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Evaluation of Vietnam air emissions and the impacts of revised power development plan (PDP7 rev) on spatial changes in the thermal power sector

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ABSTRACT

Emission reduction in the thermal power sector is highly prioritized by the Vietnam government to combat climate change and air pollution. This study developed an updated 2019 Vietnam emission inventory (base-year) using a bottom-up approach and the future emission projections up to 2030 to evaluate the potential emission changes due to regulatory measures from the Power Development Plan 7 Revision (PDP 7 rev). Results show that emission contributions from coal-fired thermal power plants (TPP) to total emissions (i.e., SO_2, NOx, PM_{10}, and $PM_{2.5}$) ranged from 67.8% to 97.0% in 2019, and the annual emissions of global warming potential are expected to increase more than double (i.e., 335.8 Tg CO_2e) due to the increased coal-fired TPPs between 2019 and 2030. A gradual reduction in NOx is anticipated from 2025, resulting from the scheduled installation of selective catalytic reduction systems, which would trigger a shift of NOx hotspots from Northern Midland to North Central in 2030. Overall, the study illustrated that even though NOx emissions are expected to decrease in 2030 due to effective pollution controls, carbon emissions would still escalate due to the intensive use of coal-fired TPPs. It poses a challenge to Vietnam's future carbon neutrality process.

CRediT author statement

Shimul Roy: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing-original draft. **Yun Fat Lam:** Conceptualization, Investigation, Visualization, Writing - review & editing. **Johnny C.L. Chan:** Supervision, Writing - review & editing. **Ngo Tho Hung:** Data curation, Writing - review & editing. **Joshua S. Fu:** Writing - review & editing.

1. Introduction

In Vietnam, emissions of short-lived climate pollutants (SLCP) and greenhouse gas (GHG) have increased significantly, driven by the rise in electricity demand, rapid urbanization, and industrial growth from human activities. Heavy reliance on fossil fuels not only leads to deterioration of air quality in the country but also contributes to global warming (Hai and Kim Oanh, 2013; Huy and Kim Oanh, 2017; Lasko

Abbreviations: APCD, Air Pollution Control Device; BC, Black Carbon; CO_2e, CO_2 equivalent; EI, Emission Inventory; EOC, Emission and Operational Control; EF, Emission Factor; FGD, Flue Gas Desulfurization; GHG, Greenhouse Gas; GWP, Global Warming Potential; HP, Historical Projection; LNB, Low NOx Burner; MRD, Mekong River Delta; NCC, North Central and Central Coastal areas; NMM, Northern Midlands and Mountain areas; NCV, Net Calorific Value; OC, Organic Carbon; PDP, Power Development Plan; RRD, Red River Delta; SCR, Selective Catalytic Reduction; SE, South East; SLCP, Short-lived Climate Pollutants; TPP, Thermal Power Plant.

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et al., 2018). Controls of anthropogenic air emissions from various sectors (e.g., thermal power, road transportation, etc.) have become an important agenda for the Vietnam government, especially after signing the Paris agreement (COP21), which committed to reducing GHG emissions in 2030 (NDC, 2015). In the last five years, the ministry of natural resources and environment has implemented rigorous regulations on controlling air pollutants (i.e., SO_2, NOx and $PM_{2.5}$) in the major industrial sectors (Republic of Vietnam - The 14th National Assembly, 2020; MONRE, 2019). The thermal power sector was treated as the key industry for aiming air pollution and carbon emission reductions (Amann et al., 2018).

With the rapid increase in electricity consumption in the last decade, a large number of fossil fuel-fired thermal power plants (TPP) (mainly coal-fired) has been built (36 TPPs up to 2015) (Huy and Kim Oanh, 2017; Roy et al., 2021). As of 2018, the electricity production from coal-fired TPPs (41%) has overtaken hydropower (39%) and has become the leading source of electricity supplies (EVN, 2018). Moreover, it is projected that the growth from the fossil fuel-fired TPPs will be much faster than hydropower, resulting in a decreasing share of hydropower to total electricity generation (i.e., 12.4%). The reliance on coal-fired TPPs will intensify and become more apparent in the next ten years. Although the revised Power Development Plan 7 (PDP7 rev) issued in 2016 has mandated a small fraction of renewable energy to be included in the future energy mix, the amount is relatively small, not providing sufficient improvement on local air pollution. At last, in PDP7 rev, the coal-fired TPPs are expected to contribute about 53.2% of electricity generation, while hydropower will reduce to 15.5% by 2030 (Decision No. 428/QD-TTg, 2016). Hence, it is important to evaluate the emission impact from the coal-fired TPPs to safeguard the environment and reduce the consequence of global warming.

The issue of air pollution from coal-fired TPPs is not a new topic. The lack of proper regulatory controls causes substantial emissions and deteriorates air quality and the environment (Du et al., 2020; Shen et al., 2019). Improving the efficiency of power generation and installing/retrofitting emission control technologies from all new or existing coal-fired TPPs are urgently needed (ERIA, 2019). In Vietnam, the revised 'National Technical Regulation on Emission of thermal power industry (i.e., QCVN 22-MT: 2015/BTNMT), the replacement of QCVN 22: 2009/BTNMT regulation, has been adopted, which requires all TPPs to install or retrofit the best available technologies for controlling particulate matter (PM), NOx and SO_2 (Decision No. 428/QD-TTg, 2016; NDC, 2015; PV Power, 2017). These updates essentially lead to significant changes in current emissions and future projections of Vietnam's GHG and SLCP emissions. Until now, no study or inventory has been developed to address the potential emission discrepancies on the future emission projections caused by the regulation in the approved PDP (i.e., PDP7 rev). Moreover, the impacts on the spatial emission changes have not been studied elsewhere. Hence, this study developed a new emission inventory (EI) with a projection for the 2030 Vietnam's TPPs and evaluated the effects of approved/committed regulatory measures on future air and climate emissions, identifying potential issues associated with the planned expansion of TPPs reported in the PDP7 (rev).

2. Materials and methods

A new EI using 2019 emission activity data was developed and applied to evaluate the effect of new thermal power regulation on the future (2020, 2025, and 2030) emission projections in Vietnam. Three scenarios were considered, which include (1) Historical Projection (HP), (2) Emission and Operational Controls – Scenario A (EOC-A), and Emission and Operational Controls – Scenario B (EOC-B). The HP scenario applied the emission rate of change based on the actual change from 2010 to 2015 without considering any new thermal power regulations or new TPPs. This scenario is intended to mimic the emission estimates from historical projections, which is commonly done in previous air quality studies for modelling Southeast Asia emissions. The EOC-A and EOC-B adopted the planned thermal power plant growth from the Vietnam government with different emission controls, operational constraints, and pace of implementation. The emission control requirement of EOC-B (i.e., QCVN 22-MT: 2015/BTNMT with PDP7 rev) is different from the EOC-A (i.e., QCVN 22: 2009/BTNMT). A detailed description of each scenario can be found in Table S1. In Vietnam, TPPs are mainly distributed in five regions, including Red River Delta (RRD), Northern Midlands and Mountain areas (NMM), North Central and Central Coastal areas (NCC), South East (SE), and Mekong River Delta (MRD) (Fig. S1 in Supporting Information). As of 2019, a total of 43 TPPs were in operation, including 28 coal-fired, 3 oil-fired, and 12 natural gas-fired, in which seven coal-fired TPPs (total capacity of 5595 MW) were commissioned within the last three years. The newly-operating TPPs are generally clustered in the NCC region. These TPPs are equipped with super-critical pulverized coal boilers and high-efficiency emission control technologies.

2.1. Activity data and emission estimation method

To estimate TPP emissions using a bottom-up approach, activity data are indispensable. This study attempts to use all local activity data whenever it is available. Parameters such as the location of TPPs, commissioning year, plant's capacity in MW, annual fuel consumption, total electricity generation in GWh, and Net Calorific Value (NCV) of fuels were collected from multiple local sources (Table S2). In the case of local data unavailable, regional and global sources were supplemented (IPCC, 1996, 2006; UN Environment, 2017; UNFCCC, 2019a, b). Table S2-S3 summarizes the activity data for TPPs operated in 2019. The activity data for the operating, permitted, and under-construction TPPs used in the emission projection are presented in Table S4. Emissions for the 2019 base-year and the projected years (i.e., 2020, 2025, and 2030) in PDP7 (rev) were estimated using the annual fuel consumption by individual TPPs, NCV of fuels, emission factor (EF) relevant to emission species, and emission control efficiency of the air pollution control device (APCD) or system of the TPPs (e.g., Electrostatic Precipitator, Flue Gas Desulfurization – wet scrubber (FGD), Dry Sorbent Injection, Sea-water FGD, Low NOx Burner (LNB), and Selective Catalytic Reduction (SCR) for controlling SO_2, NOx, and PM species. Details of the emission calculation method can be found in our previous work (Roy et al., 2021).

2.2. Emission factor

For EI development, EFs were gathered from wide-ranging regional and global sources (APEG, 1999; Bond et al., 2004; EMEP/EEA, 2016; IPCC, 1996, 2006; Kato and Akimoto, 1992; Kupiainen and Klimont, 2007; Reddy and Venkataraman, 2002; Streets et al., 2003; Streets et al., 2001; UNEP, 2012; USEPA, 1995). Table S5 presents the EFs used for estimating emission range and best emission estimation. Note that in this study, the EFs of SO_2 were calculated using the plant-specific sulfur content of the fuel, sulfur retention in ash (αs), and NCV of fuels (Table S6) for attaining accurate SO_2 emission results. The detailed calculation method can be found in our previous work (Roy et al., 2021). The calculated EFs of SO_2 for each category of TPP are presented in Table S7-S9.

2.3. Estimation of emission range and uncertainty analysis

To better reflect the uncertainty of emission results, all emissions are presented as selected, low, and high estimates for each pollutant. The emission range for each pollutant is produced based on the ranges of EFs (Table S5). The variation in emission estimation (i.e., low and high estimates) compared to the best emission estimation reflects the uncertainty. The detailed calculation method for uncertainty analysis can be found in our previous work (Roy et al., 2021). Generally, uncertainties in EIs for TPPs varied considerably due to different factors, including activity data, sources of EFs (i.e., local, regional, global), EI approach (e.g., top-down or bottom-up), and types of emission control technology used for SO_2, NOx, PM controls and their control efficiencies, as reported in several studies (Chen and Meng, 2017; Kurokawa et al., 2013; Pham et al., 2008; Streets et al., 2003). Note that in this study, uncertainty in EI was analyzed based on the range of EFs but not based on the activity data. As activity data were collected from local sources, low uncertainties were assumed. The Intergovernmental Panel on Climate Change (IPCC) stated that the use of local activity data in EI results in low uncertainty (±5%) (IPCC, 2006). However, EFs used in emission estimation were gathered from multiple regional and global sources (mentioned earlier), as local EFs for TPPs were unavailable. Therefore, variation in EFs is expected to be the major source of uncertainties in emission estimation.

2.4. Estimation of global warming potential

The Global Warming Potential (GWP) of emissions in CO_2 equivalent (CO_2e) of GHGs and different SLCPs released from the TPPs were calculated, as these have significant climate impacts. The basic equation for estimating the GWP of emissions is presented in Equation (1), where the total emission of individual species is multiplied by the corresponding GWP. This study has prioritized using the GWP reported for Southeast Asia (Koch et al., 2007). Wherever not available, other reported values have been considered. These include GWP values reported for tropical regions (Naik et al., 2005), GWP for Asia (Berntsen et al., 2005), IPCC Fourth Assessment Report (AR4) values (Solomon et al., 2007), and the GWP reported for the global context (Collins et al., 2002).

$$GWP\ of\ emission\ (CO_2e)_{i,j,k} = \sum Em_{i,j} \times GWP_i \tag{1}$$

where *Em* is the emission of species *(i)* from the category of TPP *(j)* in the year *(k)*; GWP is the global warming potential of emission species *(i)* in a 20-yr time horizon.

2.5. Emission projections for TPPs

The Vietnam government has approved the revised power development plan 2011–2020 with the vision to 2030 under the PDP7 rev, aiming to boost electricity generation with minimal environmental impacts through policy interventions in the thermal power sector (Decision No. 428/QD-TTg, 2016). This study projected emissions of multiple pollutants and the GWP of emissions (in CO_2e) for the TPPs for different future years (i.e., 2020, 2025, and 2030). Different key policy interventions such as technological improvements in the APCD system and operational requirements were included according to QCVN 22: 2009/BTNMT, QCVN 22-MT: 2015/BTNMT, and PDP7 (rev) (MOIT, 2020). We are particularly interested in future NOx emission and its control, and the change of spatial distribution in Vietnam. Table S1 summarizes the factors that have been considered for the emission projections under different scenarios, including the historical projection (i.e., HP) scenario, and emission and the operational control scenarios (i.e., EOC-A and EOC-B).

3. Results and discussion

3.1. Base-year emission inventory

Table 1 summarizes the EI results for the TPPs in the 2019 base-year. In 2019, the average consumption of coal, oil, and natural gas was 551.00, 252.44, and 167.21 tonnes per kWh of electricity generation, respectively. Similar to the 2010 EI (not shown) (Huy and Kim Oanh, 2017; Roy et al., 2021) and 2015 EI (Roy et al., 2021), the coal-fired TPPs contributed much higher emissions than the oil-fired and natural gas-fired TPPs. The 2019 emissions to overall emissions from the coal-fired TPPs were 67.8%, 80%, 97.0%, and 93.6% for SO_2, NOx, PM_{10}, and $PM_{2.5}$, respectively. In contrast, emissions from oil-fired TPPs and gas-fired TPPs only ranged from 0.5% to 32.0% and 0.1%–26.2%, respectively. This study shows that the increased number of coal-fired TPPs (i.e., 36 to 43) between 2015 and 2019 has boosted the overall electricity generation capacity from 20,153 to 27,033 MW in the thermal power sector and resulted in an increase in the overall CO_2, CH_4, N_2O, NOx, CO, NMVOC, and PM emissions. The observed emission growths ranged between +36.9% and +124.8% (Table 1). For GWP, the total CO_2e also showed an increasing trend from 87,549 Gg in 2015 to 158,488 Gg in 2019. The increase in CO_2e compared to the 2014 value (i.e., 54,502 Gg) reported in MONRE (2019) was +60.6% for 2015, and 190.8% for 2019, indicating a large increase in CO_2e from coal-fired TPPs in those five years. As the Vietnam national power development authority has already set out the plan to construct more coal-fired TPPs in the near future under PDP7 (rev), it is expected that more emissions will be released from the thermal power sector even with the planned emission control measures are in place (Decision No. 428/QD-TTg, 2016).

The decision to build more coal-fired TPPs over other modes of power generation could be related to energy security. With the intense fluctuation of natural gas prices in recent years, investing in cleaner fuels like natural gas in the TPP sector may be risky and hinder economic development (VPI, 2016). With oversea coals available from various supplies in different countries (e.g., Indonesia, Australia etc.) at a relatively low price compared to natural gas, it provides a buffer for price fluctuation. In terms of emission uncertainty, Fig. S2 and Table S10 show the low and high estimates of the emission data. The ratio of the difference between these estimates to the best estimates represents the

Table 1
2019 Emissions from TPPs in Vietnam.

Emission species	2019 Emission, Gg/yr (Emission per kWh electricity generation, g/kWh)			Total emission (Gg/yr)		Rate of emission change (%) (2019–2015)
	Coal-fired	Fuel oil-fired	Natural gas-fired	2019	2015[#]	
CO_2	126,058 (1194)	1398 (886)	23,476 (464)	150,931	82,848	+82.2%
CH_4	1.30 (0.01)	0.05 (0.03)	0.42 (0.01)	1.77	1.04	+70.1%
N_2O	1.94 (0.02)	0.011 (0.01)	0.04 (0.00083)	2.00	0.94	+112.4%
SO_2*	50.64 (0.48)	23.89 (15.15)	0.11 (0.0021)	74.64	54.53	+36.9%
NOx*	193.68 (1.83)	4.50 (2.85)	43.94 (0.87)	242.12	164.11	+47.5%
CO	23.28 (0.22)	0.27 (0.17)	8.37 (0.17)	31.92	20.26	+57.6%
NMVOC	6.47 (0.06)	0.04 (0.03)	2.09 (0.04)	8.60	5.13	+67.7%
PM_{10}*	26.47 (0.25)	0.46 (0.29)	0.37 (0.01)	27.30	12.65	+115.8%
$PM_{2.5}$*	10.49 (0.10)	0.35 (0.22)	0.37 (0.01)	11.21	5.27	+112.8%
BC*	0.09 (0.001)	0.018 (0.011)	0.009 (0.00018)	0.112	0.05	+124.8%
OC*	0.37 (0.003)	0.007 (0.004)	0.008 (0.00016)	0.38	0.18	+112.7%
GWP (CO_2e)	132,663.5	270.4	25,554.4	158,488.3	87,549	+81.0%

Notes: * PM control efficiency ranges between 98.4% and 98.5% (CEMM, 2019); Low NOx burner with 30% removal efficiency (USEPA, 1995); SCR with 58%–88.4% removal efficiency, and FGD control efficiency for SO_2 ranges 90%–95% (CEMM, 2019); Grey colour indicates APC has been applied; [#] EI results of our previous work for 2015 emission base-year (Roy et al., 2021), which has been incorporated to show the emission growth rate.

uncertainty in emission estimation.

In this study, the uncertainty (in percent) ranged from −95.8% to +31.8% in 2019. The most considerable uncertainties were observed in Organic Carbon (OC) and Black Carbon (BC) (i.e., −95.8% and −85.1%, respectively), attributed to the usage of EFs from limited international sources and small emission amounts. For criteria pollutants, the highest and second-highest uncertainties came from NOx (i.e., −17.5% to +31.8%) and SO_2 (−26.3% to +25.7%), respectively, which were similar to the 2015 results. These uncertainties were mainly caused by the uncertainty of EFs for the coal-fired TPPs, extracted from global and regional (i.e., Asia) EIs (EMEP/EEA, 2016; IPCC, 2006; Kato and Akimoto, 1992). Detailed emission comparisons with different regional inventories (e.g., EDGAR, GAINS-Asia, MIX, and GPED) for the 2015 base-year can be found in Roy et al. (2021).

3.2. Effects of regulatory measures on current emissions

The emissions of individual TPPs in different regions (i.e., RRD, NCC, MRD, SE, and NMM) in Vietnam have been presented in Fig. 1 and Table S11. It reveals that there were multiple high emission polluters clustered in the MRD, RRD, and NCC regions. These include *Duyen Hai 1 (I&II)* and *Duyen Hai 3 (I&II)* from MRD, *Mong Duong 1 (I&II)* and *Quang Ninh (I&II) from RRD, and Vung Ang 1 (I&II) and Vinh* Tan *4 (I&II)* from NCC. In general, these coal-fired TPPs had a design capacity of over 1000 MW and were built between 2014 and 2018 under the rule of the National Technical Regulation on Emission of thermal power industry - QCVN 22: 2009/BTNMT, which only high efficient PM and SO_2 APCDs (i.e., 99.5% and 97.75%, respectively), and low efficient NOx APCD (i.e., 30%) were required. Overall, NOx contributed the largest portion of the overall emission in these coal-fired TPPs. It should also be noted that the Vinh Tan 4 extension had only operated for three months in 2019. The actual emissions, as well as the estimated emissions at the fully operating condition, were presented in Table S11.

For the gas-fired TPPs, there were 12 TPPs, mainly located in the MRD and SE regions. The two largest gas-fired polluters are *Ca Mau and Phu My 1,* with a capacity larger than 1000 MW. As NOx emission in the gas-fired units is, in general, lower than in the coal-fired TPPs, no APCD is required under the current regulation. Finally, for oil-fired TPPs, the two largest polluters (i.e., *Thu Duc* and *Can Tho*) were located in SE and MRD regions. These facilities contributed extremely high SO_2 emissions (i.e., 12.1 Gg and 10.6 Gg, respectively) to the overall inventory, but with small energy generation (i.e., capacities of 279 MW and 185 MW). Since these oil-fired TPPs are in the process of decommissioning, no APCD requirement is imposed under the current regulation. Overall, the total emissions of gas-fired TPPs were higher than the oil-fired TPPs (except for SO_2), as many gas-fired TPPs were in operation with a larger capacity (Fig. 1) compared to the oil-fired TPPs (i.e., 12 vs 3).

Besides identifying high emission polluters, Fig. 1 also sheds light on understanding the influence of imposing emission control measures on coal-fired TPPs. From our previous work (not shown), the highest SO_2 emission in 2015 was from *Pha Lai 1* coal-fired TPP in RRD, attributed to the uncontrolled condition (Roy et al., 2021). Operating TPPs without SO_2 APCD was previously permissible to some TPPs (built at the early stage, i.e., 1977–1983 of power sector development) under the National Technical Regulation on Emission of thermal power industry - QCVN 22: 2009/BTNMT, which had been identified as the major loophole of the regulation (PV Power, 2017). As the revised National Technical Regulation on Emission of thermal power industry - QCVN 22-MT: 2015/BTNMT was implemented in 2017, all coal-fired TPPs without PM and SO_2 controls must install the modern APCDs, where no exemption was given to any TPPs (Decision No. 428/QD-TTg, 2016). As a result, the electrostatic precipitator with dry sorbent (limestone) injection technology was introduced to *Pha Lai 1* in 2018, and the annual emission of SO_2 (i.e., 17.96 Gg in 2015 level) was drastically reduced to 1.39 Gg in 2019 (NDC, 2015). Similar situations have also been observed at *Ninh Binh, Nong Son,* and *An Khanh* TPPs, with a comparable percentage of SO_2 reductions (Roy et al., 2021). Among the desulfurization processes, TPPs equipped with FGD contributed more SO_2 reduction than those plants using dry sorbent (limestone) injection and Seawater FGD under the revised regulation, as shown in Fig. 2.

The overall SO_2 reductions from the FGD, dry sorbent (limestone) injection, and seawater FGD implementation were 23.7 Gg, 9.3 Gg, and 17.6 Gg, with relative contributions of 46.9%, 18.3%, and 34.8% to the overall reduction, respectively. The percentage contribution from FGD (i.e., 46.9%) in Vietnam is similar to the value (i.e., 54%) reported by Liu et al. for China, where considerable SO_2 reduction was achieved because of the extensive installation of FGD (Liu et al., 2015). In summary, the calculated annual SO_2 emission for coal-fired TPPs in 2019 (i.e., 50.64

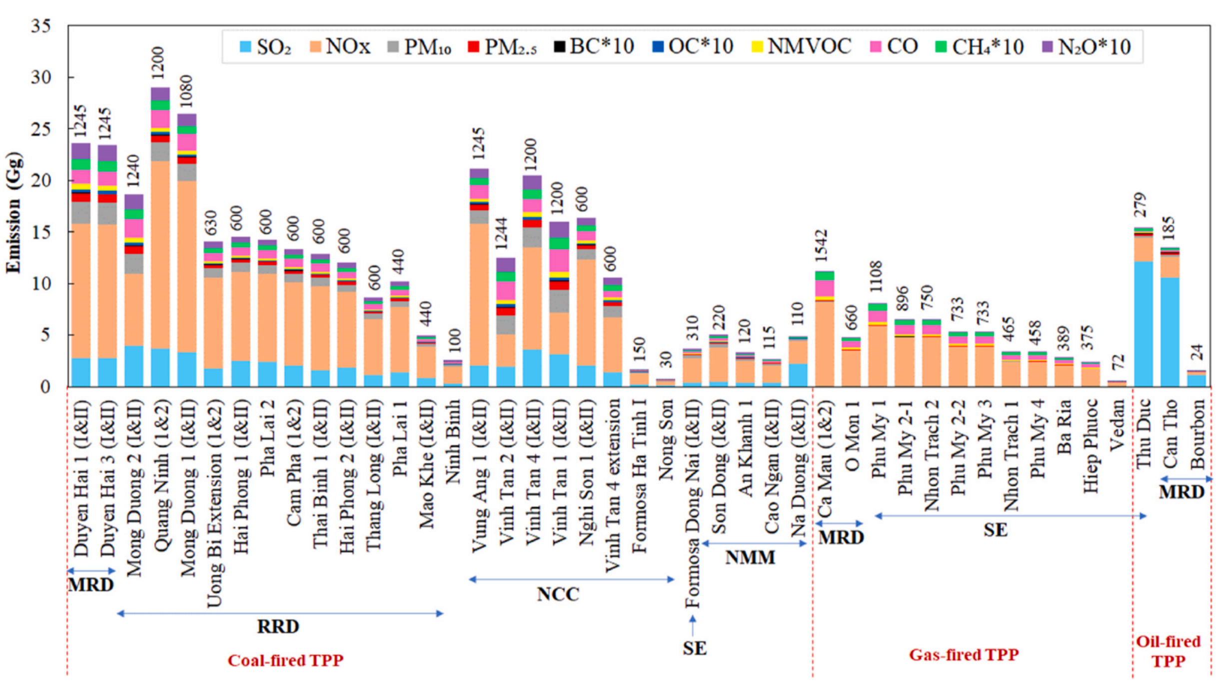

Fig. 1. Emissions of TPPs in different regions of Vietnam in 2019; Values on the top of each bar represent the design capacity (MW) of the TPPs.

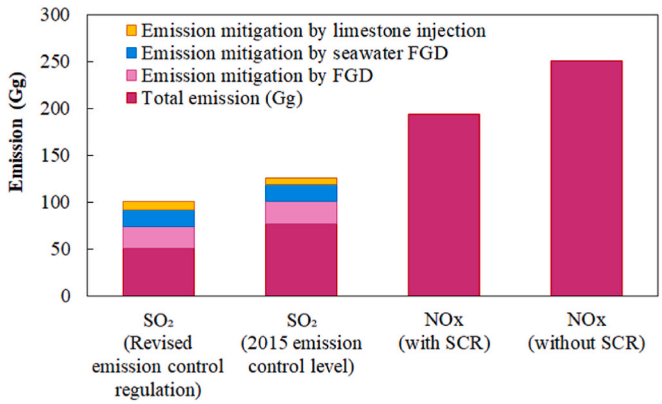

Fig. 2. Effects of regulatory measures on emission reduction in 2019.

Gg) for Vietnam was 35% lower than the value (i.e., 77.49 Gg) estimated considering the 2015 emission control level. The result reflects the importance of updating the existing 2015 EI to the 2019 level before performing the future projections.

The advantage of updating the existing inventory to the 2019 base-year not only captures the changes made in the TPPs that have just installed the retrofitted APCDs but also allows more up-to-date and accurate information (e.g., control efficiency) from the newly built TPPs to be incorporated into the development. For example, *Vinh* Tan *2* (1244 MW) was equipped with LNB and SCR for NOx removal. From our previous work, we had assumed a generic value of 60% as the removal efficiency for all SCR with LNB, which had deviated from the actual efficiency by about 28% (88% for actual). Such difference had resulted in an overestimation of 5 Gg of NOx in *Vinh* Tan *2* (Roy et al., 2021). When we are comparing the difference between *Vinh* Tan *2* (1244 MW) and *Nghi Son 1* (600 MW), it is easy to prejudge that the overall emission in *Vinh* Tan *2* should be larger than in *Nghi Son 1* since the capacity of *Vinh* Tan *2* is double of *Nghi Son 1*. However, in our 2019 inventory, this is not the case as *Nghi Son* 1 has equipped only LNB, which has much lower removal efficiency (i.e., 30%) than the one used in *Vinh* Tan *2* (i.e., 88% for SCR with LNB) as reflected in Fig. 1. Among the NOx control technologies, The LNB and LNB with SCR are the most common control devices used in the newly built coal-fired TPPs under the PDP7 (rev). The efficiency of LNB is around 30%, while the LNB with SCR ranges between 58% and 88.4% (Table S12). The impact of implementing the revised National Technical Regulation on Emission of thermal power industry - QCVN 22-MT: 2015/BTNMT has resulted in a 22.8% reduction of overall NOx emission in 2019. At last, as there was a wide range of values for the efficiency of NOx APCDs, taking the most updated and accurate inputs would be important for updating the emission inventory.

3.3. Projected emissions and effects of regulatory measures in 2030

3.3.1. Projected emissions from TPPs

In Vietnam, energy demand is expected to increase significantly from 2015 to 2030. According to PDP7 rev, coal-fired TPPs will be the primary growth sector for meeting the future electricity demand. It is projected that the share of electricity generation from coal-fired TPPs will increase from 49.3% (i.e., 131,000 GWh) in 2020 to 53.2% (i.e., 304,000 GWh) in 2030, and the amount of coal consumed will rise from 63 million tonnes in 2020 to 129 million tonnes in 2030 (Decision No. 428/QD-TTg, 2016). Table 2 shows the estimated emissions (i.e., 2020, 2025, and 2030) from three projection scenarios. Please note that the study had assumed the full operation condition for all TPPs in the base year estimation (i.e., 2019), which allowed a more accurate estimate of the future emissions (e.g., 2020–2030). In historical projection - HP, emissions were calculated based on the rates of emission change (−4% to 24%) between 2010 and 2015 (i.e., not 2010 to 2019), mimicking the projection estimates from the gridded regional/global inventories. For the EOC-A and EOC-B scenarios, we adopted the information-rich bottom-up approach by including all planned and committed power development from the PDP7 (rev) and COP21. It should be mentioned that the projected ranges of total coal consumption of the newly-commissioned, permitted, and under-construction coal-fired TPPs are 6.09 to 6.56, 59.58 to 64.16, and 68.23 to 73.48 million tonnes in 2020, 2025, and 2030, respectively under the EOC-A and EOC-B scenarios (Fig. S3).

In general, emission projections from HP are much lower than from the EOC-A and EOC-B scenarios. For instance, the projected CO_2 (i.e., 226,013 Gg) and GWP (i.e., 241,016 Gg CO_2e) emissions in 2030 from HP are nearly 1/3 lower than the projected values reported in the EOC-A and EOC-B scenarios. These discrepancies are mainly caused by the differences in the projected electricity generation between the HP (+12%) and EOC scenarios (+98%), which triggered large differences in future emissions. As the HP scenario assumed the rate of change in the electricity generation in the future conditions is the same as the emission change between 2010 and 2015, which is strongly underestimated, it has resulted in large underestimations for the future conditions. The worst projection in the HP scenario is found in SO_2. For instance, a negative rate of change (i.e., significant emission reduction from retrofitting APCD to the existing TPPs) was reported in the calculation (see Table 2), which has caused the projected SO_2 emission (i.e., 24.08 Gg) 1/5 lower than the projected emissions in EOC cases (122.40–131.82

Table 2
Projected emissions (Gg) from TPPs in Vietnam.

Emis. Species	2019 (157,738.7 GWh)	2020 (181,455–195,746.5 GWh)			2025 (277,850–299,556.5 GWh)			2030 (290,522–313,184.5 GWh)		
		Scenario			Scenario			Scenario		
		HP	EOC-A	EOC-B	HP	EOC-A	EOC-B	HP	EOC-A	EOC-B
CO_2	150,931	130,564	198,830	184,470	178,288	331,440	308,840	226,013	354,480	327,810
CH_4	1.77	1.39	2.31	2.15	1.73	3.63	3.37	2.08	3.86	3.56
N_2O	2.00	2.05	2.71	2.52	3.17	4.82	4.48	4.28	5.16	4.79
SO_2	74.64	44.38	117	108.42	34.23	122.94	114.15	24.08	131.82	122.40
NOx	242.12	248.15	344.85	319.92	332.20	625.32	580.39	416.24	672.70	279.53
CO	31.92	28.13	40.47	37.53	36.01	62.26	57.76	43.88	65.93	60.74
NMVOC	8.60	7.21	11.09	10.29	9.29	18.13	16.82	11.37	19.26	17.76
PM_{10}	27.30	26.49	37.34	34.67	40.34	65.42	60.74	54.18	70.02	65.00
$PM_{2.5}$	11.21	9.88	15.38	14.27	14.50	26.17	24.30	19.11	28.00	25.97
BC	0.11	0.06	0.162	0.15	0.06	0.22	0.20	0.07	0.23	0.22
OC	0.38	0.36	0.52	0.49	0.55	0.91	0.85	0.74	0.98	0.91
GWP (CO_2e)	158,488	138,705	208,850	193,780	189,861	355,773	330,204	241,016	379,227	335,837

Note: Grey colour represents the 2019 base-year emissions; Historical projection (HP) is calculated based on the average historical rate of change between 2010 and 2015 using the 2015 base-year (Roy et al., 2021); EOC-A and EOC-B represent the emission control scenarios projected according to the 2019 base-year emissions; The values with the bracket under the specific year display the range of total electricity generation in GWh for the base-year and projected years.

Gg). Fig. 3 shows the projected NOx emissions for all three scenarios. Obviously, the linear projection approach used in the HP scenario has underestimated the growth of future NOx emissions. A similar situation is observed in the REAS v3.0 and GAINS-Asia regional inventories (i.e., lines with triangular dots), indicating that the historical projection approach may not be sufficient to project future emissions for the fast-growing countries like Vietnam. Hence, more frequent updates on gridded regional emissions using local data (if possible) may be essential to maintain and improve the accuracy of regional inventory for air quality modelling.

In EOC-A and EOC-B, nearly all projected emissions in 2030 have increased significantly as both scenarios projected a large increase in electricity generation. For example, SO_2 emissions in 2030 are estimated to be 76.6% and 64.0% higher than 2019 for EOC-A and EOC-B, while the emissions for other pollutants (except NOx) range from +104.6% to +158.4%, and +90.3% to +139.9%, respectively. In general, emissions in the EOC-B scenario are lower than in the EOC-A scenario as the maximum allowable operation hours in EOC-B are shorter. In terms of NOx, there is a large difference in emission change between EOC-A (i.e., +177.8%) and EOC-B (i.e., +15.5%) due to the implementation of advanced NOx APCD and an increase in non-hydroelectric renewable energy (8%) in EOC-B.

Fig. 3 shows the emission change in NOx and GWP. As the NOx APCD is projected to be in place after 2025, therefore, it is observed that the projected emissions for EOC-A and EOC-B in 2025 are similar in magnitude (i.e., 625.32 Gg and 580.39 Gg), respectively, while the emissions in 2030 are quite different (i.e., 672.70 Gg and 279.53 Gg). It should be aware that the expected time for SCR installation may be varied in different studies (MOIT, 2021). It could result in a discrepancy in NOx projections or trends between 2020 and 2030.

Overall, a 51.8% reduction in NOx is expected between 2025 and 2030, contributed by the NOx control committed in the QCVN 22-MT: 2015/BTNMT and PDP7 (rev). The efficiency of advanced NOx control (i.e., LNB with SCR) is expected to be between 60% and 88%, depending on the operational condition. It is promising to see that the magnitude of NOx emission in 2030 is almost the same as the value reported in the 2019 base-year (i.e., 242.12 Gg vs. 279.53 Gg) (Table 2). The success of implementing NOx APCD to all coal-fired TPPs on schedule would be essential for mitigating NOx and O_3 air pollution in Vietnam. In terms of GWP, considerable increases in carbon emissions have been observed in both EOC scenarios in 2030. The rates of change in GWP between 2019 and 2030 were estimated to be +139.3% and +111.9% for EOC-A and EOC-B, respectively. More effort to reduce future carbon emissions would be required in the thermal power sector for the Vietnam government.

3.3.2. Regional emission shares and spatial emission distribution of NOx

In Vietnam, regional emission share from the thermal power sector is expected to change significantly due to the planned commission of more coal-fired TPPs in rural areas and decommissioning small oil TPPs from the urban centre (See Fig. S1, black triangles). In 2019–2020, the most substantial emissions (i.e., 30.7%–46.6%) were released in the RRD region (i.e., the Hanoi area), with a total capacity of 8730 MW (47.5% of the total coal-fired TPP capacity in 2019, see Fig. 1). Apart from RRD, considerable emissions were released from the NCC (15.8%–34.9%) and MRD (16.2%–24.8%) regions (Fig. S4 and Table S13). Nearly all large coal-fired TPPs with a capacity greater than 600 MW were located in these three regions in 2019–2020. In terms of NOx (see Fig. 4), larger emission sources were mainly clustered in the northern provinces of RRD and NCC in 2020, within a reasonable distance from the city of Hanoi, to provide a steady electricity supply to the Hanoi capital region/metropolitan area. As all TPPs in the northern provinces were coal-fire powered with larger thermal capacities, more NOx emission was observed in the northern provinces. Another hotspot observed in Fig. 4 was the south part of NCC and the east part of SE regions, which were in the vicinity of the Ho Chi Minh metropolitan area. Lower NOx emission was observed in Ho Chi Minh metropolitan area than in the Hanoi capital region/metropolitan area due to the abundance of gas-fired TPPs in the southern region.

In 2025, the regional emission share is expected to change noticeably. For instance, the emission contribution from the NCC region is projected to be comparatively higher than the RRD for most pollutants (except for SO_2 and NOx). There will be more new TPPs commissioning in the NCC region (i.e., six TPPs with 6120 MW) than in the RRD region (i.e., four TPPs with 4080 MW) between 2020 and 2025, resulting in higher overall emissions in the NCC region after 2025. As the RRD region is already overwhelmed with coal-fired TPPs and local Vietnamese coals are no longer sufficient to support the growing coal demands for these TPPs in the future. To supply sufficient fuels for the newly built coal-fired TPPs, the government has become more reliant on imported coal from Australia and Indonesia. Selecting TPP sites along the coast of NCC provides a cheap and convenient way of transporting imported coal to these TPPs (Roy et al., 2021; S&P Global, 2020). Moreover, it allows better pollution dispersion. Another urban cluster with a significant increase in the emission share is the MRD region. In 2019, there were only two coal-fired and two oil-fired TPPs operating in the region. With the growing demand for electricity from the labouring region (i.e., Ho Chi Minh), the MRD region has become the powerhouse for the neighbouring provinces. Five additional coal-fired TPPs are expected to operate before 2025 with a total designed capacity of 6260 MW (Table S4), making the MRD region the third-largest emission region

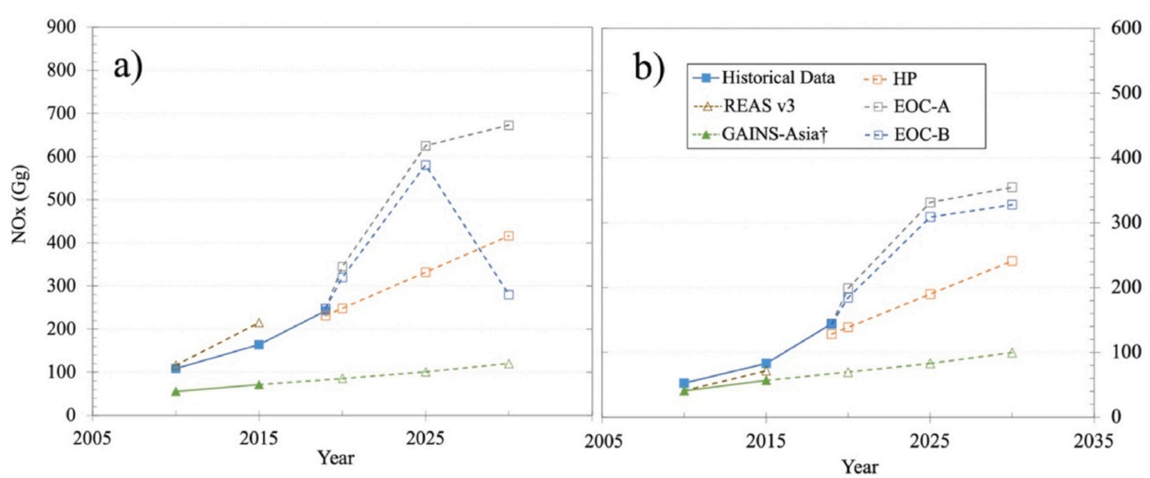

Fig. 3. Future emission projections: a) NOx and b) GWP in CO_2e. Notes: Solid and dash lines represented the reported and projected emissions, respectively. † Gross emission only covers RRD and MRD, not entire Vietnam.

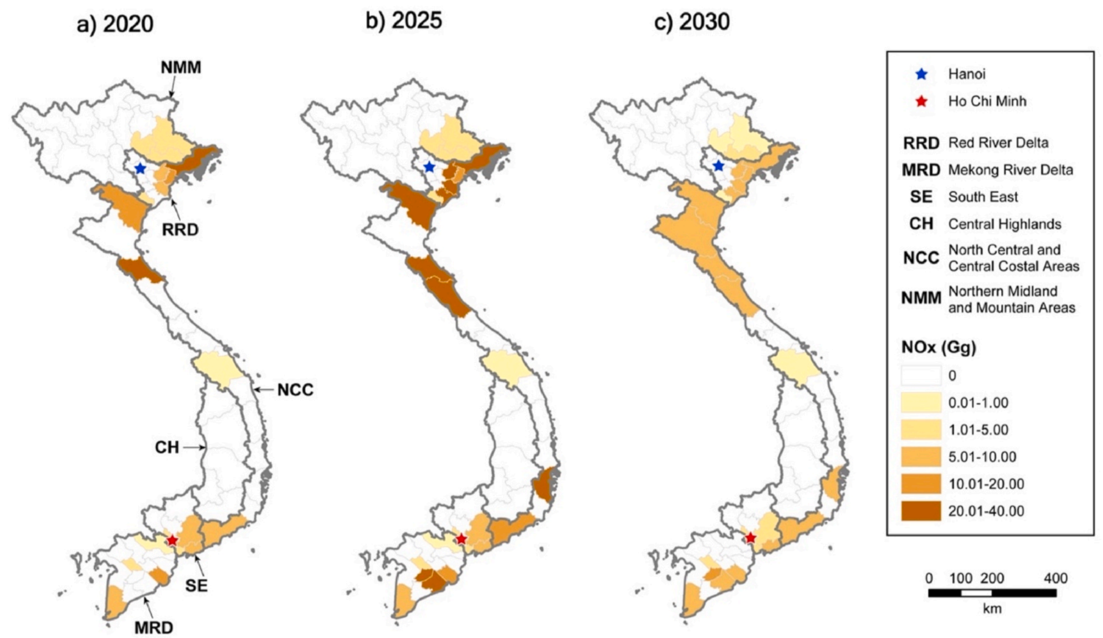

Fig. 4. Spatial emission distribution of NOx in the projected years.

(Table S13). Regarding NOx emission (Fig. 4), higher emissions are expected in the eastern part of RRD, northern and southern parts of NCC, and the eastern part of MRD in 2025. It is projected that collectively 61.69 Gg, 102.05 Gg, and 99.98 Gg of NOx will be emitted from the newly commissioned TPPs in the RRD, NCC, and MRD regions, respectively.

For 2030, a similar emission contribution is expected with the highest share from the NCC areas (i.e., 31.4%–36.8%) (Table S13). The result shows that although more TPPs will be operated in RRD than in NCC in 2030 (i.e., 18 vs. 14), the emission share from NCC is still the largest. The reason is that the majority of newly commissioned TPPs in the NCC region will be using the low-graded bituminous coals imported from Indonesia and Australia, which requires more coals to be burnt for the same amount of energy produced. As a result, higher emissions are expected. In terms of NOx, this study shows that provincial NOx emission intensity will reduce significantly by 2030 (Fig. 3). The significant NOx reduction is due to the proposed SCR installation (i.e., average emission control efficiency of 75%) by 2030 as a policy intervention to meet the 'National Technical Regulation'. As shown in Fig. 4, NOx emission intensity is expected to reduce to less than 10 Gg for all provinces, except for Hau Giang province, where multiple large TPPs (e.g., Song Hau 2 - I&II) are located. The significant changes in the spatial distribution of NOx emissions among the major regions in Vietnam, mainly the RRD, NCC, and MRD (Fig. 4), influence not only local air quality but also the prevailing downwind areas. As easterly winds are observed during the dry season from the South China Sea (Fig. S5), the change of spatial TPP emissions (e.g., increased emissions in the north of NCC) could have a stronger air quality influence on the adjoining Southeast Asian countries (e.g., Middle part of Laos, and east of Thailand). Places such as Laos's Nakai-Nam Theun National Park could receive more pollution impacts via regional emission transport in 2030.

3.3.3. *Future GWP of emissions*

Fossil fuel-fired TPPs are the significant source of GHG emissions (e.g., CO_2, CH_4, and N_2O) and SLCPs (e.g., BC, NOx, CO, NMVOC, SO_2, and OC), which have significant impacts on global warming. Table 3 presents the GWP of these pollutants' emissions (in CO_2e) from the EOC-B scenario. This study shows substantial increases (+15.5% to +139.9%) of individual net GWP between 2019 and 2030 for all GHGs and SLCPs due to the rise in the number of coal-fired TPPs. Overall, the net GWP is projected to increase more than double (111.9%) from 158.48 Tg in 2019 to 335.84 Tg CO_2e in 2030 under PDP7 (rev).

Table 3
GWP of emissions in emission base-year and projected year.

Forcing agents	GWP^{a}_{20}	Total emissions in 2019 (Gg)*	Projected emissions in 2030 (Gg)[b]	GWP of emissions (Gg CO_2e)	
				2019*	2030
Warming agents					
CO_2	1[c]	150,931	327,810	150,931	327,814
CH_4	72[c]	1.77	3.56	127.35	256.32
N_2O	289[c]	2.0	4.79	577.07	1384.31
BC	1700[d]	0.11	0.22	191.07	374.00
NOx	43[e]	242.12	279.53	10,411.10	12,019.79
CO	13[f]	31.92	60.74	415.01	789.62
NMVOC	14[g]	8.60	17.76	120.41	248.64
Subtotal 1:				162,773.49	342,886.41
Cooling agents					
SO_2	−57[d]	74.64	122.4	−4254.57	−6976.8
OC	−80[d]	0.38	0.91	−30.64	−72.8
Subtotal 2:				−4285.21	−7049.6
Total net GWP				158,488.29	335,836.81

Notes: * Base-year emissions; **a.** The GWP in a 20-yr time horizon; **b.** Projected emissions from TPP under the best emission estimation scenario (i.e., EOC-B); **c.** Solomon et al. (2007); **d.** Koch et al. (2007); **e.** Naik et al. (2005); **f.** Berntsen et al. (2005); **g.** Collins et al. (2002).

Among these pollutants, CO_2 will remain the most significant contributor to net GWP with 95% contribution in 2019 and 98% in 2030, while the contribution from the second-largest contributor, NOx, will drop significantly from 6.6% to 3.6% in 2030, benefiting from NOx control policy (Decision No. 428/QD-TTg, 2016). Our reported values are similar to the values reported by Huy and Kim Oanh in the 2010 EI (Huy and Kim Oanh, 2017).

4. Conclusions

In summary, emissions from TPPs have increased significantly in Vietnam due to the commissioning of more coal-fired TPPs to boost electricity generation. In 2019, pollutants' emissions increased between 36.9% and 124.8% compared to 2015 due to increased TPPs (i.e., from 36 to 43 by 2019), with the capacity increased from 20,153 MW to 27,033 MW. As the rates of change in emissions between 2015 and 2019 were much higher than the historical record in 2010–2015, it is necessary to update the existing 2015 inventory to 2019 before performing the future emission projections. In terms of regional emission contribution, changes were also observed between 2015 and 2019. In 2019, the RRD contributed the most significant proportion due to the abundance of coal-fired TPPs (i.e., 13 out of 28). However, due to the newly-commissioned coal-fired TPPs in the NCC region during 2015–2019, the annual emission contribution from NCC had already overtaken the lead from the RRD region. For studies where location is important (e.g., air quality modelling), the location discrepancy found in the emission projection may result in a large error in the model simulation without a better quality of emission inventory.

In the analysis of future emission projection under PDP7 (rev), it is clear that the historical projection (i.e., HP scenario) has resulted in a huge underestimation in the future emissions for most pollutants (except SO_2, where emission controls (e.g., FGD) may have been considered during the period). Hence, any climate and air emission inventories (e.g., GAINS-Asia) that have taken the same approach might suffer from a considerable underestimation in the future projection. The uncertainty level for the Vietnam estimates could be as much as 200%. In the EOC-B scenario, the future emissions are expected to have a noticeable increase with a significant change in the regional distribution. In general, a considerable increase (nearly double) in all pollutants except NOx is projected as more coal-fired TPPs are scheduled to be operated during 2020–2030. The regional contribution of air pollutants in 2030 is ranked as follows: NCC > RRD > MRD > NMM > SE. From the perspective of air pollution control policy, this study reveals a considerable level of emission reduction through the progressive implementation of the QCVN 22-MT: 2015/BTNMT in the thermal power industry, which indicates a significant step towards the future emission reduction in Vietnam's thermal power sector. For instance, a substantial NOx emission reduction is expected during 2025–2030 under the emission control scenario (i.e., EOC-B). The projected NOx emission change would be −51.8% during this period, but +87.2% between 2020 and 2025. This significant reduction is due to retrofitting SCR to all coal-fired TPPs. The results also revived the regional spatial change in emission contribution in NOx would cause a location shift on transboundary impact, possibly more air quality influence to mid-part of Laos and east of Thailand due to their proximity to NCC. It is recommended that a follow-up modelling study, which utilizes the newly developed TPP inventory, should be performed to evaluate the air quality impacts in the surrounding areas. As inventories only provide emission source information without taking into account physical (i.e., topology and meteorology) and chemical (i.e., atmospheric composition) influences on air pollution, it is necessary to use air quality models to convert emission amounts into pollutant concentrations for further air quality assessment (Li et al., 2021; Thunis et al., 2021).

In terms of climate change policy, our study concludes that by 2030, GHG emissions would increase significantly under both EOC-A and EOC-B scenarios due to increased coal-fired TPPs (i.e., 28 in 2019 to 45 in 2030). The Vietnam government has signed the COP21 agreement to reduce national GHG emissions by 2030, with the approval of more coal-fired TPPs with limited renewable energy production until 2030 in PDP7 (rev) (Roy et al., 2022). According to this study, it is a challenge for carbon emission reduction under the scenario of intense coal usage (i.e., EOC-A and EOC-B). To comply with the COP21 agreement, the government should consider not only adding more renewable alternatives (e.g., solar, wind, municipal solid wastes, etc.) in the thermal power sector but also consider the possibility of retrofitting carbon capture technology to the existing coal-fired TPPs to reduce CO_2 emission.

During the development of this paper, the draft PDP8 was released and presented at the COP26 meeting in late 2021. In this new PDP, the Vietnam government has proposed not to build more coal-fired TPPs after 2025. Moreover, they plan to adopt cleaner thermal power technology (e.g., nature gas) with fewer carbon emissions for future electricity production. These changes will directly remove some of the carbon emissions mentioned in the EOC-B case without the need of using carbon capture technology. Based on the drafted PDP8, at least two 1200 MW power plants (See Table S4) that are scheduled to be commissioned between 2025 and 2030 will be cancelled. Moreover, some planned coal-fired TPPs will be switched to natural gas-powered. As the PDP8 has not been finalized and officially released by the Vietnam government, no further assessment or comparison will be performed under this study.

Declaration of competing interest

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

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Appendix A. Supplementary data

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References

Amann, M., Klimont, Z., Truong, A.H., Rafaj, P., Kiesewetter, G., Gomez Sanabria, A., Nguyen, B., Thi, T.N., Kim, M.T., Schöpp, W., Sander, R., Gómez-Sanabria, A., Borken-Kleefeld, J., Hoglund-Isaksson, L., Wagner, F., Heyes, C., Cofala, J., Trung, N. Q., Dat, N.T., Ban, N.K., Tung, N.N., 2018. Future Air Quality in Ha Noi and Northern Vietnam. http://www.iiasa.ac.at/web/home/research/researchPrograms/air/news/Future_air_quality_in_Ha_Noi.pdf. (Accessed 3 June 2019). accessed.

APEG (The Airborne Particle Expert Group), 1999. Source Apportionment of Airborne Particulate Matter in the United Kingdom. Department on the Environment, Transport and Regions, the Welsh Office, the Scottish Office and the Department of the Environment (Northern Ireland). http://cedadocs.ceda.ac.uk/id/eprint/992.

Berntsen, T.K., Fuglestvedt, J.S., Joshi, M.M., Shine, K.P., Stuber, N., Ponater, M., Sausen, R., Hauglustaine, D.A., Li, L., 2005. Response of climate to regional emissions of ozone precursors: sensitivities and warming potentials. Tellus B 57, 283–304. https://doi.org/10.1111/j.1600-0889.2005.00152.x.

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

Chen, H., Meng, J., 2017. Emissions inventory and scenario analyses of air pollutants in Guangdong Province, China. Front. Earth Sci. 11, 46–62. https://doi.org/10.1007/s11707-016-0551-x.

Collins, W.J., Derwent, R.G., Johnson, C.E., Stevenson, D.S., 2002. The oxidation of organic compounds in the troposphere and their global warming potentials. Climatic Change 52, 453–479. https://doi.org/10.1023/A:1014221225434.

Decision no. Decision No. 428/QD-TTg, 2016. Approval of the Revised National Power Development Master Plan for the 2011-2020 Period with the Vision to 2030.

Du, X., Jin, X., Zucker, N., Kennedy, R., Urpelainen, J., 2020. Transboundary air pollution from coal-fired power generation. J. Environ. Manag. 270 https://doi.org/10.1016/j.jenvman.2020.110862, 110862-110862.

EMEP/EEA, 2016. Air Pollutant Emission Inventory Guidebook - 2016. https://www.eea.europa.eu/publications/emep-eea-guidebook-2016/emission-factors-database. (Accessed 14 June 2019). accessed.

ERIA (Economic Research Institute for ASEAN and East Asia), 2019. Viet Nam Country Report. Analysis on Energy Saving Potential in East Asia Region, ERIA Research Project Report 2007 No. 6-1, pp. 316–333. Chiba. http://cedadocs.ceda.ac.uk/id/eprint/992.

EVN, 2018. Power Supply in 2019: Many Challenges. https://www.evn.com.vn/d6/news/Cung-ung-dien-nam-2019-Nhieu-thach-thuc-6-12-22666.aspx. (Accessed 4 December 2020). accessed.

Hai, C.D., Kim Oanh, N.T., 2013. Effects of local, regional meteorology and emission sources on mass and compositions of particulate matter in Hanoi. Atmos. Environ. 78, 105–112. https://doi.org/10.1016/j.atmosenv.2012.05.006.

Huy, L.N., Kim Oanh, N.T., 2017. Assessment of national emissions of air pollutants and climate forcers from thermal power plants and industrial activities in Vietnam. Atmos. Pollut. Res. 8, 503–513. https://doi.org/10.1016/j.apr.2016.12.007.

IPCC, 1996. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (Cambridge, UK).

IPCC, 2006. Guidelines for National Greenhouse Gas Inventories. Default Values of Uncontrolled Emission Factors.

Kato, N., Akimoto, H., 1992. Anthropogenic emissions of SO2 and NOx in Asia : emission inventories. Atmos. Environ. Part A, General topics 26, 2997–3017. https://doi.org/10.1016/0960-1686(92)90291-R.

Koch, D., Bond, T.C., Streets, D., Unger, N., van der Werf, G.R., 2007. Global impacts of aerosols from particular source regions and sectors. J. Geophys. Res. Atmos. 112, D02205. https://doi.org/10.1029/2005JD007024 n/a.

Kupiainen, K., Klimont, Z., 2007. Primary emissions of fine carbonaceous particles in Europe. Atmos. Environ. 41, 2156–2170. https://doi.org/10.1016/j.atmosenv.2006.10.066.

Kurokawa, J., Ohara, T., Morikawa, T., Hanayama, S., Janssens-Maenhout, G., Fukui, T., Kawashima, K., Akimoto, H., 2013. Emissions of air pollutants and greenhouse gases over Asian regions during 2000-2008: regional Emission inventory in ASia (REAS) version 2. Atmos. Chem. Phys. 13, 11019–11058. https://doi.org/10.5194/acp-13-11019-2013.

Lasko, K., Vadrevu, K.P., Nguyen, T.T.N., 2018. Analysis of air pollution over Hanoi, Vietnam using multi-satellite and MERRA reanalysis datasets. PLoS One 13. https://doi.org/10.1371/journal.pone.0196629 e0196629-e0196629.

Li, X., Hussain, S.A., Sobri, S., Md Said, M.S., 2021. Overviewing the air quality models on air pollution in Sichuan Basin, China. Chemosphere 271, 129502. https://doi.org/10.1016/j.chemosphere.2020.129502.

Liu, F., Zhang, Q., Tong, D., Zheng, B., Li, M., Huo, H., He, K.B., 2015. High-resolution inventory of technologies, activities, and emissions of coal-fired power plants in China from 1990 to 2010. Atmos. Chem. Phys. 15, 13299–13317. https://doi.org/10.5194/acp-15-13299-2015.

MOIT (Ministry of Industry and Trade), 2020. The Socialist Republic of Vietnam. https://moit.gov.vn/web/guest/tin-chi-tiet/-/chi-tiet/bao-ve-moi-truong-nhin-tu-nha-may-nhiet-%C4%91ien-gan-50-nam-tuoi-17639-22.html. (Accessed 14 June 2020). accessed.

MOIT, 2021. Strategic Environment Report of the National Electrical Development Plan for 2021-2030, Vision to 2045 (Pdp Viii Draft) accessed 4 August 2020.

MONRE, 2019. The Third National Communication of Vietnam to the United Nations Framework Convention on Climate Change. Vietnam Publishing House Of Natural Resources, Environment And Cartography, Hanoi, Vietnam.

Naik, V., Mauzerall, D., Horowitz, L., Schwarzkopf, M.D., Ramaswamy, V., Oppenheimer, M., 2005. Net radiative forcing due to changes in regional emissions of tropospheric ozone precursors. J. Geophys. Res. Atmos. 110, D24306. https://doi.org/10.1029/2005JD005908 n/a.

NDC, 2015. Intended Nationally Determined Contribution of Viet Nam. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Viet%20Nam%20First/VIETNAM%27S%20INDC.pdf. accessed 7 November 2019.

Pham, T.B.T., Manomaiphiboon, K., Vongmahadlek, C., 2008. Development of an inventory and temporal allocation profiles of emissions from power plants and industrial facilities in Thailand. Sci. Total Environ. 397, 103–118. https://doi.org/10.1016/j.scitotenv.2008.01.066.

PV Power (Petro Vietnam), 2017. Environmental Solutions at EVN's Coal-Fired Power Plants. https://www.pvpower.vn/giai-phap-moi-truong-tai-cac-nha-may-nhiet-dien-than-cua-evn/. accessed 19 July 2020.

Reddy, M.S., Venkataraman, C., 2002. Inventory of aerosol and sulphur dioxide emissions from India: I—fossil fuel combustion. Atmos. Environ. 36, 677–697. https://doi.org/10.1016/S1352-2310(01)00463-0.

Republic of Vietnam - The 14th National Assembly, 2020. Law on Environmental Protection (LEP). https://thuvienphapluat.vn/van-ban/Tai-nguyen-Moi-truong/Luat-so-72-2020-QH14-Bao-ve-moi-truong-2020-431147.aspx. accessed 02 April 2022.

Roy, S., Lam, Y.F., Hung, N.T., Chan, J.C.L., Fu, J.S., 2021. Development of 2015 Vietnam emission inventory for power generation units. Atmos. Environ. 247, 118042. https://doi.org/10.1016/j.atmosenv.2020.118042, 1994.

Roy, S., Lam, Y.F., Hossain, M.U., Chan, J.C.L., 2022. Comprehensive evaluation of electricity generation and emission reduction potential in the power sector using renewable alternatives in Vietnam. Renew. Sustain. Energy Rev. 157, 112009. https://doi.org/10.1016/j.rser.2021.112009.

S&P Global, 2020. Local News. https://www.spglobal.com/platts/en/market-insights/latest-news/coal/110620-vietnams-thermal-coal-imports-seen-resilient-through-2021-despite-funding-challenges-ahead. accessed 23 March 2021.

Shen, J., Zheng, C., Xu, L., Zhang, Y., Zhang, Y., Liu, S., Gao, X., 2019. Atmospheric emission inventory of SO3 from coal-fired power plants in China in the period 2009–2014. Atmos. Environ. 197, 14–21. https://doi.org/10.1016/j.atmosenv.2018.10.008, 1994.

Solomon, S., Qin, D., Manning, M., Alley, R.B., Berntsen, T.K., Bindoff, N.L., Chen, Z., Chidthaisong, A., Gregory, J.M., Hegerl, G.C., Heimann, M., Hewitson, B., Hoskins, B.J., Joos, F., Jouzel, J., Kattsov, V., Lohmann, U., Matsuno, T., Molina, M., Nicholls, N., Overpeck, J., Raga, G., Ramaswamy, V., Ren, J., Rusticucci, M., Somerville, R., Stocker, T.F., Whetton, P., Wood, R.A., Wratt, D., 2007. Technical summary. In: Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/ipccreports/ar4-wg1.htm. accessed 03 March 2021.

Streets, D.G., Gupta, S., Waldhoff, S.T., Wang, M.Q., Bond, T.C., Yiyun, B., 2001. Black carbon emissions in China. Atmos. Environ. 35, 4281–4296. https://doi.org/10.1016/S1352-2310(01)00179-0.

Streets, D.G., Bond, T.C., Carmichael, G.R., Fernandes, S.D., Fu, Q., He, D., Klimont, Z., Nelson, S.M., Tsai, N.Y., Wang, M.Q., Woo, J.H., Yarber, K.F., 2003. An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. J. Geophys. Res. Atmos. 108, 8809. https://doi.org/10.1029/2002JD003093 n/a.

Thunis, P., Crippa, M., Cuvelier, C., Guizzardi, D., de Meij, A., Oreggioni, G., Pisoni, E., 2021. Sensitivity of air quality modelling to different emission inventories: a case study over Europe. Atmos. Environ. X 10, 100111. https://doi.org/10.1016/j.aeaoa.2021.100111.

UN Environment, 2017. Reducing Mercury Emissions from Coal Combustion in the Energy Sector in Vietnam, UN Environment. Chemicals and Health Branch, Geneva, Switzerland. https://web.unep.org/globalmercurypartnership/reducing-mercury-emissions-coal-combustion-energy-sector-vietnam. accessed 13 October 2020.

United Nation Environmental Program (UNEP), 2012. Atmospheric Brown Cloud (ABC) Emission Inventory Manual (EIM). Nairobi, Kenya. http://www.rrcap.ait.asia/Publications/ABC%20Emission%20Inventory%20Manual.pdf. accessed 05 June 2019.

UNFCCC, 2019a. Clean Development Mechanism (CDM) Report of Nam Chim Hydro Power Project no. 5310. https://cdm.unfccc.int/Projects/DB/KBS_Cert1317458082.1/view. accessed 03 October 2019.

UNFCCC, 2019b. Clean Development Mechanism (CDM) Report of Za Hung Hydro Power Project no. 4551. https://cdm.unfccc.int/Projects/DB/BVQI1299431617.8/view. accessed 03 October 2019.

USEPA, 1995. Emission Factors & AP-42, Technology Transfer Network Clearinghouse for Inventories & Emissions Factors 2005. https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors#older. accessed 03 June 2019.

VPI (Vietnam Power Industry), 2016. Industry Overviews in 2016. https://vcbs.com.vn/vn/Communication/GetReport?reportId=4793. accessed 01 October, 2020.