An Assessment of the Long-term Impact of Socio-economic Development on the Air Quality Using Numerical Models in Hanoi, Vietnam

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Abstract

Air pollution has accompanied rapid socioeconomic development worldwide, including several big cities in Southeast Asia, including Hanoi, the capital of Vietnam. Because air pollution can adversely affect human health as well as ecosystems, effective countermeasures based on scientific evidence are required. However, such evidence has not yet been established in the case of Hanoi, although several sources of air pollution have been investigated, such as transport, agriculture, industry, residential activities, and long-range transport of air pollutants from outside the city. In this study, the impact of various emission sources of air pollutants in Hanoi was quantitatively estimated by developing a comprehensive emission inventory of air pollutants and conducting numerical model simulations using an air quality model. In addition, the future air quality in Hanoi was also evaluated based on the action plans developed by local authorities. The key results of this study are summarized as follows:

Firstly, an emission inventory was developed for Hanoi for 2017 and 2018, including several sectors, such as agriculture, transport, industry, residential activities, commercial activities, and others (gas stations and solvent usage). In addition, an emission inventory for the coal-fired power plants located around Hanoi was also developed. The total emissions in 2017 were: 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. The power plants located near Hanoi were estimated to emit more NO_x and SO_2 (82.5 Gg NO_x and 41.6 Gg SO_2, respectively) than those within Hanoi. In Hanoi, transport, industry, and agriculture were the predominant sources of $PM_{2.5}$, BC, OC, NO_x, SO_2, NMVOC, and CO, contributing 89.1%, 92.2%, 81.4%, 97.8%, 97.6%, 84.3%, and 97.0%, respectively. Agriculture was the main source of NH_3 and CH_4, contributing 84.2% and 76.6%, respectively. The future emissions of selected sectors were also developed for 2025 and 2030 considering the future socio-economic action plans proposed by the government of Hanoi. The emissions from the transport sector were predicted to increase by 23.1% (NO_x) – 120.8% (NH_3) and by 26.8% (CH_4) – 245.8% (NH_3) by 2025 and 2030, respectively. For domestic cooking, the emissions of NO_x were predicted to increase by 16.0% and 22.0% and the emissions of NMVOC were predicted to increase by 31.0% and

40.0% by 2025 and 2030, respectively. The emissions of other species were predicted to decrease by 3.0% – 46.7% by 2025 and by 10.4% – 50.8% by 2030, respectively. The emissions from the municipal solid waste (MSW) burning were predicted to increase by 33.3% (BC) – 53.8% (NO_x) and by 66.7% (BC) – 100% (NO_x) by 2025 and 2030, respectively. In the commercial sector, the emissions of NMVOC were predicted to increase 687%, while those of other species were predicted to decrease by 7.1% – 93.6% due to the switch from coal to LPG. Ban on the burning of open crop residue in Hanoi is predicted to considerably reduce the emissions of most air pollutants.

Secondly, using the Weather Research and Forecasting (WRF)-Community Multiscale Air Quality (CMAQ) air quality modelling system, the concentrations of $PM_{2.5}$ in Hanoi during the period from 1 July 2017 to 30 June 2018 were investigated using a self-developed emissions inventory. The WRF simulations well simulated the temporal variations of the meteorological parameters but slightly underestimated the relative humidity (RH_2) and overestimated the wind speed (WS). The CMAQ well-reproduced both the temporal variations and the magnitude of $PM_{2.5}$ concentrations in Hanoi. In addition, the ISAM (Integrated Source Apportionment Method) system was used to investigate the relative contribution of several emission sectors and the boundary condition (BCON) to the concentrations of $PM_{2.5}$. The ISAM simulations were conducted for April, June, October, and December, which represent the four seasons in Hanoi. The results indicate that the BCON was the key contributor of $PM_{2.5}$ in Hanoi, contributing 59.6% (April), 24% (June), 35.3% (October), and 49.2% (December). Agriculture was a major source of $PM_{2.5}$ in June and October, contributing 27.8% and 18.8%, respectively, but it made up only 6.5% and 9.5% in April and December, respectively, because no crop residue was burned during these two months. Industrial facilities contributed 15.4%–23.6%, residential and commercial activities accounted for 8.0%–10.8%, and the transport sector contributed 5.8%–10.1% to the total concentrations of $PM_{2.5}$ within Hanoi.

Lastly, the future concentrations of $PM_{2.5}$ in Hanoi in 2030 were predicted based on the future emissions estimated considering various action plans by Vietnam and local governments regarding on-road transport, domestic and commercial cooking, municipal solid waste burning, and agricultural activities. The results suggested that in April and

December, the concentrations of $PM_{2.5}$ will increase by 0.5 and 1.6 μg/m^3 in 2030, respectively, primarily due to the increase in emissions from the transport sector; while in October and June, the concentrations of $PM_{2.5}$ were predicted to decrease by 1.5 and 3.2 μg/m^3, mainly due to the removal of the emissions from crop residue burning and water heating.

Key words: *Emission inventory, $PM_{2.5}$ components, Hanoi, WRF-CMAQ-ISAM, source apportionment, future predictions.*

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Chapter 1: Introduction

1.1. Studies on air quality in Southeast Asia

Southeast Asia is one of the fastest developing areas worldwide. In recent years, the demand for combustion fuel has risen in Southeast Asian countries due to the increase in population and fast-growing economies. As a result, the increase in energy consumption has led to an increase in the emissions of air pollutants, affecting human health and worsening the air quality (Frankenberg et al., 2005; Perera, 2017). According to The 2020 World Air Quality Report**,** some Southeast Asian countries, such as Indonesia, Myanmar, and Vietnam, were the most polluted in the world in 2020, with the annual mean concentrations of $PM_{2.5}$ of 40.8 µg/m^3, 29.4 µg/m^3, and 28.0 µg/m^3, respectively (IQAir, 2020). Although Thailand ranked fifth out of the nine Southeast Asian countries considered in IQAir, (2020), 10 of the 15 most-polluted regional cities in 2020 were located in Thailand. However, the most-polluted city in Southeast Asia was South Tangerang (Indonesia), with the annual mean concentration of $PM_{2.5}$ reaching 74.9 µg/m^3. This value was 1.4 times higher than that of the second most-polluted city in Southeast Asia, which was Pai (Thailand) (IQAir, 2020). In Southeast Asia between 1990 and 2014, transport (36%), residential activities (19%) and industry (18%) were the predominant anthropogenic sources of $PM_{2.5}$, while natural sources contributed a small percentage $PM_{2.5}$ (14%) (Karagulian et al., 2015). In addition, the Southeast Asian region is very sensitive to agricultural burning. In addition, the Southeast Asian region is especially sensitive to agricultural burning, which contributes approximately 5–30% of the total anthropogenic emissions in the region (CCAC and UNEP, 2019).

Recognising the impact of air pollution on human health and the ecology systems, various studies have been conducted on Southeast Asian region and countries. Nguyen et al. (2019a) investigated the effects of aerosol on $PM_{2.5}$ and O_3 over Southeast Asia using the WRF-CMAQ system. Furthermore, Lee et al. (2019) investigated the impact of future fuel consumption on air quality in Southeast Asia, using the WRF-Chem model, under various scenarios. Permadi et al. (2018) assessed the impacts of black carbon emission reduction on air quality and radiative forcing in Southeast Asia. Along with studies that use AQM to investigate air pollution, national and local emissions inventories have also been developed. Recently, an emission inventory from the residential sector was developed for the Southeast Asian region (Huy et al., 2021). In addition, nationwide emission inventories have been developed as well. For example, Thao et al. (2021) developed an emission inventory of anthropogenic atmospheric mercury for Thailand in 2018. Additionally for Thailand, an emission inventory of various air pollutants for the industrial sector and power plants has been created (Pham et al., 2008). In Indonesia, Permadi et al. (2017) developed a comprehensive emission inventory for greenhouse gases and air pollutants in Indonesia to evaluate the effectiveness of the kerosene ban. In Myanmar, the (International Vehicle Emission) IVE model was used to establish an emission inventory for on-road vehicles in Greater Yangon (Huy et al., 2020). In Vietnam, an emission inventory for key emission sources such as the residential, industrial, and on-road transport sectors has also been developed (Ho et al., 2019).

1.2. Studies on air quality in Hanoi.

The air environment of Hanoi is currently deteriorating due to such rapid socioeconomic development. The observational data from the Centre for Environmental Monitoring (CEM) indicated that the annual mean concentrations of $PM_{2.5}$ in Hanoi from 2010–2018 ranged from 36.7 $\mu g/m^3$ in 2012 to 66.5 $\mu g/m^3$ in 2010. These values exceeded the acceptable concentration of $PM_{2.5}$ (25 $\mu g/m^3$) set by the Ministry of Natural Resources and Environmental (MONRE). 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 $\mu g/m^3$ during 2020, with 69.4% of the days with daily $PM_{2.5}$ concentrations $\geq$ 25 $\mu g/m^3$ (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).

To date, there have been several studies focusing on the air quality in Hanoi. For example, Hien et al. (2021) analyzed the components of PM_{10} and $PM_{2.5}$ using the samples collected from one sampling site located in a residential area within Hanoi. Ly et al., (2018) used newly developed highly sensitive sensors to investigate the temporal variation of $PM_{2.5}$ concentrations in Hanoi in 2016 and 2017. Hai and Kim Oanh, (2013) investigated the characteristics of $PM_{10\text{-}2.5}$ in Hanoi from December 2016 to February 2017. Cohen et al. (2010) investigated the characteristics and the source apportionment of $PM_{2.5}$ in Hanoi from 2001 to 2008. Snider et al. (2016), investigated the components of $PM_{2.5}$ in several cities worldwide, including Hanoi, using the filter sampling method. However, these studies have some drawbacks on their own. Firstly, the studies used the data collected from limited sampling sites; therefore, their results may not be representative of the air quality of the entire city. Secondly, some of the studies were only conducted during a specific season and may have overlooked the air quality in Hanoi in other seasons. Thirdly, most of the studies are outdated. Air quality modelling can be used to simulate the concentrations of an air pollutant for the entire simulation domain. Some air quality models, such as WRF-CMAQ or WRF-Chem, have been widely used for air quality research worldwide (Canty et al., 2015; Ikeda and Tanimoto, 2015; Q. Li et al., 2019; Nguyen et al., 2019a, 2019b; Nguyen et al., 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.

1.3. Existing global-scale and regional-scale emission inventories for air quality modelling research.

However, unlike countries such as the US, China, or Japan, where their national-wide emission inventories are readily available as input for AQMs, air quality research using AQMs in developing countries (such as Vietnam) considerably depends on global or continental-scale emission inventories, 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). **Table 1.1** lists the information about the global and regional emission inventories which have been widely used for numerical modelling studies.

Table 1.1: Existing global and regional emission inventories

	Year	Horizontal resolution	Species	Coverage	Reference
REASv 3.1	1950 – 2015	0.25°× 0.25°	SO_2, NO_x, CO, PM_{10}, $PM_{2.5}$, BC, OC, NMVOC, NH_3, CO_2	East, Southeast and South Asia	Kurokawa and Ohara (2020)
EDGAR v5.0	1970 – 2015	0.1°× 0.1°	SO_2, NO_x, CO, PM_{10}, $PM_{2.5}$, BC, OC, NMVOC, NH_3, CO_2, CH_4	Global	EC-JRC (PBL) (2019)
GAINS	1990 – 2030 (5-year increment, projection starting in 2015)	0.5°× 0.5°	SO_2, NO_x, CO, PM_{10}, $PM_{2.5}$, TSP, BC, OC, NMVOC, NH_3, CO_2, CH_4, N_2O, F_{gases}	Global	Amann et al. (2008)

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). Therefore, using such emission inventories for air quality modelling studies on an urban scale would lead to high uncertainty in the results, especially when they are used for source apportionment purposes (Nguyen et al., 2020). In Nguyen et al. (2020), the contributions to the total concentrations of $PM_{2.5}$ of the transport, industrial, and residential sectors in Hanoi in December 2010 were estimated to be 2%, 40%, and 39%, respectively, using the WRF-CMAQ model with the REAS emission inventory. The low contribution of the transport sector might have been due to the use of the REAS emission inventory. Because REAS, EDGAR, and GAINS are regional and global emission inventories, their spatial resolutions are quite rough (0.25°, 0.1°, and 0.5°, respectively) for air quality simulations at the city scale. Moreover, most of the abovementioned international and national emission inventories include only the monthly or annual variations in emissions. Some of them (e.g. REAS or GAINS) lack detailed information about diurnal variations which are important for modelling studies.

City-scale emission inventories are crucial for air quality modelling purposes as well as for the developments of air pollution control policies (Zhao et al., 2015). In addition, a high-resolution emission inventory can help to identify the contribution of emission sources or be used as input into 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 emission inventory of air pollutants for Hanoi is essential in order to conduct studies on air quality at a city scale using AQMs, and especially for revealing the contributions of various emission sectors to air pollution as well as the trends. Previous studies have also shown that air quality models tend to produce more consistent results when using local emission data as input (Timmermans et al., 2013). Researchers have made attempts to develop emission inventories for Vietnam and for Hanoi for individual emission sectors. For example, the IVE model was used to develop an emission inventory for the motorcycle fleet in Hanoi for 2008 (Kim Oanh et al., 2012) and cars, buses, and taxis in Hanoi for 2010 (Trang et al., 2015). Another attempt was made to create an emission inventory for the industrial and power sectors across Vietnam for 2010 (Huy and Kim Oanh, 2017). Similarly, Roy et al. (2020) developed an emission inventory for power generation units in Vietnam in 2010 and 2015. Recently, a study focusing on CH_4, N_2O, and NH_3 emissions was conducted for livestock for the Red Delta River area in Vietnam, including the region Hanoi (Truong et al., 2018); the temporal coverage of the study was from 2000 to 2030, with a 5-year increment projection.

Although these studies provide detailed and comprehensive information on emissions, they include many drawbacks. First, most of the studies lack information on the spatial distribution of the emission sources that are essential for air quality modelling studies. Second, they included only one or two sectors, and thus, the importance and contribution of other sectors are not considered. Third, some studies were developed for 2010 and are outdated. To date, the most comprehensive study on the emission inventory for Hanoi has been conducted for the transport, industrial, and residential sectors (Hung, 2010). However, Hung (2010) conducted the study for 2008, making it not suitable for the current air quality modelling studies. Two studies on power plants in Vietnam lacked detailed information on the actual fuel consumption and fuel use characteristics (ash content, sulphur content, and net calorific value) of each power plant, which could lead to large uncertainties (Huy and Kim Oanh, 2017; Roy et al., 2020). In addition, because Roy et al. (2020) only developed a yearly emission inventory for thermal power plants, there is a substantial uncertainty because emissions are strongly seasonal and can be affected by other types of power plants, such as hydroelectric dams (Huy and Kim Oanh, 2017).

1.4. Purpose of this study

Considering the drawbacks of previous studies, this study aims to fulfil the following objectives: 1) to develop a high-resolution emission inventory for Hanoi for 2017 and 2018; 2) to develop a projected future emission inventory for selected emission sectors based on the action plans proposed by Vietnam and local governments; 3) to understand the current status of air quality in Hanoi and the contributions of various emission sources to air pollution in Hanoi using numerical models; and 4) to predict the future air quality in Hanoi using numerical models.

1.5. Structure of this dissertation

This dissertation is divided into five chapters: Chapter 2 is a brief introduction of the study areas of Hanoi; Chapter 3 focuses on the development of the current and future emission inventory for Hanoi; Chapter 4 investigates the contributions of different emission sources and the impact of emission changes on the concentrations of $PM_{2.5}$ in Hanoi; Chapter 5 provides the key findings and conclusions of the study.

Chapter 2: Study area

2.1. Area and population of Hanoi

Location and map of Hanoi are shown in **Figure 2.1**. Hanoi covers an area of 3,358.59 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 and 19 are rural. In 2017, 3,770 and 3,891 million people lived in urban and rural districts, which increased to 3,874.3 million and 3,978.3 million in 2018, respectively (HSO, 2019). The centre of Hanoi is surrounded by several industrial zones (**Figure 2.1**). Some of the main industries in Hanoi include paper and pulp, brick, food, beverage, textile manufacturing, and printing industry. These industries are the prominent sources of air pollution.

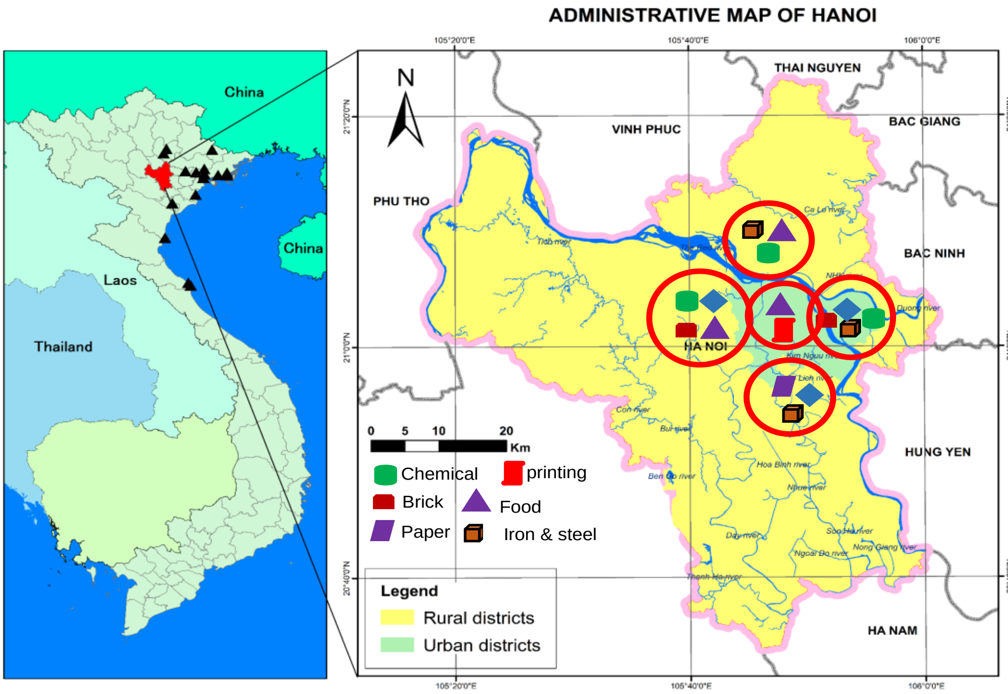


Figure 2.1: Location of Hanoi in Vietnam; the black triangles represent the coal-fired power plants (Left). Administrative map of Hanoi, including rural (yellow) and urban (green) districts (Right); rural and urban districts are classified according to Hanoi Statistical Yearbook 2018 (HSO, 2019). The locations of some key industrial zones are identified on the map.

2.2. Meteorological characteristics of Hanoi

Figure 2.2 presents the monthly mean temperatures and rainfall in Hanoi in 2017 and 2018. 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.

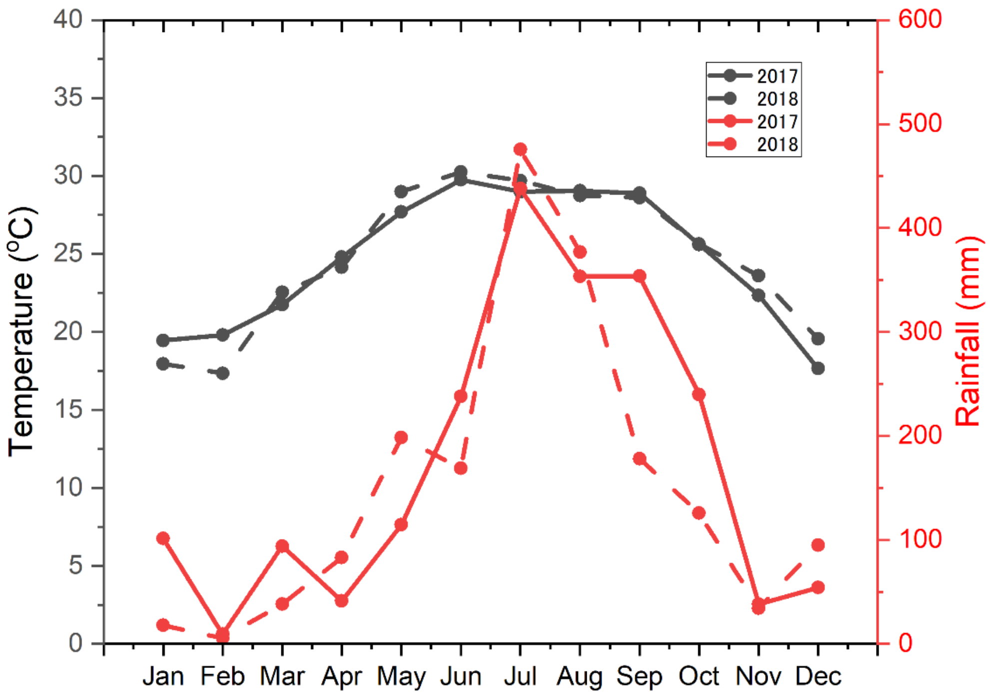


Figure 2.2: Monthly mean temperatures and rainfall in Hanoi in 2017 and 2018. The black and red solid lines represent the temperatures and rainfall in 2017, while the black and red dash lines represent those in 2018. High rainfall amounts occurred during the summer season from June to August. The rainfall may have an impact on the concentrations of air pollutants, such as $PM_{2.5}$.

Chapter 3: Development of a high-resolution emission inventory for Hanoi

3.1. Emission inventory for Hanoi and the coal-fired power plants located in northern Vietnam in 2017 and 2018.

3.1.1. Approaches for developing an emission inventory

Two popular approaches are usually used for estimating an emission inventory: bottom-up and top-down. According to the Atmospheric Brown Cloud Emission Inventory Manual (ABC-EIM; Shrestha et al., 2012), the top-down approach uses general emission factors combined with regional, national, or region level activity data to estimate the emissions for a country or region. In addition, national or regional emissions can be scaled down using surrogate data, including geographic, demographic, economic data. This approach should only be used when the local data are not available or the cost of collecting such data is high. This approach does not require a significant effort to collect data, but the emissions created by this approach generally have a high level of uncertainty. However, this approach can be applied when local data are not obtainable. In contrast, in the bottom-up approach, the emissions of individual emission sources are estimated and summed to obtain the state- or country-level emissions. Although using this method is expected to lead to a more reliable emission inventory in comparison with the top-down approach, it requires a much greater effort to collect site-specific data on the emission sources, activity levels, and emission factors. Thus, the bottom-up method is usually used to estimate the emissions from point sources. Therefore, we only applied the bottom-up method to estimate the emissions from the coal-fired power plants and non-combustion industrial processes.

3.1.2. Covered sectors

Detailed information about the emission inventory is provided in **Table 3.1**. 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).

Table 3.1: Details regarding the coverage of the emission inventory developed in this study.

Sector	Agriculture	Livestock (enteric fermentation (CH_4), manure management (NH_3, CH_4)), fertiliser application (NH_3), and crop residue burning
	Residential	Cooking, water heating for bathing (hereafter referred to as water heating), and municipal solid waste (MSW) burning
	Transport	On-road vehicles (Motorcycles, cars, trucks, buses, taxis) and domestic shipping
	Commercial	Hotels and restaurants
	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 fertilizer, beverage, and other subsectors.
	Power plant	Coal-fired power plants located in nothern Vietnam
	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	

3.1.3. Equations for estimating emissions

This section provides the general formula (Equation 1) and briefly describes the activity data used for estimating the emissions of a particular pollutant from an emission source. More details regarding the equations used for estimating the emissions from each sector and subsector are provided in Table A1.

$$Em_{i,j} = A_{i,j} \times E_i \times \frac{(100-R_{i,j})}{100} \quad (1) \text{ (Shrestha et al., 2012)}$$

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

In general, to estimate the emissions from a certain source, one should multiply its activity data with the emission factor. The activity data of a certain emission sector is usually the amount of fuel consumed, output product, and distance travelled over one year. The emission factor is the emissions per unit of activity data. The emission control efficiency is the effectiveness of the emission control devices applied.

3.1.4. Activity data

This section discusses the activity data used for estimating emissions. The activity data vary according to emission sectors. In this study, local input data were prioritised when developing the emission inventory for Hanoi. For example, the data of fuel consumption used for domestic cooking were collected through face-to-face interviews with people living in the urban and rural areas. Facility-level industrial production data, which was used to estimate the non-combustion processes, were collected from the local government. Similarly, the local government provided the number of on-road vehicles to estimate the emissions from on-road transport and the projected number of on-road vehicles for 2025 and 2030, which was used to estimate the future emissions. Additionally, emissions from the coal-fired power plants were estimated using the facility-level activity data (coal consumption, ash content, and sulfur content) and the emission control efficiencies provided by the operating companies. Such local activity data were expected to improve the reliability of the emission inventory.

Transport: For on-road transport, this study estimated the hot emissions, cold emissions, tyre wear, brake wear, road wear, and evaporative emissions. On-road vehicles include motorcycles, cars, taxis, intercity buses, transit buses, and trucks. Motorcycles, cars, and taxis use gasoline, while buses and trucks use diesel oil. The number of active vehicles in Hanoi, which was estimated based on the number of registered vehicles, was used for the emission estimations (Chung, 2017; Hanoi Police Department, Personal communication, 2019; Vietnam Register, 2018). To collect the data on the number of on-road vehicles, requests were sent to the Hanoi Police Department and Vietnam Register to collect the number of motorcycles and 4-wheeled vehicles. 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 the registered vehicles. The vehicle kilometres travelled (VKT) (km/vehicle/day) were obtained from the studies conducted by Roy et al. (2021) for motorcycles and cars, Chung (2017) for trucks and transit buses, and Trang et al. (2015) for taxis. Unlike transit buses, intercity buses also travel into 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 summarized in Table A2 and A3, respectively.

In addition, the intrusion of the EURO standards was also considered (Table A3). For domestic shipping, the ratio between the total number of domestic vessels registered in Hanoi and Vietnam (Vietnam Register, 2018) was applied to the total amount of fuel oil used for domestic navigation in Vietnam, which was obtained from the World Energy Statistics 2019 (IEA, 2019a). This provided an estimate of the amount of fuel oil consumed by vessels in Hanoi.

Agriculture: For livestock, emissions from enteric fermentation for beef cattle, dairy cattle, buffaloes, pigs, goats, and horses and from manure management were calculated for all the livestock and poultry. The number of livestock was collected from the Statistical Yearbook of Hanoi for 2017 and 2018 (HSO, 2019, 2018a) and from the Statistical Office of Hanoi (HSO, 2018b, 2017). 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). For crop residue burning, the amount of dry biomass burned on the field (kg/year) was calculated using Equation A13. The data for the crop production (kg/year) were collected from the Statistical Yearbook of Hanoi for 2017 and 2018 (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 crop residue burning in Southeast Asia and Hanoi (Dong et al., 2014; Kim Oanh et al., 2018).

Industrial sector: Details of the industrial subsectors covered in this study are provided in Table 3.1. We estimated the emissions of the industrial sector for combustion and non-combustion processes. Facility-level data on industrial output production were collected through a request to the Hanoi Statistical Office. We also tried to obtain facility-level data on fuel consumption, but these data were confidential. Thus, 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 subsector for Vietnam (IEA, 2019a) to derive the fuel consumption of that specific facility in Hanoi. In addition, because the data on fuel consumption for 2018 were not available, the same data for 2017 were used to estimate the fuel consumption for Hanoi for both years. Industrial facilities in Hanoi use different types of fuel for combustion, including coal, gaseous fuels, kerosene, diesel, fuel oil, and solid biofuels (IEA, 2019a). The emissions from non-combustion processes were calculated for the chemical, metal production, non-metallic mineral, paper and pulp, food, and beverage industries. The emission control efficiencies were applied to the pulp and paper industry. Details about the emission control efficiencies are provided in Section 3.1.5.

Residential sector: For domestic cooking, a face-to-face survey was conducted in October 2019, with the help of the professors and students at Vietnam University of Science, to obtain the necessary data to estimate the emissions. To calculate the number of samples, the Cochran formula was used with a 90% confidence interval and a standard error of 0.05 (Formula A1; Cochran, 1963). In total, 273 households (136 households in urban areas and 137 households in rural areas) across Hanoi were investigated. A sample of the questionnaire used to collect the necessary information is included in the supplementary material. The survey was designed to collect information regarding the number of members in each household surveyed, the type and amount of fuel used, and the period of cooking. The number of members and the type and amount of fuel used were used to estimate total emissions and the period of cooking was used for the temporal distributions.

For water heating, the energy needed to heat 30 L of tap water (the capacity of a typical water heater used in Hanoi) from the monthly ambient temperatures to 36 °C, the desired water temperature for bathing (Otani et al., 2015) was used to estimate the emissions

(Sadavarte et al., 2019). The number of households in Hanoi 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 A5.

For MSW burning, the MSW_{GR} values in Hanoi's urban and 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. ε 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). The data on fuel consumption by hotels and restaurants were selected based on the results of the Japan International Cooperation Agency (JICA, 2016).

Power plants: Our study estimated the emissions for eighteen power plants located in northern Vietnam, which could impact the air quality in Hanoi (**Figure 2.1**). To collect enough data to develop an accurate emission inventory for the power plants, different governmental organisations were contacted. For example, the data on fuel consumption and monthly electricity production at each power plant were collected from Vietnam Electricity, and the data on the sulfur content, ash content, and net caloric value were collected from various governmental organisations, such as the Institute of Energy, Pollution Control Department, and General Directorate of Energy. Similarly, the emission control efficiencies were collected from Vietnam Electricity, Institute of Energy, Pollution Control Department, General Directorate of Energy, and Electricity and Renewable Energy Authority. Such detailed input data, which have not been well considered in previous studies, are expected to improve the quality of the emissions of the coal-fired power plants compared with the existing databases (Huy and Kim Oanh, 2017; Roy et al., 2020). Sixteen out of the eighteen power plants used anthracite coal, one (Formosa Hatinh) used sub-bituminous coal, and one (Naduong) used lignite as the combustion fuel. Eleven out of the eighteen power plants used pulverised coal (PC) combustion technology, while seven used a circulating fluidised bed (CFB). For the activity data, eighteen power plants produced a total of 48.2 and 58.8 billion kWh of electricity and consumed 23.7 million t and 28.5 million t of coal in 2017 and 2018, respectively. In addition, the emission control efficiencies of the power plants were provided by the operating companies and selected from the study by Huy and Kim Oanh (2017) and the ABC emission inventory guideline. This study estimated the emissions from eighteen power plants using facility-specific input data on the coal (ash content, sulfur content, and net calorific values) used at each power plant. Details regarding the parameters used to estimate the emissions from each power plant, including the emission control efficiencies, are provided in the supplementary material (Table A8, A9, and A10).

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 A19 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 in Hanoi in 2017, the ratio of the amount of gasoline sold in Hanoi and that in entire Vietnam, which was 17.1% Huy and Kim Oanh (2020), was applied to the total amount of gasoline consumed by the on-road transport sector, from the World Energy Statistic 2019 (IEA, 2019a). Accordingly, the amount of gasoline consumed by the gas stations in Hanoi was 841.32 kt in 2017.

3.1.5. 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 crop residue burning and fertiliser application were obtained from the ABC EIM. For the transport sector, the EFs for 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 A3 in Appendix). 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 the OC and BC for other types of vehicles complying with the EURO standards. The EFs for NMVOC for all the vehicles were calculated as the difference between VOC and CH_4. We applied the ratio VOC/HC = 0.933 for motorcycles, 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, EMEP/EEA emission inventory guidebook. 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 (IEA, 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:

$$EF_{SO2} = 2 \times \left(\frac{CS_{fuel}}{100}\right) \times \left(\frac{100-\alpha_S}{100}\right) \times \frac{1}{H_u} \times 10^6 \times \left(\frac{100-\eta_{cd}}{100}\right) \quad (2)$$ (Shrestha et al., 2012)

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 (%).

For the power plants, the EFs for NO_x were obtained from “Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories”, which considers not only the fuel types but also the combustion technologies used. Different combustion technologies might have different impacts on NO_x emissions (IPCC, 1996). For example, NO_x emissions from power plants equipped with CFBs are much lower than those from power plants equipped with PCs owing to the lower furnace temperatures of CFBs. The EFs for other pollutants were obtained from the ABC manual, with the specific local ash content collected for each power plant to estimate the EFs for $PM_{2.5}$. Equation 14 was also used to calculate the EFs for SO_2 for eighteen power plants, with the facility-specific input data on the coal collected for each power plant (CS_{fuel} and H_u) (IE, 2016; PCD, 2016, personal communication; EVN, 2020, personal communication).

The EFs for the NMVOC emissions from paint application, paint manufacturing, ink manufacturing, and glue manufacturing were obtained from 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 (EPA, 2020, 2015).

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 emissions, and electrostatic precipitators (ESP), which remove 91.96% 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 the other industrial subsectors than those mentioned above and from non-fuel combustion of all the industrial subsectors, 0% removal efficiency was assumed (Huy and Kim Oanh, 2017).

Detailed information regarding the EF values used in this study is provided in Tables A10 and A11 in the Appendix.

3.1.6. NMVOC speciation

Almost all the existing emission inventories for Vietnam and Hanoi have ignored the speciation of NMVOC. This could be because no NMVOC speciation profiles have been specifically developed for Hanoi or Vietnam. Huy and Kim Oanh, (2020) applied the NMVOC speciation profile developed by EPA to the gas stations in Vietnam. NMVOC speciation is important for AQMs because it plays an essential role in the formation of secondary species. Therefore, this study is the first to speciate the NMVOC emissions in Hanoi. In this study, we relied on the profiles developed for China to conduct the NMVOC speciation for Hanoi. Because China has been recognised as the most significant contributor of NMVOC in Asia, the NMVOC speciation profiles developed for China are also suitable for other Asian countries, including Vietnam (Huang et al., 2017). In this work, we used the NMVOC speciation profiles which were developed based on ambient measurements and emission ratios against CO (Li et al., 2019). The study developed an emission inventory for NMVOC for five sectors: transportation, crop residue burning, stationary combustion of fossil fuel, solvent utilisation, and industrial processes. Each of the five sectors was then classified into subsectors, including off-road transport, on-road transport, crop residue, firewood, power sector, and residential consumption, among others. The study classified NMVOC into 152 species and built a speciation profile for each subsector accordingly. In our study, we used the same profiles for the 152 species to conduct the NMVOC speciation for Hanoi.

3.1.7. Spatial distributions

As mentioned previously, while many existing emission inventories have focused on the total emissions of a certain source (e.g. only the total annual emissions were presented), only a few have considered the spatial distributions of the emissions (Hung, 2010). The spatial distribution of emissions could help to identify the hotspots of air pollution in Hanoi. Therefore, it can help policymakers manage air pollution in the city. The spatial distribution is also an essential aspect of any emission inventory used for numerical simulations. In this study, various proxies were used to allocate the emissions of each species into 1 km × 1 km grid cells.

Emissions from livestock other than swine and poultry were allocated based on 1 km × 1 km grassland 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 distribution, 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). Emissions from crop residue burning were allocated based on 1 km × 1 km cropland cover from the Global Land Cover-SHARE provided by the FAO.

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, the locations of the hotels and the restaurants considered in this study were investigated using Google Maps (https://www.google.com/maps) and Open Street Map (https://www.openstreetmap.org). Google Maps were used to find the corresponding coordinates of each emission source based on its address, while Open Street Map (ArcGIS Editor) was used to spatially distribute the emissions. The emissions were then allocated according to the corresponding location of each hotel and restaurant.

For the emissions from the road transport sector, we used Open Street Map to create the road network and classified 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 distribution because the locations of the construction sites were unobtainable. 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 the individual emission sources were investigated using Google Maps and Open Street Maps. The spatial distributions of all the emission sectors were allocated to the map at a 1 km × 1 km spatial resolution.

3.1.8. Temporal distribution

Similar to the spatial distribution, the temporal distribution is also a crucial aspect of any emission inventory. However, while most of the existing emission inventories for Vietnam and Hanoi have considered only yearly emissions (Roy et al., 2021, 2020), few have considered the monthly profiles (Huy and Kim Oanh, 2020, 2017) or diurnal emissions (Huy and Kim Oanh, 2020). To overcome such drawbacks, this study attempted to include more detailed temporal variations (monthly, day-of-week, and diurnal profiles) in the major emission sources. Accurate temporal distribution of emissions is a determining factor in the accuracy of any modelling simulation.

For livestock, the monthly number of livestock in Hanoi, air temperature (T_2), and WS were used to allocate the monthly emissions using the equations provided in Guevara et al. (2019) (Equation A3). The diurnal profile was also developed based on T_2 and WS. For the emissions from fertiliser application, the monthly area of planted crops (together with T_2 and WS) was used for the monthly distribution. For crop residue burning, the seasonal harvested crop production was used to create a monthly emission profile. Spring crops are mainly harvested in May and June and winter crops from September to October. The diurnal profile was adopted from the study by Kanabkaew and Kim Oanh (2011).

For domestic cooking, the monthly variation was kept flat, while the diurnal variations were calculated based on the face-to-face 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 daily variations were assumed to be evenly distributed among seven days of the week due to a lack of information. Commercial cooking activities occur from 4:00 am until late at night, with the highest activity from 18:00 to 22:00 (Hai and Kim Oanh, 2013).

For the transport sector, the monthly emissions from each type of vehicle in Hanoi were calculated based on the monthly travel distance (MTD), which was calculated using the daily travel distance (DTD). The day-of-week profile was created using the traffic count data from a previous study on BTEX (benzene, toluene, ethylbenzene, and xylene) emissions in Hanoi (Truc and Kim Oanh, 2007). The hourly fractional distributions of the vehicles, which were calculated based on the traffic count data observed in 2014 in Hanoi (NILU et al., 2015), were used to create the diurnal profiles for the on-road transport sector.

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

For the power sector, the monthly electricity production of each coal-fired power plant was used to create the monthly emission profiles (EVN, 2020, personal communication), while the diurnal electricity consumption in Vietnam during the dry and rainy seasons was used to create the profile of diurnal emissions (Otani et al., 2015). In addition, the day-of-week profile developed for the power sector in Thailand by Pham et al. (2008) was applied for Hanoi, given that Thailand and Vietnam are similar in terms of socioeconomic development and technologies.

3.1.9. Uncertainty analysis with Monte Carlo approach

As with 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 socioeconomic status as Vietnam were used instead. There are two methods to estimate the uncertainty of an emission inventory: propagation of error and the Monte Carlo method. Monte Carlo simulations are highly preferable because the propagation of error method is not suitable when the uncertainty is high, the distribution is not normal, or the equation is complex. Therefore, 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 lognormal distribution to the emission factors and ran 10,000 Monte Carlo simulations for each subsector with a 95% confidence interval. Details regarding the Monte Carlo simulation have been described in Nguyen et al., (2021) and Anna et al. (2017).

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 5% uncertainty, as suggested by the EMEP/EEA emission inventory guidebook (EEA, 2019). This uncertainty range was applied to the agricultural, on-road transport, and non-combustion industrial sectors, solvent use, and power plants. 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.

3.2. Future prediction of emissions from selected sectors in 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 future socioeconomic scenarios proposed by both the Vietnam and local governments. The projected emissions were compared with the base emissions in 2017 to evaluate how the emissions will change in the future. We included the key emission sectors in our predictions, such as on-road transport, residential sector, and crop residue burning. However, due to a lack of information regarding plans within the industrial sector, we excluded this sector from our predictions, which could be considered as one of the drawbacks of this study. Details regarding the sectors and scenarios are summarised in **Table 3.2**.

Table 3.2 Sectors and scenarios considered for future prediction.

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 A3)[a]. Engined vehicles other than motorcycles are to meet EURO 5 standard from 2022[b].	Hanoi People's Committee, (2017)[a] 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% of the total population of Hanoi) and 9.8 million people in 2030 (urban population accounts for 65% of the 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 day per capita in Hanoi's urban and rural areas will be 1.51 kg and 0.99 kg in 2025 and 1.72 kg and 1.13 kg 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 restaurants	The use of coal is to be banned in Hanoi as of 2021.	Directive 15/CT-UBND
Agriculture	Crop residue burning	Crop residue burning is to be banned in Hanoi as of 2021[a]. The growth rate of agricultural production will be 4.1% (4.0–4.3%) per year from 2021 to 2030[b].	Directive 15/CT-UBND[a] Decision 124/QĐ-TTg[b]

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

3.3. Results and discussion

3.3.1. Emission inventory for Hanoi and coal-fired power plants.

Although this study aims to develop an emission inventory for Hanoi for 2017 and 2018, only the results from 2017 are presented in the main body of this thesis; the results for 2018 are presented in the Appendix.

3.3.1.1. Emissions in Hanoi in 2017

Figure 3.1 presents the relative contributions (%) of each emission sector to the emission inventory for Hanoi. The total emissions of pollutants in Hanoi (with the uncertainties in absolute values in parentheses) were estimated as 14.9 (±4.3) Gg $PM_{2.5}$, 1.6 (±0.53) Gg BC, 2.9 (±2.6) Gg OC, 56.7 (±11.3) Gg NO_x, 19.1 (±5.5) Gg SO_2, 109.2 (±29.0) Gg NMVOC, 23.0 (±11.5) Gg NH_3, 37.9 (±4.4) Gg CH_4, and 472.7 (±285.0) Gg CO. In Hanoi, the industrial sectors, transport, and agriculture (crop residue burning) were the predominant emission sources of $PM_{2.5}$, contributing 35.2%, 32.1%, and 21.8% to the total emissions of this species, respectively. Transport was the main source of BC (46.6%), followed by crop residue burning (30.0%), and the industrial sector (15.6%). Transport and crop residue burning were the key sources of OC, contributing 42.3% and 23.8%, respectively. Transport and industry were the two leading sources of NO_x, contributing 72.5% and 25.2%, respectively. The industrial and transport sectors were also the major sources of SO_2, contributing 65.0% and 32.5%, respectively. The NMVOC emissions were predominantly contributed by transport (52.1%) and solvent use (35.2%). As expected, agriculture was the dominant source of NH_3 and CH_4 emissions, contributing up to 84.2% and 76.6%, respectively. In contrast, the transport sector was the highest emitter of CO, contributing 72.5%, followed by crop residue burning (20.0%).

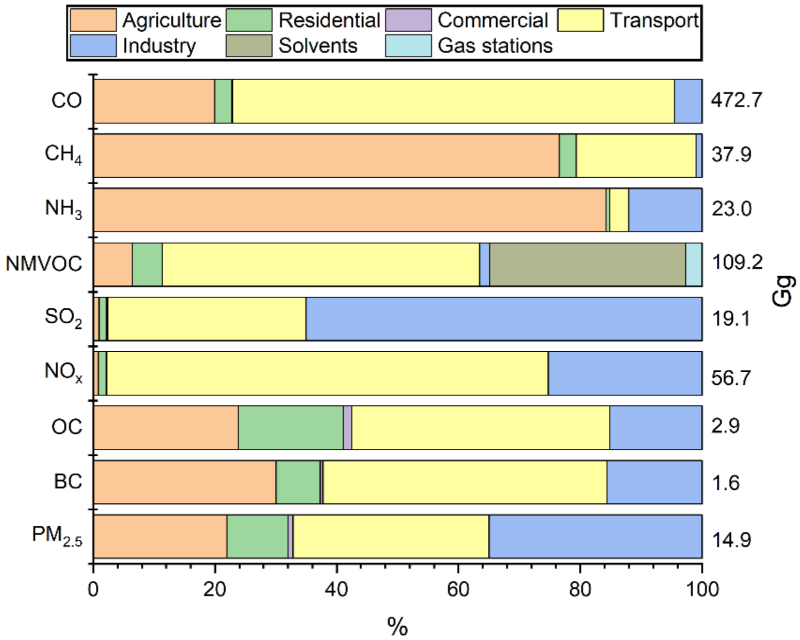


Figure 3.1: Contribution of each emission sector in Hanoi (%) to the annual total emission of air pollutants in 2017

Figure 3.2 (a) illustrates the relative contributions of each vehicle type to the total emissions of the transport sector. Buses, motorcycles, and trucks were the predominant emitters of $PM_{2.5}$, contributing 97.3% of the total emissions of $PM_{2.5}$. The same trend was observed for OC, for which buses, motorcycles, and trucks together comprised 98.9% of the total emissions. Buses and trucks contributed 98.4% of the total emissions of BC and 58.8% of the total emissions of NO_X. A fleet of non-compliant buses and trucks in Hanoi was found to have exceptionally 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, motorcycles and taxis were the leading emission sources of CO, contributing 81.6% of the total emissions of CO from the transport sector. Trucks and buses were the key sources of SO_2, accounting for 74.3% of the total emissions. Motorcycles and taxis were the main sources of NMVOC, contributing 51.1% and 26.2%, respectively, to the total emissions for the transport sector.

Figure 3.2 (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 textile and leather subsectors. For SO_2, the combustion processes of the textile and leather and non-combustion processes of the non-metallic minerals subsectors (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 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 NMVOC. The combustion processes of the non-metallic minerals and textiles and leather subsectors were identified as the predominant sources of CO and CH_4 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%.

The relative contributions of domestic cooking (%) to the total residential sector emissions of $PM_{2.5}$, BC, OC, NO_x, SO_2, NMVOC, NH_3, CH_4, and CO were 49.7%, 50.9%, 37.9%, 68.2%, 74.2%, 77.5%, 46%, 51.2%, and 60.7%, respectively; the contributions of water heating were 20.7%, 24.1%, 9.1%, 15.4%, 15.9%, 9.7%, 24.7%, 19.6%, and 24.7%, respectively; and the contributions of MSW were 29.5%, 24.9%, 46.7%, 18.4%, 9.8%, 3.3%, 29.1%, 29.1%, and 14.5%, respectively.

The printing industry and paint application were the leading sources of NMVOC, contributing 87.7% to the total NMVOC emissions from solvent use, while other sources, such as paint, glue, and adhesive tape manufacturing, contributed 12.3%.

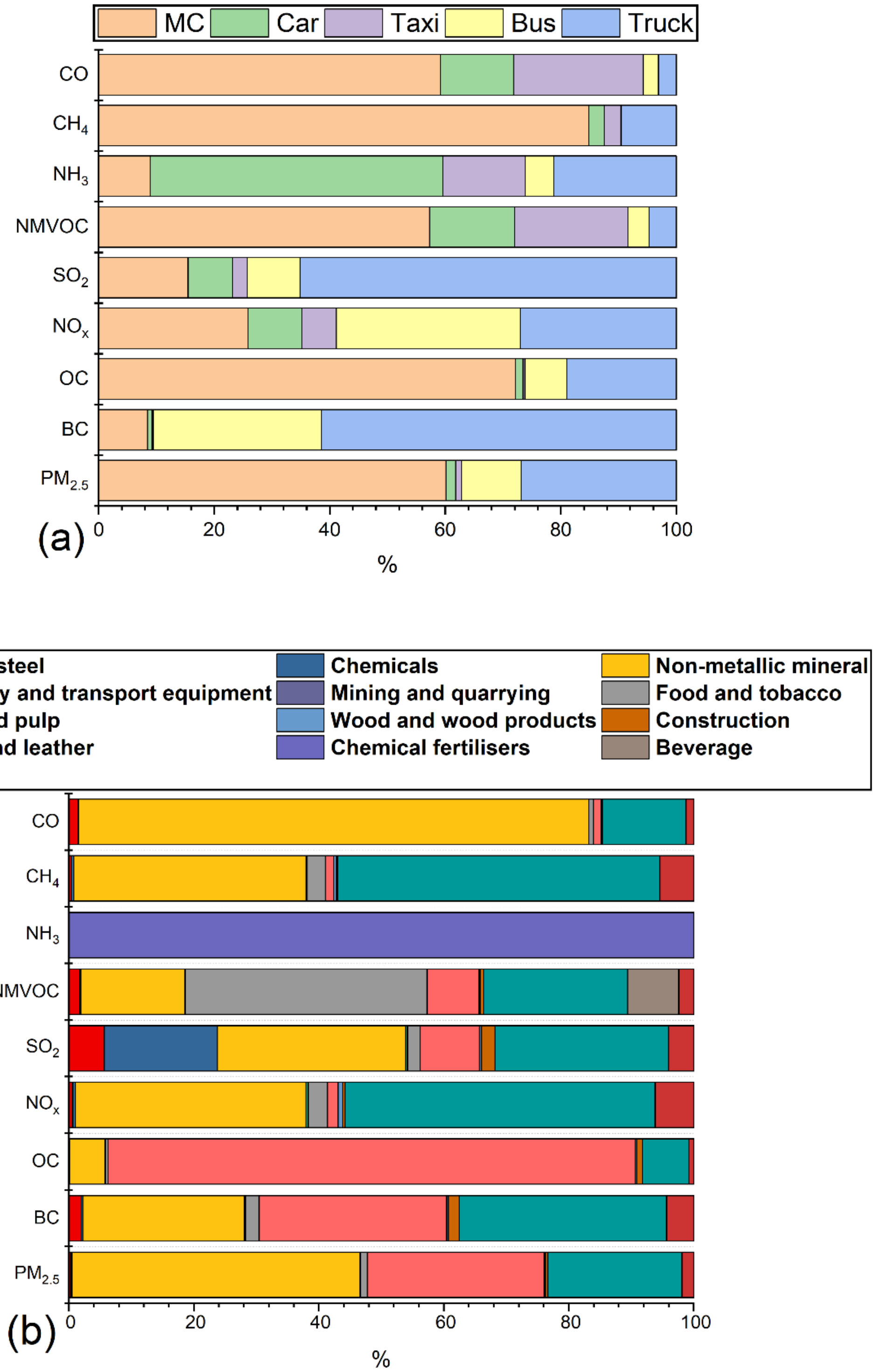


Figure 3.2: Contributions to the total emissions of air pollutants (%) by each vehicle type **(a)** and industrial subsector **(b)** in Hanoi in 2017. MC = Motorcycle

3.3.1.2. Emission contributions from urban and rural areas in Hanoi

Emissions in urban areas in Hanoi vary from those in rural areas due to the differences in the area of agricultural lands, number of livestock, and amount of fuel consumption for residential activities. **Figure 3.3** provides the contribution of Hanoi's urban and rural areas (%) to the total emissions of each pollutant for the entire city. We found that the transport sector emitted more pollutants such as $PM_{2.5}$, CO, or SO_2 in the urban areas than in the rural areas, while agriculture (crop residue burning) and residential activities were the predominant emission sources in the rural areas. A large fraction of the rural population used coal and wood for cooking, which in turn emitted a substantial amount of pollutants such as $PM_{2.5}$, CO, or NO_x. Rural areas dominated the emissions of NH_3 and CH_4 due to the higher amout of livestock and cropland, which were the main emission sources of these two species.

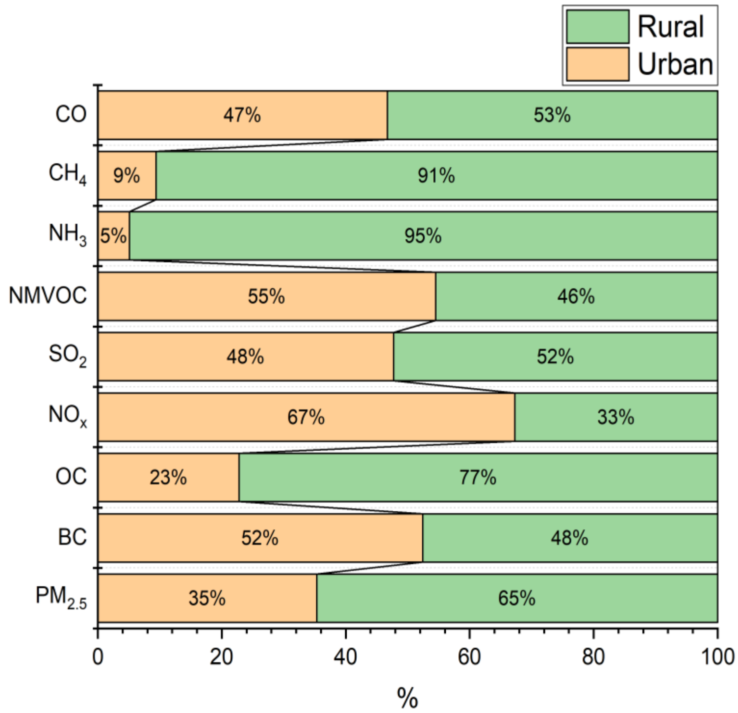


Figure 3.3: Contribution of Hanoi's urban and rural areas (%) to the total emission of each pollutant

Figure 3.4 shows the emissions per area (a) and per capita (b) in the rural and urban areas, and in Hanoi. Although the total emissions of some species, such as $PM_{2.5}$, SO_2, and CO in urban areas were smaller than those in rural areas as shown in **Figure 3.3**, the emissions per km^2 in the urban areas of $PM_{2.5}$, NO_x, SO_2, NMVOC, and CO (17.2, 124.1, 32.4, 193.6, and 718.4 t/km^2, respectively) were much larger than those in the rural areas (3.2, 6.0, 2.9, 16.3, and 85.5 t/km^2, respectively) because of much larger accumulation of emission sources, such as population, vehicle, and industrial activities, in the urban areas than in the rural areas. Additionally, while the emissions per km^2 in the urban and rural areas of CH_4 were almost identical (11.6 t/km^2 and 11.2 t/km^2, respectively), the NH_3 emissions per km^2 in the rural areas were higher than those in the urban areas (7.2 t/km^2 and 3.8 t/km^2, respectively). The emissions per capita of $PM_{2.5}$, OC, NH_3, CH_4, and CO (2.4, 0.6, 5.6, 8.8, and 64.6 kg/capita, respectively) in the rural areas were found to be significantly larger than those in the urban areas (1.4, 0.18, 0.31, 0.95, and 58.6 kg/capita, respectively). In contrast, the emissions per capita of NO_x, NMVOC, SO_2, and BC in the urban areas were 10.1, 15.8, 2.6, and 0.22 kg/capita, respectively, which are larger than those in the rural areas (4.8, 12.7, 2.3, and 0.2 kg/capita, respectively). The difference in the values of the emissions per capita must reflect the differences in the lifestyles, particularly the prevalent fuel type for various daily activities, in urban and rural areas.

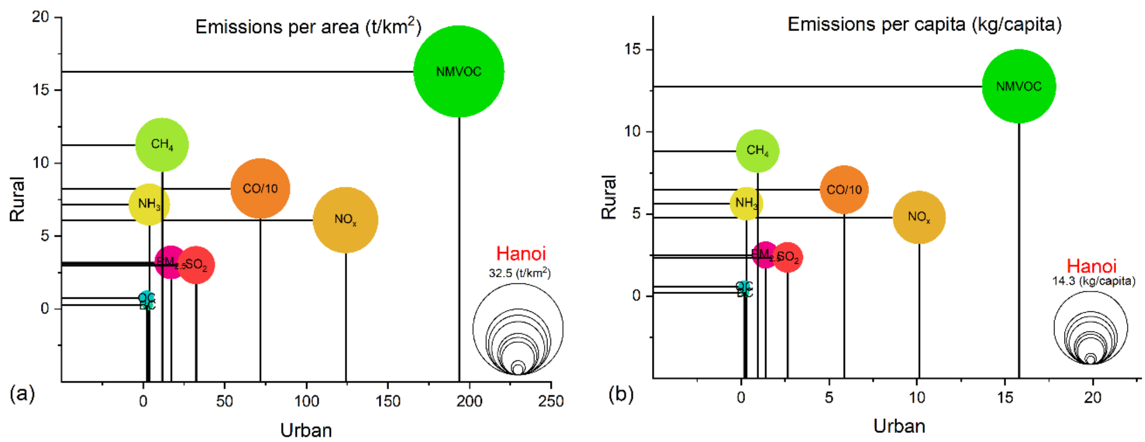


Figure 3.4: (a) Emissions per area (ton/km2) in urban areas (X-axis), rural areas (Y-axis), and Hanoi (Bubble size); (b) Emissions per capita (kg/capita) in urban areas (X-axis), rural areas (Y-axis), and Hanoi (Bubble size)

3.3.1.3. Emissions from power plants

Most of the power plants are located to the north and east of Hanoi (**Figure 2.1**). In winter, strong north-easterly winds frequently occur and transport air pollutants emitted from the power plants to Hanoi, causing a deterioration in the air quality of the city. **Figure 3.5** provides the emissions of each power plant considered in this study. In total, the emissions from the power plants in 2017 (with the uncertainties in absolute values in parentheses) were 1.9 (±0.17) Gg $PM_{2.5}$, 0.03 (±0.003) Gg BC, 0.24 (±0.007) Gg OC, 82.5 (±0.14) Gg NO_x, 41.6 (±0.19) Gg SO_2, 2.8 (±0.16) Gg NMVOC, 0.00014 (±0.002) Gg NH_3, 0.3 (±0.15) Gg CH_4, and 9.94 (±0.16) Gg CO. The emissions of $PM_{2.5}$, BC, OC, and SO_2 were kept low owing to the application of the control devices. Although the SO_2 emission control devices were utilised in most of the power plants, this sector still produced 66.5% of the total SO_2 emissions, considering the entire emission inventory. The emissions of SO_2 from power plants ranged from 0.6 Gg to 10.5 Gg during 2017. Phalai 1 emitted up to 10.5 Gg SO_2 because of the lack of SO_2 emission control devices. Naduong and Caongan were other significant sources of SO_2, emitting 4 Gg and 2.9 Gg, respectively, because of the high sulfur content in the coal used (3.5% and 5.43%, respectively). These two power plants used coal from the Khanhhoa, Nuihong (Caongan), and Naduong (Naduong) coal mines, which produce coal with high sulfur contents (GDE, 2016). The coal used by Sondong was from the Vangdanh mine, which also has a relatively high sulfur content (1.1%). The sulfur content of the coal used in the other power plants ranged from 0.4% to 0.87%. Although Ninhbinh has not yet been equipped with an SO_2 emission control device, owning to its low capacity and coal consumption, it only emitted 1.8 Gg SO_2.

The $PM_{2.5}$ emissions ranged from 0.006 Gg to 0.34 Gg, with the largest contributor being Quangninh (0.34 Gg). Ninhbinh emitted only 0.006 Gg $PM_{2.5}$ because it uses coal with a low ash content (IE, 2016). The Thaibinh power plant began operations in the middle of 2017; therefore, its emissions were relatively low in 2017 compared with 2018 (Figure A4). The relatively low emissions of $PM_{2.5}$ from the power plants were due to the high efficiencies of the ESP. The NO_x emissions from the power plants were high, which comprised 59.2% of the total emissions of this species, for the emission inventory overall. The largest emitter of NO_x was Haiphong (18.9 Gg), and the smallest emitter was Caongan (0.26 Gg). According to our estimates, the power plants that used the CFB technology emitted 6.9 Gg NO_x, which was much lower than that of those using the PC technology (75.6 Gg), owing to the lower furnace temperature required ith the CFB technology. The NO_x emissions from Quangninh, Formosa Hatinh, Mongduong 2, and Vungang 1 were 12.4 Gg, 4.7 Gg, 1.0 Gg, and 1.3 Gg, respectively. Although the NO_x emissions from Quangninh and Formosa Hatinh were smaller by 30% owing to the application of low-NO_x burners, the NO_x emissions from these power plants were still high because of their high fuel consumption. Thus, the power plants that use the PC combustion technology must be equipped with NO_x emission control devices or switch to cleaner combustion technologies to reduce emissions in the future.

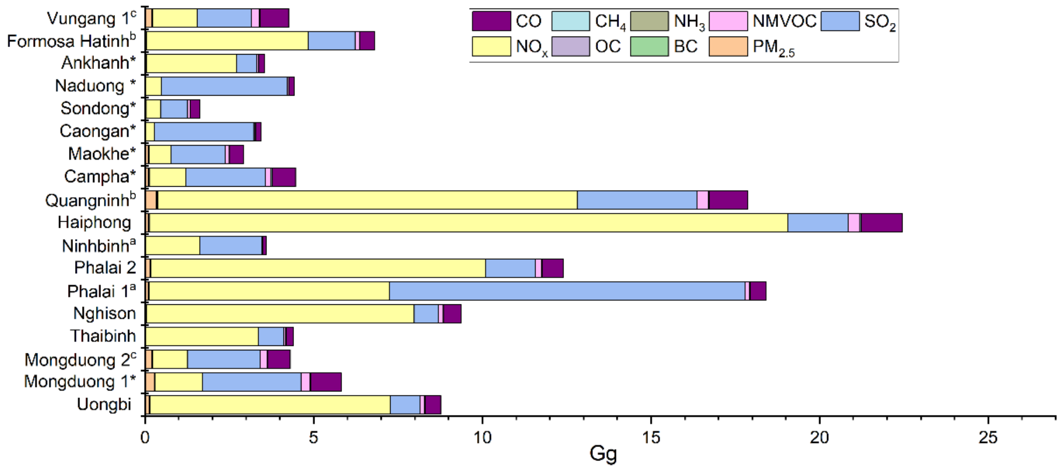


Figure 3.5: Emissions from each power plant considered in this study in 2017 (Gg). *The power plants that used circulating fluidised bed (CFB); [a]No emission control devices for SO_2; [b]Low-NO_x burners equipped; [c]Selective catalytic reduction (SCR) equipped

3.3.2. Comparison with other emission inventories

3.3.2.1. Comparison of emissions in Hanoi with other studies

We compared the results of our work with those from the existing global or regional emission inventories, such as 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 3.3** 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 A14).

Our estimates of $PM_{2.5}$, BC, OC, and NH_3 were smaller than those estimated by the other inventories by 1.2 to 4.0 times. In contrast, our estimate of NMVOC was slightly greater than the values estimated in REAS and EDGAR (1.0 and 1.2 times, respectively). Our estimate of NO_x was greater than the values estimated in REAS and EDGAR by 3.1 and 1.2 times, respectively, but smaller than that estimated by GAINS (1.2 times). In terms of SO_2, our estimate was close to the values estimated in REAS and GAINS, but 1.8 times smaller than that of EDGAR. Our estimation of CH_4 was 4.3 times smaller than that of EDGAR. Lastly, our estimation of CO was greater than the value estimated in REAS but smaller than that in EDGAR.

Regarding the agricultural sector, our estimated emissions of most species were smaller than those estimated in EDGAR, except for NH_3 and CO. Our value for NH_3 was also greater than that in REAS. For the residential sector, our estimations were smaller than those estimated in REAS and EDGAR by 2.9 to 18.5 times, respectively. Concerning the transport sector, our estimate of the emissions of $PM_{2.5}$, BC, NO_x, and NMVOC was found to be 1.1–4.2 times smaller than the values estimated in Roy et al. (2021). In contrast, our estimates of OC, SO_2, CH_4, and CO were 1.4–3.5 times greater than the values estimated in Roy et al. (2021). Our estimates of the pollutants were greater than those estimated by REAS and EDGAR for most species, except for NH_3, where our estimate was smaller than that estimated in REAS. Our estimate of CH_4 was 1.4 times smaller than the value estimated in Kim Oanh et al. (2012) and Trang et al. (2015). For the industrial sector, while our estimations of most species were smaller than those estimated in REAS and EDGAR, the estimates of NO_x and NH_3 were 2.3–2.6 times greater than those estimated in REAS. Our estimate of NH_3 was also smaller than that estimated in EDGAR. Our estimate of NMVOC emission from solvents was 1.4 times higher than the value estimated by EDGAR, while our estimate of NMVOC emissions from the gas stations was substantially higher than the values estimated by Huy and Kim Oanh, (2020).

The possible factors for the discrepancies were the selected data (i.e. activity data, EFs, and emission control efficiencies) and the number and types of emission sources considered in each study. For example, the difference between the $PM_{2.5}$ values in our study and REAS could be due to the exclusion of crop residue burning in REAS.

Table 3.3: Comparisons between emissions in Hanoi

Pollutant	This study (2017)	REAS 3.2[1] (2015)	EDGAR 5.0[2] (2015)	GAINS[3] (2015)
$PM_{2.5}$	14.9	18.2	27.6	23.5
BC	1.6	3.7	3.8	-
OC	2.9	9.1	11.7	-
NO_x	56.7	18.5	48.4	66.6
SO_2	19.1	18.8	34.9	17.8
NMVOC	109.2	104.5	93	-
NH_3	23.0	25.2	30.6	23.3
CH_4	37.9	-	165.1	-
CO	472.7	360.2	490.73	-

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)

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 during this study, REAS, and EDGAR are included in the supplementary data to illustrate the differences between the spatial distributions in each study (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.

3.3.2.2. Comparison of emissions from power plants with other studies.

The power plant emissions developed in this study were compared with those developed by Roy et al. (2020), Huy and Kim Oanh (2017), EDGAR, and REAS. For the studies by Roy et al. (2020) and Huy and Kim Oanh (2017), only the emissions from coal-fired power plants compared with our results.

Table 3.4: Comparisons between emission inventories developed by different studies for power plants.

Pollutant	This study	Roy et al. (2020)[1]	Huy and Kim Oanh (2017)[2]	REAS 3.2 (2015)[3]	EDGAR 5.0 (2015)[4]
$PM_{2.5}$	1.89	4.82	7.94	20.28	96.96
BC	0.028	0.03	0.013	0.30	6.74
OC	0.244	0.16	0.096	-	4.69
NO_x	82.5	117.99	91.8	189.57	230.72
SO_2	41.6	50.09	124.4	141.18	532.69
NMVOC	2.69	2.96	1.33	3.29	1.89
NH_3	0.000133	-	0.0001	0.22	0.07
CH_4	0.3	0.6	0.16	-	1.52
CO	9.508	11.58	3.06	13.13	30.90

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

[1] Roy et al. (2020)

[2] Huy and Kim Oanh, (2017)

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

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

Table 3.4 compares the emission inventories developed by different studies for power plants. Our estimates of $PM_{2.5}$ were 2.5 –51 times lower than the values estimated by the other emission inventories. The main reason for these variations could be the differences in the emission control efficiencies applied in each study. In this study, the emission control efficiencies for $PM_{2.5}$ ranged from 99% to 99.9%, while those applied in Roy et al. (2020) ranged from 98.4% to 99.5%, and Huy and Kim Oanh (2017) chose an emission control efficiency of 94% for all power plants. High emissions of $PM_{2.5}$ could be observed in EDGAR, although the emission control devices were considered, with emission control efficiencies for $PM_{2.5}$ ranging from 98.3% to 99.6%, depending on the technology applied (Crippa et al., 2018). The emission control technologies for the power sector in EDGARv5.0 were reported to have been updated compared with EDGARv4.3.2. However, these updates were only made for European countries, China, and the US (https://edgar.jrc.ec.europa.eu/overview.php?v=50_AP). Therefore, the emission control efficiencies for Vietnam's power sector were assumed to be the same as those reported in EDGARv4.3.2 (Crippa et al., 2018). For that reason, the high emissions of $PM_{2.5}$ in EDGARv5.0 could have been because of fuel consumption or EFs, rather than the emission control efficiencies.

In the case of NO_x emissions, while our estimate was only 1.4 and 1.1 times smaller than those of Roy et al. (2020) and Huy and Kim Oanh (2017), respectively, it was 2.3 and 2.8 times smaller than the values given by REAS and EDGAR, respectively. This difference could be because we considered the impact of the combustion technologies on the NO_x emissions, while the other studies did not. Additionally, Roy et al. (2020) assumed that all the coal-fired power plants that used PC were equipped with emission control devices (Low-NO_x burner), and Huy and Kim Oanh (2017) assumed that no NO_x emission control devices were utilised. These rough assumptions may be a source of uncertainty in the previous studies.

For SO_2, our estimate was 1.2 times smaller than the value estimated by Roy et al. (2020) but three times smaller than that of Huy and Kim Oanh (2017). Our SO_2 estimate was also found to be 3.4 and 12.8 times smaller than the estimates of REAS and EDGAR, respectively. This could be because we applied a higher range of emission control efficiencies for SO_2 than the other emissions inventories (e.g. this study applied emission control efficiencies for SO_2 ranging from 89.9% to 95%, while Roy et al. (2020) applied emission control efficiencies from 85% to 95%, and Huy and Kim Oanh (2017) chose 80% for all power plants). Our NH_3 emissions are identical to that calculated in Huy and Kim Oanh (2017). No large differences in NMVOC emissions were observed between the five emission inventories. Additionally, the emissions from the coal-fired power plants located in southern Vietnam, which were intentionally excluded from our study, are also a reason for the variations between the results of our study and those of the others.

3.3.3. NMVOC speciation

The total NMVOC emissions 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 in Hanoi. **Figure 3.6** represents the 25 most abundant NMVOC species. Transport was the primary source of some NMVOC species, such as ethyne (5.86 Gg), toluene (3.24 Gg), and m/p-xylene (2.31 Gg). These species were predominantly emitted from gasoline vehicles, such as motorcycles, cars, or taxis, with motorcycles as the largest emitter, contributing 90%. Motorcycles and taxis together constituted 84% of the total emissions of toluene and 85.8% of the total emissions 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).

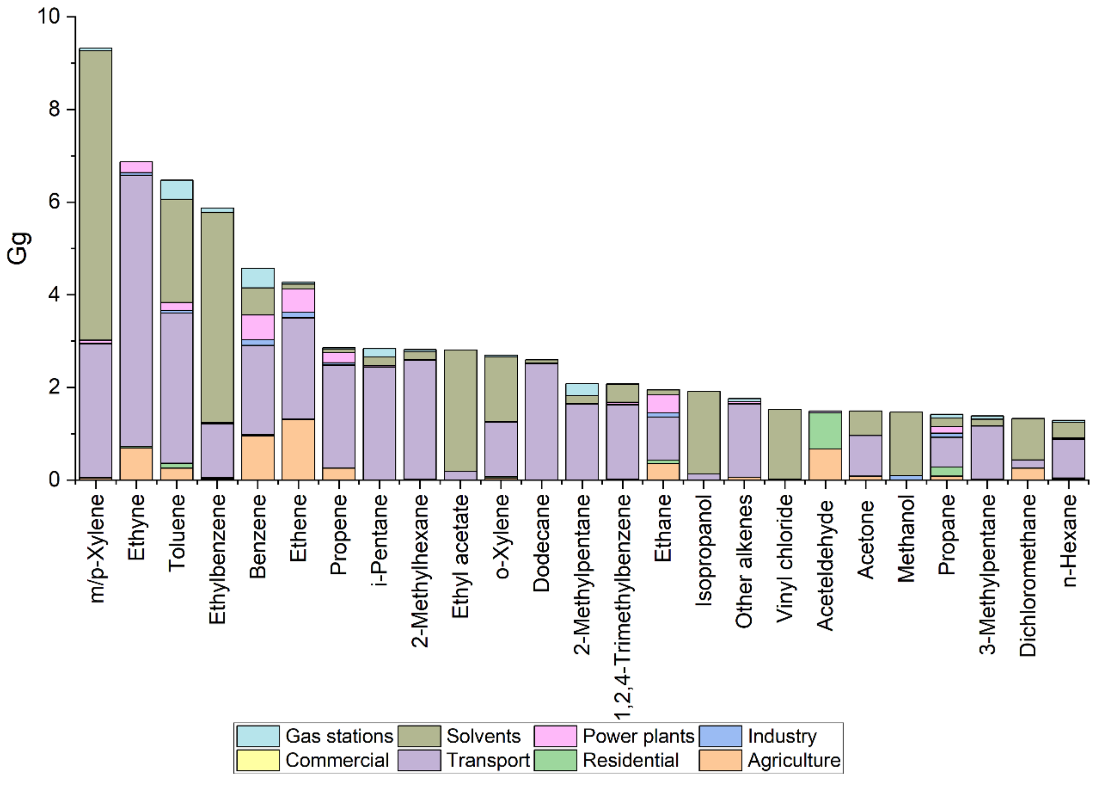


Figure 3.6: Emissions of 25 most abundant NMVOC species by sectors in 2017

3.3.4. Spatial and temporal distributions

The spatial distributions of $PM_{2.5}$, NMVOC, NO_x, and NH_3 for 2017 are provided in **Figure 3.7**. High emissions can mostly be found in the centre of the city due to a high population density and numerous small industrial facilities, restaurants, 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 and gas stations. 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 dominant number of 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.

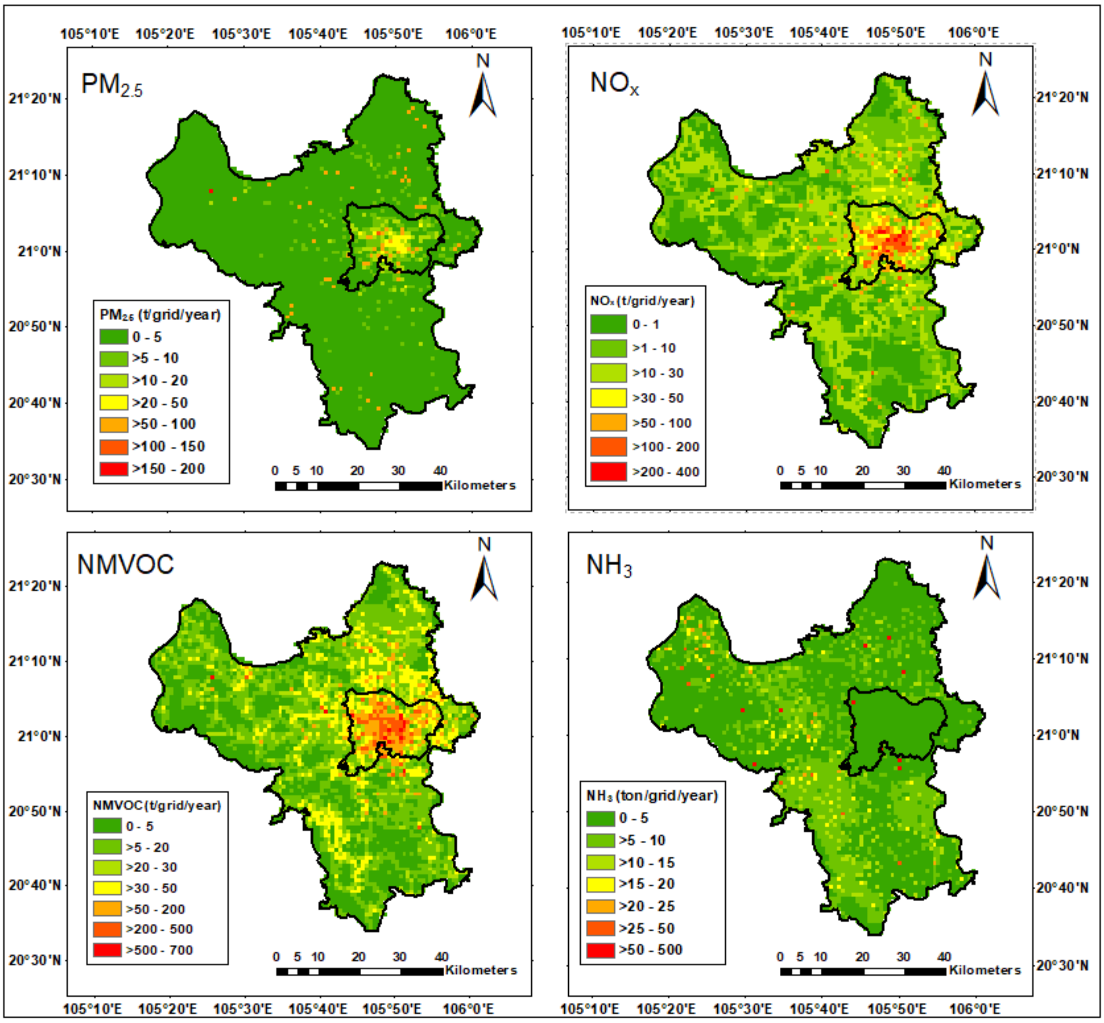


Figure 3.7: Spatial distributions annual total emission of PM2.5, NOx, NMVOC, and NH3 in Hanoi in 2017 (the area inside the black line is the urban area)

Figures 3.8, **3.9**, and **3.10** illustate the monthly, day-of-week, and diurnal variation profiles (fraction) for several emission sources. The monthly variation profile (fraction) for the industrial sector was the average of those for the industrial subsectors. The monthly variation profile for domestic cooking was equally distributed between 12 months due to a lack of information. The monthly variation profile for solvent manufacturing was distributed based on the monthly IPI in 2017 and 2018 (GSO, 2019b). The emissions from crop residue burning coincided with the harvest season, with emission peaks in May and June. 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 emissions 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 increasing cold. 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. The monthly emission profile for the power plants exhibit high emissions from January to June and from October to December and low emissions from July to September. This was because of the increase in the electricity production of hydroelectric dams from July to September (MOIT, 2017, 2016).

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 emissions profile of crop residue burning indicated that burning usually occurred during the daytime from 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 higher 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 profiles of the power sector followed the variations in electricity usage, which was highest between 8:00 and 21:00. 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 estimated 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 hours, with a small fraction of taxis visiting the gas stations at night (Huy and Kim Oanh, 2020).

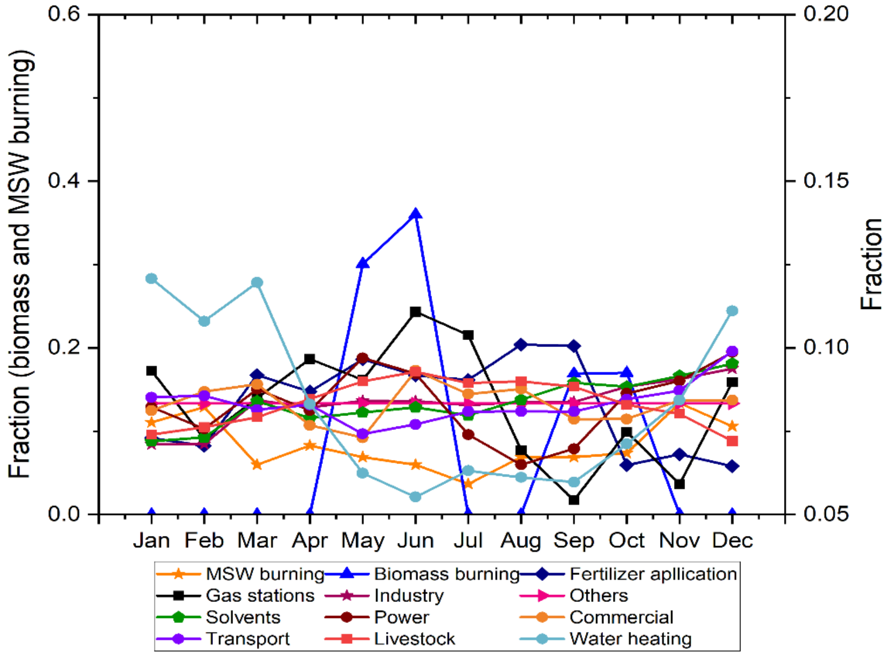


Figure 3.8: Monthly temporal profiles for all sectors

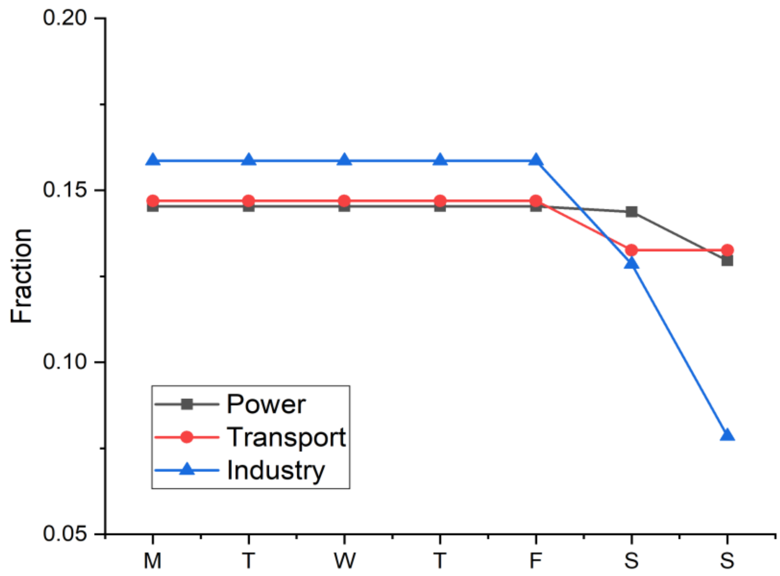


Figure 3.9: Day-of-week temporal profiles for the power, transport, and industrial sector

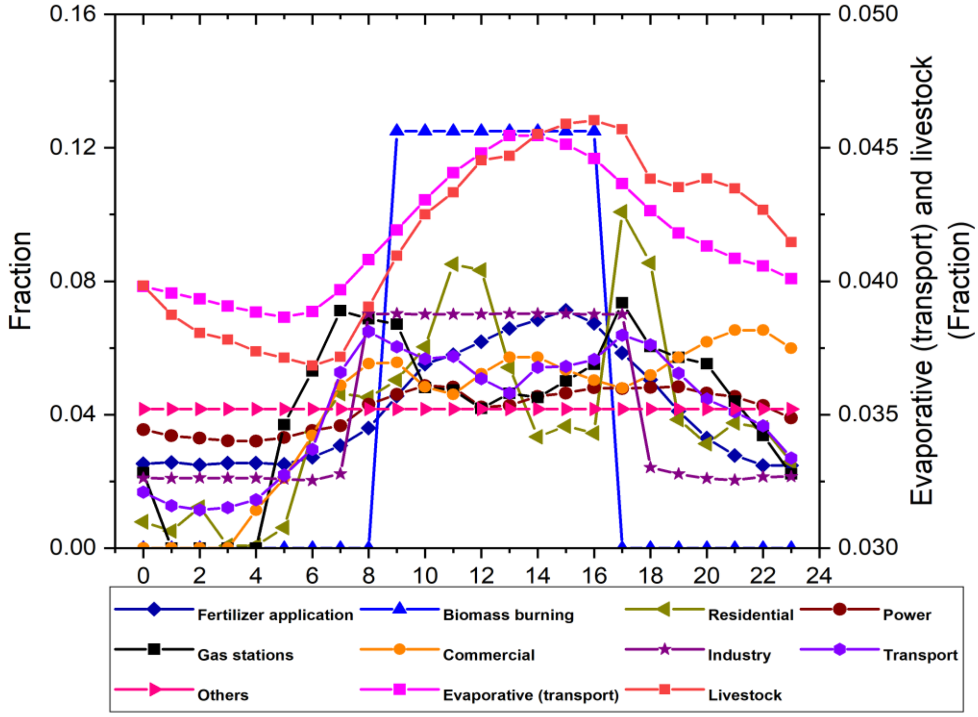


Figure 3.10: Diurnal temporal profiles for all sectors

3.3.5. Projected emissions from selected emission sectors for 2025 and 2030

Table A15 and **Figure 3.11** provide the projected emissions of pollutants from selected sectors (transport, residential activities, and crop residue burning) for 2025 and 2030, as well as those from 2017. Furthermore, for the commercial sector, the impact of switching from coal to LPG for cooking was evaluated assuming the conditions of 2017.

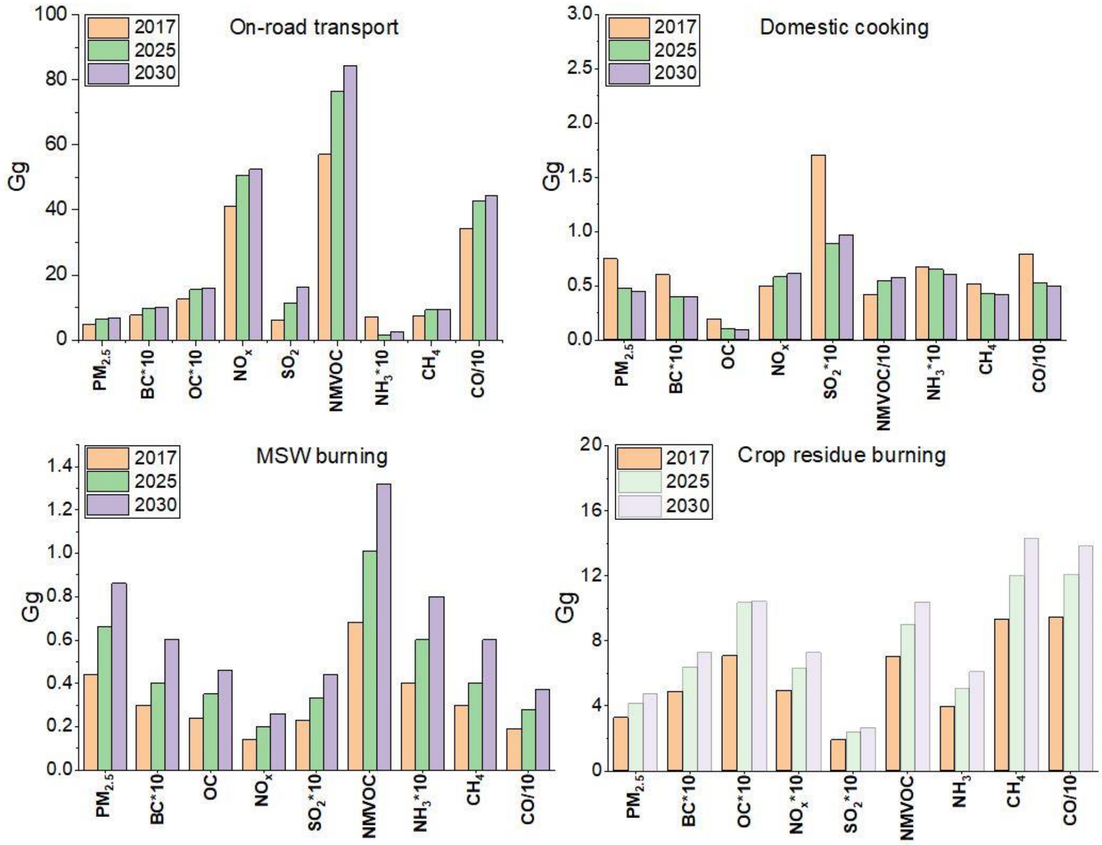


Figure 3.11: Future predicted emissions from selected sectors. Note that the projections of the emissions from agricultural residue burning are an estimate of the amount of pollutants reduced under the effect of Directive 15/CT-UBND, which bans agricultural residue burning in Hanoi as of 2021; thus, the value bars are in faded colours.

For the on-road transport sector, we estimated the future emissions using the number of vehicles predicted by the Hanoi People's Committee (2017) and the projected VKT for each vehicle type (Table A2 and A3). We also considered the effect of the EURO 5 standard on vehicles other than motorcycles. The emissions of $PM_{2.5}$, BC, and OC were predicted to increase by 31.3%, 28.0%, and 23.2% by 2025 and 41.7%, 34.7%, and 27.2% by 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 120.8% and 245.8% by 2025 and 2030, respectively. The 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 by 23.0%, 34.3%, 23.7%, and 24.3% by 2025 and 27.4%, 48.2%, 26.99%, and 299.6% by 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 air pollutants from the on-road transport sector were predicted to increase by 2025 and 2030.

For domestic cooking, the emissions of most species were predicted to decrease from 3% to 50.8%, depending on the species, except for NO_x and NMVOC. The emissions of these two species were predicted to increase by 16.0% and 31.0%, by 2025 and 22.0% and 40.0% by 2030. The reason for this increase was that LPG has higher emission factors for NO_x and NMVOC than coal. For 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 by 50%, 33.3%, and 45.8% and 95.4%, 66.6%, and 91.6% by 2025 and 2030, respectively. The emissions of NO_x, SO_2, NMVOC, NH_3, CH_4, and CO were projected to increase by approximately 50% by 2025 and 100% by 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 687% due to the transition because of the extremely high EF used in this study for NMVOC in comparison with that of coal (18.8 g/kg and 0.664 g/kg for LPG and coal, respectively). Lastly, the emissions of $PM_{2.5}$, BC, OC from crop residue burning were predicted to increase by 27.5%, 33.3%, and 47.1% by 2025 and by 45.5%, 52.0%, and 48.9% by 2030, respectively. The emissions of gaseous species were predicted to decrease by 26.3%–47.1% by 2025 and 42.1%–54.8% by 2030, respectively. Therefore, if Directive 15/CT-UBND comes into effect and the people living in Hanoi strictly comply with the directive, a considerable amount of air pollutants will be prevented from entering the atmosphere. The emissions from crop residue burning were not considered for the future simulation due to Directive 15/CT-UBND.

3.4. Summary

A high-resolution emission inventory for Hanoi and the coal-fired power plants located in northern Vietnam were developed for 2017 and 2018. For Hanoi, the sectors included were agriculture, residential activities, commercial activities, transport, industry, and others (use of solvents and other products and gas stations). The horizontal resolution of the emission dataset was 1 km × 1 km. In addition, we predicted the future emissions from the on-road sector, domestic cooking, MSW burning, commercial sector, and crop residue burning for 2025 and 2030 based on the scenarios proposed by the Vietnamese and local governments.

In Hanoi, industry, transport, and agriculture (crop residue burning) were the three predominant emission sources of $PM_{2.5}$, contributing 35.2%, 32.1%, and 21.8% to the total emissions, respectively. Transport was the main source of BC (46.6%), followed by crop residue burning (30.0%), and the industrial sector (15.6%). Transport and crop residue burning were the leading sources of OC, contributing 42.3% and 23.8%. Transport and industry were the two key sources of NO_x, contributing 72.5% and 25.2%, respectively. The industry and transport sectors were also the main sources of SO_2, contributing 65.0% and 32.5%, respectively. NMVOC emissions were predominantly contributed by transport (52.1%) and solvents use (35.2%). As expected, agriculture was the dominant source of NH_3 and CH_4 emissions, contributing 84.2% and 76.6%, respectively. In contrast, the transport sector was the main emitter of CO, producing 72.5%, followed by crop residue burning (20.0%). The power plants emitted as much as 82.5 Gg NO_x and 41.6 Gg SO_2, which is 1.5 and 2.2 times larger than the emissions of the same species inside Hanoi.

Future predictions of emissions of transport, crop residue burning, and domestic activities were conducted, considering the scenarios proposed by the government, to evaluate the changes in emissions in Hanoi for 2025 and 2030. For the on-road transport, the emissions of the pollutants 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 31.1% to 40.0% by 2025 and 2030, respectively. However, the emissions of other species will decrease between 3.0% (NH_3) and 59.3% ($PM_{2.5}$) by 2025 and 10.5% (NH_3) and 60.3% ($PM_{2.5}$) 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, by banning crop residue burning in the fields, the amount of 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.

Chapter 4: Numerical simulations of $PM_{2.5}$ in Hanoi

In Chapter 3, the predominant emission sources of air pollutants in Hanoi are identified. However, the concentrations of air pollutants are not solely governed by emission intensity but also by other factors; in particular, the impacts of meteorological factors, especially WS and wind direction (WD), on the concentrations of $PM_{2.5}$ should not be ignored. WS and WD can transport air pollutants from the neighbouring province and countries to Hanoi, deteriorating the air quality of the city. Therefore, the contributions to the concentrations of $PM_{2.5}$ of various emission sources located inside and outside Hanoi should be evaluated. In addition, the extent to which the changes in emissions between 2017/2018 and 2030 affect the concentrations of $PM_{2.5}$ over Hanoi should also be investigated. For these purposes, an air quality modelling system (WRF-CMAQ-ISAM system) was used to simulate the concentrations of $PM_{2.5}$. Firstly, a base-case simulation of the $PM_{2.5}$ concentrations from July 2017 to June 2018 was conducted using the WRF-CMAQ system, and the results were compared with the observations to verify the model's ability to reproduce the observations. Secondly, source apportionment simulations were run using ISAM for April, June, October, and December to determine the key sources of $PM_{2.5}$ concentrations in Hanoi. Lastly, CMAQ simulations, with the predicted emission data, were also conducted for April, June, October, and December to evaluate the changes in the $PM_{2.5}$ concentrations between 2017/2018 and 2030. The model configuration, emissions, and results are presented below.

4.1. Model description and configurations

4.1.1. WRF

The Weather Research and Forecasting (WRF) model is a numerical weather prediction system designed for both atmospheric studies and weather forecasting applications. The WRF system contains two dynamical solvers, referred to as the ARW (Advanced Research WRF) core and the NMM (Nonhydrostatic Mesoscale Model) core. The ARW has been developed and maintained by NCAR's Mesoscale and Microscale Meteorology Laboratory. The NMM core was developed by the National Centers for Environmental Prediction (NCEP) and is currently used in their HWRF (Hurricane WRF) system.

In this study WRF-ARW version 3.8.1 (Hereafter WRFv3.8.1) was used to create the meteorological fields for the air quality model. WRF-ARW can be used for simulations across scales raging from metres to thousands of kilometres, including:

• Idealised simulations (e.g. LES, convection, baroclinic waves)
• Parameterisation research
• Data assimilation research
• Forecast research
• Real-time NWP
• Hurricane research
• Regional climate research
• Coupled-model applications

Figure 4.1 presents the flow chart of the WRF-ARW

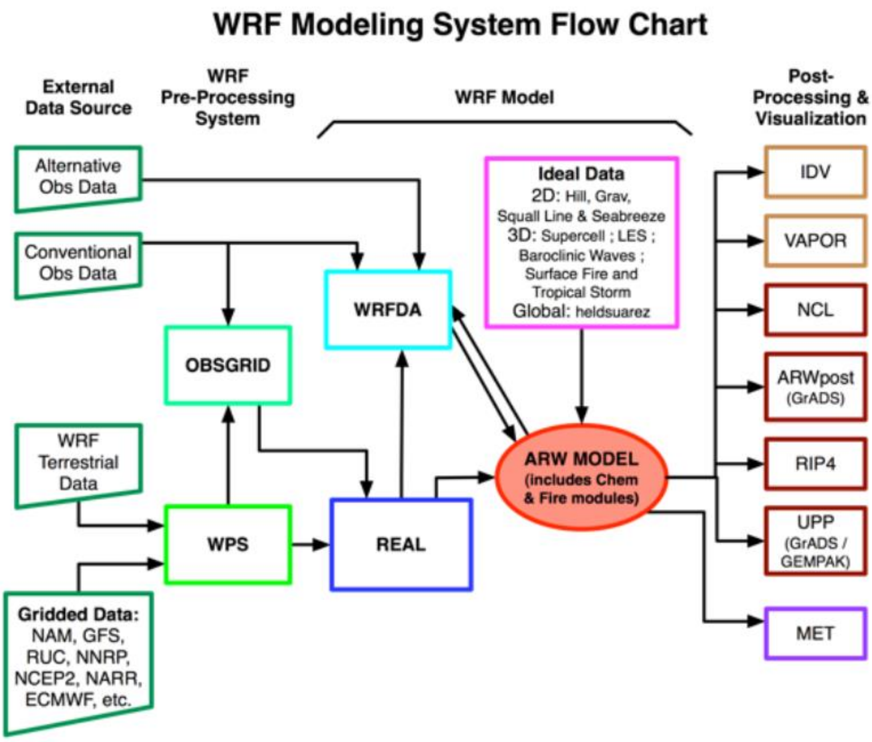


Figure 4.1: Flow chart for the WRF modelling system

In general, the WRF model consists of four main programs:

• The WRF Preprocessing System (WPS)
• WRF-DA

• ARW solver

• Post-processing & Visualization tools

In this study, a triple nested domain was used with the outer-most domain (d01), covering all of Vietnam, most of the neighbouring countries, and the southern part of China. The second domain (d02) covers the northern part of Vietnam, and the third domain (d03) covers all of Hanoi (**Figure 4.2**). The horizontal resolution of these domains was 36 km, 12 km, and 4 km, respectively, and the total number of grids were 100 × 100, 100 × 100, and 110 × 110, respectively. The number of vertical layers was 30. The WRF configuration included the unified Noah land surface model for the land surface scheme, the WRF single-moment three-class scheme, the Dudhia scheme for shortwave radiation, the rapid radiative transfer model (RRTMG) for longwave radiation, and the Yonsei University scheme for PBL. The USGS 24 category land cover data were used during the simulations. In urban areas, the urban land cover with a roughness length of $Z_0 = 1.0$ was used to represent the drag force of the buildings. The initial conditions (ICONs), boundary conditions (BCONs), and analysis nudging data were taken from the 1° × 1° NCEP FNL (Final) Operational Global Analysis data. The WRF simulation was performed from 24 June 2017 to 30 June 2018, with the first 7 days serving as the spin-up time.

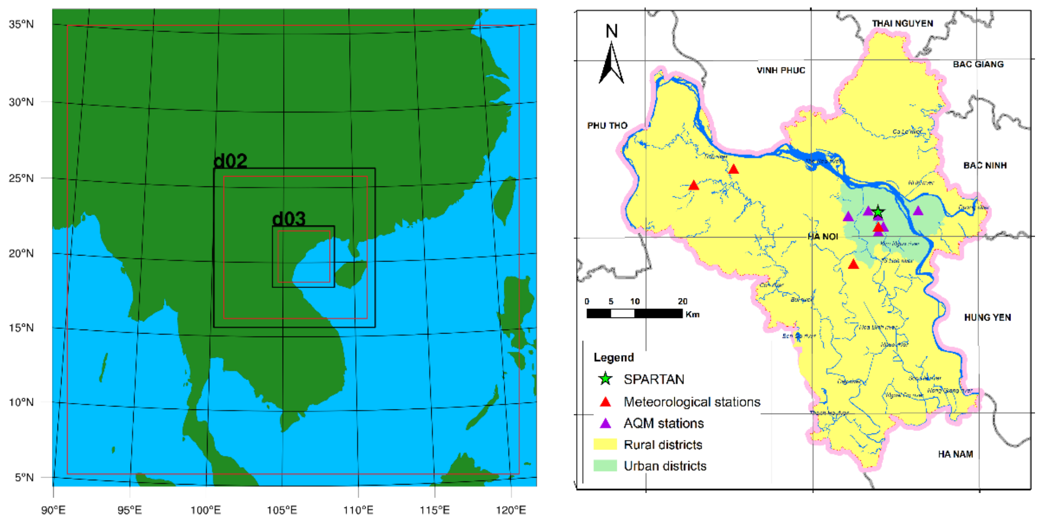


Figure 4.2: Left: Three nested domains for WRF (black boxes) and CMAQ (red boxes) simulations; Right: Map of Hanoi and the locations of air quality stations (purple triangles), weather stations (red triangles), and the SPARTAN station (green star).

4.1.2. CMAQ

The CMAQ model is a numerical air quality model that can predict the concentrations of airborne gases and particles and the deposition of these pollutants onto Earth's surface. Because it includes information about the emissions and properties of the compounds and classes of compounds, CMAQ can also inform users about the chemical composition of a mixture of pollutants. This is particularly useful when measurements only give insight into aggregate details, such as the total particulate mass.

CMAQ allows users to explore different types of air pollution scenarios. For example, CMAQ is often used to test the impact of future emission regulations. Often, people want to know more about which individual emission sources or groups of sources contribute the most to the air pollution at a site. This can be explored using the Integrated Source Apportionment Method (ISAM) in the CMAQ-ISAM model.

The CMAQ model includes the following components:

• Meteorology-Chemistry Interface Processor (MCIP)

• Initial Conditions Processor (ICON)

• Boundary Conditions Processor (ICON)

• CMAQ Chemistry Transport Model (CCTM)

Figure 4.3 provides the flowchart of the modelling system used in this study.

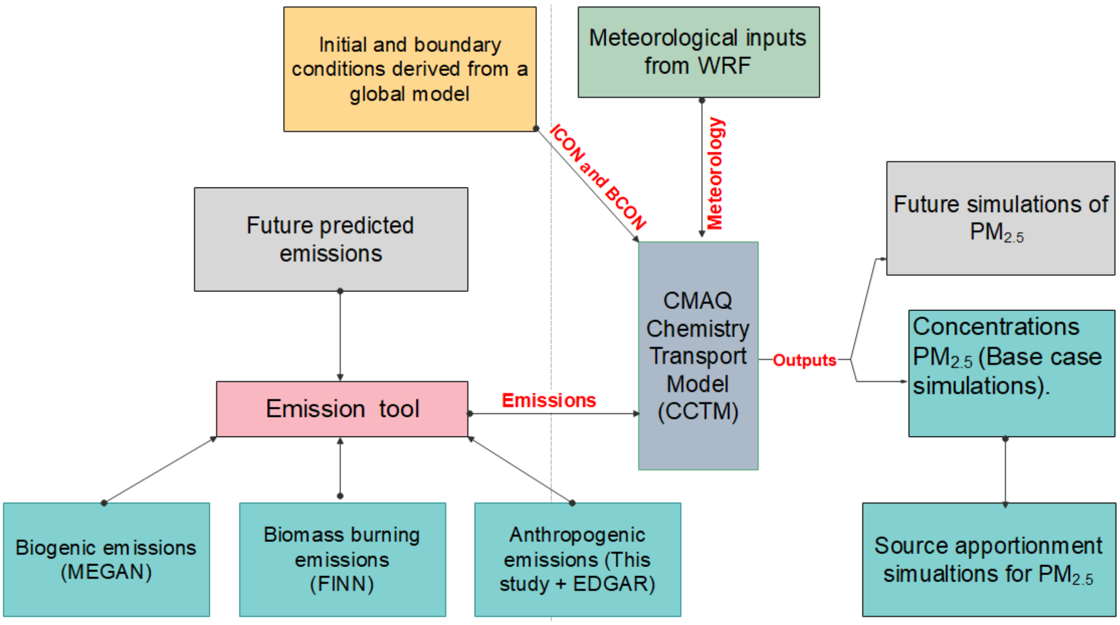


Figure 4.3: Flowchart of the modelling system used in this study.

In this study, CMAQv5.0.2 was used to run the simulations for $PM_{2.5}$. The ICON and BCON used for d01 were from the Model Ozone and Related Chemical Tracer (MOZART) version 4. This is an offline global chemical transport model for studying the troposphere. The standard MOZART-4 mechanism includes 85 gas-phase species, 12 bulk aerosol compounds, and 39 photolysis and 157 gas-phase reactions. The chemical mechanism includes an updated isoprene oxidation scheme and an improved treatment of volatile organic compounds, with three lumped species to represent alkanes and alkenes with four or more carbon atoms and aromatic compounds (called BIGALK, BIGENE, and TOLUENE) (Emmons et al., 2010). The MOZART model is driven by the meteorological fields from the Goddard Earth Observing System Model Version 5 (GEOS-5). The CMAQ configuration includes the Carbon Bond mechanism (CB05) for gas-phase chemistry and the sixth generation CMAQ aerosol module (AERO6) for the aerosol process. For $PM_{2.5}$, CMAQ can simulate the primary and secondary fine particles in the Aitken mode (I) and accumulation mode (J). The total $PM_{2.5}$ can be considered as the sum of its components, such as primary organic carbon (POCI and POCJ), primary elemental carbon (PECI and PECJ), sulfate (ASO4I + ASO4J), nitrate (ANO3I + ANO3J), and ammonium (ANH4I + ANH4J). The Photolysis Rate Processor (JPROC) was used to calculate the photolysis rates for the CMAQ simulation. The base-case CMAQ simulation was performed from 28 June 2017 to 30 June 2018, with the first 3 days serving as the spin-up time. The meteorological parameters simulated using WRF, such as T_2, RH, WS, or WD, were converted into CMAQ-ready files using the CMAQ meteorological pre-processor (MCIPv4.2).

4.1.3. Emissions

For the anthropogenic emissions, in addition to the emission inventory developed in this study, the EDGAR emissions database version 5.0 was used for the emissions outside Hanoi within the modelling domains. The emission results from this study for the coal-fired power plants in northern Vietnam were used for the simulations. The emissions of the power plants in other parts of Vietnam and other countries were obtained from EDGAR. EDGAR is a multipurpose, independent, global database of anthropogenic emissions of greenhouse gases and air pollution on Earth. EDGAR provides independent emission estimates, compared with those reported by the European Member States or by

Parties under the United Nations Framework Convention on Climate Change (UNFCCC), using international statistics and a consistent IPCC methodology. EDGAR provides emissions as both the national totals and grid maps at 0.1° resolution at the global level, with yearly, monthly, and up to hourly data. FINNv1.5 was used for biomass burning. FINN provides 1 km x 1 km resolution for the global emissions of open burning; these emissions have been developed to provide inputs needed for atmospheric models at local to global scales. FINN includes a wide range of pollutants and greenhouse gases, such as CO_2, CO, CH_4, NO_x, NO, NO_x, NMHC, and $PM_{2.5}$ (Wiedinmyer et al., 2011). To avoid double-counting using the FINN data, the emissions from the open burning of agricultural waste in EDGAR were not considered in the CMAQ simulations outside Hanoi. However, the self-developed emissions from crop residue burning were used for the CMAQ simulations instead of the FINN emissions inside Hanoi. The biogenic emissions were calculated with the Model for Emission of Gases and Aerosol from Nature (MEGAN) v2.10. For the input data, the monthly average leaf area index (LAI) data for 2003 was used. The plant function type (PFT) data and meteorological data for MEGAN were obtained from the WRF simulation, which are the same as the data used for CMAQ. The NMVOC speciation used for the CMAQ simulations was determined using the profile developed by Li et al. (2019). The future simulations of $PM_{2.5}$ were performed for the year 2030 using the emission inventory mentioned in Chapter 3. In addition, this study also excluded the emissions from water heating from the future scenarios because it is assumed that with the increasing growth rate of water heater ownership, by 2030, 100% of the population in Hanoi will not need to rely on combustion fuel to heat water. **Table 4.1** lists the total emissions of pollutants in 2017 and 2018 by the major emission sources of $PM_{2.5}$ within domain 3 used in this study.

Table 4.1: total emissions of primary $PM_{2.5}$ species and precursor gases in d03

Sectors	**$PM_{2.5}$**	**BC**	**OC**	**NO_x**	**SO_2**	**NMVOC**	**NH_3**
	Gg			$\times 10^6$ mol			
Crop residue burning	3.2	0.47	0.8	15.95	2.98	21.4	231.1
FINN	100.2	5.7	53.0	1383.7	73.1	5216.6	862.0
Livestock	0	0	0	0	0	0	367.1
Fertiliser application	0	0	0	0	0	0	539.6
Residential & commercial activities	84.0	9.9	38.8	551.5	371.3	4806.5	1568.1
MSW burning	0.4	0.003	0.2	4.37	0.35	31.9	2.5
On-road transport	9.7	3.03	3.2	3449.3	237.8	5885.8	60.1
Non-metallic mineral	13.9	0.35	3.08	0.0	15.1	0.63	1.99
Food and paper	9.6	0.2	0.4	441.4	4673.4	21910.44	0.0
Chemical fertilizer industry	0	0	0	0	0	0	162.9
Iron and steel industry	0.2	0.005	0.0	0.52	10.39	170.01	0.0
Industrial combustion	39.7	5.3	13.06	5058.0	2528.27	244407.2	206.4
Power plants	2.1	0.04	0.23	2998.8	865.4	89.7	1.4
Solvents	0	0	0	0	0	3536.7	0
Gas stations	0	0	0	0	0	129.8	0

4.1.4. Model evaluation

The model output was compared with the observational data collected from stations located inside Hanoi. A summary of the stations used in this study is presented in **Table 4.2**.

For the statistical metrics, the following parameters were used to evaluate the performance of the WRF and CMAQ models: correlation (R), mean bias (MB), E_{MAGE}: mean absolute gross error, root mean square error (RMSE), normalised mean bias (NMB), normalised mean error (NME), mean normalised bias (MNB), mean normalised error (MNE), mean fractional bias (MFB), mean fractional error (MFE), normalised mean bias factor (BNMBF), and normalised mean absolute error factor (ENMAEF). The average value of the grid point nearest to each monitoring station was used for the comparison with the average observational data. The simulation results of the innermost domain (d03) were compared with the observations and used to calculate the statistical metrics.

Table 4.2: Information regarding the stations used for model evaluation

Station name	Latitude	Longitude	Station type	Parameter used
NVC	21.05°	105.88°	AQ	$PM_{2.5}$, T_2, Wind speed (WS), Wind direction (WD).
Phamvandong	21.05°	105.78°	AQ	$PM_{2.5}$
EPD	21.01°	105.8°	AQ	$PM_{2.5}$, T_2, RH_2, WS, WD
US Embassy	21.02°	105.81°	AQ	$PM_{2.5}$
Hangdau	21.04°	105.8°	AQ	$PM_{2.5}$
Minhkhai	21.04°	105.74°	AQ	$PM_{2.5}$
Lang	21.02°	105.8°	Weather	T_2, RH_2
Bavi	21.1°	105.43°	Weather	T_2, RH_2
Sontay	21.13°	105.51°	Weather	T_2, RH_2
Hadong	20.95°	105.75°	Weather	T_2, RH_2

Note: AQ = Air quality monitoring stations; Weather = Weather stations

Figure 4.4 provides the comparisons of T_2, RH_2, WS, and WD between models and observations.

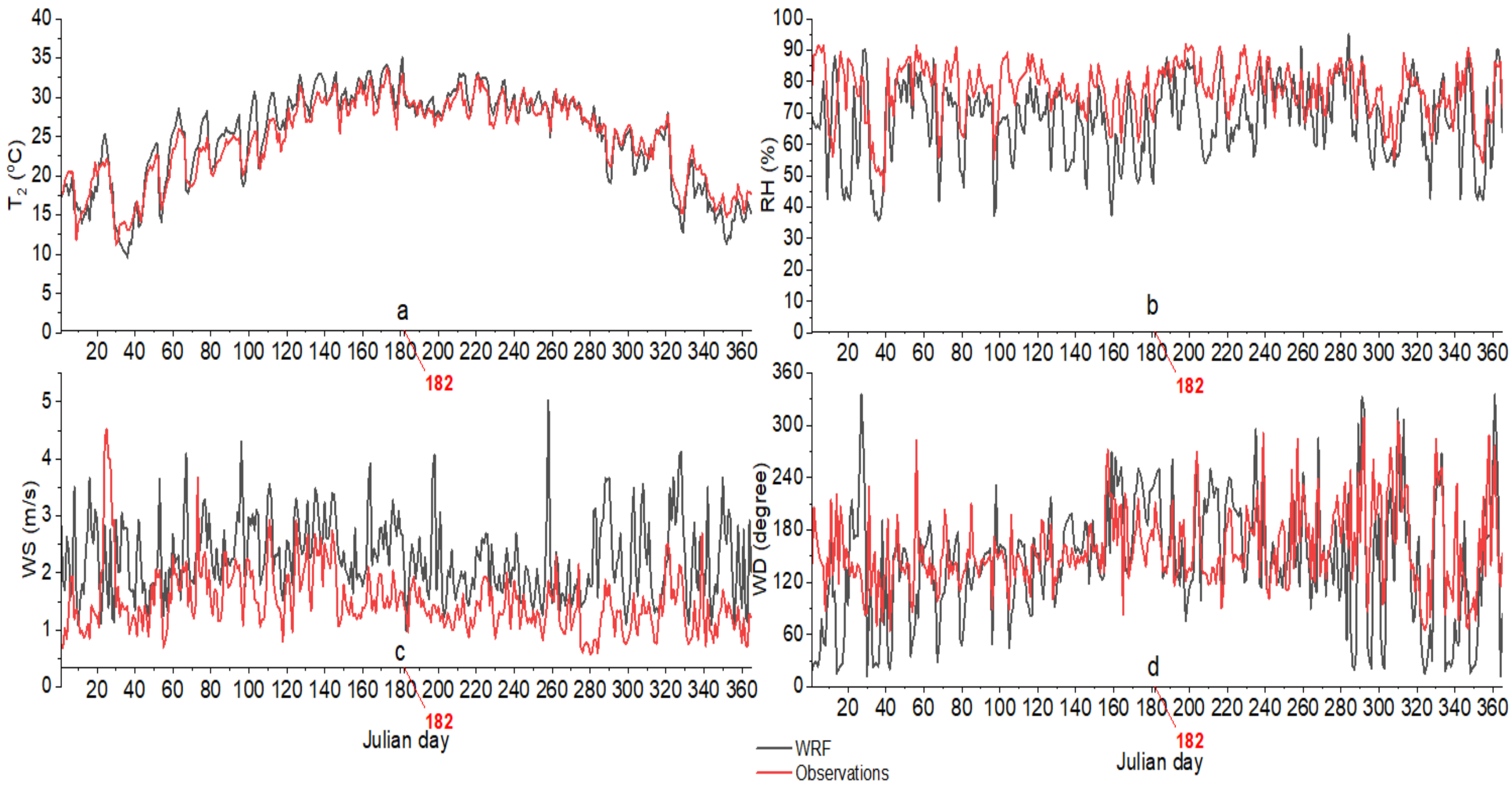


Figure 4.4: Comparison of (a) temperature (T_2), (b) relative humidity (RH), (c) wind speed (WS) and (d) wind direction (WD. The values were averaged across all stations located in Hanoi. The simulation results for 2018 (from January to June) are presented first, followed by those of 2017 (from July to December). The number "182" is the 182nd day of 2017 which is 1 July. The daily mean values were used for model evaluation.

Table 4.3: Statistical evaluation for T_2 and RH simulated using WRF

		R	MB	MAGE	Mean WRF	Mean Obs	RMSE
			°C				
T_2	Jan	0.04	-2.43	3.66	15.59	18.02	0.82
	Feb	0.96	-0.3	1.82	17.03	17.33	0.4
	Mar	0.88	1.74	1.94	24.21	22.46	0.4
	Apr	0.91	1.83	2.19	25.97	24.14	0.46
	May	0.82	1.55	1.59	30.56	29	0.33
	Jun	0.86	1.31	1.35	31.51	30.2	0.3
	Jul	0.84	0.48	0.78	29.39	28.91	0.16
	Aug	0.84	1.11	1.16	30.27	29.15	0.28
	Sep	0.58	0.24	0.73	29.17	74.21	0.18
	Oct	0.96	-0.67	0.94	24.85	25.52	0.21
	Nov	0.97	-1.16	1.35	21.22	22.38	0.28
	Dec	0.86	-2.1	2.1	15.59	17.69	0.42
	Year	0.95	0.13	1.63	24.65	24.51	2.17
	Criteria		**≤ ± 0.5**	**≤ 2**			
RH		**R**	**MB**	**MAGE**	**Mean WRF**	**Mean Obs**	**RMSE**
			%				
	Jan	0.27	-13.41	20.81	65.4	78.81	4.3
	Feb	0.93	-7.54	8.49	66.08	66.49	1.86
	Mar	0.8	-9.83	10.39	68.19	78.02	2.1
	Apr	0.66	-9.83	10.34	67.3	77.1	2.13
	May	0.58	-11.91	12.19	65.12	77.03	2.53
	Jun	0.85	-14.06	14.06	59.76	71.43	2.81
	Jul	0.72	-10.19	10.45	73.03	83.22	2.27
	Aug	0.68	-11	11	70.91	81.91	2.31
	Sep	0.43	-1.95	5.96	74.21	73.71	1.38
	Oct	0.82	-6.46	7.57	71.91	78.37	1.68
	Nov	0.67	-6.1	8.65	67.35	71.08	1.91
	Dec	0.85	-8.5	9.56	65.4	73.9	2.12
	Year	0.63	-9.47	10.98	67.91	77.38	13.48
	Criteria						

Table 4.3 (cont): Statistical evaluation for WS and WD simulated using WRF

		R	MB	MAGE	Mean WRF	Mean Obs	RMSE
			(m/s)				
WS	Jan	0.2	0.42	1.27	2.17	1.75	0.27
	Feb	0.48	0.71	0.72	2.04	1.33	0.27
	Mar	0.46	0.54	0.65	2.39	1.85	0.27
	Apr	0.49	0.83	0.85	2.59	1.75	0.27
	May	0.83	0.69	0.7	2.69	2	0.27
	Jun	0.71	0.94	0.94	2.47	1.53	0.27
	Jul	0.32	0.73	0.75	2.07	1.35	0.27
	Aug	0.79	0.64	0.64	2.05	1.41	0.27
	Sep	0.57	0.57	0.57	1.87	1.3	0.27
	Oct	0.69	1.19	1.19	2.28	1.09	0.27
	Nov	0.64	0.93	0.99	2.35	1.42	0.27
	Dec	0.65	0.97	0.98	2.17	1.2	0.27
	Year	0.42	0.76	0.86	2.26	1.5	0.27
	Criteria		**≤ ± 0.5**				**≤ 2**
WD		**R**	**MB**	**MAGE**	**Mean WRF**	**Mean Obs**	**RMSE**
			(degree)				
	Jan	0.32	-38.29	95.61	109.31	147.59	20.07
	Feb	0.22	-37.31	54.65	99.01	136.32	13.79
	Mar	0.23	-14.95	36.63	125.42	140.37	8.06
	Apr	0.46	-6.5	24.83	135.55	142.04	6.67
	May	0.12	5.81	27.75	157.64	151.83	6.31
	Jun	0.33	20.51	47.05	197.39	176.88	9.95
	Jul	0.43	14.35	41.3	172.43	158.08	9.52
	Aug	0.52	21.88	40.48	183.96	162.08	9.05
	Sep	0.42	-16.15	38.56	153.21	169.35	8.88
	Oct	0.62	-56.32	74.33	133.44	189.76	16.09
	Nov	0.83	-21.97	43.57	158.3	180.27	9.47
	Dec	0.64	-35.56	68.05	109.31	144.86	13.52
	Year	0.47	-13.6	45.49	144.77	158.37	64.28
	Criteria		**≤ ± 10**	**≤ 30**			

Table 4.3 provides the statistical evaluation for the meteorological parameters for the WRF simulations in Hanoi. The WRF model well simulated the annual variation of T_2, with the correlation ranging from 0.82 to 0.97. The statistical parameters also indicate that the WRF model tends to slightly underestimate T_2 during winter and overestimate T_2 during summer. The low R values for January and September indicate that WRF did not perform well for these 2 months. Considering the entire simulation period, the value of MB falls within the acceptable range proposed by Emery et al. (2001). In terms of MAGE, the values for most months are within the benchmark, except for those for January, April, and December. Regarding the entire year, the MAGE value is within the benchmark. Concerning the RH, the results indicate that WRF underestimated the observations. However, the diurnal variations of the observed RH were well-reproduced by WRF. Similar to our previous study, one of the possible reasons for the underestimation of RH in WRF simulation is because WRF underestimated the water vapour mixing ratio in the urban area, leading to the underestimation of RH (Nguyen et al., 2020). For the WS, although this study considers the urban land use as well as a surface roughness (Z_0) value suitable for urban land use, the model still tended to overestimate the observations. This implies that these considerations of urban land use are still not enough to fully represent the actual impact of buildings on the WS in Hanoi. However, WRF simulated the temporal variations of WS relatively well. The R values for WS are outside the benchmark, while RMSE values are within the benchmark. In terms of WD, WRF well simulated the temporal variations of WD throughout the year. However, the MB and MAGE values fall outside the benchmark. Nguyen et al. (2019b) argued that the low values of R and large value of MAGE for WD could be the result of treating the WD vector as a scalar in the statistical calculation.

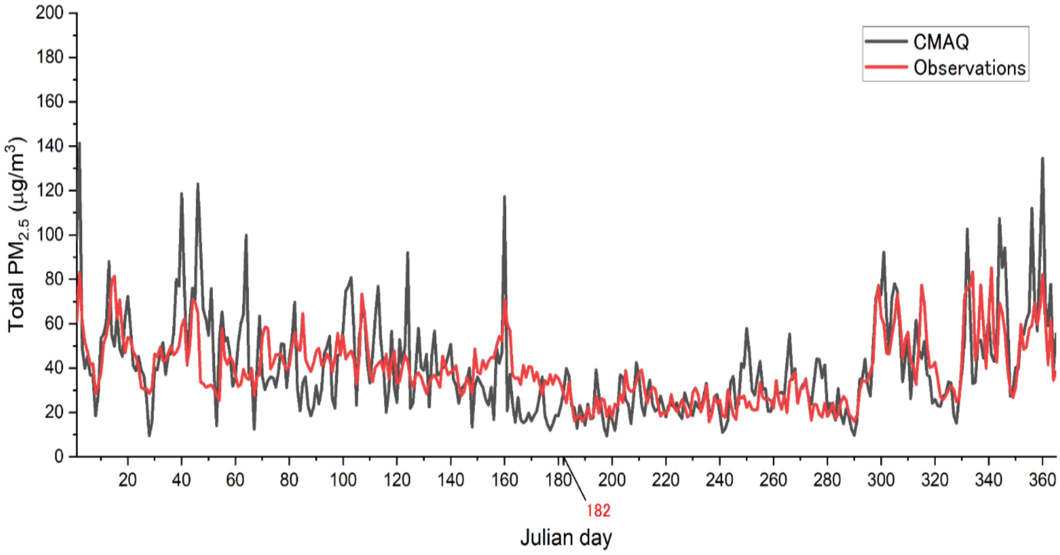


Figure 4.5: Comparison of simulated (black) and observed (red) $PM_{2.5}$. The values were averaged across all stations located in Hanoi. The simulation result of the year 2018 (from January to June) are presented first, followed by that of the year 2017 (from July to December). The number "182" is the 182^{nd} day of 2017 which is July 1^{st}. The daily mean values were used for model evaluation.

Table 4.4: Statistical evaluation for $PM_{2.5}$ concentrations in Hanoi

	Year	**Dec**	**Nov**	**Oct**	**Sep**	**Aug**	**Jul**	**Jun**	**May**	**Apr**	**Mar**	**Feb**	**Jan**	**Criteria**
MB	1.3	8.3	-6.1	5.2	6.8	-1.1	-1.3	-13.9	3.2	2.1	-2.6	15.9	0.2	
ME	11.9	15.5	11.7	8.8	8.3	4.8	6.6	17.5	9.5	13.3	15.7	18.6	13.1	
RMSE	16.6	21.2	16.2	11.7	11.7	5.8	8.2	19.8	13.3	16.7	20.2	26.0	18.0	
NMB	3.4	15.4	-12.6	16.0	25.7	-4.7	-5.1	-33.9	8.8	4.6	-6.1	35.0	0.3	**< ±30**
NME	30.4	28.8	24.2	27.2	31.4	20.4	26.2	42.6	26.2	29.7	36.1	41.0	26.5	**< 50**
MNB	4.8	16.2	-11.0	17.6	29.6	-2.3	-3.4	-36.4	8.8	5.1	-2.0	38.9	-1.7	
MNE	30.8	27.4	23.4	32.3	34.8	20.5	2	42.6	26.3	30.5	37.3	46.3	25.5	
MFB	-2.5	11.1	-15.9	10.2	20.8	-5.5	-8.6	-50.9	3.5	-1.5	-12.6	24.8	-6.7	**< ±60**
MFE	29.8	24.2	25.9	27.4	26.5	21.5	27.5	5	24.5	29.8	37.3	33.8	26.4	**< 75**
R	0.66	0.6	0.7	0.9	0.2	0.3	0.5	0.7	0.4	0.4	0.1	0.5	0.7	**> 0.4**
NMBF	0.03	0.1	-0.1	0.1	0.2	-0.05	-0.05	-0.5	0.09	0.04	-0.07	0.2	0.004	
NMAEF	0.3	-0.6	-0.7	-0.7	-0.6	-0.8	-0.7	-0.8	-0.7	-0.6	-0.6	-0.4	-0.7	
OVER or UNDER	OVER	OVER	UNDER	OVER	OVER	UNDER	UNDER	UNDER	OVER	OVER	UNDER	OVER	OVER	
By a factor of	1.0	1.1	1.1	1.1	1.2	1.0	1.0	1.5	1.0	1.0	1.0	1.2	1.0	
Mean CMAQ	40.6	62.1	42.1	37.6	33.4	22.7	24.0	27.2	39.5	47.1	40.7	61.3	49.7	
Mean Obs	39.2	53.8	48.	32.4	26.5	23.8	25.3	41.1	36.3	45.0	43.4	45.4	49.5	

Similar to the meteorological parameters, the average values of the daily mean $PM_{2.5}$ concentrations across all stations were used for comparison with the observations and for calculating the statistical metrics. **Figure 4.5** presents the comparison of the simulated and observed (red) $PM_{2.5}$ and **Table 4.4** provides the statistical evaluation for the $PM_{2.5}$ concentrations from the CMAQ simulation in Hanoi. The correlations between the simulated and observed $PM_{2.5}$ ranged from 0.11 in March to 0.87 in October. The simulated annual mean $PM_{2.5}$ was slightly overestimated compared with the observed $PM_{2.5}$ by a factor of 0.03 during the simulation period. The simulated $PM_{2.5}$ in 5 out of 12 months was underestimated, while that for 7 out of 12 months was overestimated compared with the observations (**Table 4.4**). Although several simulated peaks were found, the CMAQ model still did well to simulate the concentrations of $PM_{2.5}$ in terms of both the temporal variations and magnitude, and both the simulated and observed $PM_{2.5}$ demonstrated that the concentrations of $PM_{2.5}$ in winter were higher than those in summer. Nguyen et al. (2019b) also used the WRF/CMAQ model to investigate the air quality in Southeast Asia in 2014, in which the simulated daily $PM_{2.5}$ was also overestimated; however, the reason for the overestimation of $PM_{2.5}$ was not deeply investigated. The NMB and NME are mostly within the acceptable range, except for in June, when the NMB value slightly exceeds the acceptable range. Regarding the MFB and MFE, the monthly values for all months as well as for the entire year are within the acceptable range. The R values for March, April, May, August, and September are smaller than the criteria of 0.4. However, despite these low R values, the modelled results should not be ignored (Boylan and Russell, 2006; Kitagawa et al., 2021). Although some issues related to the reproductivity of $PM_{2.5}$, it can be concluded that using CMAQ with the self-developed emission inventory can well reproduce both the temporal variations and the magnitude of $PM_{2.5}$ in Hanoi. This allows us to further investigate the source apportionment of $PM_{2.5}$ in Hanoi. In this study, we used the CMAQ-ISAM system to investigate the main source of $PM_{2.5}$ in Hanoi.

4.2. Source apportionment simulations of $PM_{2.5}$ in Hanoi

To determine effective measures to manage air pollution, it is essential to understand the main source of air pollutants. Source apportionment is a way to deduce the relative contribution of different emission sources to the concentration of an air pollutant at a certain location, usually with the aid of numerical models. One approach that has been widely used to identify the main source of air pollution is the "brute force" method. In this method, two model simulations are required; one is the base-case run with the unperturbed input emission data and the other model runs with the perturbed input emission data (usually the perturbation of the input emission data either fully or partly removes the emission source of interest). The difference between these two runs is then assumed to be the contributions of the removed source. Although this method is easy to apply and straightforward, it requires multiple model simulations if the number of sources of interest is large. In addition, completely or largely removing an emission source in a highly nonlinear atmospheric chemical system can lead to non-negligible errors in the source apportionment. To solve this problem, the ISAM has been developed and implemented in the CMAQ system. The ISAM does not directly modify the input emissions but tracks the contributions from ICON, BCON, and any emission sectors defined by the users. In general, ISAM tags each precursor and quantifies its contribution (in terms of mass) to the pollutant concentrations. With this method, the input emissions do not change and therefore, there are no nonlinear errors between the emissions and concentrations.

This study considered not only the contributions of sources located inside Hanoi but also those located outside the city. Additionally, along with considering the monthly contributions of each emission sector to the monthly mean $PM_{2.5}$ concentrations, several peak concentrations of $PM_{2.5}$ were selected to investigate the key reasons leading to such events. The relative contributions of the following 12 source categories were considered: agriculture (including crop residue burning, livestock, fertiliser application, agricultural soil; AGR), energy (the coal power plants located outside Hanoi; ENER), industrial emission sources located inside and outside Hanoi (INDUS_0 and INDUS_1, respectively), residential and commercial activities (including cooking, water heating, emissions from building, solid waste landfill, and MSW burning) inside and outside Hanoi (RCO_0 and RCO_1, respectively), transport sectors (including no-resuspended on-road transport, tyre and brake wear, evaporative emissions, domestic navigation, and aviation) inside and outside Hanoi (TRANS_0 and TRANS_1, respectively), FINN, BCON, ICON, and other sectors (OTHR). Using ISAM could help to solve the problem of the non-linearity of the "brute force" method. However, running the ISAM requires considerable computational resources and time. For those issues, although we ran the base-case simulation of $PM_{2.5}$ for one year, we selected only four months, April, June, October, and December, which represent the four seasons in Hanoi to investigate the source apportionment. **Table 4.5** lists the $PM_{2.5}$ species that can be tagged using ISAM:

Table 4.5: $PM_{2.5}$ components

AECI + AECJ	Primary elemental carbon
APOCI + APOCJ	Primary organic carbon
APNCOMI + APNCOMJ	Primary organic non-carbon
ASO4I + ASO4J	Sulfate (SO_4^{2-})
ANO3I + ANO3J	Nitrate (NO_3^-)
ANH4I + ANH4J	Ammonium (NH_4^+)
ACLI + ACLJ	Chlooride (Cl^-)
ANAI + ANAJ	Sodimun (Na^+)
AMGJ; AKJ; ACAJ; AFEJ; AALJ; ASIJ; ATIJ; AMNJ	Magnesium (Mg_2^+); Potassium (K^+); Calcium (Ca); Iron (Fe); Aluminium (Al); Siliconn (Si), Titanium (Ti); Manganese (Mn)
AOTHRI + AOTHRJ	Primary unspeciated fine particles

I = Aitken mode; J = accumulation mode; The sum of both modes is regarded as $PM_{2.5}$.

As mentioned earlier, this study used the EDGAR version 5.0 data for the anthropogenic emissions outside Hanoi; therefore, the results of the CMAQ-ISAM simulation relied not only on the self-developed emissions in Hanoi but also on EDGAR emission inventory. **Figure 4.6** presents the monthly mean source contributions (%), while **Figure 4.7** provides the daily mean source contributions (in absolute values) of BCON, ICON, and each emissions source to the concentrations of total $PM_{2.5}$ in April, June, October, and December. In addition, **Table 4.6** provides the monthly contributions in absolute values and the minimum and maximum daily mean values of BCON, ICON, and each emission sector to the $PM_{2.5}$ concentration in Hanoi during each selected month. **Figure 4.8** illustrates the spatial distribution of the source contribution of BCON and each emission sector in d03. The same figures for ICON and OTHR are not shown because their contributions are negligible.

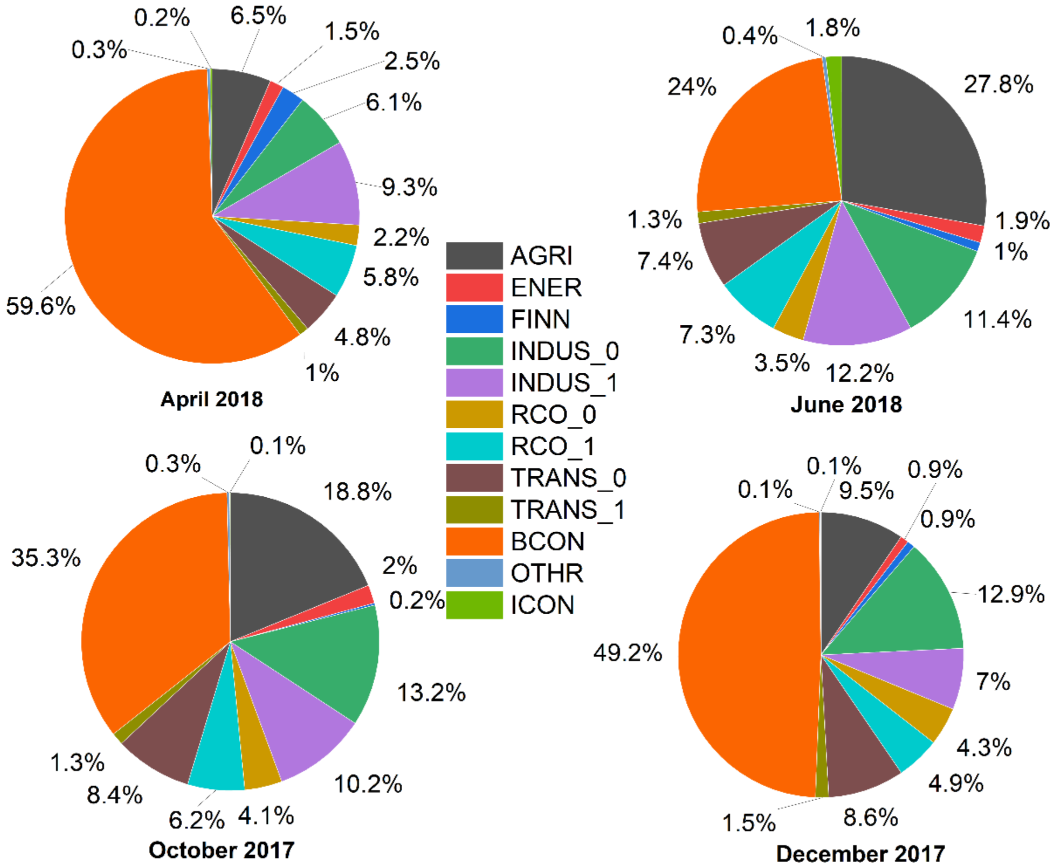


Figure 4.6: Contributions of each emission source to the monthly concentrations of $PM_{2.5}$ in Hanoi in April, June, October, and December.

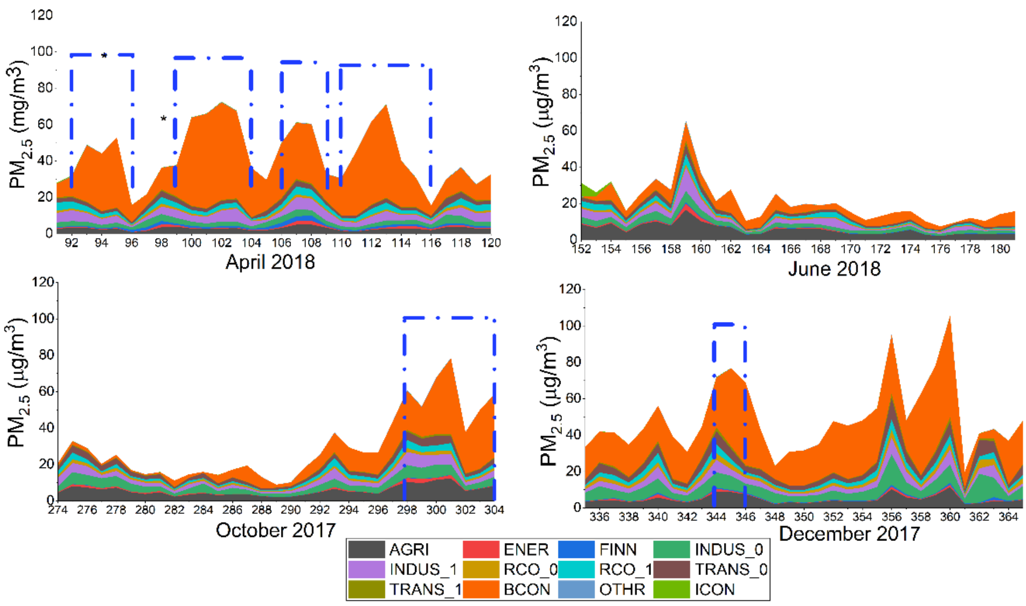


Figure 4.7: Daily mean contributions to the concentrations of $PM_{2.5}$ of each sector and BCON in April, June, October, and December. The blue dash-dot lines are the selected periods of high $PM_{2.5}$ concentrations.

Table 4.6: Monthly contributions to the $PM_{2.5}$ concentration in absolute values and the minimum and maximum daily mean values of BCON, ICON, and each emission sector in Hanoi in each selected month.

	April (µg/m³)	June (µg/m³)	October (µg/m³)	December (µg/m³)
Agriculture	2.75 (0.7 – 5.0)	5.76 (2.1 – 16.5)	5.5 (2.0 – 12.3)	4.6 (1.9 – 11.3)
Energy	0.6 (0.05 – 2.1)	0.38 (0 – 3.4)	0.58 (0.02 – 2.4)	0.5 (0.07 – 1.8)
FINN	1.0 (0.3 – 2.9)	0.2 (0.05 – 0.8)	0.06 (0.01 – 0.2)	0.4 (0.1 – 1.5)
INDUS_0	2.6 (1.3 – 4.8)	2.4 (1.1 – 6.1)	3.9 (1.4 – 7.3)	6.4 (2.5 – 16.8)
INDUS_1	3.9 (0.7 – 7.0)	2.5 (0.2 – 13.0)	3.0 (0.7 – 7.1)	3.4 (1.3 – 9.1)
RCO_0	0.9 (0.3 – 1.6)	0.7 (0.15 – 1.7)	1.5 (0.6 – 2.7)	2.1 (0.8 – 4.6)
RCO_1	2.5 (0.4 – 4.6)	1.5 (0.3 – 5.5)	1.8 (0.4 – 4.4)	2.4 (0.7 – 5.7)
TRANS_0	2.0 (0.4 – 4.6)	1.5 (0.6 – 5.2)	2.5 (0.9 – 5.2)	4.2 (1.8 – 11.8)
TRANS_1	0.4 (0.05 – 0.9)	0.3 (0.03 – 2.1)	0.4 (0.07 – 1.0)	0.7 (0.1 – 2.4)
BCON	25.4 (5.5 – 53.5)	4.9 (0.04 – 12.9)	10.4 (0.6 – 41.6)	24.1 (2.8 – 55.7)
OTHR	0.1 (0.01 – 0.3)	0.08 (0 – 0.85)	0.08 (0 – 0.3)	0.06 (0 – 0.2)
ICON	0.09 (0.02 – 0.3)	0.36 (0 – 7.6)	0.03 (0 – 0.09)	0.04 (0 – 0.3)

The ISAM results demonstrate that the contribution from BCON dominates the concentrations of $PM_{2.5}$ in Hanoi during the four selected months, contributing 59.6%, 24.0%, 35.3%, and 49.2% in April, June, October, and December, respectively. This result indicates that a large amount of air pollutants was injected into the innermost domain (d03) of Hanoi from the outer domains (d02 and/or d01). In April, the monthly mean contribution of BCON to the concentration of $PM_{2.5}$ in Hanoi was 25.4 µg/m³. In April, the impact of BCON on Hanoi primarily came from southern Vietnam. The impact of BCON during the selected periods in April also came from southern Vietnam, except during the period from 16–19 April, when the contribution of BCON mainly came from northern Vietnam. The contribution of BCON during the selected periods in April ranged from 20 to 30 µg/m³, except for the period of 9–4 April, when the contribution of BCON ranged from 40 to 50 µg/m³. In October and December, the contribution of BCON mainly came from northern and north-eastern Vietnam, implying that these contributions were coming predominantly from China. The contribution of BCON in December was greater than that in October (24.1 µg/m³ and 10.4 µg/m³, respectively). The selected periods of 25– 31 October and 10–12 December indicate that the BCON coming from the north could reach 20 – 50 µg/m³, depending on the season.

Agriculture was also revealed to be a major source of $PM_{2.5}$ in Hanoi, especially in June and October when crop residue burning occurred. The monthly mean contributions of agriculture to the $PM_{2.5}$ in Hanoi were 2.7µg/m³ in April, 5.7 µg/m³ in June, 5.5 µg/m³ in October, 4.6 µg/m³ in December. In April and December, when crop residue was not burned, other agricultural sectors, such as agricultural soil emissions, manure management, or fertiliser application could have been the primary sources of $PM_{2.5}$. The

$PM_{2.5}$ concentrations caused by the agricultural sector in June and October were found to be higher than those in April and December. In general, the agricultural contributions to the total $PM_{2.5}$ in Hanoi in April, June, October, and December are 6.5%, 27.8%, 18.8%, and 9.5%, respectively.

As mentioned previously, the biomass burning emission data from FINN inside Hanoi was not used in the CMAQ simulations in this study; therefore, the contribution deduced using FINN in this study should be purely the impact from outside the city. As shown in Figure 4–8(c), the contribution of the FINN emissions was predominantly found in April and can be seen mainly to the west, southwest, and northeast of Hanoi. However, the FINN data were found to have little impact on the air quality inside Hanoi. One of the main reasons is that the WD does not favour the transport of air pollutants to Hanoi. During the period of 16–19 April, the contribution of FINN to the $PM_{2.5}$ in Hanoi was only 2–4 μg/m^3.

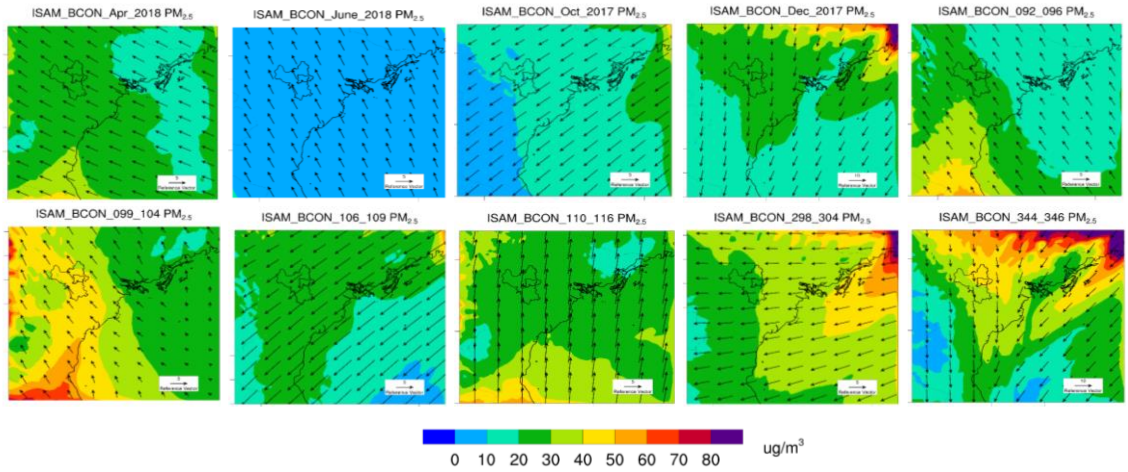
The concentrations of $PM_{2.5}$ caused by INDUS_0 were found mainly in the centre part of Hanoi. The monthly mean contributions of $PM_{2.5}$ from INDUS_0 were 2.6, 2.4, 3.9, and 6.4 μg/m^3 in April, June, October, and December, respectively. Higher contributions of INDUS_0 occurred in October and December than in April and June. In Hanoi's centre, the concentration of $PM_{2.5}$ contributed by INDUS_0 could exceed 20 μg/m^3, as shown in Figure 3–8(d). In addition, INDUS_0 also had an impact on the areas surrounding Hanoi depending on the wind speed and direction. During the selected periods, the contributions of INDUS_0 were higher in October and December than in April. In terms of emissions from INDUS_1, the emissions of this sector were obtained from EDGAR and mainly allocated to the east of Hanoi. Therefore, when winds blow from the eastern or north-eastern directions, they can transport air pollutants from industrial activities to Hanoi. According to the ISAM simulations, the industrial facilities located outside Hanoi contributed 3.9, 2.5, 3.0, and 3.4 μg/m^3 in April, June, October, and December, respectively, to the total concentrations of $PM_{2.5}$ in Hanoi. Interestingly, the contributions of the industrial facilities outside Hanoi in April and June were larger than those of the industrial facilities located inside Hanoi. This implies the significance of WS and WD to the contributions of $PM_{2.5}$ emitted from sources located around Hanoi to the concentrations of $PM_{2.5}$ inside the city.

For RCO_0, the monthly mean contributions of this sector in April, June, October, and December were 0.9, 0.7, 1.5, and 2.1 μg/m^3, respectively. Interestingly, the contributions of RCO_1 for those four months were 2.5, 1.5, 1.8, and 2.4 μg/m^3, respectively, which are greater than those of RCO_0. Similar to INDUS_1, substantial emissions could be seen in the areas located to the east of Hanoi, which then could be transported into the city due to the impact of the WS and WD. The spatial distributions of RCO_0 indicate that the impact of this source on the $PM_{2.5}$ concentration in Hanoi was smaller than from the other sectors in Hanoi, such as INDUS_0 or TRANS_0. In December, the concentration of $PM_{2.5}$ of RCO_0 increased in comparison with those in the other three months, implying the contribution of water heating. In addition, a small section of RCO_0 contribution in the northwest part of Hanoi implies the contribution of a large MSW burning facility located there.

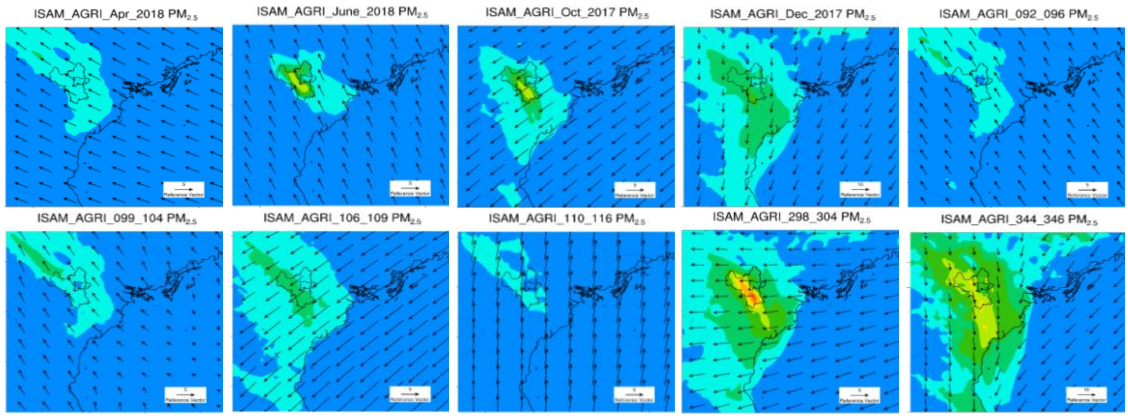
For the TRANS_0, the contributions to the $PM_{2.5}$ concentrations in Hanoi were 2.0, 1.5, 2.5, and 4.2 μg/m^3 in April, June, October, and December, respectively. The contributions from TRANS_1 for the same four months were relatively small, which were only 0.4, 0.3, 0.4, and 0.7 μg/m^3, respectively. The impact of TRANS_0 on the $PM_{2.5}$ concentrations in Hanoi was found to be highest in December, partly because of the cold emissions which tend to be higher during cold seasons. The selected periods suggest that in December, due to the impact of wind, a considerable amount of $PM_{2.5}$ can be transported from Hanoi to the nearby provinces, affecting the air quality in those locations. In contrast, the contributions of TRANS_1 to the $PM_{2.5}$ concentrations in Hanoi were quite small.

One of the main reasons for determining the emissions from coal-fired power plants is to evaluate the impact of this source on the air quality in Hanoi. The ISAM simulations indicate that although the pollutants emitted by the coal-fired power plants located around Hanoi can reach the city, the impact was relatively small. During the four selected months, the contributions of this sector were only 0.6, 0.38, 0.58, and 0.5 μg/m^3, respectively. However, this study considered the emission control efficiencies that were noted by the operating company that have greatly helped to reduce emissions; notably, the emission control devices may not always be in operation due to maintenance. In addition, the emission control devices may not be able to maintain 100% efficiencies, leading to higher emissions from these sources. Future studies should consider estimating the emissions from this source by applying the detailed method mentioned in the ABC guideline or directly monitoring the emissions at each plant. Among the selected periods, the power plants have the largest impact on Hanoi during the period of 16–19 April. The $PM_{2.5}$ concentrations caused by this source ranged from 1 to 2 μg/m^3 during this period.

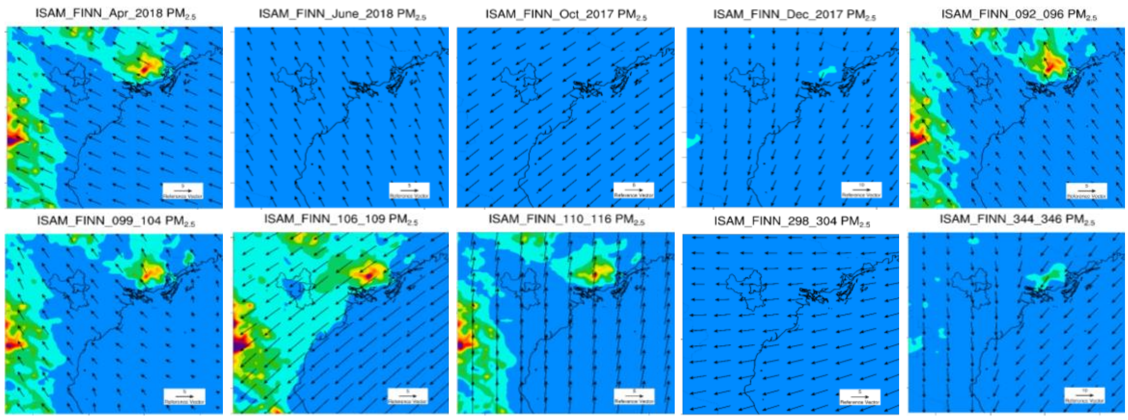
(a) BCON



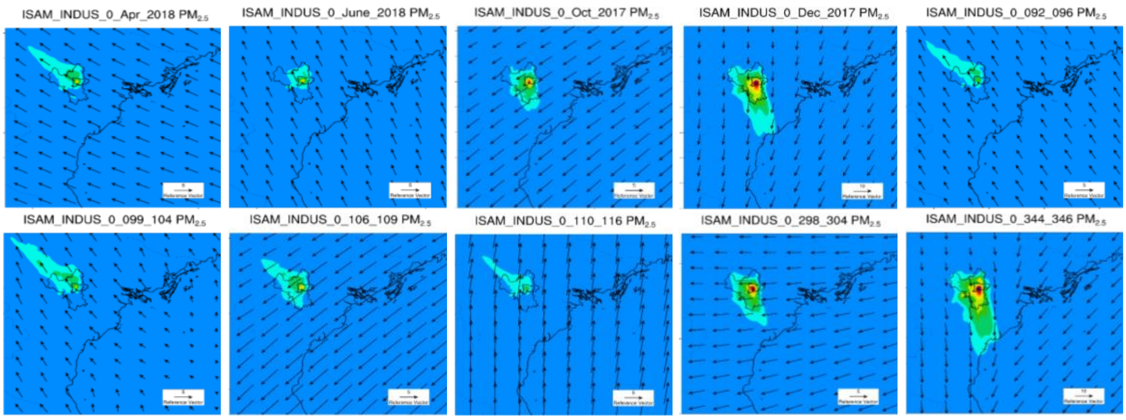
(b) Agriculture



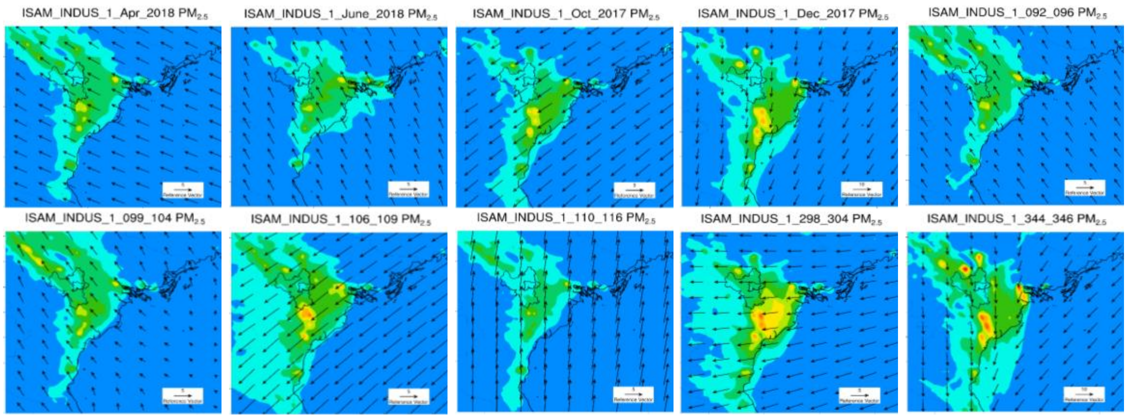
(c) FINN



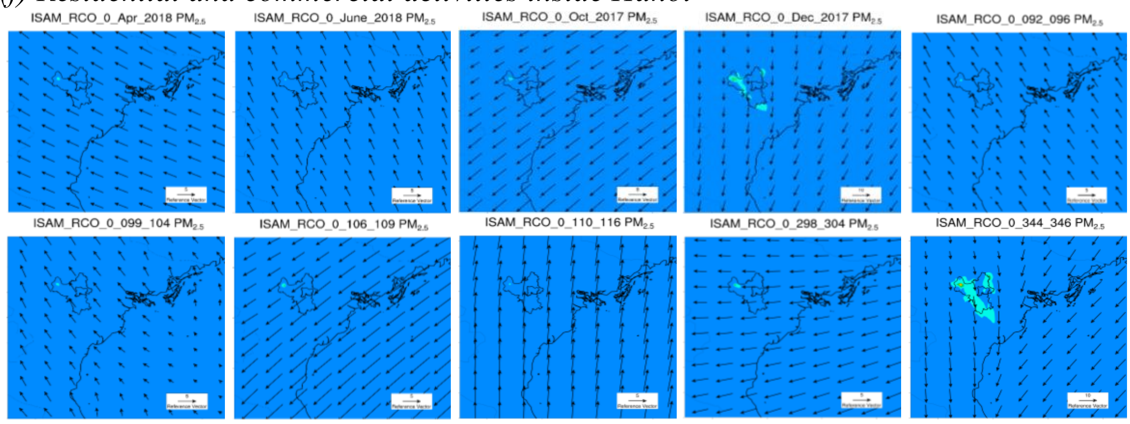
(d) Industries inside Hanoi



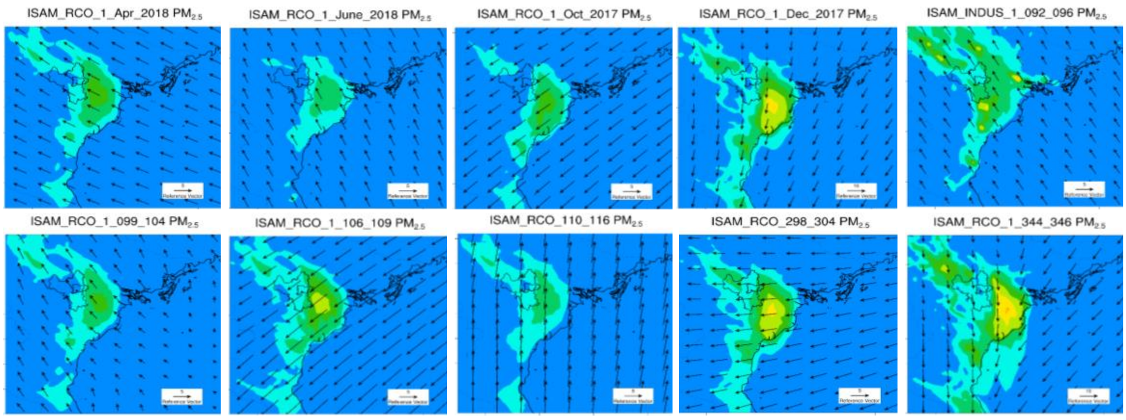
(e) Industries outside Hanoi



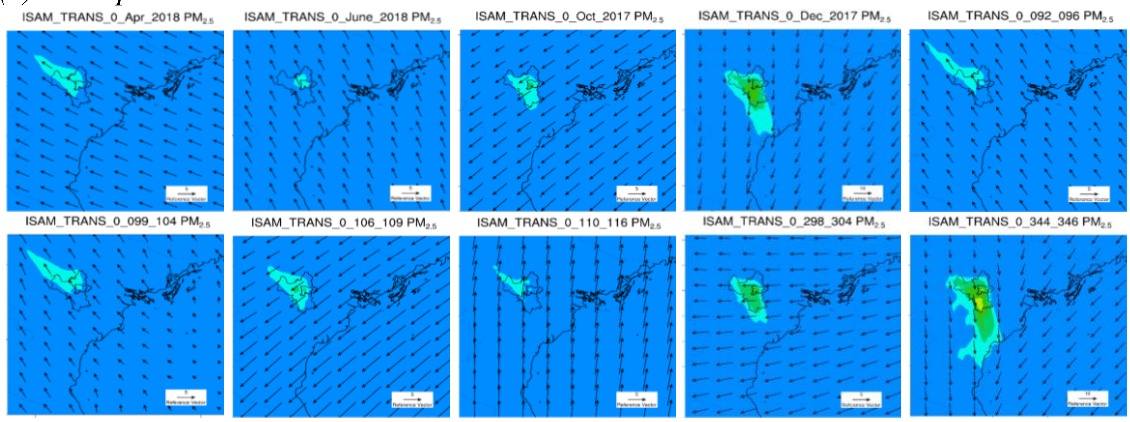
(f) Residential and commercial activities inside Hanoi



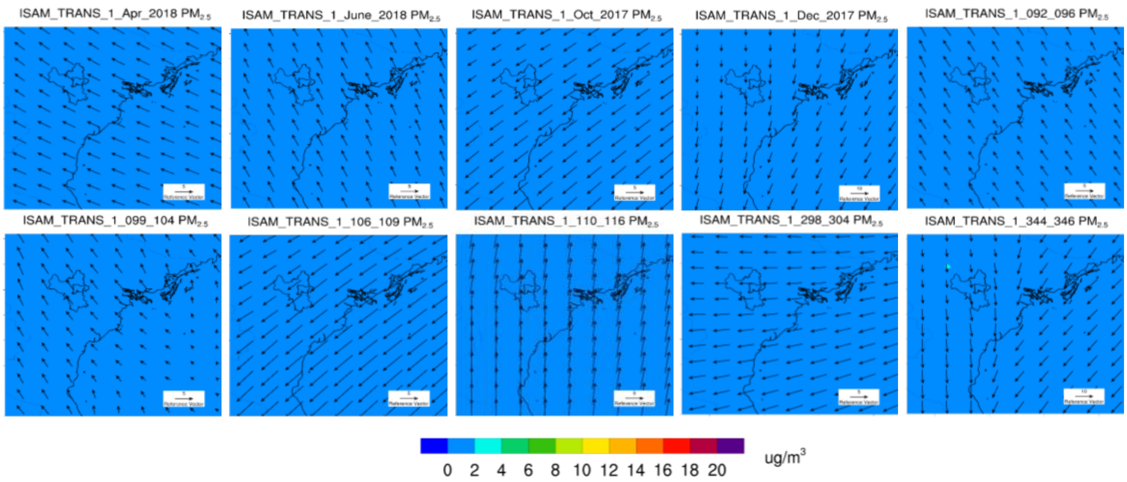
(g) Residential and commercial activities outside Hanoi



(h) Transport inside Hanoi



(i) Transport outside Hanoi



(j) Power plants

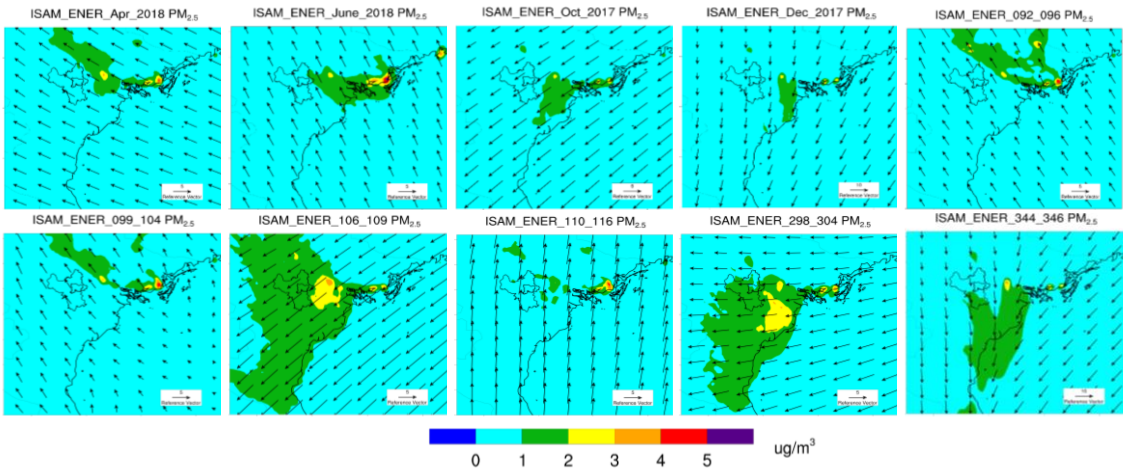


Figure 4.8: Spatial distribution of the contribution of BCON and other source sectors in d03. The four maps from the left of the top row in each figure are the monthly contributions during the four selected months (April, June, October, and December, from right to left), and the others are the contributions during six selected periods The scale bars for the sectors other than BCON and power plants are the same as that shown for the transport outside of Hanoi.

4.3. Future simulations of $PM_{2.5}$ in Hanoi to evaluate the effectiveness of the action plans by the government

In Chapter 2, the future emissions in Hanoi were estimated according to the governmental action plan and future scenarios. In April 2030, the emissions of all species were predicted to increase in both the urban and rural areas in Hanoi. One of the main reasons for this increase is the increase in the number of on-road vehicles in Hanoi. Therefore, the emissions of air pollutants were predicted to increase more in the urban areas than in the rural areas in Hanoi. The increase in the emissions of NO_x and NMVOC is particularly large in April. In December, a large increase in the emissions of air pollutants can be observed for the urban areas due to the increase in on-road transport vehicles. This impact was inflected in the increase in the emissions of NO_x and NMVOC, with substantial emissions by on-road vehicles. However, the increase in the emissions of NO_x and NMVOC can be observed not only in the urban areas but also over the entire area due to the combined impact of the increase in on-road transport and cooking activities in April and December. However, in June and October, the emissions of primary $PM_{2.5}$ and NH_3 were predicted to decrease. This can be attributed to the complete prohibition of crop residue burning in Hanoi from Directive 15/CT-UBND. Furthermore, switching from coal to LPG for cooking and stopping the use of combustion fuel for water heating were also a joint cause of this decrease in emissions in Hanoi's rural areas. However, the emissions of $PM_{2.5}$ and NH_3 in urban areas were predicted to increase, mainly due to the increase in the number of on-road vehicles. The emissions of NO_x and NMVOC were predicted to increase in the centre part of Hanoi and its surrounding areas. In some rural areas of the city, the emissions of NMVOC were predicted to decrease. The emissions of SO_2 were predicted to increase in Hanoi's urban area during all four seasons, meaning that the main contributor was on-road transport vehicles. Similarly, the emissions of all the pollutants were predicted to increase at the waste burning sites located northeast of Hanoi due to the increase in population in 2030.

The CMAQ system was used to evaluate how these changes in emissions will affect the $PM_{2.5}$ concentrations in Hanoi in the future. Although the future emissions were estimated for 2025 and 2030, the CMAQ model was used to run the future simulations for the year 2030 only. In addition, as mentioned earlier, the main purpose of the future simulation was to evaluate the effectiveness of the action plans and the impact of the future scenarios; therefore, the results of the WRF model were not changed, which means only the impact from emission changes in the future was estimated. The emissions changes of the four selected sectors, including on-road transport, MSW burning, domestic and commercial cooking, were considered. In addition, the emissions from crop residue burning and water heating were completely removed from the CMAQ simulations. Other emission sources, such as FINN or MEGAN, were kept the same as the base-case simulations. The future simulations were carried out for d03 only, with the ICON and BCON extracted from the base-case simulation because the future emission changes only in Hanoi were the target of these simulations. Similar to the ISAM simulations, April, June, October, and December were selected for the future simulations. Figures A5 to A8 illustrate the difference between the emissions of primary $PM_{2.5}$ and its precursor gases in 2017/2018 and 2030 in d03.

Figure 4.9 provides the spatial distributions of the total $PM_{2.5}$ concentrations. In April and December, the concentrations of total $PM_{2.5}$ were found to increase in both Hanoi's urban and rural areas, these increases, along with the impact of WS and WD, may affect the surrounding areas. In contrast, in June and October, the concentrations of $PM_{2.5}$ in Hanoi were found to increase in the city centre but decreased in the rural areas and part of the urban areas (Figure 4–9), except for the locations of the solid waste incinerators, where the concentrations of $PM_{2.5}$ were found to increase.

Figure 4.10 demonstrates the change in the monthly mean concentrations of different $PM_{2.5}$ species from the present (2017/18) to the future (2030) for the selected four months, averaged separately over the urban and rural areas in Hanoi. This figure indicates that some main components of $PM_{2.5}$, such as primary organic carbon (POC), will decrease in the urban area by 1.0 and 0.4 μg/m^3 and in the rural area by 1.6 and 1.0 μg/m^3 in June and October, respectively, while the same components were predicted to increase by 0.1 and 0.4 μg/m^3 in the rural area and 0.2 and 0.5 μg/m^3 in the urban area in April and December, respectively. The reduction in the concentrations of POC in June and October could be mainly because of the complete removal of crop residue burning in Hanoi. In addition, the transition from coal to LPG for cooking, as well as the increase in the ownership of electric water heaters, will also help to reduce the emissions of primary $PM_{2.5}$ and its precursors. Furthermore, the concentrations of the primary unspeciated fine particles (OTHR) were also decreased in 2030 in June and October. As the rural population mainly accounts for crop residue burning, cooking using coal, and heating water with combustion fuels, the reduction in the $PM_{2.5}$ concentrations in 2030 predominantly occurred in Hanoi's rural areas. In contrast, the concentrations of primary elemental carbon (PEC) were found to increase in the centre part of Hanoi (urban areas), particularly in April and December, primarily due to the increase in the total number of on-road vehicles, such as trucks and buses. The PEC concentrations were predicted to decrease by 0.2 μg/m^3 in the rural areas and increase by 0.06 μg/m^3 in the urban areas in June. The PEC concentrations in October were predicted to increase by 0.4 and 0.02 μg/m^3 in Hanoi's urban and rural areas, respectively. In the urban areas of Hanoi, the concentrations of PEC, POC, and OTHR were predicted to increase by 0.3, 0.2, and 0.1 μg/m^3 in April, respectively, and by 0.8, 0.5, and 0.5 μg/m^3 in December, respectively. The increases in the concentrations of the same species in rural areas in the same months were 0.2, 0.1, and 0.07 in April, respectively, and by 0.5, 0.4, and 0.4 μg/m^3 in December, respectively. These results imply that completely removing crop residue burning and switching from coal to cleaner combustion fuels could help to improve the air quality in Hanoi, particularly in June and October (Summer and Fall). However, the results also indicated that on-road transport is and will remain a major source of $PM_{2.5}$ in Hanoi, especially in urban areas. Additionally, the future predicted emissions for June 2030 demonstrated that there will be an increase in the emissions of primary $PM_{2.5}$ and its precursor gases in Hanoi's urban areas, the concentrations of $PM_{2.5}$ were predicted to decrease. This could be because of the impact of meteorology, which affects the concentrations of $PM_{2.5}$. The action plans on crop residue burning and switching from coal to LPG for cooking proposed by the government will help to reduce the concentrations of $PM_{2.5}$ in Hanoi’s rural and urban areas in June and October (Summer and Fall). However, in April and December, the concentrations of $PM_{2.5}$ were found to increase, which is partly because of the increase in the number of on-road vehicles. Therefore, the government of Vietnam should continue focusing on policies for reducing the emissions of this sector in Hanoi in the future.

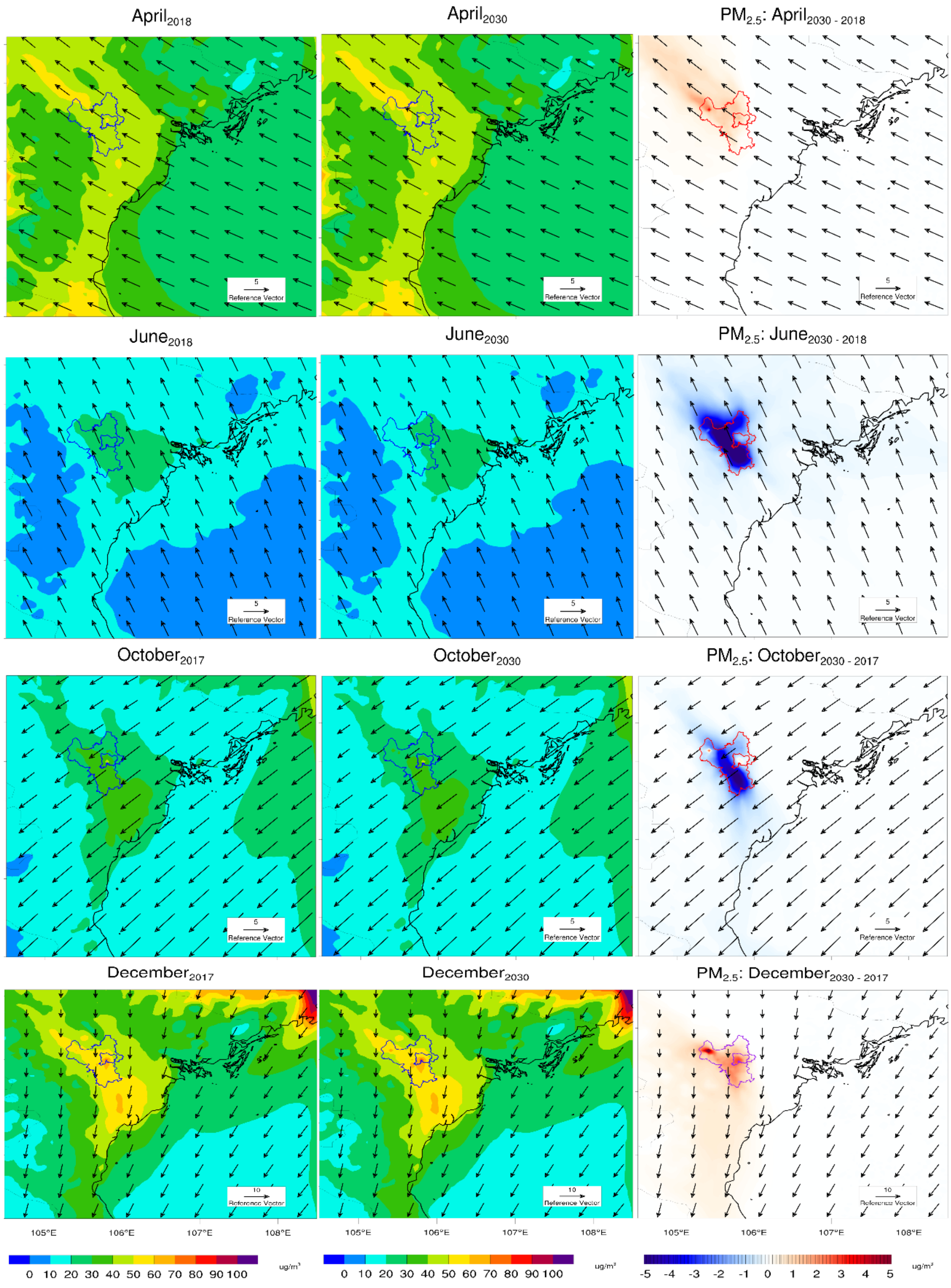


Figure 4.9: Spatial distributions of total $PM_{2.5}$ concentrations in d03 in April, June, October, and December (from top to bottom) in 2018/2017 (left) and 2030 (middle), and the difference between the two (right).

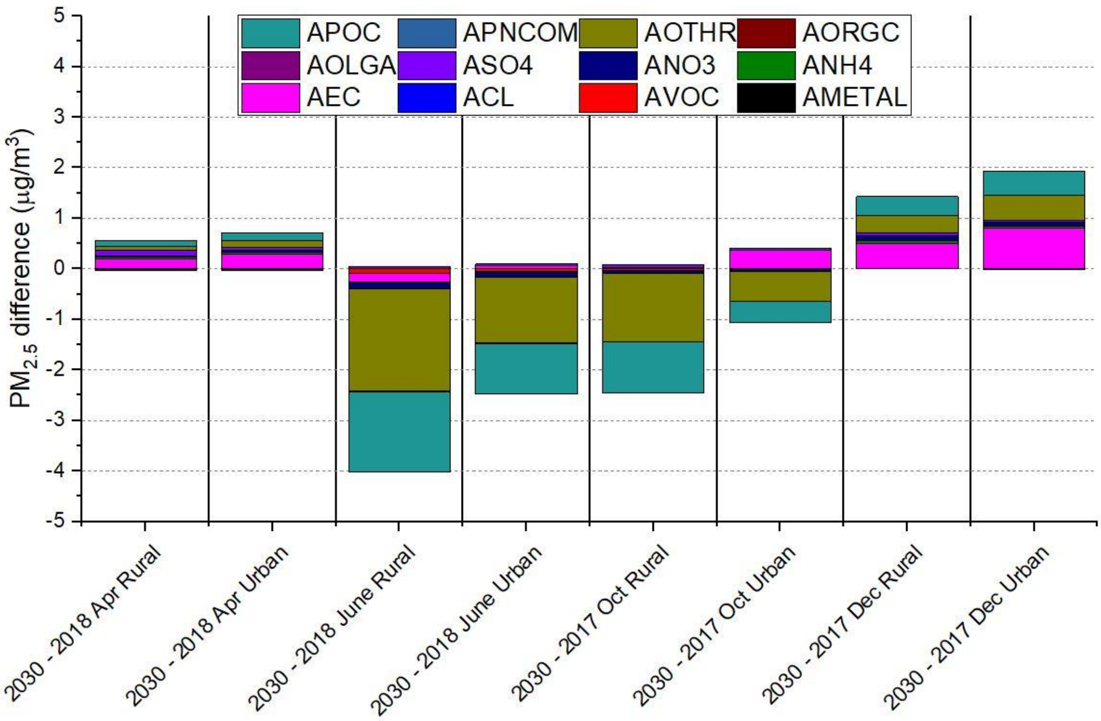


Figure 4.10: Changes in $PM_{2.5}$ components in April, June, October, and December between 2017/2018 and 2030.

4.4. Summary

In this chapter, a yearlong simulation of $PM_{2.5}$ in Hanoi from 1st July 2017 to 30th June 2018 performed by the WRF-CMAQ system is presented. Three nested domains were used with the horizontal resolutions of 36 × 36 km (d01), 12 × 12 km (d02), and 4 × 4 km (d03), respectively: The innermost domain (d03) includes the entire Hanoi area. The input emissions data of air pollutants for the CMAQ simulation include the self-developed emission inventory for Hanoi, EDGARv5.0, FINNv1.5, and MEGANv2.1. The boundary (BCON) and initial (ICON) conditions for d01 were obtained from the MOZART model and those for d02 and d03 were created from its parent domain. The model simulations were validated against the observational data collected from weather and air quality monitoring stations located in Hanoi. The results indicated that WRF reproduced T_2, RH_2, WS, and WD relatively well when considering the entire simulation period. However, WRF performed poorly on T_2 in January and September. In terms of RH_2, WRF well-reproduced the temporal variations of RH_2 but underestimated the actual values. One of the possible reasons could be the impact of urban land, which tends to reduce the water vapour mixing ratio (Q_2). Although urban land with a roughness length of 1.0 was used to represent the drag on the wind by tall buildings in Hanoi, the WS simulated using WRF was still overestimated compared with the observed WS, meaning that the urban land use with a roughness length of 1.0 was still insufficient to represent the urban topography of Hanoi. The temporal and the magnitude of WD were reproduced rather well by WRF. Although the CMAQ model occasionally overestimated the observed $PM_{2.5}$ concentrations, overall, it still reproduced the $PM_{2.5}$ concentration well in Hanoi during the simulation period, not only for the temporal variations but also the level of $PM_{2.5}$ concentrations. The CMAQ results indicated that $PM_{2.5}$ concentrations in Hanoi in winter tend to be higher than those in summer.

CMAQ-ISAM was used to estimate the relative contributions of BCON, ICON, and emission sectors to the total concentrations of $PM_{2.5}$ in Hanoi (i.e. the source apportionment of $PM_{2.5}$ in Hanoi) in April, June, October, and December. The results for these four months showed that BCON was the largest contributor of $PM_{2.5}$, contributing approximately 24–60%, depending on the season. The agricultural sector was also a major source of $PM_{2.5}$, contributing approximately 7–28% during the four selected months. The $PM_{2.5}$ concentrations caused by the agricultural sector were higher in June and October than in April and December, implying the importance of the emissions from crop residue burning. In April and December, industrial facilities were also a major source of $PM_{2.5}$, contributing approximately 15–24% to total $PM_{2.5}$ concentrations. On-road vehicles emissions inside Hanoi were found to have larger contributions than those outside Hanoi, and the combined contribution of the transport sector inside and outside of Hanoi was approximately 6–10%. The residential and commercial activities contributed approximately 8–11% to the concentrations of $PM_{2.5}$ in Hanoi.

Future predictions of the concentration of $PM_{2.5}$ in Hanoi were carried out considering the changes in the emissions from on-road transport, domestic and commercial activities, MSW, crop residue burning, and water heating in 2030 estimated in Chapter 3. The emissions of other sectors, FINN, and MEGAN were kept the same as the base-case simulation. The future simulations were carried out for April, June, October, and December. The results indicated that some main components of $PM_{2.5}$ such as primary organic carbon (POC) and unspeciated fine particles (OTHR) will decrease in June and October, while the same components were predicted to increase in April and December. The PEC concentrations were predicted to decrease in Hanoi's rural areas but those in the urban areas were predicted to increase in June. The PEC concentrations were predicted to increase in both the urban and rural areas in October. The effectiveness of the governmental action plans and projections on the air quality in Hanoi has been evaluated using the WRF-CMAQ system. The results clearly demonstrated that the action plans on crop residue burning and switching from coal to LPG for cooking would help to reduce the fine particulate air pollution in Hanoi. However, on-road vehicles will remain a notable source of air pollution in the future, and the government should continue making efforts to reduce the air pollutants coming from this source.

Chapter 5: Conclusions

5.1. Development of a high-resolution emission inventory for Hanoi

In this study, a high-resolution emission inventory for recent years (2017 and 2018) was developed for Hanoi. The sectors considered were agriculture (crop residue burning, livestock, fertiliser application), transport (on-road hot, cold, and evaporative emissions, domestic shipping), residential activities (domestic cooking, water heating, and MSW burning), commercial activities (hotels and restaurants), industrial activities (combustion and non-combustion processes), solvent usage, gas stations, and coal-fired power plants located outside Hanoi. The horizontal resolution of the emission dataset was 1 km × 1 km.

In Hanoi, industry, transport, and agriculture (crop residue burning) were the three main emission sources of $PM_{2.5}$, contributing 35.2%, 32.1%, and 21.8% to the annual total emissions of $PM_{2.5}$, respectively. Transport was the predominant source of BC (46.6%), followed by crop residue burning (30%) and the industrial sector (15.6%). Transport and crop residue burning were the key sources of OC, contributing 42.3% and 23.8%. Transport and industry were the two main sources of NO_x, contributing 72.5% and 25.2%, respectively. The industrial and transport sectors were also the main sources of SO_2, contributing 65.0% and 32.5%, respectively. The NMVOC emissions were predominantly contributed by transport (52.1%) and solvent use (35.2%). As expected, agriculture was the dominant source of NH_3 and CH_4 emissions, contributing 84.2% and 76.6%, respectively. In contrast, the transport sector was the primary emitter of CO, contributing 72.5%, followed by crop residue burning (20.0%). The coal-fired power plants located near Hanoi emitted 82.5 Gg NOx and 41.6 Gg SO2, respectively, which were far larger than the emissions of those species within Hanoi (The coal-fired power plants considered in this study accounted for 59.3% and 68.5% of the total emissions of these two species, considering the entire emission inventory.

5.2. Development of future emissions inventory for selected sectors for Hanoi for 2025 and 2030

Predictions of future emissions from the transport sector, crop residue burning, and domestic activities were conducted for 2025 and 2030, taking into consideration the future socioeconomic scenarios proposed by Vietnam and local governments. These enable us to evaluate the likely changes in emissions in Hanoi for 2025 and 2030. For on-road transport, the emissions of the pollutants were predicted to increase by 23.1% (NO_x) to 120% (NH_3) in 2025 and by 26.9% (CH_4) to 245.8% (NH_3) in 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% in 2025 and 2030, respectively, and the emission of NMVOC will increase by 31.1% to 40.0% in 2025 and 2030, respectively. However, the emissions of other species will decrease by 3.0% (NH_3) – 59.3% ($PM_{2.5}$) in 2025 and by 10.5% (NH_3) – 60.3% ($PM_{2.5}$) in 2030, respectively. Regarding MSW burning, the emissions of pollutants were predicted to increase by 33.3% (BC) – 53.8% (NO_x) in 2025 and by 66.6% (BC) – 100% (NO_x, SO_2, and NH_3) in 2030. Finally, for the agricultural sector, by banning crop residue burning on the fields, the amount of pollutants prevented from entry into the atmosphere will range from 0.24 Gg (SO_2) to 120.8 Gg (CO) in 2025 and 0.27 Gg (SO_2) to 138.4 Gg (CO) in 2030, respectively.

5.3. Base case simulation of meteorology and $PM_{2.5}$ in Hanoi

WRFv3.8 and CMAQv5.0.2 were used to simulate the meteorology and $PM_{2.5}$ concentrations in Hanoi. The triple nested domain was used with the outer-most domain (d01) covering all of Vietnam, most of the neighbouring countries, and the southern part of China. The second domain (d02) covers the northern part of Vietnam, and the third domain (d03) covers all of Hanoi. The horizontal resolution of these three domains were 36 km, 12 km, and 4 km, respectively. The base-case CMAQ simulation was conducted from 28 June 2017 to 30 June 2018, with the first 3 days serving as the spin-up time. Overall, WRF performed quite well for the meteorology in terms of temporal variations; however, it overestimated the WS throughout the simulation period, despite the use of urban land use, meaning that using the urban land cover with the roughness length Z_0 = 1 was not sufficient to represent the characteristics of the tall buildings in the city. WRF well simulated the temporal variations of the WD throughout the year. The CMAQ model reproduces the concentrations of $PM_{2.5}$ in Hanoi well in terms of both the temporal variations and concentration magnitude.

5.4. Source apportionment of $PM_{2.5}$ in Hanoi

The ISAM system was used to evaluate the relative contribution of the BCON and emission sources to the total concentrations of $PM_{2.5}$ in four selected months: April, June, October, and December. The sectors considered include agriculture, residential and commercial activities inside and outside Hanoi, the transport sector inside and outside Hanoi, industrial activities inside and outside Hanoi, and other sectors. Due to the high computational resource requirement, the ISAM simulations were run for the innermost domain (d03). BCON injected from the outskirts of the simulation domain (d02) were found to be the largest source of $PM_{2.5}$ in Hanoi, contributing 59.6%, 24%, 35.3%, and 49.2%, respectively. The agricultural sector, especially crop residue burning, was also a major source of $PM_{2.5}$, contributing 6.5%, 27.8%, 18.8%, and 9.5%, respectively, in the four selected months. In April and December, industrial facilities were also a major cause of $PM_{2.5}$, contributing 15.4%, 23.6%, 23.4, and 19.9% to the $PM_{2.5}$ concentrations. On-road vehicles in Hanoi were found to contribute more than those outside Hanoi (**Figure 4.6**). Together, the transport sector contributed 5.8%, 8.7%, 9.7%, and 10.1%, respectively. The residential and commercial activities contributed 8%, 10.8%, 10.3%, 9.2%, respectively, to the concentrations of $PM_{2.5}$ in Hanoi. Coal-fired power plants and FINN emissions had a small impact on the air quality in Hanoi. The contributions of the coal-fired power plants were 1.5%, 1.9%, 2%, and 0.9%, respectively and the contributions of FINN were 2.5%, 1%, 0.2%, and 0.9%, respectively.

5.5. Future prediction of $PM_{2.5}$ in Hanoi in 2030

To control the air pollution in Hanoi, the Vietnamese and local governments will need to determine various countermeasures in the future. This study attempted to evaluate the effectiveness of these countermeasures, as well as the changes in population and vehicle number, to the air quality in Hanoi in 2030. For that purpose, the WRF results were kept the same as the base-case simulations, indicating that the impact of future climate change is not the focus of this study.

The results of the future simulations indicate that some of the main components of $PM_{2.5}$, such as POC and AOTHR, will decrease significantly in June and October but slightly increase in April and December in both Hanoi's urban and rural areas. In general, these changes in POC and OTHR were predicted to be larger in the rural than in the urban areas. Because the main drivers of these changes (i.e. crop residue burning, cooking using coals, and heating water with combustion fuels) were more pervasive in rural areas than in urban areas, the concentrations of PEC were predicted to increase in almost all the selected months in both the urban and rural areas, except in the rural areas in June. This increase in PEC was primarily due to the increase in the total number of on-road vehicles, such as trucks and buses, by 2030.

5.6. Implications of the study and directions for future studies

Firstly, the purpose of developing a high-resolution emission inventory for Hanoi is to provide researchers with a reliable source of data, which can be used for simulations of atmospheric pollution. The emission inventory itself is also a good indicator of the main sources of air pollutants in Hanoi. As demonstrated in Section 5.1, industry, agriculture, and transport are the three main emission sectors of primary $PM_{2.5}$ and precursor gases. The Vietnamese and local governments have taken necessary actions to control the air pollution in Hanoi. For example, Directive 15/CT-UBND, which enforces the ban of crop residue burning in Hanoi, indicates that a significant amount of air pollutants will be prevented from entering the atmosphere, assuming that the locals comply completely with the directive. In contrast, 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. Therefore, in addition to enforcing the higher EURO standards 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. As for MSW burning, cleaner waste management methods should be considered to replace waste burning methods to reduce the emissions from this source.

Although this study has included all the major sources of emissions in Hanoi. Several minor emission sources were ignored due to a lack of activity data, including cremation, aviation, crop cultivation, and particulate matter resuspension. Ignoring these sources may lead to the underestimation of actual total emissions in Hanoi; therefore, future studies should consider including these sources. Furthermore, the results of this study can be the first step in developing a comprehensive long-term high-resolution emission inventory for Vietnam.

The EFs used in this study were collected from various sources, ranging from international studies to local studies. Some of the EFs used in this study did not necessarily represent the actual situation of Vietnam or Hanoi. Therefore, using such EFs could definitively lead to some uncertainties. Researchers should attempt to develop a local database for EFs for Vietnam and Hanoi, which can then help to improve the quality of the local emission inventories.

In this study, the WRF-CMAQ-ISAM system was applied to simulate the concentrations of $PM_{2.5}$ in Hanoi in recent years. The results of the CMAQ base-case simulations could be used to support studies on human health (e.g. using BenMAP) and policy-making decisions (e.g. where to build a new power plant or industrial facility). In addition, the key air pollutant of interest in this study was total $PM_{2.5}$. However, other pollutants, such as ozone, also cause damage to human health or crops. Due to a lack of observational data on ozone in Vietnam and Hanoi, this study could not evaluate such damage. The Vietnamese government should monitor the ozone concentrations to support modelling studies as well as identify the proper solutions for ozone pollution in the future.

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Appendices

Research Center for Environmental Monitoring and Modeling

No: ……../CEMM/2019

SOCIALIST REPUBLIC OF VIETNAM
Independence – Freedom – Happiness

Date:………………October 2019

QUESTIONNAIRE ON FUEL CONSUMPTION IN HOUSEHOLDS IN HANOI

I. Household information:

1. Name of the respondent: ....

2. Address: ....

....

3. Cellphone : ....

4. Number of people in the household: ....

II. Information on daily fuel used:

1. Period of use

Morning: ......h...... - ......h...... Afternoon:......h...... - ......h..... Evening : ......h...... - ......h......

=> Estimated period of use: .... h/day*

2. Purpose of use:

☐ Cooking ☐ Others:

☐ Water heating

Fuel type	Amount of fuel used (estimated)
☐ Gas	☐ 1 cylinder / month ☐ 3 cylinders / 2 months ☐ 2 cylinders / month ☐ Others : .... cylinder / .... month ☐ 3 cylinders / month Net wt / 1 cylinder: .... kg => Amount of fuel used: .... kilogram/day*
☐ Coal	☐ .... kilogram / .... day ☐ .... kilogram / .... week ☐ .... kilogram / .... month
☐ Firewood	.... kilogram/day
☐ Straw	.... kilogram/day
☐ Kerosene	.... kilogram/day
☐ Others	.... kilogram/day

* This value was calculated by the interviewer

Equation A1: Formula used for calculating sample size

$$n_o = \frac{Z^2pq}{e^2} \text{ Cochran (1963:75)}$$

$$n = \frac{n_o}{1+\frac{(n_o-1)}{N}} \text{ Grenn (2003)}$$

where:
n_o : sample size for large population
z : z-score (z = 1.65)
p : estimated proportion of an attribute that is present in the population (p = 0.5 for maximum variability)
q : 1 - p
e : margin of error (e = 0.05)
n : sample size for small population
N : population size（7661000）

Equation A2: Formulas to estimate monthly variation for emissions from livestock

$$L(t) = \frac{T(t)^{0.89} * V(t)^{0.26}}{\sum_{t=1}^{n} T(t)^{0.89} * V(t)^{0.26}}$$

where T(t) and V(t) are temperature (°C) air velocity or wind speed (m/s), respectively.

Equation S3: Formulas to estimate monthly variation for NH_3 emissions from fertilizer application:

$$M(t) = \frac{e^{0.0223*T(t)} * e^{0.0419*W(t)}}{\sum_{t=1}^{n} e^{0.0223*T(t)} * e^{0.0419*W(t)}}$$

where T(t) and W(t) are temperature (°C) and wind speed (m/s) for month (t), respectively.

Figure A1: Spatial distribution of total $PM_{2.5}$ in Hanoi according to REASv3.2 (Left) and EDGARv5.0 (Right)

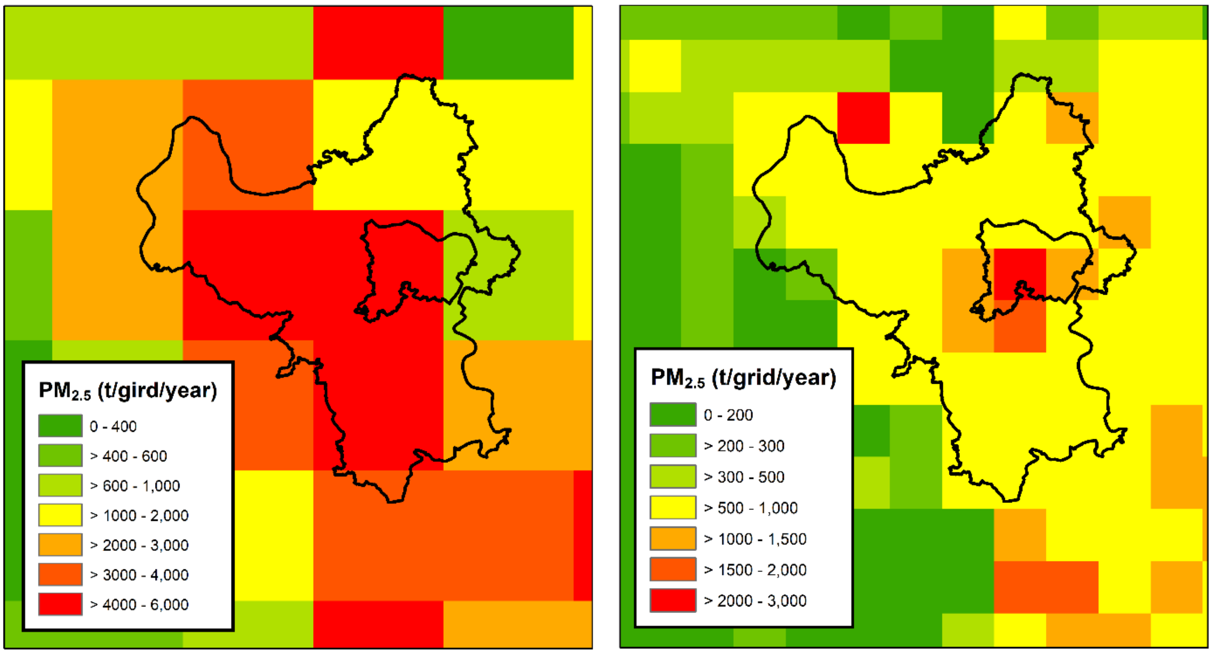


Figure A2: Water temperature profiles used for calculating emissions from water heating (adapted from Otani et al. (2015))

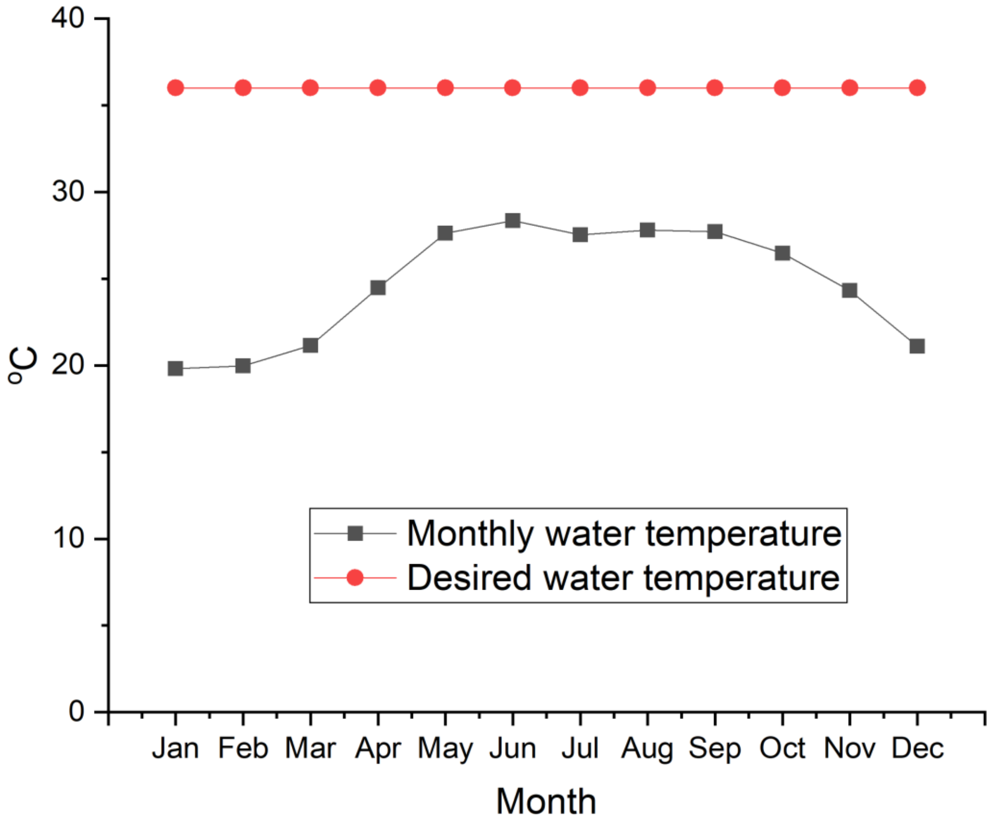


Figure A3: Monthly profiles of industrial subsectors

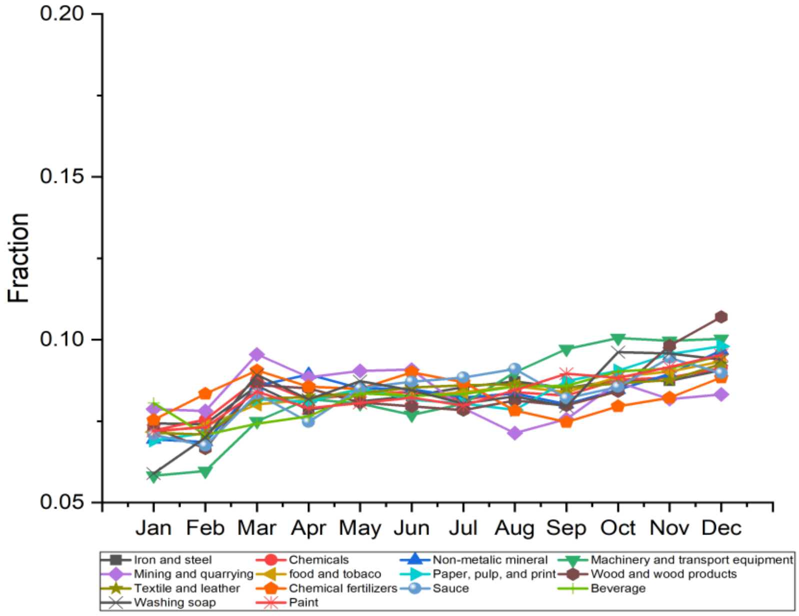
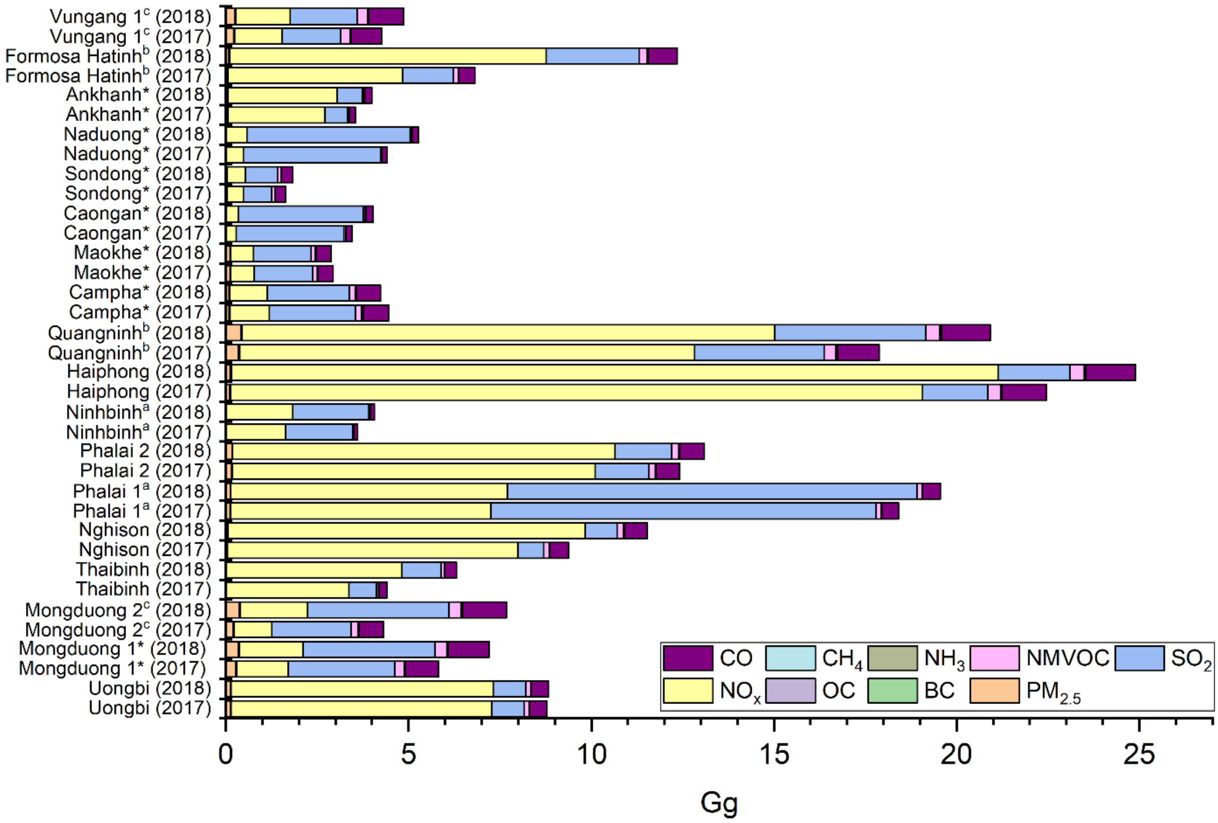


Figure A4: Emissions from each power plant in 2017 and 2018. *The power plants which use CFB. [a]No emission control devices for SO_2. [b]Low-NO_x burners equipped. [c]SCR equipped.



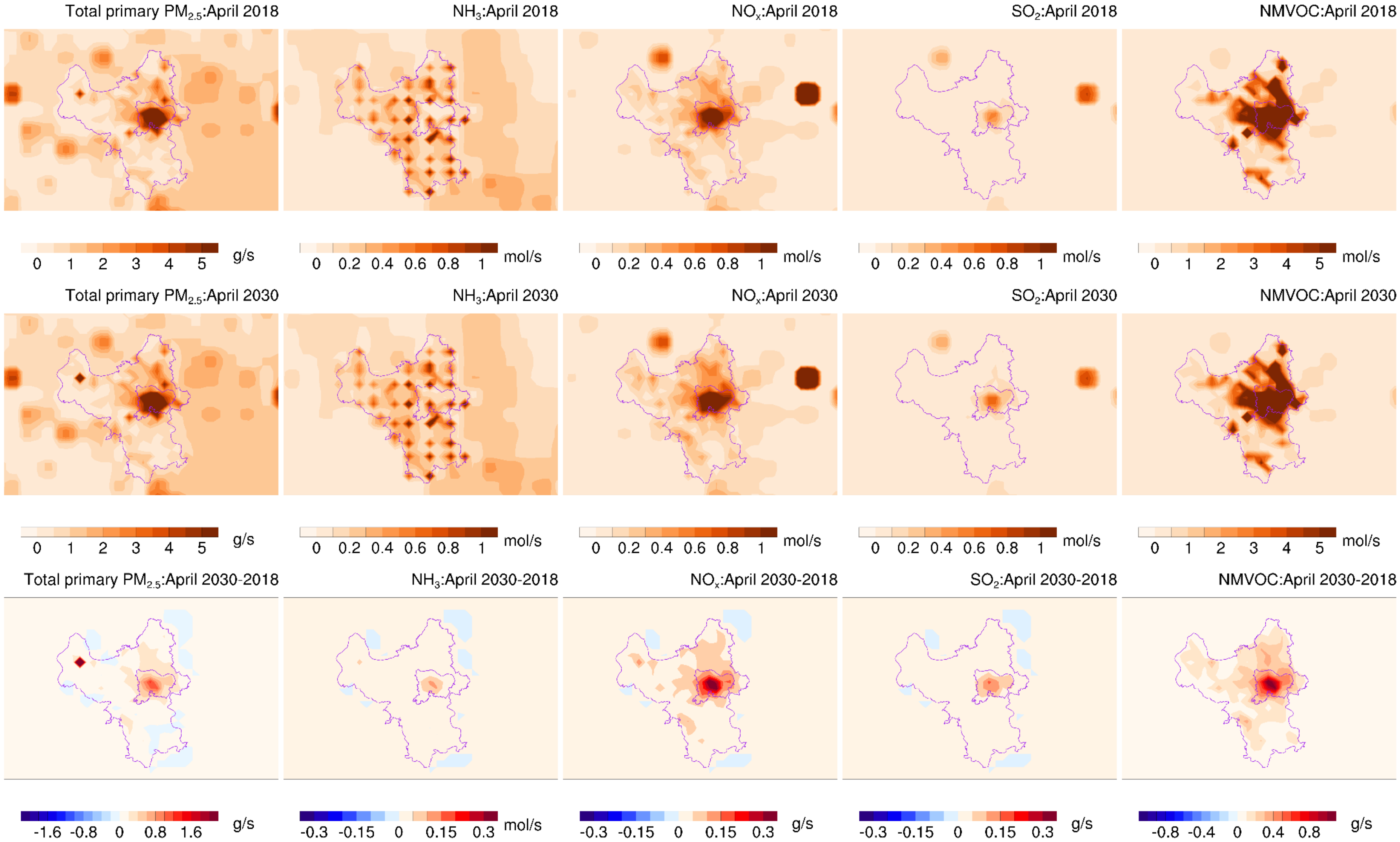


Figure A5: The emissions of total primary $PM_{2.5}$, NH_3, NO_x, SO_2, and NMVOC in April 2018 and April 2030 and the difference between these emissions in d03.

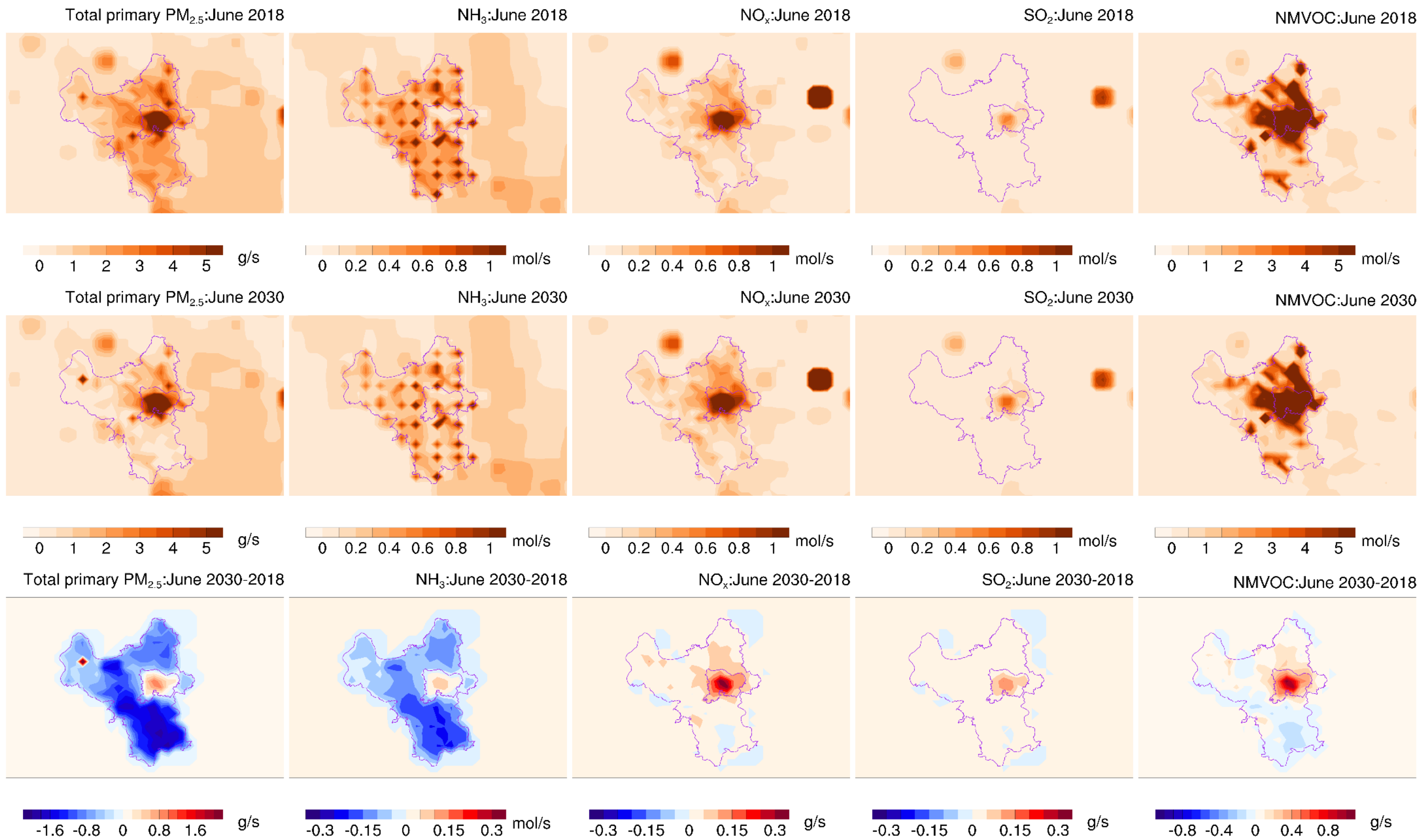


Figure A6: Same as figure A5 but for June 2018 and June 2030

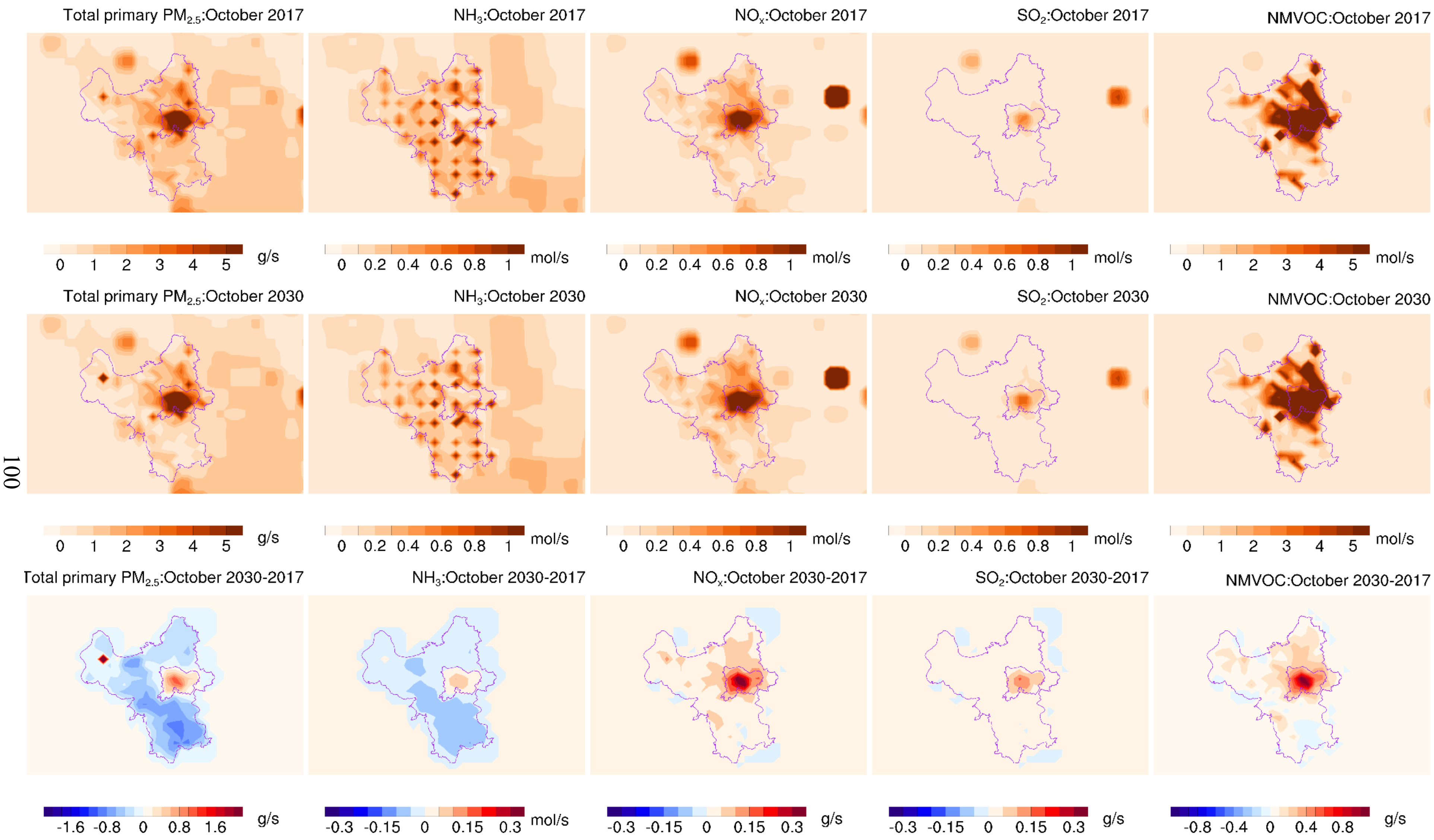


Figure A7: Same as figure A5 but for October 2017 and October 2030

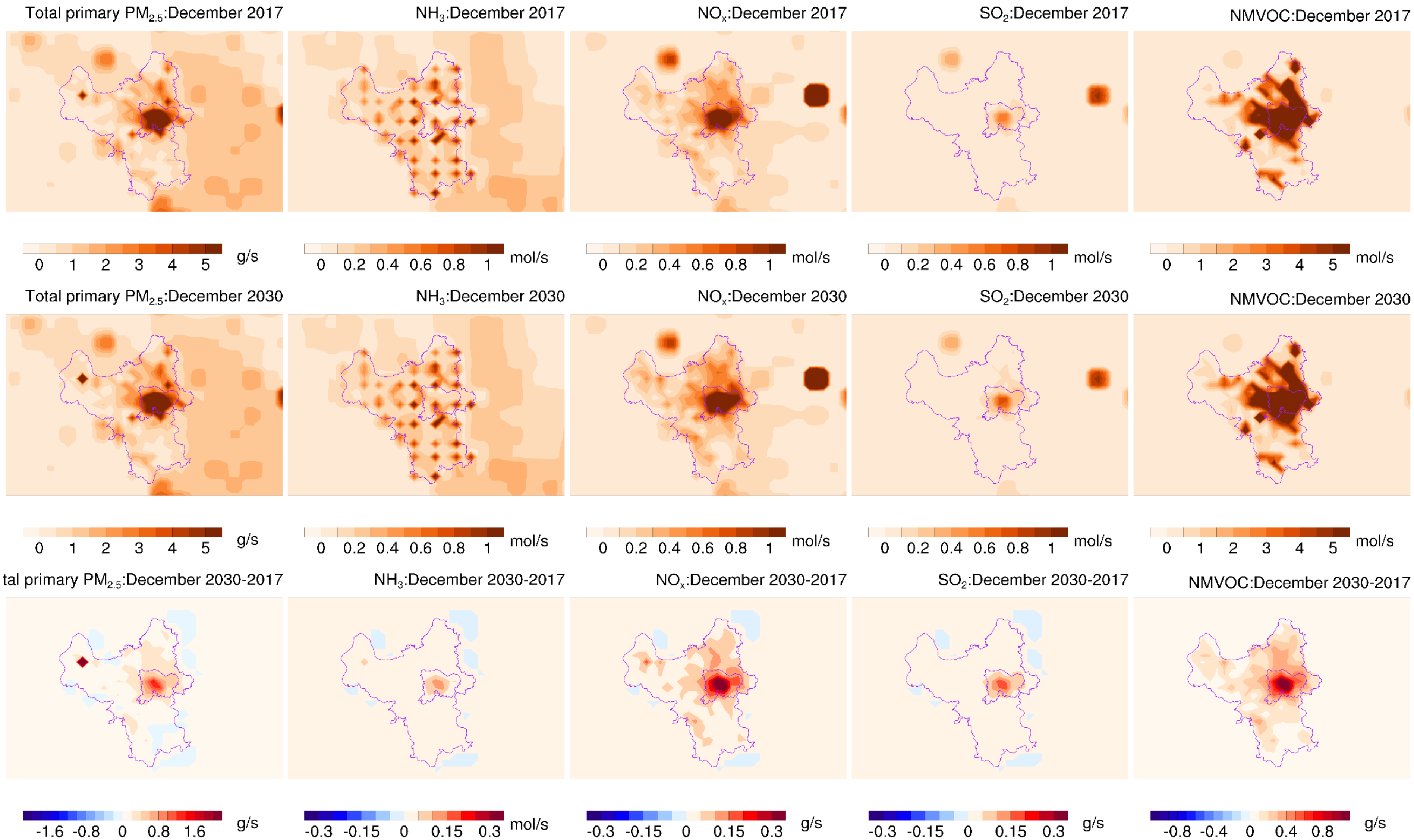


Figure A8: Same as figure A5 but for December 2017 and December 2030

Table A1: Summary on the formulas and activity data used for emission estimation.

Sector	Sub-sector	Equation
Transport	Hot emission	$\boldsymbol{Em_{HOT,i,j} = \sum_T NV_j \times ATD_j \times E_{HOT,i,j}}$ $\boldsymbol{(A6)}$ (Kurokawa and Ohara, 2020) where $Em_{HOT,i,j}$ is the hot emission of pollutant i from vehicle type j, NV_j is the actual total number of active vehicles of type j, and ATD_j is the annual travelled distance of vehicle type j in Hanoi. $E_{HOT,i,j}$ is the hot emission factor (EF).
	Cold emission	$\boldsymbol{Em_{COLD,i,j} = \sum_T NV_j \times ATD_j \times E_{HOT,i,j} \times \beta_i \times \left(\frac{E_{COLD}}{E_{HOT}}\middle\| i-1\right)}$ $\boldsymbol{(A7)}$ (EEA, 2019) where $Em_{COLD,i,j}$ is the cold emissions of pollutant i from vehicle type j; E_{HOT}, NV_j and, ATD_j are the same as those of Equation 6. β_i is the fraction of mileage driven with a cold engine or the catalyst operated below the light-off temperature for pollutant i. $E_{COLD}/E_{HOT}\|i$ is the cold/hot emission quotient for pollutant i.
	Tyre wear, brake wear, road wear emission	$\boldsymbol{Em_{WEAR,i,j} = \sum NV_j \times ATD_j \times E_{i,j}}$ $\boldsymbol{(A8)}$ (EEA, 2019) where $Em_{WEAR,I,j}$ is the emissions of $PM_{2.5}$ from tyre wear, brake wear, and road wear. NV_j and, ATD_j are the same as those of $Em_{HOT,i,j}$ and $E_{i,j}$ is the EF for pollutant i of vehicle type j.
	Evaporation emission	$\boldsymbol{Em_{NMVOC,i,j} = \sum NV_j \times E_{NMVOCj} \times 365}$ $\boldsymbol{(A9)}$ (EEA, 2019) where $Em_{NMVOC,i,j}$ is the emissions from gasoline evaporation, NV_j is the same as in equation 1 and E_{NMVOCj} is the temperature-dependent EF of NMVOC for vehicle type j.
	Domestic shipping	The following emission was used to estimate the emissions from domestic shipping in Hanoi. $\boldsymbol{Em_j = \sum A_j \times E_j}$ $\boldsymbol{(A10)}$ (Shrestha et al., 2012) where Em_j is the emission fuel type j (g), E_j is the emission factor, and A_j is the activity data which is the shipping fuel consumption/sold.
Agriculture	Livestock and fertilizer application	$\boldsymbol{Em_{i,j} = \sum Na_i \times E_{i,j}}$ $\boldsymbol{(A11)}$ (Shrestha et al., 2012) where $Em_{i,j}$ is the emission of pollutant i (CH_4 and NH_3) and livestock type j, Na_i is the number of animals or amount of fertilizer used, and $E_{i,j}$ is the emission factors
	Crop residue burning	$\boldsymbol{Em_{i,j} = \sum A_j \times E_{i,j}}$ $\boldsymbol{(A12)}$ (Shrestha et al., 2012) where $Em_{i,j}$ is the emission of pollutant i from crop type j, $EF_{i,j}$ is the emission factor (EF) (g/kg of dry matter), and A_j is the activity data which is the amount of burned biomass from crop type j (kg/yr). $\boldsymbol{A_j = P_j \times S_j \times D_j \times B_j \times \eta_j (A13)}$ (Shrestha et al., 2012) where P_j is the seasonal crop production (kg/year). S_j is the crop-specific residue-to-production ratio (fraction). D_j is the dry matter-to-drop residue ratio (fraction). B_j is the fraction of dry matter residue burned in the field and η_j is the crop-specific burn efficiency ratio (fraction).

Table A1 (Cont)

Sector	Sub-sector	Equation
Industry		$$Em_{i,j} = \sum A_j \times E_{i,j} \times (1 - R_{i,j}) \quad (A14)$$ (Kurokawa et al., 2013) where $Em_{i,j}$ is the emission of pollutant i from an industrial facility belonging to subsector j, and A_j is activity data, which represent annual production or annual fuel consumption at each industrial facility. $E_{i,j}$ is the unabated EF from combustion or non-combustion processes, and R is the removal efficiency.
Residential sector	Domestic cooking MSW burning Water heating	$$Em_{i,j} = \sum Pop \times A_j \times E_{i,j} \quad (A15)$$ (Shrestha et al., 2012) where $Em_{i,j}$ is the emission of pollutant i for fuel type j, Pop is the total population in Hanoi, or the percentage of the rural population in Hanoi that relied on combustion fuel for water heating (capita). A_j is activity data, which are the fuel consumption per capita for domestic cooking and water heating (kg). In the case of MSW burning, A_j is the amount of MSW burned (kg), which was calculated using equation S16. $E_{i,j}$ is the EF for the pollutant i of fuel type j. $$A_j = MSW_{GR} \times \varepsilon \times \delta \times \lambda \times \eta \times 365 \quad (A16)$$ (Shrestha et al., 2012) where MSW_{GR} is the per capita MSW generation factor (kg/capita/day), ε is the MSW collection efficiency, δ is the fraction of combustible MSW, λ is the fraction of waste burned relative to the total amount of waste disposed of, and η is the burning/oxidation efficiency.
Commercial sector	Hotels and restaurants	$$Em_{i,j} = \sum A_j \times E_{i,j} \quad (A17)$$ where $Em_{i,j,k}$ is the emission of pollutant i from fuel type j; A_j is the activity data, which is the fuel consumption rate per hotel or restaurant, and $E_{i,j}$ is the EF from fuel type j.
Power plants	Coal-fired power plants	$$Em_{i,j} = \sum A_j \times E_{i,j} \times (1 - R_{i,j}) \quad (A18)$$ where $Em_{i,j}$ is the emission of pollutant i from power plant j, A_j is activity data, that are the energy input or fuel consumption, $E_{i,j}$ is the unabated EF, and R is removal efficiency for pollutant i from power plant j.
Other sectors	Solvents and other products use	$$Em_{NMVOC,i,j} = \sum A_j \times E_{NMVOCj} \quad (A19)$$ where $Em_{i,j}$ is the emission of NMVOC i from subsector j, A_j is activity data, that represent the amount of solvent consumed in total or per capita, $E_{i,j}$ is the EF. For the NMVOC emissions from paint manufacturing,

Table A2: Daily VKT of each vehicle typesin Hanoi in 2017 and projected VKT of each vehicle type in 2018, 2025, and 2030

Vehicle type	2017	2018[1,*]	2025[1,*]	2030[1,*]
Motorcycle	20[1]	22	30	38
Intercity bus	87[2]	79	106	134
Transit bus	348[3]	315	425	539
Taxi	157[4]	159	215	270
Personal car	28[1]	30	41	51
Truck	90[3]	91	123	158

[1] Roy et al. (2021)
[2] Self-calculation
[3] Chung (2017)
[4] Trang et al. (2015)
* The ratio between VKT in 2019, 2025, and 2030 in Roy et al. (2021) were applied to calculate the VKT in 2025 and 2030 from the VKT in 2017 in this study.

Table A3: The number of active vehicles in Hanoi from 2005 to 2018 and projected number of vehicles in Hanoi from 2020 to 2030.

Year	Motorcycles[1]	Intercity bus[1]	Transit bus[1]	Trucks[1]	Passenger cars[1]	Taxis[1]
2005	1585218	8930	1047	25931	38073	6821
2006	1721816	9234	1076	29890	43860	7602
2007	1927453	10880	1106	34659	58866	8383
2008	2270248	12024	1136	41554	80156	9164
2009	2599452	13051	1168	49052	109206	9944
2010	2861632	13443	1199	57055	133591	10725
2011	3184056	14505	1224	63280	161397	13408
2012	3555301	15241	1259	66228	167528	13920
2013	3728608	15385	1318	67905	171464	14103
2014	3881904	16399	1332	74857	189463	15063
2015	4036537	16805	1333	82312	205338	15412
2016	4204196	19435	1391	99072	246844	15412
2017	4386650	22033	1451	116015	273866	16192
2018	4549200	22202	1482	116955	294138	16973
2019	4714309	27974	1843	120347	396437	18486
2020	4879418	33746	2205	123740	498736	20000
2021	5023910	36916	2299	135363	573623	20400
2022	5168402	40085	2394	146985	648511	20800
2023	5312893	43255	2488	158608	723398	21200
2024	5457385	46424	2583	170231	798286	21600
2025	5601877	49594	2677	181853	873173	22000
2026	5682530	53339	2772	195584	943690	22400
2027	5763184	57083	2866	209315	1014206	22800
2028	5843837	60828	2961	223045	1084723	23200
2029	5924490	64573	3055	236776	1155239	23600
2030	6005144	68318	3150	250507	1225756	24000

Note: The number of active vehicles from 2020 to 2030 were projected from the growth rate of active vehicles between 2020, 2025, and 2030. The number of vehicles in 2020, 2025, and 2030 were projected by Hanoi People's Committee, (2017).
The coloured cells show the year of adoption of the different EURO emission standards for on-road vehicles, not the number of vehicles complying with the standards.

Conventional	EURO 1	EURO 2
EURO 3	EURO 4	EURO 5

Table A4: The amount of agricultural production projected for 2025 and 2030.

Crop (Ton)					
Type	**2017**	**2018**	**2020[a]**	**2025[a]**	**2030[a]**
Paddy	1051042	1024584	1114593	1362605	1665802
Maize	94445	83971	91347	111673	136522
Potatoes	33411	28062	30527	37319	45624
Cassava	22911	20951	22791	27862	34062
Sugarcane	2105	1751	1904	2328	2846
Oil crop	22117	12204	13276	16230	19841

[a] Projected from the growth rate of the crop from 2010 to 2018

Table A5: Parameters used for calculating fuel consumption for water heating

Parameters	Value	Units
Density of water	1000	g/l
Heat capacity of water	4.182	J/(K kg)
Monthly water temperature	figure S2	°C
Desired water temperature	36	°C
The volume of water required	30	litre

Table A6: Total fuel consumption for domestic cooking.

Fuel type	Fuel consumption		Unit
	Urban	**Rural**	
LPG	141	63.8	Gg
Coal	16.17	20.5	Gg
Oil	0	41.7	Gg
Firewood	0	41.7	Gg

Table A7: Total fuel consumption at hotels and restaurants

Fuel type	Fuel consumption	Unit
LPG	0.022	Gg
Coal	15.4	Gg
Heavy oil	0.013	Gg
Diesel oil	0.99	Gg

Table A8: Information for each power plant considered in this study in 2017

A	B	C	D	E	F	G	H				
Power plant	Capacity (MW)	Fuel type	Combustion technology	Production (10^6 kwh)[2]	Fuel consumption per unit (g/kWh)[3]	Total fuel consumption (Gg)[2]	Emission control efficiencies (in per cent)[*]				
							$PM_{2.5}$[6]	BC[6]	OC[6]	SO_2[10]	NO_x
Uongbi	765	A	PC	2468	448.9	1108	99[7]	98	96	95[7]	-
Mongduong 1	1080	A	CFB	4756	498.3	2370	99.2	98	96	90	-
Thaibinh	600	A	PC	925	529.7	490	99.9[2]	98	96	89.9[2]	-
Nghison	600	A	PC	2640	436.0	1151	99.8	98	96	95[2]	-
Phalai 1	440	A	PC	1807	614.3	1110	99.2	98	96		-
Phalai 2	600	A	PC	3220	480.1	1546	99.2	98	96	90	-
Ninhbinh	100	A	PC	329	735.6	242	99.7[1]	98	96		-
Haiphong	1200	A	PC	6334	455.8	2887	99.7[7]	98	96	95[1]	-
Quangninh	1200	A	PC	5813	492.5	2863	99.1[2]	98	96	90[2]	30[1]
Campha	660	A	CFB	3013	632.6	1906	99.7[8]	98	96	90[8]	-
Maokhe	440	A	CFB	3007	351.8	1058[4]	99.2	98	96	90	-
Caongan	115	A	CFB	655	674.8	442	99.8[7]	98	96	90	-
Sondong	220	A	CFB	1129	664.3	750	99.8[7]	98	96	95[7]	-
Naduong	110	L	CFB	639	719.9	460	99.8[8]	98	96	90[8]	-
Ankhanh	120	A	CFB	599	824.7	494	99.2	98	96	90	-
Formosa HT	650	B	PC	2360	465.0	1097[4]	99.2	98	96	90[8]	30[9]
Mongduong 2	1240	A	PC	3784	463.8	1755	99.2	98	96	90	90[8]
Vung Ang 1	1200	A	PC	4737	418.8	1984	99.2	98	96	95.1[11]	90[8]
Total				**48215**		**23713.3**					

Table A9: Information for each power plant considered in this study in 2018

A	B	C	D	E	F	G	H				
Power plant	Capacity (MW)	Fuel type	Combustion technology	Production (10^6 kwh)[2]	Fuel consumption per unit (g/kWh)[3]	Total fuel consumption (Gg)[2]	Emission control efficiencies (in per cent)[*]				
							$PM_{2.5}$[6]	BC[6]	OC[6]	SO_2[10]	NO_x
Uongbi	765	A	PC	2370	470.0	1114	99[7]	98	96	95[7]	-
Mongduong 1	1080	A	CFB	5720	512.8	2933	99.2	98	96	90	-
Thaibinh	600	A	PC	2195	319.8	702	99.9[2]	98	96	89.9[2]	-
Nghison	600	A	PC	3221	439.6	1416	99.8	98	96	95[2]	-
Phalai 1	440	A	PC	1974	597.3	1179	99.2	98	96		-
Phalai 2	600	A	PC	3614	451.0	1630	99.2	98	96	90	-
Ninhbinh	100	A	PC	381	716.5	273	99.7[1]	98	96		-
Haiphong	1200	A	PC	6967	459.2	3199	99.7[7]	98	96	95[1]	-
Quangninh	1200	A	PC	6993	479.1	3350	99.1[2]	98	96	90[2]	30[1]
Campha	660	A	CFB	2716	668.3	1815	99.7[8]	98	96	90[8]	-
Maokhe	440	A	CFB	2949	351.8	1038[4]	99.2	98	96	90	-
Caongan	115	A	CFB	791	651.1	515	99.8[7]	98	96	90	-
Sondong	220	A	CFB	1287	655.8	844	99.8[7]	98	96	95[7]	-
Naduong	110	L	CFB	776	707.5	549	99.8[8]	98	96	90[8]	-
Ankhanh	120	A	CFB	749	742.3	556	99.2	98	96	90	-
Formosa HT	650	B	PC	4277	465.0	1989[4]	99.2	98	96	90[8]	30[9]
Mongduong 2	1240	A	PC	6585	474.7	3126	99.2	98	96	90	90[8]
Vungang 1	1200	A	PC	5252	431.5	2266	99.2	98	96	95.1[11]	90[8]
Total				**50826**		**28493.3**					

Notes for tables S8 and S9: A: Anthracite, B: Sub-Bituminous, L: Lignite, PC: Pulverized coal, CFB: circulating fluidized bed

[1] Institute of Energy (2019)

[2] Vietnam Electricity (2020)

[3] F = G/E (Estimated using the actual annual fuel consumption and total electricity production)

[4] G = E×F (Estimated using the fuel consumption per unit of electricity production and total electricity production)

[5] Ministry of Industry and Trade (2019)

[6] Shrestha et al. (2012)

[7] Pollution Control Department (2014)

[8] General Directorate of Energy (2016)

[9] Electricity and Renewable Energy Authority (2016)

[10] Huy and Kim Oanh (2017)

* All power plants are quipped with ESP for PM, BC, and OC emissions control; power plants using PC combustion technology are equipped with FGD, while those using CFB combustion technology use limestone injection for SO_2 emissions control (Except Phalai 1 and Ninhbinh which are not yet applied); Quangninh and Formosa Hatinh are equipped with low-NO_x burners while Mongduong 2 and Vungang 1 are equipped with SRC for NO_x emission control.
"-" No emission control devices equipped

Table A10: Characteristics of coals used by power plants

A	B	C	D	E	F	G
Power plant	Capacity MW)	Combustion techonology	CS_{fuel}[1]	α_s[4]	NCV[1]	A[1]
			%		KJ/kg	%
Uongbi	765	PC	0.85[2]	5	20756.8[2]	27.7[2]
Mongduong 1	1080	CFB	0.65	5	19079.0	37.5
Thaibinh	600	PC	0.8	5	22258.9	29.0
Nghison	600	PC	0.65	5	22258.9	29.0
Phalai 1	440	PC	0.5[2]	5	20710.8[2]	30.3[2]
Phalai 2	600	PC	0.5[2]	5	20710.8[2]	30.3[2]
Ninhbinh	100	PC	0.4[2]	5	21547.6[3]	22.2[3]
Haiphong	1200	PC	0.65[2]	5	21154.3[2]	27.2[2]
Quangninh	1200	PC	0.41[2]	5	20041.4[2]	30.5[2]
Campha	660	CFB	0.65	5	18200.4	42.0
Maokhe	440	CFB	0.8	5	19754.8	33.4
Caongan	115	CFB	3.5[3]	5	19623.0[3]	29.6[5]
Sondong	220	CFB	1.1[1]	5	18828.0[3]	42.5[1]
Naduong	110	CFB	5.43[3]	25	16003.8[3]	30.0[3]
Ankhanh	120	CFB	0.65	5	17322.2	37.5
Formosa HT	650	PC	0.85	25	20070.0	9.8
Mongduong 2	1240	PC	0.65	5	19079.0	37.5
Vung Ang 1	1200	PC	0.87[5]	5	21314.9[5]	31.0[5]

[1] Vietnam Electricity (Personal communication)
[2] Institute of Energy (2016)
[3] Pollution Control Department (Personal communication)
[4] Shrestha et al. (2012)
[5] General Directorate of Energy (2016)

Table A11: Emission factors for some major emission sources in this study with the selected uncertainty (in percent) shown in the parenthese.

Sectors	$PM_{2.5}$	SO_2	CO	NO_x	NH_3	CH_4	NMVOC	BC	OC
1. Agriculture									
1.1. Enteric fermentation									
Dairy cattle						50.46[a]			
Beef cattle						64.15[a]			
Swine						1[a]			
Horse						18[b]			
Goat						5[b]			
Buffalo						82.3[a]			
Poultry						-			
1.2. Manure management									
Dairy cattle					5.6 [a]	16[a]			
Beef cattle					3 [a]	1[a]			
Swine					1.5[a]	4[a]			
Horse					7[b]	1.64[b]			
Goat					1.1[b]	0.17[b]			
Buffalo					3.4[a]	2[a]			
Poultry					0.12 [a]	0.018 [a]			
1.3. Crop residue burning									
Rice	8.3[c]	0.51[c]	93[c]	0.49[e]	4.1[j]	9.6[j]	7[e]	0.69[d]	3.3[d]
Maize	3.9[d]	0.4[d]	114.7[f]	0.39[h]	1.3[d]	4.4[e]	7[d]	0.69[d]	3.3[d]
Potatoes	3.9[d]	0.2[e]	86.2	0.7[d]	1.3[d]	4.6[d]	7[d]	0.47[d]	0.7[k]
Cassava	3.9[d]	0.2[e]	34.6[g]	1.7[i]	1.3[d]	4.6[d]	7[d]	0.69[d]	3.3[d]
Sugarcane	3.8[e]	0.2[e]	34.7[e]	2.6[g]	1[e]	0.4[e]	2.2[e]	0.78[e]	3.3[d]
Oil crops	3.9[e]	0.2[e]	86.2	0.7[d]	1.3[d]	4.6[d]	7[d]	0.47[d]	0.7[k]
2. Transport (g/km)									
Motorcycles	0.19[aj]	0.03[p]	13.2[l]	0.13[l]	0.002[r]	0.41[n]	0.78[l]	0.0035[q]	0.05[q]
Buses	1.05[l]	0.64[p]	20.412[m]	30.3[m]	0.04[n]	0[n]	4.403[m]	0.48[n]	0.21[nl]
Trucks	1.1[o]	1.06[p]	8.8[o]	10.82[l]	0.04[o]	0.25[o]	1.38[l]	0.44[o]	0.22[o]
Cars	0.09[l]	0.17[p]	76.05[m]	2.28[m]	0.13[n]	0.43[n]	12.85[m]	0.008[n]	0.028[n]
Taxis	0.09[l]	0.17[p]	140.63[m]	3.8[m]	0.11[n]	0.54[n]	2.36[m]	0.002[n]	0.008[n]
3. Industry (Combustion) (kg/TJ)									
Bituminous coal and anthracite	52.4[k]	145[v]	150[w]	300[w]	0.00028[y]	10[w]	20[w]	3.7[aa]	1.2[aa]

Sub-Bituminous coal	42.11[k]	150[v]	20[w]	300[w]	0.00028[y]	1[w]	5[w]	3.66[k]	1.8[ab]
Lignite	270[k]	650[v]	150[w]	300[w]	0.00028[y]	10[w]	20[w]	10.6[k]	229.4[k]
Coke	4[t]	595[v]	15[w]	300[w]	0	10[w]	20[w]	1.1[t]	0.26[t]
Natural gas	0.04[t]	0.25[v]	2000[w]	53[x]	1.31[y]	1[w]	5[w]	0.02[t]	0.02[t]
LPG	0	8.45[v]	10[w]	56[x]	0	1[w]	5[w]	0	0
Gasoline	22.9[k]	5[v]	10[w]	373[x]	0.005[z]	3[w]	5[w]	0.44[k]	5.35[k]
Kerosene	10[u]	14[v]	15[w]	167[x]	0	3[w]	5[w]	0.06[t]	1.7[t]
Diesel	0.83[s]	184[v]	15[w]	222[x]	0.007[z]	3[w]	5[w]	3.9[k]	0
Fuel oil	16.17[h]	1492[v]	15[w]	145[x]	0.101[y]	3[w]	5[w]	0.9[k]	0.37[t]
Solid biofuel	126[t]	497[v]	4000[w]	100[w]	0	30[w]	50[w]	60[u]	60[t]
4. Power plants									
Anthracite	437.8 – 845.75[s]	See note	20[ac]	31 - 310[s]	0.00028[y]	0.6[ac]	5.74[s]	2.94[k]	12.63[k]
Sub-bituminous	242.06[s]		20[ac]	310[s]	0.00028[y]	0.6[ac]	5.74[s]	2.94[k]	12.63[k]
Lignite	660[s]		20[ac]	63[s]	0.00028[y]	1[ac]	5[ac]	1[t]	12.66[k]
5. Residential and commercial activities									
LPG	0.26[ad]	0.33[ad]	3.72[ad]	1.76[ad]	0	0.56[w]	18.8[ak]	0.01[k]	0.033[ai]
Coal	7[ae]	2.67[ad]	71.3[ad]	0.914[ad]	0	2.92[ad]	0.664[ad]	0.3[t]	2.3[ai]
Oil	0.13[ad]	0.025[ad]	7.39[ad]	1.1[ad]	0	0.56[w]	0.22[ai]	0.04[ai]	0.16[k]
Firewood	8.2 [ae]	0.008[ad]	77.5[ag]	1.2[ad]	1.29[ah]	5.06[ad]	7.5[ag]	0.85[t]	1.7[al]
Diesel oil	9.23	0.1	56.37	12.1	0	3.55	6.86	3.02	6.84
Heavy oil	0.5	18.97	0.65	2.45	0	0	0	0.04	0.15

[a] Le et al., 2017, [b] Dong et al., (2006), [c] Kim Oanh et al. (2011),[d] Andreae and Merlet (2001), [e] Kim Oanh et al. (2018), [f]Zhang et al. (2008), [g] Dennis et al. (2002), [h]Athiwat (2016), [i]Sahai et al. (2017), [j]Christian et al. (2013), [k]Reddy and Venkataraman (2002a), [l] HUTEI (2015), [m] Trang et al. (2015), [n]Kim Oanh et al. (2015): based on a survey in Bandung Indonesia to generate composite EFs using the IVE model; [n1] The emission factors of BC and OC for buses in Hanoi were estimated using same BC/PM and OC/PM ratios for buses in Indonesia [n]Kim Oanh et al. (2015). [o]PTT Project, 2015 composite EFs based on International Vehicle Emission (IVE) model for Bangkok, [p] Department of Transport (2015), [q]CPCB, 2000, India. Applicable for Indian cars 1995-2005 model. Values are recommended for other Asian countries. [r]EMEP/CORINAIR, 2006, [s]USEPA (1995) estimated using the % ash content at each power plant, [t]Bond et al., 2004, [u]Street et al. (2001), [v] Estimated based on thee sulphur contents using equation 14 in the manuscript.,[w]IPCC (2006), [x]Kato and Akimoto (1992), [y]Batye et al. (1994), [z]EMEP/CORINAIR, 1992, [aa]Ge et al. (2001), [ab]Hangebrauck et al. (1964), [ac]IPCC 1997 and 2006, [ad]Zhang et al. (2000), [ae] Kim Oanh et al. (1999), [af] Jayarathne et al. (2018), [ag]Bhattacherya et al. (2002), [ah]Bertschi et al. (2003),[ai] Permadi et al. (2017), [aj] Kim Oanh et al. (2012): estimated by averaging out the emission factors of motorcycles without emission control technologies, [ak]Smith et al, 2000, [al]Venkataraman et al. (2005).

Table A12: Emission factors for solvents and other products use and gas stations

Sector	Emission factor	Unit	
Solvents and other products use			
Paint application	516	kg/tonne	
Adhesive tape	60	kg/tonne	
Paint manufacturing	15	kg/tonne	
Glue	20	kg/tonne	
Printing industry	350	kg/tonne	
Application of glues and adhesives	600	kg/tonne	
Gas stations			
Filling underground tank	1.62		
Vehicle refuelling	1.65		
Spillage	0.11		
Underground tank breathing and emptying	0.16		

Shrestha et al. (2012). The value for paint application was averaged out from emission factors for automobile manufacture, industry, and decorative purposes.

Table A13: Emissions by sector in 2017 and 2018

	Sectoral emissions of air pollutants in 2017 (Gg/year)								
	$PM_{2.5}$	BC	OC	NO_x	SO_2	NMVOC	NH_3	CH_4	CO
Agriculture	3.27	0.48	0.70	0.49	0.19	7.0	19.4	29.0	94.4
Residential	1.02	0.12	0.38	0.73	0.23	5.32	0.14	1.0	13.0
Commercial	0.12	0.007	0.04	0.026	0.04	0.017	0	0.048	1.15
Transport	4.8	0.75	1.25	41.1	6.2	57.0	0.72	7.44	342.9
Industry	5.2	0.25	0.45	14.34	12.4	1.7	2.77	0.37	21.3
Solvents						35.2			
Gas stations						2.978			
	Sectoral emissions of air pollutants in 2018 (Gg/year)								
	$PM_{2.5}$	BC	OC	NO_x	SO_2	NMVOC	NH_3	CH_4	CO
Agriculture	3.13	0.46	0.67	0.47	0.18	6.76	19.5	29.4	90.5
Residential	1.16	0.13	0.45	0.78	0.24	5.62	0.16	1.1	13.9
Commercial	0.12	0.007	0.04	0.026	0.04	0.017	0	0.048	1.15
Transport	5.3	0.79	1.98	47.2	7.4	67.9	0.91	8.80	399.6
Industry	5.6	0.27	0.46	16.25	13.6	2.1	2.82	0.42	22.6
Solvents						36.3			
Gas stations						2.978			

Table A14: Comparisons by sector between emission inventories in Hanoi

Sector	EI[1]	Emission (Gg/yr)								
		$PM_{2.5}$	BC	OC	NO_x	SO_2	NMVOC	NH_3	CH_4	CO
Agriculture	This study	3.27	0.487	0.71	0.496	0.191	7.05	19.36	29.01	94.39
	REAS 3.2[1]							15.88		
	EDGAR 5.0[2]	7.191	0.65	4.83	3.13	0.392	8.167	11.84	37.82	76.23
	GAINS[3]									
Residential	This study	1.48	0.12	0.51	0.73	0.23	4.12	0.14	1.0	13.0
	REAS 3.2	11.01	1.90	6.93	3.48	3.85	31.07	2.59	-	174.70
	EDGAR 5.0	8.97	0.98	4.24	2.15	8.77	20.3	2.53	7.29	108.09
	GAINS									
Transport	This study	4.79	0.755	1.25	41.17	6.215	56.98	0.72	7.44	342.9
	REAS 3.2	0.84	0.56	0.18	6.9	0.41	40.32	0.83	-	97.60
	EDGAR 5.0	1.80	0.564	0.521	14.8	2.38	23.67	0.05	0.56	230.22
	GAINS									
	Kim Oanh et al, 2012[5] Trang et al, 2015[6]		0.1	0.07	13.3	0.4	46.9		10.46	197.7
	Roy et al., 2021	5.48	3.21	0.7	50.6	1.75	79.49	-	4.04	236.6
Industry	This study	5.2	0.25	0.45	14.3	12.4	1.71	2.76	0.375	21.3
	REAS 3.2	6.32	1.24	2.0	6.25	14.5	3.48	1.07		87.55
	EDGAR 5.0	8.58	1.36	2.06	24.6	26.41	10.34	0.13	0.62	45.3
	GAINS									
Solvents	This study						31.7			
	REAS 3.2						22.80			
	EDGAR 5.0									
	GAINS									
Gas stations	This study						2.97			
	REAS 3.2									
	EDGAR 5.0									
	GAINS									
	Huy and Kim Oanh (2020)[8]						2.58			
Power plants	This study	1.9	0.028	0.2445	82.5	41.67	2.83	0.00014	0.3093	9.94
	Roy et al. (2020)[9]	5.27	0.051	0.178	164.11	54.53	5.13	-	1.04	20.26

	Huy and Kim Oanh (2017)[10]	8.01	0.02	0.1	141	142	2.29	0.49	0.6	11.3
	REAS 3.2[11]	20.28	0.3	-	189.57	141.18	3.29	0.22	-	13.13
	EDGAR 5.0[12]	96.96	6.74	4.69	230.72	532.69	1.89	0.07	1.52	30.9

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

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

[3] Data for each emission sector are not available in Amann et al. (2018)

[4] Emission inventory for HCMC in 2017 (Ho et al., 2019)

[5,6] Emissions were estimated for motorcycles in 2008 (Oanh et al., 2012) and for 4-wheeled vehicles in 2010 (Trang et al., 2015) using IVE model.

[8] NMVOC emissions for 2010

[9, 10, 11] Emissions from power plants for 2015

[12] Emissions from power plants for 2010

: Not available

Table A15: Projected emissions from selected sectors in 2017, 2025, and 2030 in Hanoi.

		$PM_{2.5}$	BC	OC	NO_x	SO_2	NMVOC	NH_3	CH_4	CO
On-road transport	**2017**	4.8	0.75	1.25	41.14	6.21	56.9	0.72	7.44	342.9
	2025	6.3	0.96	1.54	50.6	11.2	76.4	1.59	9.2	426.1
	2030	6.8	1.01	1.59	52.41	16.22	84.34	2.49	9.44	444.5
Domestic cooking	**2017**	0.74	0.06	0.19	0.5	0.17	4.12	0.067	0.517	7.94
	2025	0.48	0.04	0.10	0.58	0.089	5.4	0.065	0.43	5.29
	2030	0.44	0.04	0.09	0.61	0.097	5.77	0.06	0.42	4.97
MSW burning	**2017**	0.44	0.03	0.24	0.13	0.02	0.68	0.04	0.29	1.9
	2025	0.66	0.04	0.35	0.20	0.03	1.01	0.06	0.44	2.84
	2030	0.86	0.05	0.46	0.26	0.04	1.32	0.08	0.57	3.69
Commercial sector	**BAU**	0.11	0.007	0.04	0.03	0.04	0.02	0	0.049	1.15
	Switch from coal to LPG	0.01	0.003	0.007	0.02	0.003	0.14	0	0.007	0.08
Crop residue burning	**2017**	3.27	0.48	0.70	0.49	0.19	7.05	3.94	9.31	94.4
	2025	4.17	0.64	1.03	0.63	0.24	9.02	5.08	12.0	120.8
	2030	4.76	0.73	1.04	0.73	0.27	10.42	6.1	14.3	138.4

Table A16: Comparisons between simulated and observed major $PM_{2.5}$ components. The observed $PM_{2.5}$ components in Hanoi were collected from SPARTAN network (https://www.spartan-network.org/data). OC was not directly observed, however, Residue Matter (RM) in SPARTAN is dominated by organics. It was used to compare with OC in CMAQ.

Year	Sampled period	SO_4^{2-}		NO_3^-		NH_4^+		OC (RM)		BC	
		OBS	CMAQ	OBS	CMAQ	OBS	CMAQ	OBS	CMAQ	OBS	CMAQ
2017	10/28 – 11/05					2.06	4.76			2.81	5.05
2017	11/06 – 11/14					2.04	2.57			3.26	5.28
2017	11/15 – 11/23					1.15	2.45			1.71	2.51
2017	11/24 – 12/02					1.68	4.87			3.03	4.63
2017	12/03 – 12/09					2.15	4.58			2.86	4.74
2017	12/10 – 12/11					5.75	8.86			7.86	9.66
2018	01/08 – 01/16			13.48	10.92	5.33	4.69			3.15	5.07
2018	01/17 – 01/21			12.65	11.77	7.31	6.61			3.33	5.75
2018	01/22 – 01/25			3.91	6.20	6.09	3.21			2.93	3.95
2018	01/26 – 01/30			48.28	5.23	15.72	2.07				
2018	02/28 – 03/08			2.71	5.69	3.03	2.57			3.84	2.76
2018	03/09 – 03/17			6.75	6.27	3.82	2.85			1.72	3.16
2018	03/18 – 03/19			1.17	3.14	3.46	0.53			5.21	1.85
2018	03/20 – 03/26			9.65	7.02	5.18	3.12			6.92	3.29
2018	03/27 – 04/04			2.25	4.39	3.6	2.05			1.55	2.21
2018	04/05 – 04/13			1.79	5.40	2.89	2.49			1.57	2.94
2018	04/24 – 04/25	9.32	4.64	0.35	5.19	2.31	2.40	11.42	6.18	2.21	1.89
2018	04/26 – 05/02	16.19	3.73	1.11	7.93	3.98	3.43	14.23	6.09	1.87	2.68
2018	06/18 – 06/19	6.22	2.07	0.28	0.96	1.45	0.88	11.8	3.35	4.54	1.51
2018	06/20 – 06/25	2.93	1.33	0.11	0.18	0.49	0.47	10.34	4.96	6.19	2.30
2018	06/26 – 06/26	6.09	5.73	0.65	0.44	1.14	2.27	29.85	0.83		
2018	06/27 – 07/05	2.18	1.79	0.11	0.46	0.29	0.77	19.31	4.19		