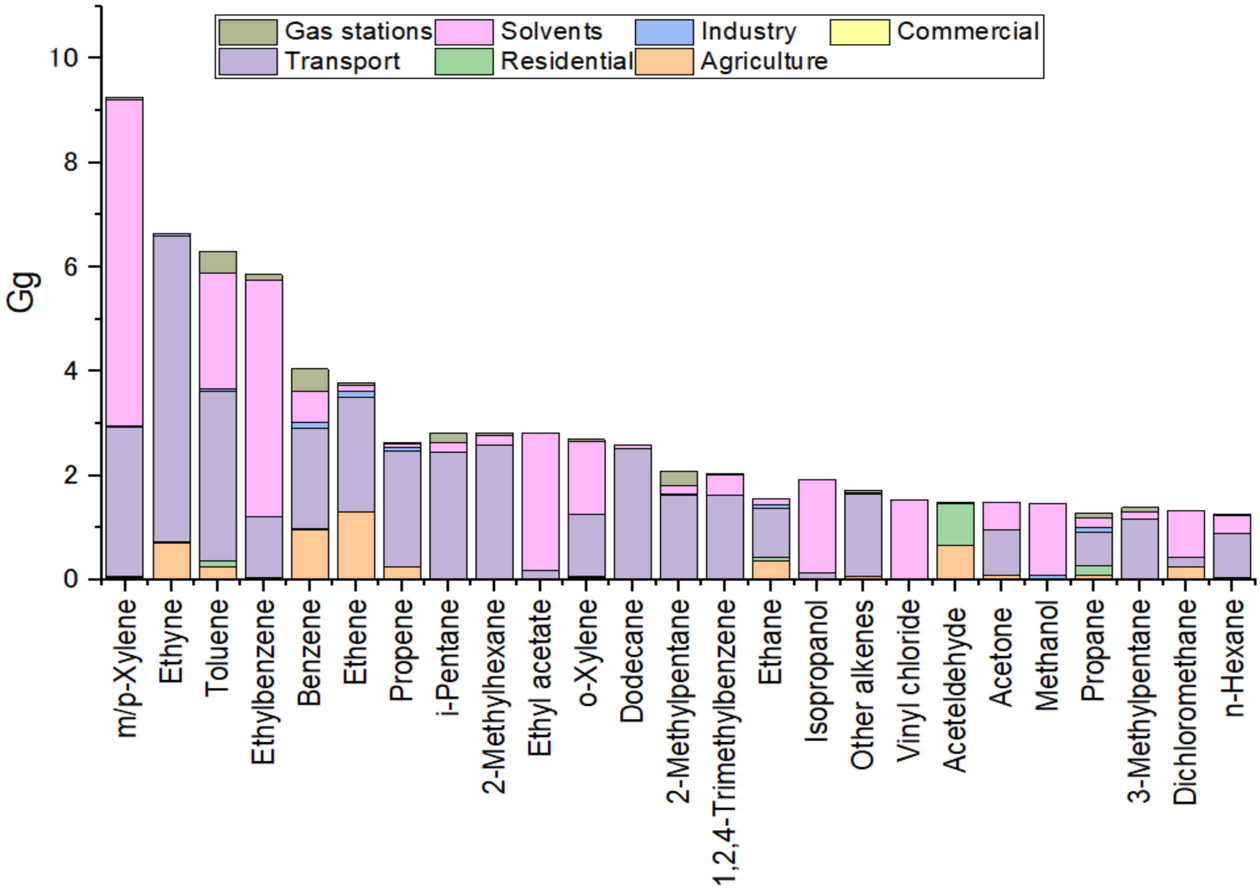


Figure 5. Emissions of 25 most abundant NMVOC species by sectors in 2017

4.4. Spatial and temporal distribution

The spatial distributions of $PM_{2.5}$, NMVOC, NO_x, and NH_3 for 2017 are provided in **Figure 6**. In addition, to better demonstrate the spatial distributions of major emission sources, the spatial distributions of the emissions of $PM_{2.5}$ (indutry), NO_x (transport), NMVOC (solvent use), and NH_3 (agriculture) were shown in **Figure 7**.

High emissions can be found in the centre of the city due to high population density and numerous small industrial facilities, and roads. Exceptions were found for NH_3 and CH_4, which were primarily emitted from livestock and fertiliser applications. Thus, high emissions of NH_3 and CH_4 were found in rural areas, containing the most livestock and cropland. Some other major sources of NH_3 were industrial facilities for fertiliser manufacturing. Non-combustion processes of the non-metallic and pulp industries accounted for a large portion of primary $PM_{2.5}$. Combustion and non-combustion emissions from on-road vehicles were also a joint cause of high primary $PM_{2.5}$ emissions in the centre of Hanoi. High emissions of NO_x and NMVOC were found along the road network throughout the city due to a high number of vehicles. Gas stations were also a joint cause of high NMVOC emissions along the road network. High NMVOC emissions at the city centre were caused by the numerous printing stores in the area. In addition, paint application was also a joint cause of high NMVOC emissions at the centre because of the high population density. In Hanoi, small roads (tertiary roads or residential roads) usually have higher traffic volumes than large roads (highways or main roads) because of the motorcycles. For this reason, higher emissions of pollutants from on-road transport can be found in the city centre. High emissions of some pollutants such as $PM_{2.5}$ or NO_x, also occurred at several locations, other than the city's centre, that contained industrial facilities or burned cropland, which contributed to the emissions of these species.

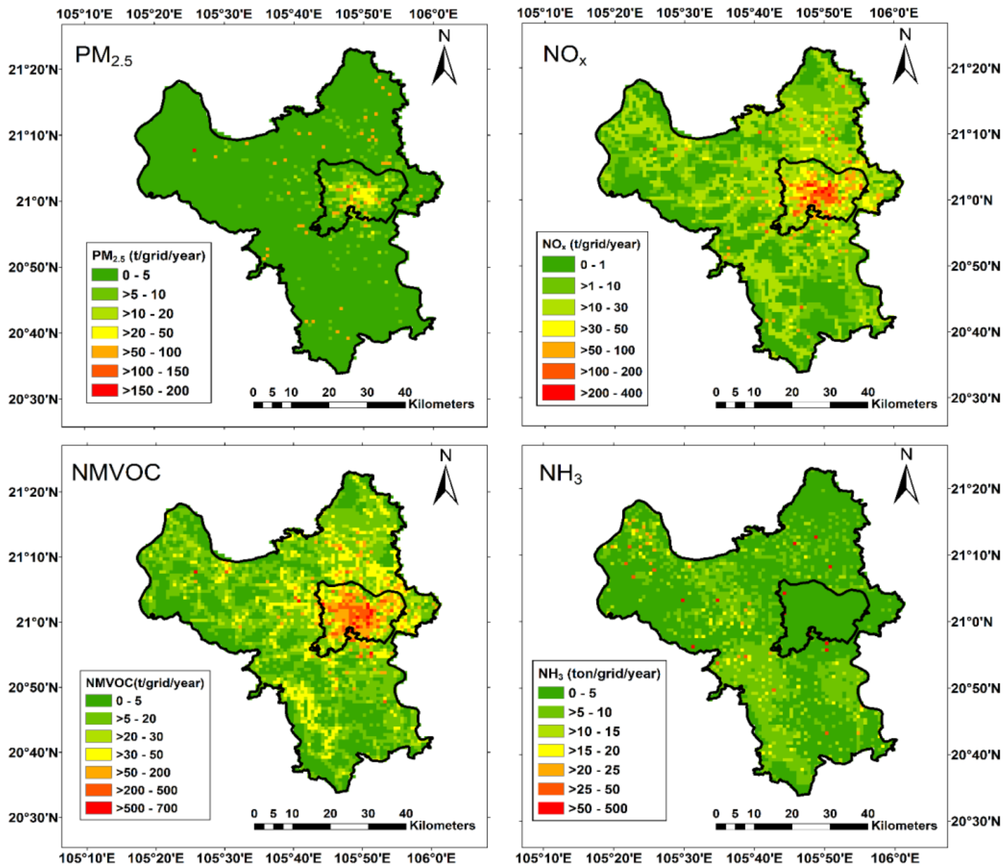


Figure 6. Spatial distributions of annual total emissions of $PM_{2.5}$, NO_x, NMVOC, and NH_3 in Hanoi in 2017 (the area inside the black line is the urban area)

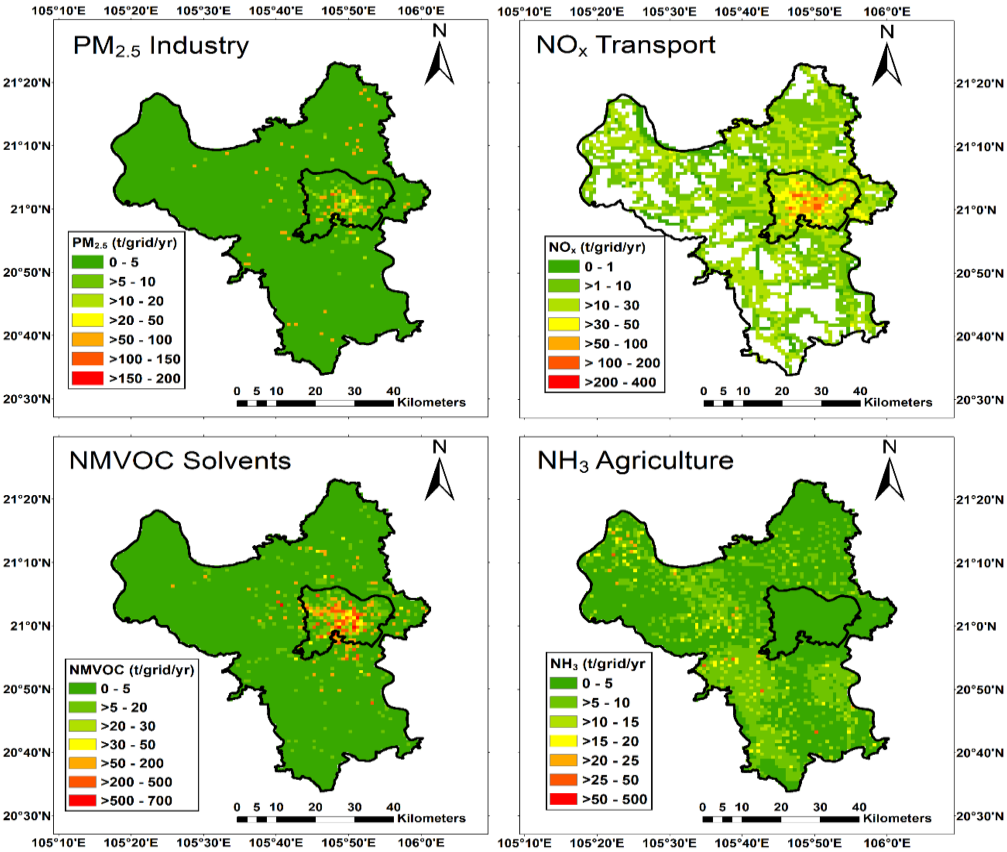


Figure 7: Spatial distributions of $PM_{2.5}$ (industry), NO_x (transport), NMVOC (solvent use), and NH_3 (agriculture) in Hanoi in 2017 (the area inside the black line is the urban area).

Figures 8, 9, and 10 illustrate the monthly, daily, and diurnal variation profiles (fraction) for several emission sources. The monthly variation profile (fraction) for the industrial sector the average of those for the industrial subsectors in **Figure S3**. The monthly variation profile for the NMVOC emissions from solvent use was distributed based on the monthly IPI in 2017 and 2018 (GSO, 2019b). The emissions from CRB coincided with the harvest season, with emission peaks in May and June. The lower emissions were found in September and October due to lower crop production in these months. The emissions from water heating follow the monthly variations of tap-water temperatures in which the emission peaked in winter (December to March). The monthly emissions from livestock and fertiliser varied proportionally with the profile of T_2, WS, number of livestock, and area of cropland. The monthly emissions from transport were determined by the cold and evaporative emissions (NMVOC), which depend on T_2. For Hanoi, winter months were found to have higher emissions from the transport sector due to higher cold emissions. Monthly emissions from the industrial sectors were the lowest in January and February due to New Year holidays; the emissions increased in the following months. The industrial emissions were the highest in December, which is the busiest month of the year.

Due to a lack of data, day-of-week profiles were only created for the transport and industrial sector, which showed lower emissions over the weekend compared with the weekdays (Pham et al., 2008; Truc and Kim Oanh, 2007).

The diurnal profile of CRB indicated that burning usually occurred during the daytime from between 9:00 to 17:00 (Kanabkaew and Kim Oanh, 2011). The diurnal variations of emissions from the livestock and fertiliser application were high during the daytime due to high temperatures. Additionally, the diurnal variations of the industrial sector were higher during the daytime from 8:00 to 17:00, the typical operation hours. Some industries, such as textiles also have a nightshift, which contributed to emissions overnight. Therefore, a small fraction of emissions from the industrial sector were produced during the night. The diurnal profile from the domestic sector exhibited clear emission peaks, which coincided with the two main meals of the day. The diurnal profile of the transport sector followed the traffic count of all types of vehicles with emission peaks usually occurring during rush hours. Lower emissions were found at night due to the nighttime operations of trucks and taxis. The diurnal profile of the evaporative emissions from the transport sector was created using the diurnal profile of T_2, obtained at meteorological and air quality stations in Hanoi, which demonstrated higher emissions during the daytime and lower emissions during the night. Finally, the diurnal profile of the gas stations indicated that vehicles are usually refuelled during the rush hour with a small fraction of taxis visiting the gas stations at night (Huy and Kim Oanh, 2020).

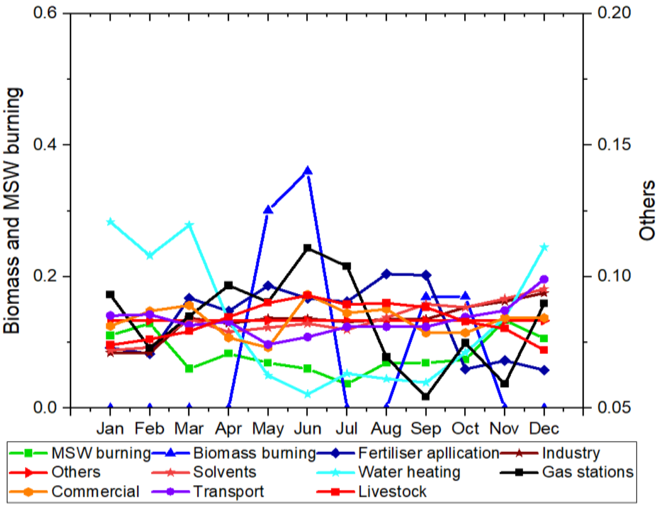


Figure 8. Monthly temporal profiles for all sectors

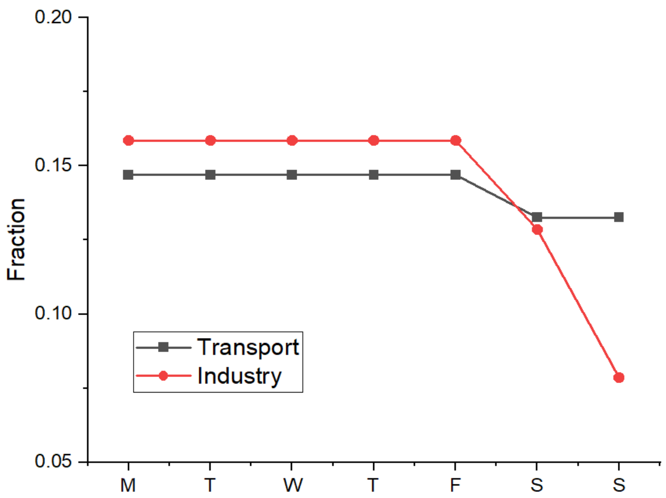


Figure 9. Day-of-week temporal profiles for the transport and industrial sector

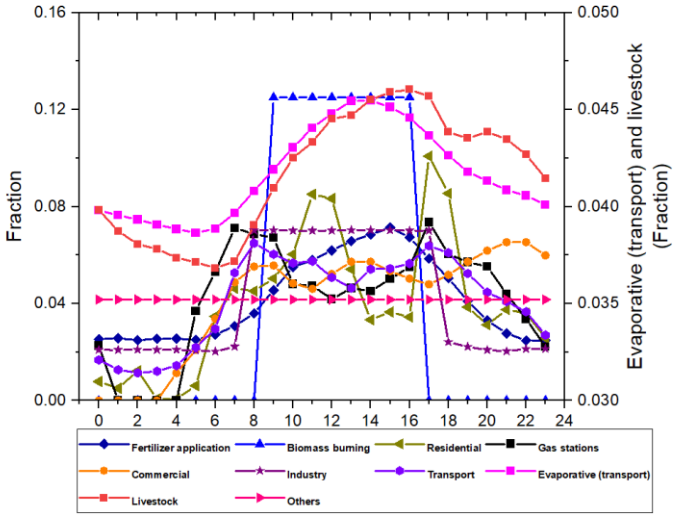


Figure 10. Diurnal temporal profiles for all sectors

4.5. Uncertainty

Table 4 shows the uncertainties for each sector while Table 5 shows the uncertainties from REASv3.2.

	$PM_{2.5}$	BC	OC	NO_x	SO_2	NMVOC	NH_3	CH_4	CO
Agriculture	14	82	56	79	168	8	30	21	6
Residential	49	47	68	39	36	45	54	72	35
Commercial	54	43	49	41	58	41		53	56
Transport	33	28	34	23	26	25	24	44	31
Industry	50	42	38	42	40	51	34	52	55
Solvent use						56			
Gas stations						43			
Total	19	31	29	20	25	22	29	19	24

Table 4: Uncertainties by sectors (%)

	$PM_{2.5}$	BC	OC	NO_x	SO_2	CO
Residential	300	296	302	158	169	241
Transport	70	72	72	57	28	78
Industry	164	194	246	79	59	155

Table 5: Uncertainties for the residential, transport, and industrial sector in Southeast Asia for 2015 that were estimated in REASv3.2 (%)

The total uncertainties of $PM_{2.5}$, BC, OC, NO_x, SO_2, NMVOC, NH_3, CH_4, and CO were 19%, 31%, 29%, 20%, 25%, 22%, 29%, 19%, and 24%, respectively. The NO_x and SO_2 emissions from crop residue burning were relatively high. The crop production was reliable because it was collected from official statistical yearbook of Hanoi, therefore other parameters, that was used to estimate activity data for this source and the EF could have been the source of uncertainties. The uncertainties for the transport sector were relatively low because the number of vehicles and the VKT were collected from local sources and studies which were conducted for Hanoi. The main source of uncertainties for the emissions from the transport sector were the non-exhaust source because the EF were selected from international sources, which could not well reflect the situation in Hanoi. The uncertainties of the residential sector came mainly from the water heating because there amount of fuel consumed were estimated using the amount of water used and the tap water temperatures. The uncertainties for the commercial sector were relatively high due to the EFs applied. For gas stations, the source of uncertainties came from both the amount of gasoline sold that was collected from international sources and the parameters that was used to estimate the EFs.

In general, the uncertainties for the residential, transport, and industrial sectors in our study were lower than those in REAS. The reason was because our study applied the activity data that were collected mainly from local sources while REAS used international activity data. Therefore, the uncertainties for these sectors were lower than those estimated for REAS.

The quality of the emission data estimated in this study are much better than those estimate in REAS. The main reason was that the activity data used in our study was more reliable than those in REAS. Our activity data were collected mainly from local sources while REAS used the data collected from international sources. However, local EFs for Hanoi are still scare and it contributed to the uncertainties of the emission sectors in this study. Therefore, studies to develop a database for EFs for Hanoi or Vietnam should be considered in the future. In addition, local data on fuel consumption at industrial facilities are important and it is recommended that efforts should be made to collect local data for this source.

4.6. Future projections of emissions in Hanoi for a period from 2025 and 2030

Table S12 and **Figure 11** show the projected emissions of pollutants from selected sectors in 2017, 2025, and 2030. For the commercial sector, the impact of switching from coal to LPG for cooking was evaluated for the year 2017.

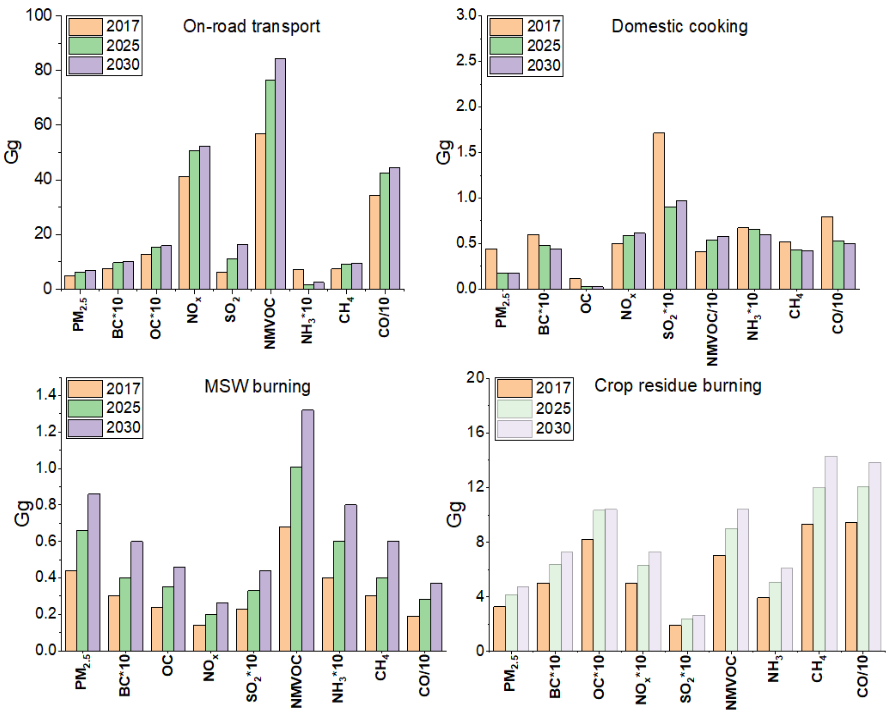


Figure 11. Future predicted emissions from selected sectors. Note that the projections of the emissions from agricultural residue burning are an estimate of the amount of pollutants reduced under the effect of Directive 15/CT-UBND, which bans agricultural residue burning in Hanoi from 2021, thus the value bars are in faded colors.

For the on-road transport, the emissions of $PM_{2.5}$, BC, and OC were predicted to increase by 31.3%, 28.0%, and 23.2% in 2025 and by 41.7%, 34.7%, and 27.2% in 2030, respectively. The emissions of SO_2 were predicted to increase by 80.4% and 161.2% and the emissions of NH_3 were predicted to increase by 120 % and 245.8%, respectively. Exceptionally high increases in the emissions of these two species could be because the EURO 5 standard does not include SO_2 and NH_3. The emissions of NO_x, NMVOC, CH_4, and CO were predicted to increase 23.1%, 34.3%, 23.7%, and 24.3% in 2025 and 27.4%, 48.2%, 26.9%, and 29.6% in 2030, respectively. Overall, despite the effect of the EURO 5 standard, due to the increase in the total number of active vehicles, the total emissions of pollutants were predicted to increase in 2025 and 2030.

For domestic cooking, the emissions of most species were predicted to decrease by 3% (NH_3) and 52.6% (OC), depending on the species, except for NO_x and NMVOC. The emissions of these two species were predicted to increase 16.0%, 22.0%, and 31.0%, 40.0% in 2025 and 2030, respectively. The reason for the increase in the emissions of NO_x and NMVOC in 2025 and 2030 was that LPG has higher emission factors of NO_x and NMVOC than coal does. In terms of MSW burning, the emissions of all species were predicted to increase due to the increase in the total population. The emissions of $PM_{2.5}$, BC, and OC were predicted to increase 50%, 33,3%, and 45.8% and 95.4%, 66.6%, and 91.6% in 2025 and 2030, respectively. The emission of NO_x, SO_2, NMVOC, NH_3, CH_4, and CO were projected to increase by approximately 50% in 2025 and 100% in 2030, in comparison with the values in 2017.

The emissions of most species except for NMVOC from the commercial sector were predicted to decrease by 7.1% (NO_x) and 93.6% (SO_2) owing to the transition from coal to LPG. The emissions of NMVOC were predicted to increase by 7.8 times due to the transition because of the very high EF of NMVOC in comparison with that of coal used in this study (18.8 g/kg and 0.664 g/kg for coal and LPG, respectively). Lastly, based on the growth rate of the crop production, the future emissions of CRB were also predicted in this study. The emissions of $PM_{2.5}$, BC, and OC from CRB were predicted to increase by 27.5%, 33.3%, and 47.1% in 2025 and by 45.5%, 52.0%, and 48.9% in 2030, respectively. The emissions of gaseous species were predicted to increase by 26.3% to 47.1% in 2025 and 42.1% and 54.8% in 2030, respectively. Therefore, with Directive 15/CT-UBND coming into effect, the amount of air pollutants prevented from entering the atmosphere will range from 0.24 Gg (SO_2) to 120.8 Gg (CO) by 2025 and 0.27 Gg (SO_2) to 138.4 Gg (CO) by 2030, respectively.

5. Suggestions for improvement to policies on urban air pollution

The Vietnamese and local governments have attempted to improve the air quality in Hanoi by implementing policies on sectors such as the on-road transport, residential and commercial, and agricultral sectors. Some policies such as ban on CRB or transition from coal to LPG for domestic use are expected to help to mitigate air pollution in Hanoi. However, to our knowledge, air pollution policies for some other major sector, like the industrial sector has not been properly considered. In this section, we discussed and proposed some suggetions that may give policymakers directions for enhancing policies on urban air pollution, based on the results in this study:

Transport:

Transport is a major source of PM, NO_x, NMVOC, and CO. Despite the enforcement of the EURO 5 standard, the emissions from the transport sector will still increase in the future due to the increase in the number of on-road vehicles. There, in addtion to enforecing the higher EURO standarts on vehicles, the government should also focus on the development of the public transport system, such as the public buses or the underground, to restrain the use of private motorcycles or cars. In addition, it is suggested that the government invest in electrical vehicles as they will significantly reduce the emissions of air pollutants (Wang et al., 2021).

MSW burning:

The most cost-effective way to prevent emissions from this source is reduce the amount of waste generated (e.g. plastic and paper packaging). Reducing the amount of waste generated will also reduce the cost of waste collection and transportation. In addition, the Vietnamese and local government should give instruction on municipal solid waste classification as it will help to minimize the amount of high-polluting and toxic waste that go to the incinerators. Lastly, it is suggested that the Vietnamese government practice environmentally-friendly waste management methods, instead of burning. For example, biodegradable waste such as food or garden waste should be converted into compost that can be added to soil to give nutrition to plants.

Industry

The industries are a major source of $PM_{2.5}$ and SO_2. These species are emitted from both combustion and non-combustion processes. Therefore, it is sugested that the government take action to reduce emissions from both processes. For example, emission control devices can be applied to high-polluting industrial facilities; using clean fuels for combustion or using clean raw materials for production. In addition, upgrading industrial processes to improve their efficiency could also help to reduce pollution.

6. Conclusion

A high-resolution emission inventory (1 km × 1 km) were developed for Hanoi for 2017 and 2018. The sectors included were: agriculture, residential and commcercial activities, transport, industry, and others (solvent use and gas stations). In addition, we predicted the future emissions from on-road transport, domestic cooking, MSW burning, the commercial sector, and CRB for 2025 and 2030 based on the scenarios proposed by the Vietnamese and local governments.

The total emissions of $PM_{2.5}$, BC, OC, NO_x, SO_x, NMVOC, NH_3, CH_4, and CO in 2017 were 14.9 Gg, 1.6 Gg, 2.9 Gg, 56.7 Gg, 19.1 Gg, 109.2 Gg, 23.0 Gg, 37.9 Gg, and 472.7 Gg, respectively. Together, the transport, industrial, and agricultural (CRB) sectors contributed 89.2%, 92.2%, and 91.3% to the emissions of $PM_{2.5}$, BC, and OC, respectively. Transport was the main source of NO_x emissions, contributing 72.4% to the total emissions of this species. Note that trucks and buses are the largest vehicular sources of NO_x, contributing 58.8%. In contrast, Industry was the predominant source of SO_2, contributing 65.0%. The combustion processes of the textile and leather subsector and the non-combustion processes of the non-metallic minerals subsector were the major industrial contributors of this species. Transport and solvent use were the two leading emitters of NMVOC, constituting 52.1% and 35.2%, respectively. A high number of conventional motorbikes and taxis were the main reason leading to the exceptionally high contribution of the transport sector to the total emissions of NMVOC. The agricultural sector contributed 84.2% to the total emissions of NH_3, with 27.1% coming from manure management, 39.9% coming from fertiliser application, and 17.1%

coming from CRB. Transport was also the leading contributor of CO, with 72.5%, due to a large fleet of motorbikes.

M/p-xylene, ethyne, toluene, and ethylbenzene were the major NMVOC species in Hanoi. These species contributed 9.2 Gg, 6.6 Gg, 5.9 Gg, and 5.7 Gg, respectively, to the total emissions of NMVOC in the city. M/p-xylene and ethylene benzene were mostly contributed by solvent use, with 6.2 Gg and 4.5 Gg while ethyne and toluene were mainly emitted by the on-road vehicles, with 5.86 Gg and 3.24 Gg, respectively.

Using the Monte Carlo simulations, the uncertainties of the transport, industrial, and residential sectors in this study ranged from 23 % (NO_x) to 44 % (CH_4), 34 % (NH_3) to 55 % (CO), and from 36 % (SO_2) to 72 % (CH_4), respectively. These uncertainty ranges were substantially lower than the uncertainties of the transport, industrial, and residential sectors in REAS, which are from 28 % (SO_2) to 78 % (CO), 59 % (SO_2) to 246 % (OC), and from 158 % (NO_x) to 302 % (OC), respectively. This study mainly used locally collected data for emission estimations. Therefore, the activity data in this study were more reliable than those used in some international emission inventories such as REAS or EDGAR.

Future emissions of the transport, residential (residential cooking and MSW burning), and agricultural (CRB) sectors were estimated, taking into consideration the action plans and predictions proposed by the Vietnamese and local governments. Despite the effectiveness of the EURO standards, the emissions from transport were predicted to increase between 23.1% (NO_x) and 120% (NH_3) by 2025 and 26.9% (CH_4) and 245.8% (NH_3) by 2030 due to the increase in the number of vehicles. As for residential cooking, by switching from coal to LPG, the emissions of NO_x will increase by 16.0% and 22.0% by 2025 and 2030, respectively. The emissions of NMVOC will also increase by 31.0% and 40.0% by 2025 and 2030, respectively. This was because of the. However, the emissions of other species will decrease between 3.0% (NH_3) and 47.4% (OC) by 2025 and between 10.4% (NH_3) and 52.6% (OC) by 2030, respectively. Regarding MSW burning, the emissions of pollutants were predicted to increase in the range from 33.3% (BC) to 53.8% (NO_x) by 2025 and 66.6% (BC) and 100% (NO_x, SO_2, and NH_3) by 2030. Finally, for the agricultural sector, the emissions of $PM_{2.5}$, BC, and OC from CRB were predicted to increase by 27.5%, 33.3%, and 47.1% in 2025 and by 45.5%, 52.0%, and 48.9% in 2030, respectively. The emissions of gaseous species were predicted to increase by 26.3% to 47.1% in 2025 and 42.1% and 54.8% in 2030, respectively. Therefore, Directive 15/CT-UBND will help to prevent a considerable amount of pollutants will be prevented from entering the atmosphere.

Some limitations in this study need to be improved in future studies. The activity data for some sectors such as the industrial combustion processes or gas stations were collected from international databases. In addition, for most of the Southeast Asian counties, including Vietnam, country-specific EFs for most of the emission sectors are not available. In this study, local EFs were applied mostly to the hot emissions from the transport sector. The lack of local activity data for some sectors and EFs is the main reason for the uncertainties in our study. Another limitation is the lack of information about the emission control efficiency for the industrial sector. Therefore, future studies should attempt to collect this information to further improve the quality of the EIs for Hanoi. In addition, for the future emission projections, there was a lack of information about the action plans of the Vietnamese and local governments regarding the industrial sector. Further investigation should be conducted regarding this information as it will help policymakers to adopt appropriate policies on this source.

Credit author statement

Thanh Hung Nguyen: Conceptualization, Methodology, Data curation, Visualization, Writing – Original Draft. **Ngo Tho Hung:** Data curation, Investigation. **Tatsuya Nagashima:** Conceptualization, Methodology, Writing – Review & Editing. **Jun Fat Lam:** Methodology, Writing – Review & Editing. Quang-Van Doan: Writing – Review & Editing. **Junichi Kurokawa:** Methodology, Writing – Review & Editing. **Satoru Chatani:** Methodology, Writing – Review & Editing. **Ahmed Derdouri:** Writing – Review & Editing. **Penwadee Cheewaphongphan:** Writing – Review & Editing. **Ansar Khan:** Writing – Review & Editing, **Dev Niyogi:** Writing – Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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