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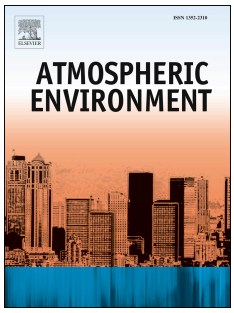

Development of 2015 vietnam emission inventory for power generation units

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PII: S1352-2310(20)30774-3

DOI: https://doi.org/10.1016/j.atmosenv.2020.118042

Reference: AEA 118042

To appear in: *Atmospheric Environment*

Received Date: 26 February 2020

Revised Date: 21 October 2020

Accepted Date: 25 October 2020

Please cite this article as: Roy, S., Fat Lam, Y., Tho Ngo, H., Chan, J.C.L., Fu, J.S., Development of 2015 vietnam emission inventory for power generation units, *Atmospheric Environment* (2020), doi: https://doi.org/10.1016/j.atmosenv.2020.118042.

Shimul ROY: Data curation, Visualization, Writing- Original draft preparation; **Yun Fat LAM:** Conceptualization, Methodology, Data curation, Writing- Original draft preparation; **Hung Tho NGO:** Data curation, Writing- Reviewing and Editing; **Johnny CHAN:** Supervision, Writing- Reviewing and Editing; **Joshua FU:** Writing- Reviewing and Editing.

Title: Development of 2015 Vietnam Emission Inventory for Power Generation Units

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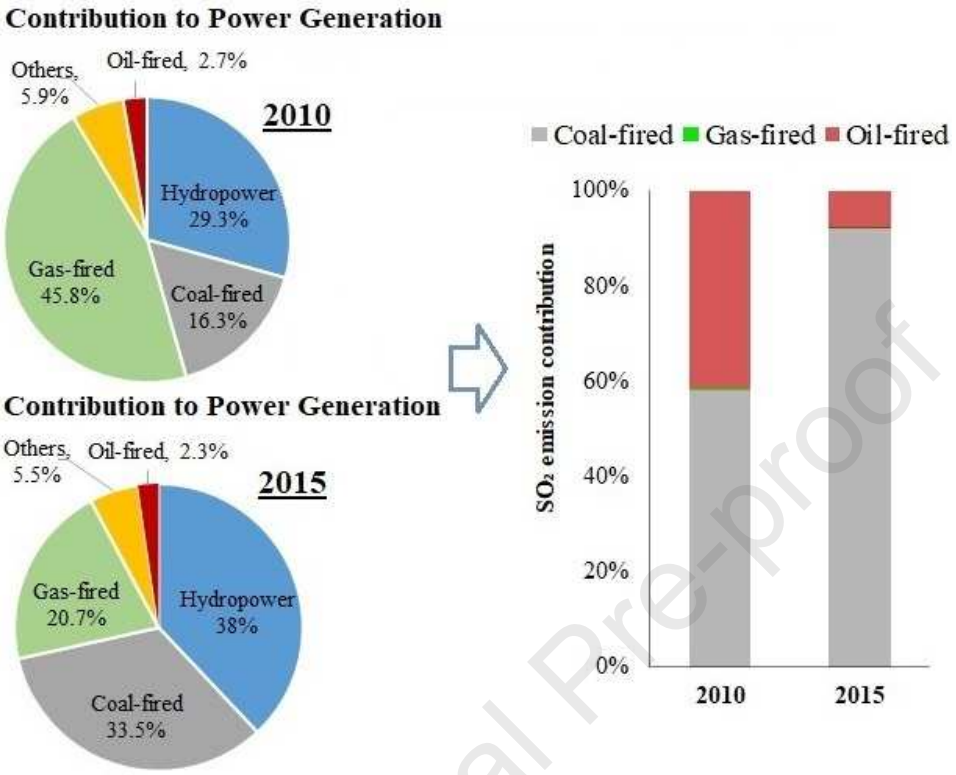
Abstract

The 2010 and 2015 Emission Inventories (EIs) for Vietnam Thermal Power Plants (TPP) were concurrently developed using the bottom-up approach. Local activity data, emission factors, and pollution control efficiencies were applied to estimate the annual emissions of individual power plants. As the EIs consider all emission control activities with relevant unit upgrades, the estimated SO_2, NOx and PM species were found to be lower than most of the reported EIs by 20-70%. An overestimation (i.e., 3.8 times) of SO_2 has been observed in Emission Database for Global Atmospheric Research (EDGAR) EI, which can possibly be attributed to the assumption of no air pollution controls in their inventory. Overall, the newly developed EIs indicate that the annual emissions of coal-fired TPPs were highest among the various types of TPPs, and the largest uncertainty occurred in NOx with ranges between -23% to +31%. In terms of regional distribution, the most significant emission sources of CO_2, N_2O, SO_2, NOx, PM_{10}, $PM_{2.5}$, BC, and OC were from the Red River Delta region resulted from coal-fired TPPs, while the Southeast region had the largest sources of CO, NMVOC, and CH_4 caused by gas-fired TPPs. The study reveals that from 2010 to 2015, the growths of NOx, CO, NMVOC, PM_{10}, $PM_{2.5}$, BC, OC, CO_2, CH_4, and N_2O emissions were 51%, 39%, 41%, 109%, 88%, 9%, 107%, 58%, 33%, and 119%, respectively, while ~19% reduction in SO_2 was found resulted from the decommission of oil-fired TPPs.

Keywords: Emission inventory; Power plants; Vietnam; Electricity generation; Air pollution

Graphical abstract



1. Introduction

Air pollution is a rising concern in Vietnam (VN) because of the fast-growing emissions from its industrial development. In recent years, pollution problems have emerged across the country in response to the heavy reliance of fossil fuels in the growing economy (Huy and Oanh, 2017; Hai and Oanh, 2013; Lasko et al., 2018). Hanoi and Ho Chi Minh City, two rapidly developing cities in VN, frequently experience heavy pollution problems. Hien et al. (2011) reported that the annual PM_{10} and $PM_{2.5}$ in Hanoi could reach up to 89 μg/m^3 and 43.0 μg/m^3, respectively, which exceeded the local air quality standards of 50 μg/m^3 and 25 μg/m^3 (GreenID, 2018; AAQS, 2013). Amann et al. (2019) suggested that one of the contributing sources of local air pollution is the fossil fuel (coal, oil, and natural gas) burning from electricity generation.

In Vietnam, coal-fired (~33.5%), hydropower (38.0%), and gas-fired (20.7%) are the major categories of power production, providing more than 99.0% of electricity (equivalent to ~161,000 GWh in 2015) to the country (IEA, 2019). In 2010, fossil-fired thermal power plants (TPPs) has become the dominant sector in the power production with a total designed capacity of 12,930 MW (i.e., 26 power plants). The choice of relying on fossil-powered over hydropower is mainly due to the consideration of energy security as there is no guarantee of steady electricity generation from hydropower (Mukheibir, 2013). Moreover, the capacity of the existing hydropower plants is not sufficient to meet the growing needs, and the exploitation of Vietnam's river system has nearly reached its maximum level (VPI, 2016). Between 2010-2015, 12 more TPPs were built across VN (WRI, 2018) with an additional 9,145 MW designed capacity (EVN, 2016). Furthermore, a number of TPPs (mainly coal-fired) were planned to be built in the next 10 years to satisfy the future electricity needs. It is expected that fossil fuels burning (dominated by coal) will continue to be the primary source of electricity, and the projected share will reach up to 64.9% by 2030 (GIZ, 2016). As these new TPPs (mainly subcritical, not supercritical nor the advanced ultra-supercritical) will not utilize the maximum achievable thermal efficient design, the lower thermal efficiency (i.e., 8%-10% lower) is expected with more CO_2 emissions (Luong, 2015; Market Forces, 2018).

Vietnam has recently pledged to reduce greenhouse gas emissions by 8% by 2030 through adapting more renewable energy (e.g., solar and wind power), as a major agreement made in COP21 to reduce dependency on fossil fuels (NDC, 2015). However, the prior arrangement of building these coal-fired TPPs, and the needs of cheap electricity for

economic development will not stop, and the rise of greenhouse gas and air emissions from the power sector will likely be continued in the next decade (Tran, 2019).

Consumption of a large amount of fossil fuels in TPPs releases an enormous amount of air pollutants (gaseous and particulates) when it is not adequately controlled. It is important to quantify the emissions from the power sector and to develop a reliable Emission Inventory (EI) for air quality management. It could be a vital asset to the local government and international communities. For instance, the newly developed EI with local activity data and updated emission control system will provide significant benefits to updating the global and regional EI databases, such as the Emission Database for Global Atmospheric Research (EDGAR) and mosaic Asian anthropogenic emission inventory under the international collaboration framework of the MICS-Asia and HTAP (MIX) (Li et al., 2017) that has been used by EDGAR and ECLIPSE developed by the International Institute for Applied Systems Analysis (IIASA, https://iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv5.html). The local activity data and emission inventory are essential for global emission inventories. Additionally, it will provide updated local emission data for global climate and air quality modeling, including Southeast Asia (SEA). Besides, it will support international organizations to review the future emission mitigation strategies and activities taken by the local government to comply with the international agreement (e.g., COP21). As the future emission contribution from SEA, including VN, is expected to increase considerably to the global annual emission due to its rapid economic development. Therefore, the VN power sector's emission estimates could significantly impact the policy measures for future emission mitigation and support the international communities to set future directions.

In Vietnam, some efforts have been made on on-road transportation EI (Bang et al., 2017; Ho and Clappier, 2011; Ho, 2017; Tung et al., 2011; Trang et al., 2015; Oanh et al., 2012). However, to the best of our knowledge, minimal effort has been made for quantifying the air pollutants and greenhouse gases emissions from TPPs. The only published local EI with limited information is for the 2010 emission base year, which is already outdated (Huy and Oanh, 2017). In this study, the 2015 EI on TPPs has been developed using a bottom-up approach where multiple emission species (SO_2, NOx, CO, NMVOC, PM_{10}, $PM_{2.5}$, BC, OC, CH_4, and N_2O) were considered. The same approach also applied for calculating the 2010 EI for better understand the change of emissions in recent years, considering the updated

emission control system of the coal-fired TPPs. Moreover, regional emission composition has been analyzed to identify the key contributing regions to the annual total emissions.

2. Methodology

2.1 Characteristics of the study area, and the locations of TPP

Geographically, VN is located at 14.0583° N and 108.2772° E of the Indochina Peninsula, with an area of about 330,966.9 km^2 (GSO, 2016), and a population of around 95 million (World Bank, 2018). The density of population is about 283 persons per km^2, with the highest population density in Ho Chi Minh City (HCMC) (4,097 persons per km^2) followed by Hanoi (2,209 persons per km^2) (GSO, 2016). The entire country consists of 63 provinces, including five municipalities (Can Tho, Da Nang, Hai Phong, Hanoi, and HCMC). It is separated into six key regions, including Red River Delta, Northern midlands and mountain areas, North Central and Central coastal areas, Central highlands, South East, and Mekong River Delta. With the long span of latitude and a varying topography across the country, the urban and industrial development has been divided into northern and southern parts with the centers at Hanoi and HCMC.

In 2015, a total of 36 TPPs were operated in VN, of which 21 were coal-fired, 3 were oil-fired, and 12 were natural gas-fired power plants (26 TPPs were operated in 2010). Fig. 1 shows the geographic location of these TPPs. These power plants are distributed among 18 provinces with thermal efficiencies between 20.7% to 40.0% (average of 35%), covering nearly all regions except for the Central highlands (World Bank, 2009; GE, 2019).

Between 2010-2015, there were 12 extra coal-fired, and 2 natural gas-fired TPPs built. In general, most of the TPPs are concentrated either in the northern (Red River Delta and Northern midland and mountain areas) and Southern (South East and Mekong River Delta) regions. It should be noted that the recently built coal-fired TPPs are clustered in the northern key economic zone, while the natural gas-fired TPPs are concentrated in the southern provinces, mainly in the southern key economic zone. As coal-fired TPPs release much higher levels of air pollutants (i.e., NOx, PM and SO_2) and CO_2 (i.e., 50% more than the natural gas-powered), it is expected the northern key economic zone will receive higher pollution influence from the power sector (LAM, 2018).

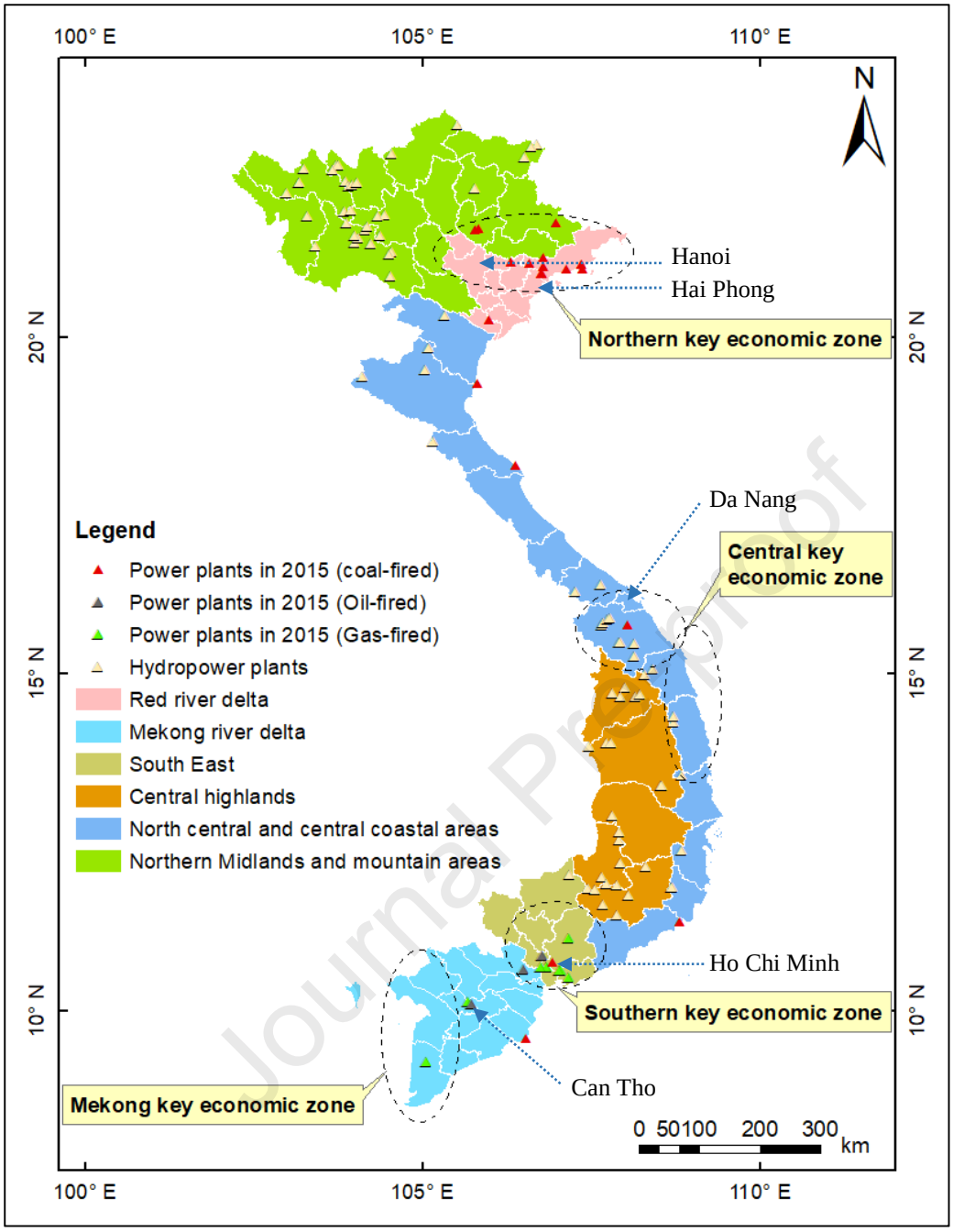


Fig. 1. Geographic location of thermal power plants in 2015.

2.2 Summary of available TPP emission databases in Vietnam

Various global and regional EI databases have reported the VN annual emissions from TPPs. In general, these databases adopt the top-down approach where emissions were calculated based on the country-wide fuel usage, providing gridded emissions for air quality management. These databases include the Emissions Database for Global Atmospheric Research (EDGAR) v4.3.2 (Crippa et al., 2018) available from 2000-2012; The Center for Global and Regional Environmental Research (CGRER) (Streets et al., 2003; Zhang et al.,

2009) available for 2006; Global Power Emissions Database (GPED) (Tong et al., 2018) available for 2010; Regional Emission inventory in Asia (REAS) v2.1 (Kurokawa et al., 2013) available for 2008; MIX-Asian EI (Li et al., 2017) available for 2008 and 2010; Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS)-Asia (IIASA, 2017) available for 2010 and 2015. It should be noted that the frequency of updating regional emission databases is around 3-5 years for developing countries. Hence, most of these EIs have already been outdated (Huy and Oanh, 2017). To the best of our knowledge, minimal effort has been made so far for estimating 2015 annual emissions (only one from IIASA, 2017) for limited air pollutants in VN.

2.3 Activity data

Activity data is essential information for estimating the annual emissions of TPPs using the bottom-up approach. In this study, activity data were collected from a wide range of sources. These include national reports and studies, international databases, and communication with local authorities. Information such as location of power plants, commissioning year, capacity of TPPs and type of fuels used were obtained from EVN (2016), UNFCCC (2019b), and WRI (2018), while annual fuel consumption on individual power plants and fuel consumed per unit of electricity generation, total electricity output (GWh) and Net Calorific Value (NCV) of fuels were collected from the local and international reports (CEMM, 2019; Thao, 2004; IPCC, 2006; UNFCCC, 2019a and b; WRI, 2018; Zhao and Zhang, 2012). It is our intention to use all local VN data whenever available, and supplement with regional and global data when local data are not available. Table 1 summarizes the activity data for TPPs that were commissioned between 2010 and 2015, and Table S1 shows the remaining activity data for the existing TPPs operated in both 2010 and 2015.

Table 1. Activity data on thermal power plants commissioned between 2010 and 2015.

Power plants	Year	Capacity (MW)[a]	Fuel type	NCV (KJ/kg)[d]	Fuel consumption (10^3 tonne)[b]	Fuel consumed (tonne/GWh)[b]	Electricity output (GWh)[l]	APC system[n]
Cam Pha (1 & 2)	2009-2010	600	A	17,857[g,1]	1985[f]	632[m]	3,141[n]	ESP, DSI
Nong Son	2014	30	A	22,640	110[m]	688[h]	160[m]	ESP
An Khanh 1	2015	120	A	22,640	164[f]	558[c]	294	ESP
Mao Khe (I & II)	2013	440	A	16,736[o]	848[m]	543[h]	1,561[m]	ESP, DSI
Hai Phong 2 (I & II)	2013	600	A	22,640	1,420	510[h]	2,783[p]	ESP, FGD
Mong Duong 1 & 2	2015	1080; 1120	A	22,640	3,019[f]; 2,013[f]	503; 503	5,800[q]; 4,000[q]	ESP, FGD; ESP, FGD;
Vinh Tan 2 (I & II)	2015	1244	A	22,640	3,097[f]	558[c]	5,550[t]	ESP, SFGD, SCR
Duyen Hai 1 (I & II)	2015	1244	B	25,800[e]	988[f]	549	1,800[r]	ESP, SFGD, SCR
Vung Ang 1 (I & II)	2014	1245	A	22,640	2,667[f]	558[c]	4,780[s]	ESP, SFGD
Nghi Son 1 (I & II)	2013	600	A	22,640	2,009[f]	558[c]	3,600[i]	ESP, FGD
Nhon Trach 2	2011	750	NG	49,500[b1]	860[f]	156	5,499[j]	-
Vedan	2015	72	NG	49,500[b1]	158[b]	156	1,008[k]	-

Note: A – Anthracite, B – Bituminous, and NG – Natural gas; APC – Air Pollution Control; ESP – Electrostatic Precipitator; FGD – Flue Gas Desulfurization; DSI – Dry Sorbent Injection/Dry FGD; SFGD – Seawater FGD; SCR – Selective Catalytic Reduction; **Grey color indicates coal-fired power TPPs with pulverized coal boiler(s).** **a.** EVN (2016); b. CEMMM (2019); **b1.** NCVs have been converted to KJ/kg; **c.** Average unit coal consumption in 2015, which has been calculated from the unit fuel consumed (g/kWh) by known coal-fired thermal power plants operated in 2015; **d.** Zhao and Zhang (2012); **e.** IPCC (2006); **f.** Annual coal consumption = Unit coal consumption (tonne/GWh) × Total electricity generation (GWh); **g.** Thao (2004); **g1.** NCV of anthracite coal, which has been converted to KJ/kg; **h.** Unit coal consumption (tonne/GWh) has been calculated using the annual coal consumption and electricity output of the power plant; **i.** GJSC (2014); **j.** VPI (2016); **k.** Total electricity generation has been calculated using the total fuel consumption divided by unit fuel consumption in 2015; **l.** WRI (2018); **m.** VINACOMIN (2015, 2016, 2018a & 2019); **n.** UN Environment (2017). **o.** VPPC (2013); **p.** PCD (2017); **q.** EVN (2015a & 2015b); **r.** VNA (2016); **s.** VE (2017); **t.** PGC (2016).

2.4 Calculation method

The TPPs are treated as point sources in this study (Ohara et al., 2007; Kurokawa et al., 2013), and the emissions are estimated using the "Simple Method" adapted from EMEP/CORINAIR (2006), as shown in Eq. (1). This method utilizes the annual fuel consumption from individual TPPs coupled with local/regional emission factors and the plant-specific pollution control efficiency to estimate the control emissions. The detailed activity data and the equipped Air Pollution Control Devices (APCDs) can be found in Table 1 and Table S1. It should be noted that all TPPs in VN are currently equipped with ElectroStatic Precipitator (ESP) with an estimated control efficiency between 98.4 and 99.5% for PM species. For NOx control, low NOx burners are assumed for all TPPs that use pulverized coal (PC) boiler with 30% control efficiency, and Selective Catalytic Reduction (SCR) system has only been considered in *Duyen Hai 1* and *Vinh Tan 2* (VTC, 2019).

$$E_{ij} = \sum(AR_{ij} \times NCV_j) \times EF_{ij} \times \left(1 - \frac{EC_i}{100}\right) \text{..... (Eq. 1)}$$

where, E_{ij} is the control emission (in Gg/yr) of species *(i)* with fuel type *(j)*; AR_{ij} is the activity rate (i.e., fuel consumption by the individual thermal power plant in the base year of EI) related to the emission of species *(i)* with fuel type *(j)* in energy input or fuel consumption by the power plant in TJ/yr; NCV_j is the net calorific value of fuel *(j)* in KJ/kg, which has been used as a conversion factor; and EF_{ij} is the uncontrol emission factors of species *(i)* in kg/TJ and fuel type *(j);* and EC is the emission control efficiency of species *(i)* in (%).

2.4.1 Emission factors

The emission factors (EFs) is critical for the calculation of annual emissions in TPPs. A summary of these EFs is shown in Table 2 gathered from wide-ranging sources including Bond et al. (2004), IPCC (1996, 2006), EMEP/EEA (2016), USEPA (1995), Kato and Akimoto (1992), Reddy and Venkataraman (2002), Streets et al. (2003), and Shrestha et al. (2012). A separate summary for the available range of EFs is also presented in Table S2. Please note that whenever local EF is not available, regional (Asia) or global EF is used in the table.

Table 2. Uncontrolled EFs (kg/TJ) used in emission estimation for power plants

Emission species	Coal			Natural gas	Fuel oil
	Anthracite	Bituminous	Lignite		
CO_2	98300[a]	94600[a]	101000[a]	56100[a]	77400[a]
CH_4	1[a]	1[a]	1[a]	1[a]	3[a]
N_2O	1.50[a]	1.50[a]	1.50[a]	0.10[a]	0.60[a]
NOx	300[a1]	300[a1]	564[g]	105[g]	249[g]
CO	20[a]	13[b]	8.70[b]	20[a1]	15.10[b]
BC	2.94[h]	2.94[h]	1[c]	0.022[b]	0.98[c]
OC	12.63[h]	12.63[h]	12.66[c]	0.019[c]	0.37[c]
PM_{10}	1274.17[d, e1]	1274.17[d, e1]	1835.73[d, f1]	0.89[b]	25.20[b]
$PM_{2.5}$	539.49[d, e1]	539.49[d, e1]	588.72[d, f1]	0.89[b]	19.30[b]
NMVOC	5[a1]	5[a1]	2.60[d]	5[a1]	2.30[b]

a. IPCC (2006); [a1] IPCC (1996); **b.** EMEP/EEA (2016); **c.** Bond et al. (2004); **d.** USEPA (1995); **e.** Zhao and Zhang (2012); **e1.** percentage of coal ash weight 27.11% (i.e. A= 27.11) for anthracite and bituminous; **f.** Thao (2004); **f1.** percentage of coal ash weight 26.76% (i.e. A= 26.76) for lignite; **g.** Kato and Akimoto (1992); **h.** Reddy and Venkataraman (2002); **i.** Streets et al. (2003).

2.4.2 EF calculation for SO_2

SO_2 emission from TPPs highly depends on the quality of fuels used in power generation (Ohara et al., 2007). To accurately estimate SO_2 emission, sulfur content (CS) of the fuel, sulfur retention in ash (αs), and NCV of fuel are incorporated in Eq. (2) to calculate the EF of SO_2 (IPCC, 1996).

$$EF_{SO_2} = 2 \times \left(\frac{CS_{fuel}}{100}\right) \times \left(\frac{100-\alpha_s}{100}\right) \times \frac{1}{NCV} \times 10^9 \text{.....Eq. (2)}$$

where EF_{SO_2} is the emission factor of SO_2 (kg/TJ); "2" is the conversion factor from S to SO_2 (kg/kg); CS_{fuel} is sulfur content in fuel (% weight); α_s is the sulfur retention in ash (%); NCV is the net calorific value of fuel (KJ/kg); 10^9 is the (Unit) conversion factor.

The sulfur retention in ash is an important parameter that influences the amount of SO_2 released during the burning, and it is particularly important for the low rank (soft) coal (e.g., lignite) where the value could reach up to 25%. In general, sulfur is converted to gaseous pollutants (e.g., SO_2 and SO_3) during the combustion. As some portion is unable to oxidize and retained in ash as solid compounds, it reduces the amount of SO_2 being generated. The quantity of retained sulfur is referred to as sulfur retention in ash (Sheng et al., 2000). Table 3 summarizes the parameters used for SO_2 calculation, and Tables S3−S5 present the calculated EFs of SO_2 for each category of power plants (i.e., coal-fired, oil-fired, and natural gas-fired).

Table 3. Parameters for calculating SO_2 EFs in TPP.

Power plants	Fuel type	NCV [a] (KJ/kg)	CS [f] (%)	α_s (%) [e1]
Cam Pha (1&2); Cao Ngan; Hai Phong 1; Ninh Binh; Pha Lai 1; Pha Lai 2; Son Dong; Quang Ninh 1;Uong Bi Extension 2; Nong Son; An Khanh 1; Mao Khe; Hai Phong 2; Mong Duong 1; Mong Duong 2; Vinh Tan 2; Vung Ang 1, and Nghi Son 1	A	16,736 - 22,640 [b1,c1,j]	0.6-0.8 [g]; 0.65	5.00
Formosa Dong Nai, and Duyen Hai 1	B	25,800 [e] - 27,546 [d1]	0.6-0.8 [g]; 0.65	5.00
Na Duong	L	16,015 [b1]	5.43	25.00
Bourbon; Can Tho, and Thu Duc	FO	45,364 [b1]	1.0-4.0 [e1]; 3.00 [h]	0.00
Ba Ria; Ca Mau (1&2); Nhon Trach 1; O Mon 1; Phu My 1; Phu My 2-1; Phu My 2-2; Phu My 3; Phu My 4; Hiep Phuoc; Nhon Trach 2, and Vedan	NG	49,500 [b1]	0.00064 [i]	0.00

Note: A-Anthracite, B-Bituminous, L-Lignite, FO-Fuel oil, NG-Natural gas, CS-sulfur content in fuel; α_s-sulfur retention in ash; **a**. Zhao and Zhang (2012); **b**. CEMM (2019); **b1.** NCVs have been converted to KJ/kg; **c**. Thao (2004); **c1.** NCVs of anthracite coal, which have been converted to KJ/kg; **d.** UNFCCC (2019a); **d1.** NCV has been converted to KJ/kg; **e.** IPCC (2006); **e1.** IPCC (1996) and IPCC (2006); **e2.** The average value of sulfur content in fuel is considered for calculating the EF of SO_2; **f.** Nguyen (2015); **g.** VINACOMIN (2018b)**; h.** Shiomi (2002); **i.** Kato and Akimoto (1992); **j.** VPPC (2013).

Regarding to the selection of values for the required parameters (as mentioned above), local sources are mainly used (Nguyen, 2015; Thao, 2004). However, the IPCC reported values are also adapted whenever local values are not available (Shrestha et al., 2012). For oil-fired TPPs, the regional CS values (annual average values for Singapore, Thailand, and Vietnam) are adopted with the IPCC values. For gas-fired TPPs, the CS values are obtained from Kato and Akimoto (1992). These values are recommended for 25 Asian countries, including VN. In terms of APCDs, majority of the TPPs are equipped with either flue-gas desulfurization (FGD), dry sorbent injection/dry FGD or seawater FGD (SFGD) systems with the control efficiencies ranged between 85.0% to 95.0%, to meet local pollution regulation (QCVN, 2009).

3. Results and discussion

3.1 Economic growth and energy status in Vietnam

Vietnam has made a robust growth in the national economy in the last two decades (Amann et al., 2019; DEA, 2017; World Bank, 2019). The energy economy of the country has shifted quickly from agricultural energy economy (i.e., biomass fuels) to a mixed energy economy. Fig. 2 shows the relationship of annual Gross Domestic Product (GPD) per capita and the energy mix from 1990 to 2030. It is observed that the GDP of VN has grown nearly 5 times (US$ 388-US$ 2065) since 2000, and it is projected to be continued to reach ~US$3675 in 2030 (World Bank, 2019). The usage of fossil fuel has also made a rapid increase in the past 15 years from 12,005 kt to 36,937 kt (+207%) (VPI, 2016), in which coal, natural gas and oil have increased from 5,755 kt to 21,213 kt (~+269%), and 19 kt to 1,761 kt (~+9,000%), 6,231 kt to 13,962 kt (~+124%), respectively. It should be noted that in the past 5 years (2010-2015), the growth of oil-powered TPPs has stopped, while the coal and natural gas-powered TPPs are still in a steady growth (i.e., 27.6% and 1.8%, respectively). As the power industry has moved towards more coal-fired intensive, the contribution of coal-fired TPPs to overall power production has increased by about 34.6%. It is projected that the overall electricity demand will reach ~572,000 GWh (equivalent to 5,560 kWh per person) by 2030 at ~ +10.0% growth annually, and the coal-fired and gas-powered production will maintain at a fast annual growth of ~11.9% and 5.8%, respectively, with the fossil-powered portion in the energy mix reaching between 55% to 70% in the next 15 years.

In terms of renewable energy, hydropower still provides a substantial portion of electricity. However, its relative contribution to the energy mix has been reduced due to the increase in fossil fuel usage in recent years. Currently, 78 hydropower plants are operating nearly at its full capacity with a total design capacity of 14,636 MW, largely concentrated in the Northern midlands and mountain areas, and Central highlands (See Fig. 1) (EVN, 2016). As hydropower production varies largely and affects by the amount of precipitation received in local rivers, the percentage contribution has fluctuated between 29% to 60% in the past 15 years. Between 2010 and 2015, there has been a slight increase in the hydropower portion from 29.0% to 36.6% due to an increase in precipitation. It is projected that hydropower will still have a slightly increasing trend (i.e., 3% from 77,910 to 89,232 GWh) in the future under the same climate condition and is attributed to the projected increase in pumped storage and small hydropower plants. However, the hydropower portion in the energy mix will drop from ~29.4% in 2020 to 15.6% by 2030. For other renewable sources (biomass, solar, wind), the

current contribution is relatively insignificant (~1.0%), and it is projected that the planned renewable energy will gradually pick up, and reach to ~10% in the energy mix in 2030 (ERIA, 2017).

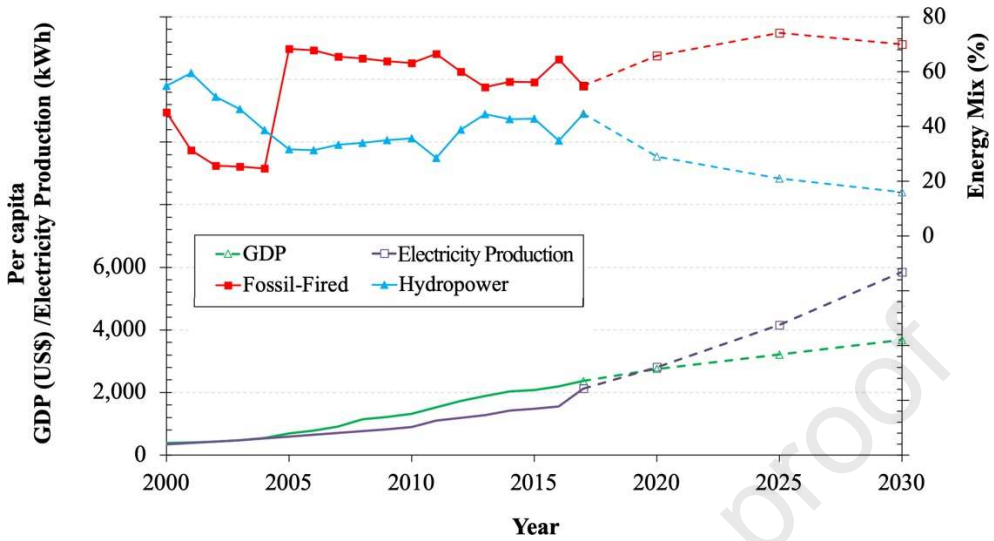


Fig. 2. Energy consumption in relation to annual GDP growth in Vietnam.

3.2 Emission estimation

3.2.1 Annual emission from thermal power plants

The annual emissions of TPPs were calculated using local activity data with uncontrolled emission factors, followed by the adjustment from APCDs. Table 4 summarizes the emission estimates of CO_2, CH_4, N_2O, SO_2, NOx, CO, NMVOC, PM_{10}, $PM_{2.5}$, BC, and OC from different types of TPPs in 2010 and 2015. In general, the coal-fired TPPs have contributed to much higher emissions (emission per kWh electricity generation) than the oil-fired and natural gas-fired TPPs, which is consistent with the finding from Huy and Oanh (2017). The average consumption of coal, oil, and natural gas per kWh electricity generation in 2015 was 558.00, 236.34, and 156.45 tonnes, respectively. As there is a significant increase in the number of TPPs (11,340 to 39,640 MW) operated in the past 5 years, noticeable increases in CO_2, CH_4, N_2O, NOx, CO, NMVOC, and PM species are observed with the percentage increase between +9.0% and +118.6%. The increases in CO_2, N_2O, NOx, CO, PM species are mainly attributed to the increase in coal burning, while the increases in CH_4 and NMVOC are due to additional natural gas burning. For SO_2, significant reductions are observed, attributed to the decommissioning of two most polluted oil-powered TPPs (uncontrolled emission) in the region. The estimated annual emission of SO_2 in 2015 is 54.53 Gg with -18.6% reduction

from 2010 to 2015. In terms of emission contribution, the emissions from coal-fired TPPs to overall emissions are 91.9%, 96.3% and 91.5% for SO_2, PM_{10} and $PM_{2.5}$, respectively in 2015.

Table 4. Calculated emissions from thermal power plants.

Pollutant	2015 Emission, Gg/yr (Emission per kWh electricity generation, g/kWh)			Emission Total, Gg/yr Year		% Diff 2015 – 2010
	Coal-fired	Fuel oil-fired	Natural gas-fired	2015	2010	
CO_2	58,388 (1,154)	253 (830)	24,207 (434)	82,848	52,560	57.6%
CH_4	0.60 (0.01)	0.01 (0.03)	0.43 (0.01)	1.04	0.78	33.3%
N_2O	0.89 (0.02)	0.002 (0.01)	0.04 (0.00077)	0.94	0.43	118.6%
SO_2*	50.09 (0.99)	4.32 (14.18)	0.11 (0.002)	54.53	67.00	-18.6%
NOx*	117.99 (2.33)	0.81 (2.67)	45.31 (0.81)	164.11	108.53	51.2%
CO	11.58 (0.23)	0.05 (0.16)	8.63 (0.15)	20.26	14.59	38.9%
NMVOC	2.96 (0.06)	0.01 (0.02)	2.16 (0.04)	5.13	3.65	40.5%
PM_{10}*	12.18 (0.24)	0.08 (0.27)	0.38 (0.01)	12.65	6.04	109.4%
$PM_{2.5}$*	4.82 (0.10)	0.06 (0.21)	0.38 (0.01)	5.27	2.81	87.5%
BC*	0.039 (0.00077)	0.003 (0.01)	0.009 (0.00017)	0.05	0.046	8.7%
OC*	0.169 (0.0033)	0.001 (0.004)	0.008 (0.00015)	0.18	0.087	106.9%

Note: * Average PM control efficiency 98.4 to 98.5% (CEMM, 2019); Low NOx burner with 30% removal efficiency (USEPA, 1995), and FGD control efficiency for SO_2 ranges 90.0 to 95.0% (CEMM, 2019). Grey color indicates ACP has been applied.

3.2.2 Emission comparison with available EIs

To identify potential issues that may arise from the newly developed EIs, it is crucial to compare the results to the existing EI studies (Pham et al., 2008; Chow et al., 2010; Kurokawa et al., 2013; Ohara et al., 2007). Table 5 shows the estimated control and uncontrol (with bracket) emissions for 2010 and 2015. As noted at the beginning, only limited inventory (i.e., GAINS-Asia) has been published for 2015. Hence, the 2010 EI was concurrently developed to serve as a benchmark case to compare with the existing 2010 EIs. These existing inventories include EDGAR v4.3.2, MIX-Asian EI, GAINS-Asia, GPED, and Huy and Oanh (2017). Overall, the newly-developed inventory (2010) aligns reasonably well with other inventories. In general, the estimates of CO_2, N_2O, and NMVOC are in similar ranges among all inventories, while less agreements are found in CH_4 and SO_2, NOx, CO, and PM species. For SO_2, a huge difference has been observed with EDGAR inventory (67 Gg/yr vs 254.25 Gg/yr), which is about 4 times higher than our best estimate. Interestingly, the value in EDGAR matches well with our uncontrol emission (shown in the bracket of Table 5 - 210.99 Gg/yr). One possible hypothesis would be the SO_2 emission estimated by EDGAR did not consider any SO_2 pollution controls in the power sector. With the inclusion

of small-scale heating sources in their inventory, it would be reasonable to have such high SO_2 estimate. The inclusion of small heating sources not only results in a higher estimate of SO_2, but also for NOx, CO and PM species.

Table 5. Comparison of total annual emission estimation with other EI works (Gg yr^{-1})

Base Year	2010						2015	
Type	Global		Regional		Local	This study	Regional	This study
Emission Inventory/ Pollutant	EDGAR	GPED	MIX Asia	GAINS-Asia	Huy and Oanh		GAINS-Asia	
CO_2*	41.49	42.02	35.42	40.60	44.78	52.56	56.90	82.84
CH_4	1.54	–	–	15.20	0.60	0.78	15.10	1.04
N_2O	0.34	–	–	0.30	0.53	0.43	0.60	0.94
SO_2	254.25	54.43	109.95	89.30	142	67.00 (210.99)	112.40	54.53 (365.93)
NOx	148.52	75.39	88.47	55.50	141	108.53 (131.49)	71.60	164.11 (226.15)
CO	39.46	–	9.90	11.60	11.30	14.59	13.30	20.26
NMVOC	2.29	–	2.51	–	2.29	3.65	–	5.13
PM_{10}	50.06	–	19.46	20.90	19.30	6.04 (321.00)	30.60	12.65 (761.99)
$PM_{2.5}$	36.70	4.55	5.36	6.90	8.01	2.81 (134.65)	11.00	5.27 (321.84)
BC	2.51	–	0.04	0.20	0.02	0.046 (0.74)	0.20	0.051 (1.75)
OC	1.76	–	–	0.20	0.10	0.087 (3.14)	0.20	0.178 (7.53)

Note: – Not available; * Tg yr^{-1}; Base year of EI is 2010 and 2015; Uncontrol emission indicates in bracket.

For other inventories such as MIX-Asia and GAINS-Asia, their SO_2 emissions fell between the controlled and uncontrolled emissions, and slightly higher than our inventory. This discrepancy may result from the difference in emission factors, fuel sulfur content, or APCD efficiency. As our inventory takes into the consideration of all TPP control policies (i.e., QCVN 22: 2009/BTNMT for NOx, SO_2 and PM controls) with plant-specific emission controls (i.e., FGD, and low NOx burner), it provides better refinement to the TPP inventory than other regional inventories (QCVN 22, 2009). In terms of PM_{10} and $PM_{2.5}$, our estimates of 6.04 and 2.81 Gg/yr are smaller than other local and regional models. The differences may be attributed to 1) the inclusion of ACP upgrades (i.e., ESP) with better APCD efficiency (98.5%) from the old TPP units (Nguyen, 2008), and 2) the difference in the type of boiler used in VN. From our local records, 2/3 of TPPs in VN are using PC boiler. The assumption of different EF ratios (0.52 and 0.66A) between PC and circulating fluidized bed (CFB) used in the other inventories may have contributed to this difference.

3.2.3 Uncertainty analysis

A variety of factors and parameters determine the range of uncertainties in the emission estimation. This includes EI approach, activity data, sources of EFs, quality of fuel, and types of ACPD technology and their efficiencies (Chen and Meng, 2017; Kurokawa et al., 2013; Pham et al., 2008; Streets et al., 2003). In this study, uncertainty is defined as the ratio of the variance between the low and high emission estimates to that of the best emission estimates for each species (shown in Eq (3)), as reported by Permadi and Oanh (2013) and Huy and Oanh (2017), and the results are shown in Fig. 3, and Table S6.

$$Uncertainty\ (high\ or\ low) = \frac{High\ or\ low\ estimate - Best\ estimate}{Best\ estimate} \times 100\% \ldots\ldots\ldots\ldots\ldots \text{Eq. (3)}$$

The uncertainty (in percent) results vary largely with pollutants and are ranged from −94% to +31% in 2015. The largest uncertainties were caused by the uncertainty of emission factors and the fuel sulfur content in the coal. As the study utilized a collection of data from both local and international sources, these uncertainties reflect the possible range of our emission outcomes, but not the real uncertainties of our emission factors.

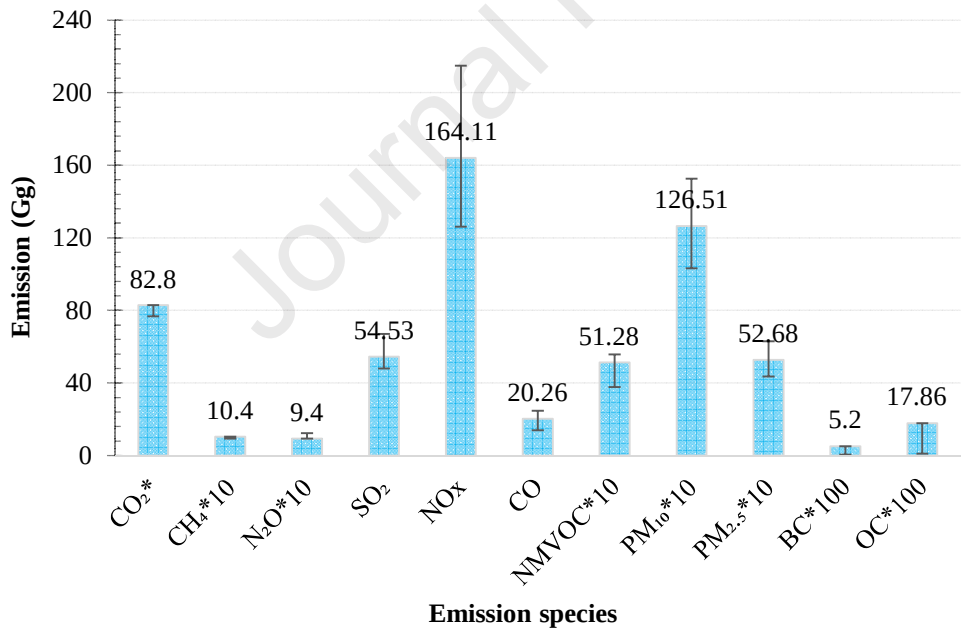


Fig. 3. Uncertainty estimates (ranges between high and low estimate) along with best estimates for different pollutants emitted in 2015. *CO_2 values are in Tg yr^{-1}. The whiskers show the low and high estimates but not the standard deviations.

Moreover, the result may be exaggerated by some international EFs that may not reflect well the situation in VN. For example, in the USA, anthracite coals are less commonly used in the energy production, and the EFs developed by the USEPA for hard coals (rated "C" or

"D" in emission factor rating) may rely on only limited plants and samples, resulting in some concerns to the reliability of their data (USEPA, 1995). Moreover, the composition of US anthracite coals is different from the coals used in VN (e.g., OC and ash contents). To reduce the effect of possible errors induced by a wide-ranging of EFs, only Tier 1 data (generic emission factor) was used, and the source-specific or technological specific emission factors (e.g., Tier 2 and 3) were discarded in the analysis. Overall, the highest uncertainty is observed in NOx with the range of -23 % to +31% attributed to the usage of various emission factors from multiple international sources. The uncertainty ranges for other pollutants are similar due to a limited number of EFs as well as comparatively lower variation in available EFs.

3.3 Local emission characteristics

The emissions of individual TPPs were plotted to identify high pollution plants and for comparing the status of emission generations among the types of TPPs, as shown in Fig. 4. The order of TPPs presented is based on the type of TPPs followed by the amount of fuel usage in 2015, and the values on the top of each bar show the design capacity of the plants. Among the coal-fired TPPs operated in 2015, *Pha Lai 1* has the highest total emission compared to other TPPs, which is attributed to the uncontrolled emission of SO_2. As *Pha Lai 1* was originally planned to be decommissioned at the end of 2015, no FGD was installed, and this has resulted in a considerable SO_2 (~18 Gg) being released (World Bank, 2009). The same situations of "no FGD" are also observed in the other three TPPs (i.e., Ninh *Binh*, *An Khanh 1* and *Nong Son*). However, due to the relatively small size in capacity (i.e., these TPPs are 3-14 times less than *Pha Lai 1* in terms of thermal capacity), these TPPs do not show up as a large emitter. For *Na Duong*, a slightly bigger portion of SO_2 is also observed, which is attributed to the usage of low-rank coal (i.e., lignite) from the local *Na Duong* mine, where lower calorific value (16,015 KJ/kg) with high sulfur (CS: 5.43%) coal is obtained. As the coal ranking is a crucial factor to reflect the quality of the coals (i.e., volatile matter, fixed carbon, moisture content), using the low-rank coal like in *Na Duong*, it results in ~6.0 times higher SO_2 when compared with *Cao Ngan* (CS of 0.65%) that uses anthracite coals with similar plant capacity and fuel consumption. Fortunately, *Na Duong* is a small TPP (capacity of 110 MW), so that the resulted SO_2 is still relatively small in the inventory. In terms of NOx, the difference in emission is controlled by the amount of fuel burned and the types of ACPD technology used. Among the TPPs, *Duyen Hai 1* and *Vinh Tan 2* have installed SCR with low NOx burner (LNB) with the overall efficiency of less than 60% (30% from LNB,

and 40% from SCR). Hence, a slightly lower overall emission has been observed in *Vinh Tan 2* when comparing to *Mong Duong 1* and *Vung Ang1*, even *Vinh Tan 2* has consumed a larger amount of coal (VTC, 2019). Currently, the magnitude of NOx emission is in general controlled by the amount of fuel used, but rather than NOx APCDs in Vietnam.

Among the gas-fired TPPs, the large polluting TPPs are *Ca Mau, Nhon Trach 1, and Phu My 1* (Fig. 4). In general, the overall emissions of gas-powered TPPs were lower than the coal-fired TPPs but were higher than the oil-fired TPPs. The lower emissions from the individual oil-fired TPPs mainly result in the difference in the plant size, and its fuel consumption, as the oil-fired TPPs tends to be very small in capacity. Moreover, compared to the oil-fired TPPs, the average emissions of CH_4, CO, and NMVOC from the gas-fired TPPs were 13, ~44, and ~60 times higher than the oil-fired TPPs, respectively. As these gas-fired TPPs will continue to operate till 2020, this relationship will likely to be maintained until the replacement of new liquid natural gas boilers to the existing gas-fired units (ERIA, 2017). Among the oil-fired TPPs, emissions from *Hiep Phuoc* was formerly highest. However, due to the recent conversion from oil-fired to gas-fired boiler, it is no longer to be considered as an oil-fired TPP. Currently, *Thu Duc* is the highest as it consumed more fuels in 2015 than other oil-fired TPPs. It is expected that these oil-fired TPPs will be decommissioned before 2025.

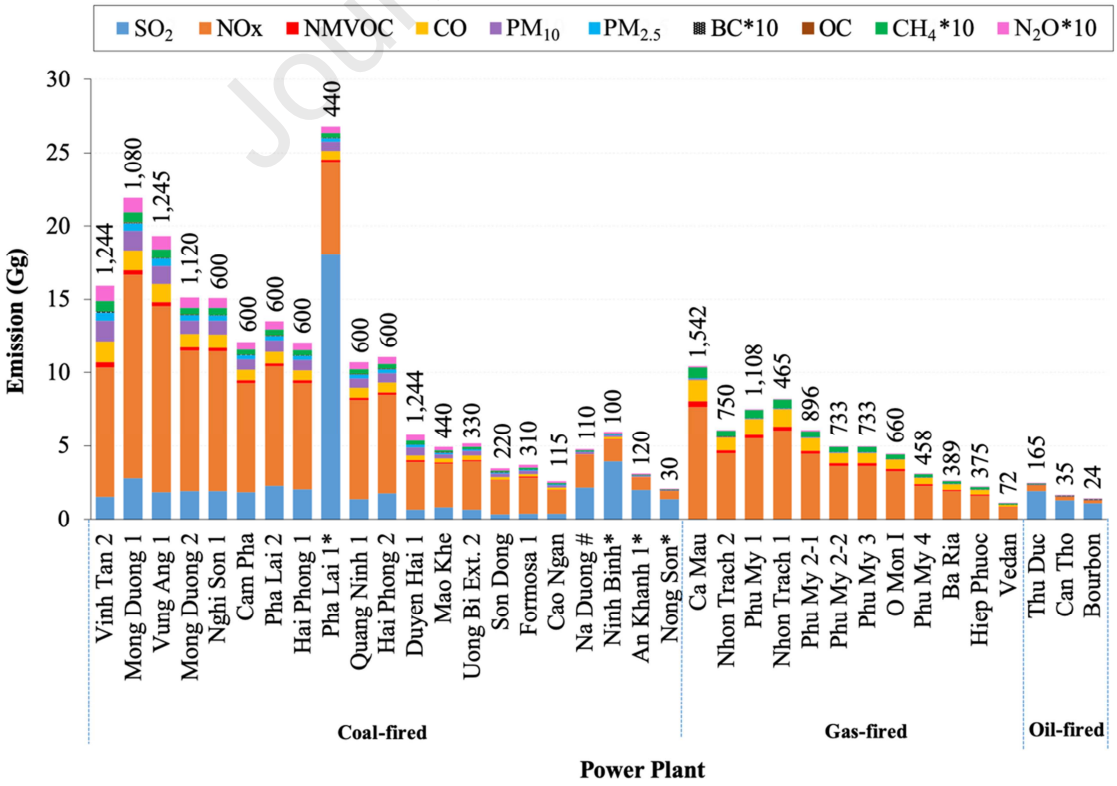


Fig. 4. Emission from different thermal power plants in 2015; *No emission control for SO_2; #Using lignite for combustion).

3.4 Regional emission shares

The regional emission shares in 2015 are presented in Fig. 5. Among the six major regions in VN (Fig. 1), the emission shares of the Red River Delta and Southeast region are significantly higher than in other regions. The differences in the regional emission shares largely depend on the number and types of TPPs found in each region. The largest shares of CO_2, N_2O, SO_2, NOx, PM_{10}, $PM_{2.5}$, BC, and OC are from the Red River Delta (34-69%) as the coal-fired TPPs are concentrated in the region. The combination of the Red River Delta and Northern midlands and mountains area, which provides electricity to the Hanoi areas, contributes to more than 78% of SO_2. Similar findings have also reported by Huy and Oanh (2017) for 2010 EI. In terms of CO, NMVOC, and CH_4, the Southeast region has similar shares (33-35%) of emissions as the Red River Delta in 2015. This is reasonable as the majority of the gas-fired TPPs is located in the Southeast region, providing steady electricity to Ho Chi Minh City areas. The region is also found to be the second-largest shares of CO_2, and NOx. The second-largest shares of SO_2, PM_{10}, $PM_{2.5}$, BC, OC, and N_2O are from the North central and Central coastal region, where multiple new coal-fired TPPs were commissioned in the last 5 years. This region is also found to be the third-largest shares of NOx, NMVOC, CO, CO_2, and CH_4. As local VN coals are no longer sufficient to support the increasing demand of coals, locating TPPs in the coastal areas provides a cheap and convenient way of transporting imported coals to the plants. As these power plants spread along the long coastline of VN, it makes less concern on air pollution problem (VTC, 2019).

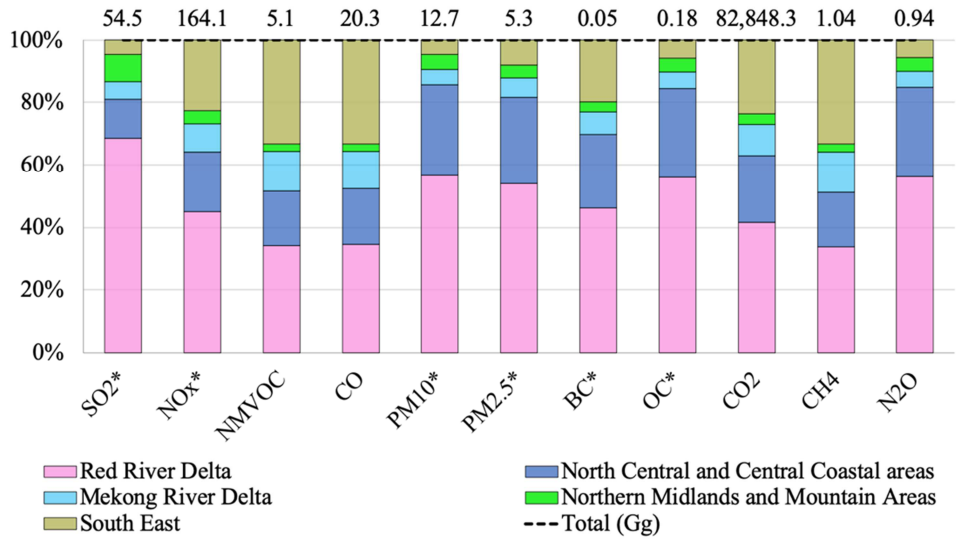


Fig. 5. Regional emission share from thermal power plants in 2015. *Emission share after considering the emission control efficiency of control devices installed in coal-fired power plants.

4. Conclusions

The unprecedented growth in urban population, rapid economic growth, industrial development, and changes in energy economy are heavily responsible for the degradation of air quality in VN. The growth of TPP emissions from 2010 to 2015 ranged 9% to 119%, while a reduction of 19% has been observed for SO_2 due to the decommissioning of old oil-fired TPPs. With the implementation of APCD for major TPPs, the estimated emissions in 2015 are 164.11 Gg NOx, 54.53 Gg SO_2, 12.65 Gg PM_{10}, 20.26 Gg CO, and 5.13 Gg NMVOC, and the results (best estimates) are comparable to other published regional EI inventories. As the refinements from using local information (e.g., better fuel consumption and APCD data), it greatly reduces the estimates of SO_2, and PM emissions compared to other inventories. For the comparison of 2010 inventories, our results reveal that the international EIs failed to provide an accurate emission estimation for Vietnam as these inventories had assumed either no or limited air pollution controls, which was deviated from the reality. The low projected growth of fossil fuel consumption (e.g., power, transportation, manufacturing industries, etc.) from 2010 to 2015 in the global inventory also caused an underestimation of 2015 air emissions for Vietnam. It should be aware that our findings not only be useful for the future development of global and regional inventory for this region but also be used for understanding the uncertainties of climate and air quality simulations that had already applied those global EIs.

Compared to different categories of TPPs, the emissions of coal-fired TPPs are highest for most of the pollutants and have been concentrated in the north part of VN, while the gas-fired TPPs are clustered in the south with substantial emissions of CH_4 and VOCs. With the recent upgrades of the TPP system in VN, oil-fired TPPs are slowly being retired and convert into gas-fired TPPs. Limited SO_2 and NOx APCDs have been found in the existing TPPs. The VN government should consider retrofitting FGD/SFGD and SCRs to their TPPs, and moreover, to require all newly designed coal-fired TPPs should equip with FGD/SFGD and SCRs. It is recommended that the VN government should invest more in the renewable energy sector to reduce the heavy reliance on coal. It will not only help to reduce local air pollution but also help to tackle global warming and climate change issues.

5. Acknowledgements

The work was supported by the Research Grants Council (RGC) of Hong Kong via the General Research Fund (GRF) (Reference No. CityU 21300214 (9048013)).

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Highlights

- A bottom-up emission inventory for Vietnam power plants has been developed.
- Emissions growth of pollutants is estimated between +9% to +119% from 2010-2015.
- SO_2 emission have been reduced by ~19% from 2010 to 2015.
- Emission overestimation has been observed in global inventories for Vietnam.

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: