Advanced Energy Partnership for Asia

QUANTIFYING IMPACTS OF RENEWABLE ELECTRICITY DEPLOYMENT ON AIR QUALITY AND HUMAN HEALTH IN SOUTHEAST ASIA BASED ON AIMS III SCENARIOS

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List of Acronyms

ACE	ASEAN Centre for Energy
AEO	ASEAN Energy Outlook
AIMS III	ASEAN Interconnection Masterplan Study III
APAEC	ASEAN Plan of Action for Energy Cooperation
APS	ASEAN Progressive scenario (also known as APAEC Target scenario)
ASEAN	Association of Southeast Asian Nations
ECLIPSE	Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants
EPA	U.S. Environmental Protection Agency
GEM	Global Energy Monitor
GEMM	Global Exposure Mortality Model
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
InMAP	Intervention Model for Air Pollution
NREL	National Renewable Energy Laboratory
PDP	power development plan
RE	renewable energy
REAS	Regional Emission Inventory in Asia
VOC	volatile organic compound
VRE	variable renewable energy

Executive Summary

Exposure to outdoor air pollution is the largest environmental risk factor for death and disease worldwide, associated with millions of cases of excess deaths each year (Burnett et al. 2018; Landrigan et al. 2018; McDuffie et al. 2021). Although many pollutants in the air affect human health, the most damaging class of pollutants is fine particulate matter, $PM_{2.5}$, which are airborne particles of diameter ≤2.5 micrometers (μm). These particles are small enough to get deep into the respiratory system, where they can then enter the bloodstream, traveling and causing damage to other bodily systems. Exposure to outdoor (ambient) $PM_{2.5}$ has been found to be the most important environmental risk factor for mortality in Southeast Asia, associated with 130,000–320,000 excess deaths in Association of Southeast Asian Nations (ASEAN) member countries in 2019 (McDuffie et al. 2021). Southeast Asia, especially in its megacities, has some of the worst air quality in the world (IQAir 2020).

Increased atmospheric $PM_{2.5}$ levels in Southeast Asia are caused by a number of human activities, such as transportation, agriculture, and industry. Another major source is power generation, which emits $PM_{2.5}$ directly (primary $PM_{2.5}$) and other pollutants that react in the atmosphere to form secondary $PM_{2.5}$. Fossil fuel combustion, especially coal but also diesel, is the main source of air pollutant emissions from power generation. While natural gas emits lower amounts of air pollutants than coal or diesel, it is nevertheless a significant emitter in the quantities combusted for power generation in Southeast Asia.

This study augments the ASEAN Interconnection Masterplan Study III (AIMS III) by quantifying changes to air quality and human health that result from renewable integration and transmission interconnection scenarios. Performing this analysis requires understanding how changes in the projected electricity generation in the AIMS III scenarios lead to changes in air pollutant emissions and using this information to develop what is known as an “emissions inventory” for each scenario and year evaluated. We then use a new reduced-complexity air quality model, Global Intervention Model for Air Pollution (Global InMAP), to transform the changes in emissions to changes in air pollutant concentration of the most damaging air pollutant for human health, $PM_{2.5}$. The model uses spatial population and demographic data in ASEAN countries to estimate changes in $PM_{2.5}$ exposure and, finally, to estimate changes in excess mortality attributable to the AIMS III scenarios. Figure ES-1 displays these methodological steps schematically.

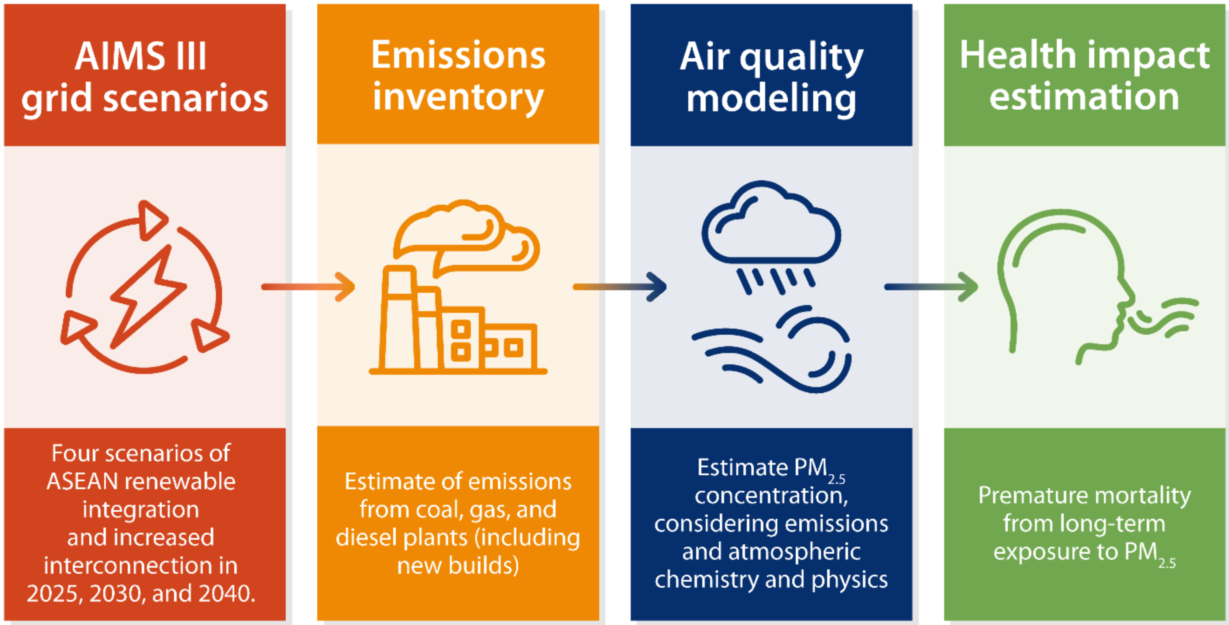

Figure ES-1. Schematic of the methodological steps of this study

Developing an Emissions Inventory for AIMS III Scenarios

An emissions inventory represents *who* emits air pollutants and *where, when,* and *how much* of *which* air pollutants are released. In this study, we compiled a database of all existing coal, diesel, and natural gas power plants in the ASEAN countries (*who*), including their locations (*where*) and plant characteristics (e.g., the height of stacks from their combustion units). Because AIMS III scenarios are projections to 2040, we also compiled a database of approved or planned new power plants and used other methods to represent as best as possible with available information the location and characteristics of future power plants that would be necessary to fulfill AIMS III-projected capacity in ASEAN member states. Figure ES-2 displays the location of power plants we modeled in this study. Data to support the development of the power plant database came from the ASEAN Centre for Energy (ACE) and its members, plus public data sources.

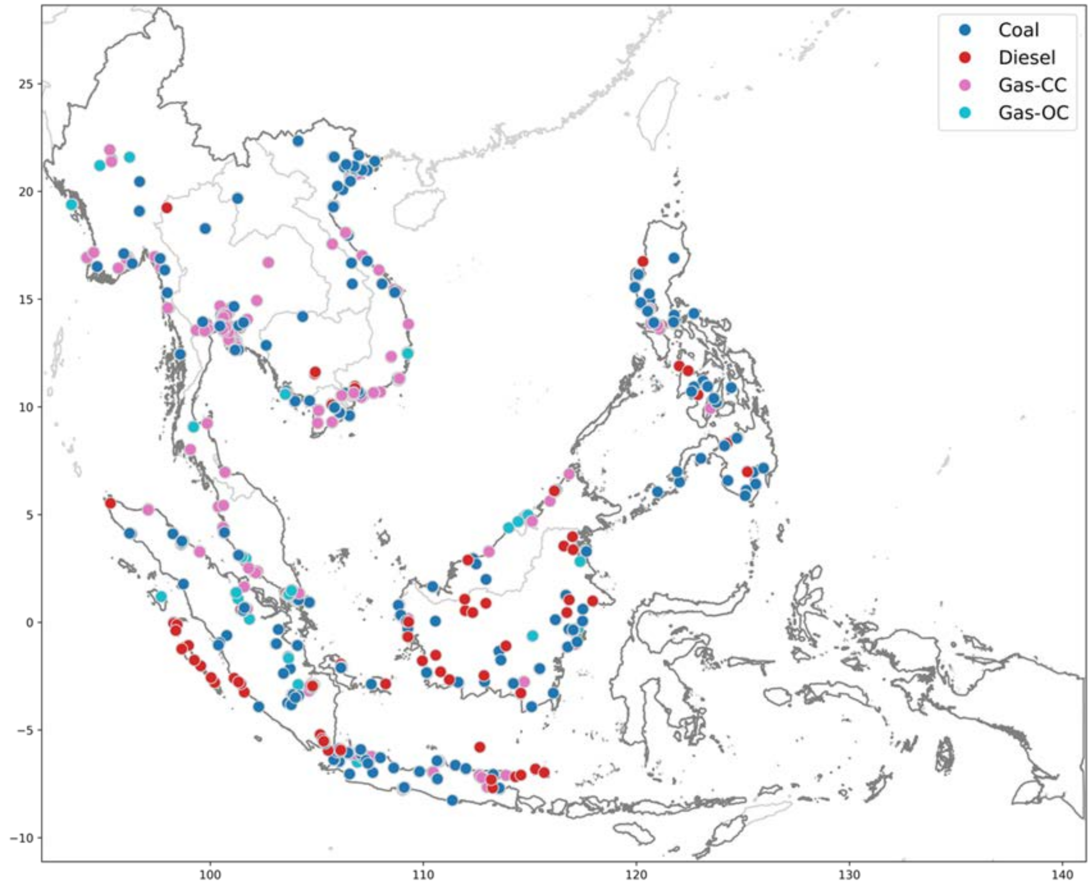

Figure ES-2. Location of coal, oil, and gas plants modeled in the study

Note: These locations were taken from various sources, including data from ACE and global data sets such as the Global Coal Plant Tracker and Global Gas Plant Tracker. Note that Eastern Indonesia was not included in AIMS III, so no thermal plants in Eastern Indonesia were modeled in our analysis (CC = combined cycle; OC = open cycle).

When pollutants are emitted is based on the AIMS III scenario projections for 2025, 2030, and 2040. *Which* pollutants are covered in our inventory include directly emitted $PM_{2.5}$ and the emissions of air pollutants that in the atmosphere transform into $PM_{2.5}$. *How much* is emitted is based on emissions factors, which express the mass of pollutants emitted per MWh of electricity annually generated, multiplied by the MWh for each power plant. The emissions factors used in this study are based on a compilation of ASEAN member state national emissions limits (standards) applicable to power generation facilities, which we compiled from public sources with the assistance of ACE and its members.

The goal of our emissions inventory was to estimate as realistically as possible the potential future annual emissions from power generation in the ASEAN region under the AIMS III scenarios; however, not only is the future unknown, but all the elements that comprise the emissions inventory have uncertainties. The locations of future power plants are notable in this regard, as are the amount of air pollutants emitted based on the assumed emissions factors. Because the resolution of the power sector modeling underlying AIMS III was at the country level, it is beyond the scope of this study to develop and test alternative assumptions for power plant location, even though the distance between emissions sources and population centers greatly influences exposure and health impacts. Additionally, we developed and tested an alternative set of emissions factors based on measured values instead of standards. Because most ASEAN countries do not report such measured emissions, we relied on measurements from other world regions where necessary; thus, these alternative emissions factors may not be more accurate than the ASEAN country-specific emissions standards.

Generation and Emissions Based on AIMS III Scenarios

AIMS III developed four scenarios, each of which is analyzed in our air quality study for 2025, 2030, and 2040 at the nodal level. Each country has one node except for Malaysia and Indonesia, where three nodes were used. The scenarios were developed using a capacity expansion model, which meets future projected power demand requirements in a least-cost manner considering other co-optimization factors that differed by scenario. The primary difference between these scenarios is their assumptions regarding renewable generation (specifically, variable renewable energy [VRE], which herein is defined as wind and solar power generation) and parameters to be optimized in the capacity expansion modeling. Figure ES-3 displays generation by fuel type for the AIMS III scenarios.

The Base scenario is a baseline formed from power development plans (PDPs) of each ASEAN country, with adjustments. The Optimum RE scenario develops optimized thermal, VRE, and transmission interconnections. The ASEAN RE Target scenario reflects VRE capacity additions based on country-level RE targets in the progressive scenario of the 6th ASEAN Energy Outlook (AEO6), with enhancements.[1] Finally, the High RE Target scenario was developed to understand the impacts of higher VRE deployment on the grids at national levels and on cross-border transmission. Biomass-based power sources were not included in the AIMS III power sector modeling.

Note that the AIMS III scenarios were developed in 2018–2019. Many countries have since updated their PDPs, and these updates are not included in our analyses. The results of this study could be updated to reflect more recent PDPs in future work.

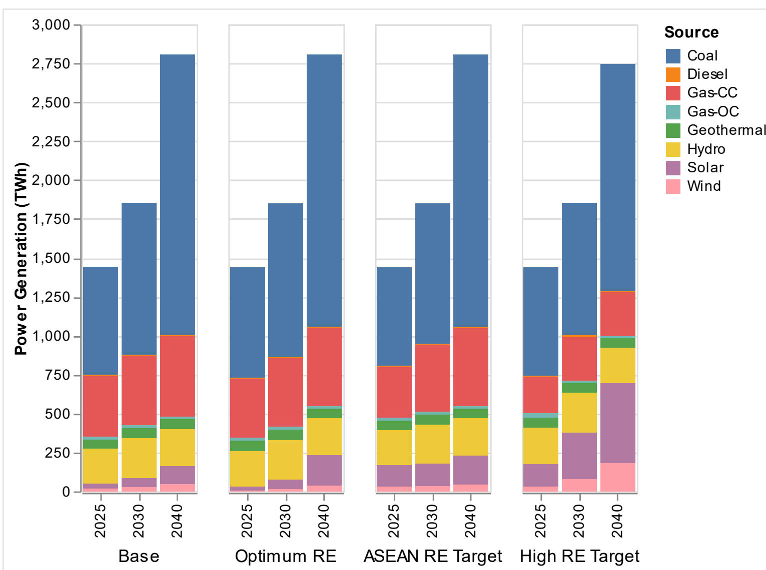

Figure ES-3. Power generation (in TWh) by different sources, including renewable (geothermal, hydropower, solar, and wind) and fossil (coal, natural gas, and oil), shown for the four AIMS III scenarios and three modeling years

Note that generation from gas plants is shown separately for open-cycle (OC) and closed-cycle (CC) units.

[1] The ASEAN Progressive scenario (APS), also known as the ASEAN Plan of Action for Energy Cooperation (APAEC) Target scenario, is a scenario in AEO6. It implies the acceleration of renewable energy by accounting for the APAEC's aspirational 23% renewable energy share target in the total energy mix.

Key points from the capacity expansion modeling of AIMS III relevant to air pollutant emissions and resulting air quality and health impacts include:

- Generation nearly doubles from 2025 to 2040 in all four AIMS III scenarios.
- Most of the increased generation is met by coal in all four AIMS III scenarios.
- While renewable generation increases in all four AIMS III scenarios, its fraction of total generation generally decreases because of the much greater increase in nonrenewable sources, mostly coal. Only in the High RE Target scenario do renewables represent a higher share in 2040 than in 2025, though even here it is at the expense of natural gas rather than coal.

These points indicate that emissions will increase from 2025 to 2040 in all AIMS III scenarios, and, in turn, increases in $PM_{2.5}$ concentration will result in increased health effects. Figure ES-4 illustrates these trends via the results of our emissions inventory calculations for NO_x emissions. (While the figure displays only NO_x, it is also true for the other pollutants analyzed.)

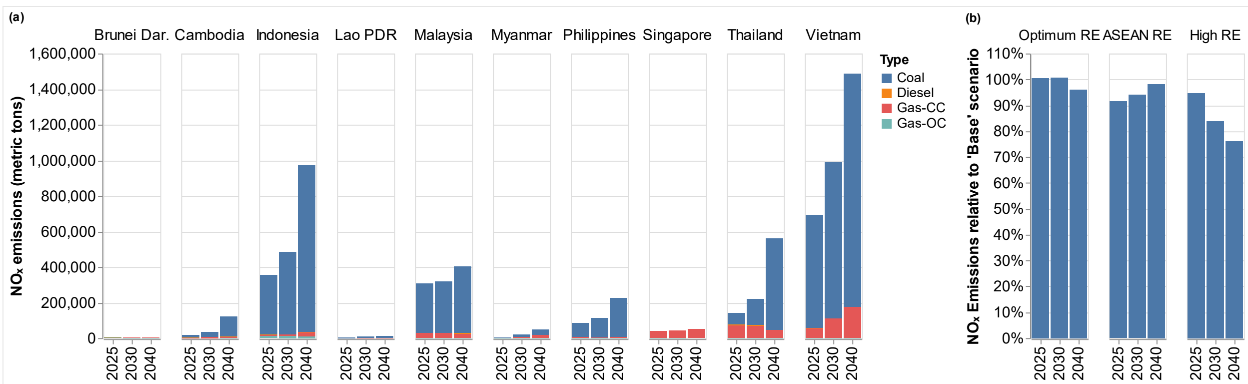

Figure ES-4. Estimated emissions of NO_x by country and unit types in the three AIMS III modeling years for the Base scenario (Frame a) and for the ASEAN region as a whole (relative to the Base scenario) for the three AIMS III scenarios (Frame b)

The High RE Target scenario yields the greatest non-fossil generation in 2040, and it likewise has the lowest NO_x emissions. Conversely, the amount of non-fossil generation is comparable across the Optimum RE, ASEAN RE Target, and Base scenarios, so their NO_x emissions are similar.

Air Quality and Human Health Results

Because emissions increase in 2040 compared to 2025 for all four AIMS III scenarios, so do $PM_{2.5}$ concentrations. Even for the High RE Target scenario, $PM_{2.5}$ concentrations are higher in 2040 compared to the Base scenario in 2025 (as shown in the left frame of Figure ES-5). Additional insight can be gained by comparing each AIMS III alternative scenario to the Base scenario in the same year. In this regard, the Optimum RE and ASEAN RE Target scenarios do not differ very much from the Base scenario in terms of $PM_{2.5}$ concentration. The High RE Target scenario, on the other hand, yields noticeably lower $PM_{2.5}$ concentration, as shown in the right frame of Figure ES-5. Figure ES-5 also illustrates that changes in $PM_{2.5}$ concentration are not evenly distributed in Southeast Asia.

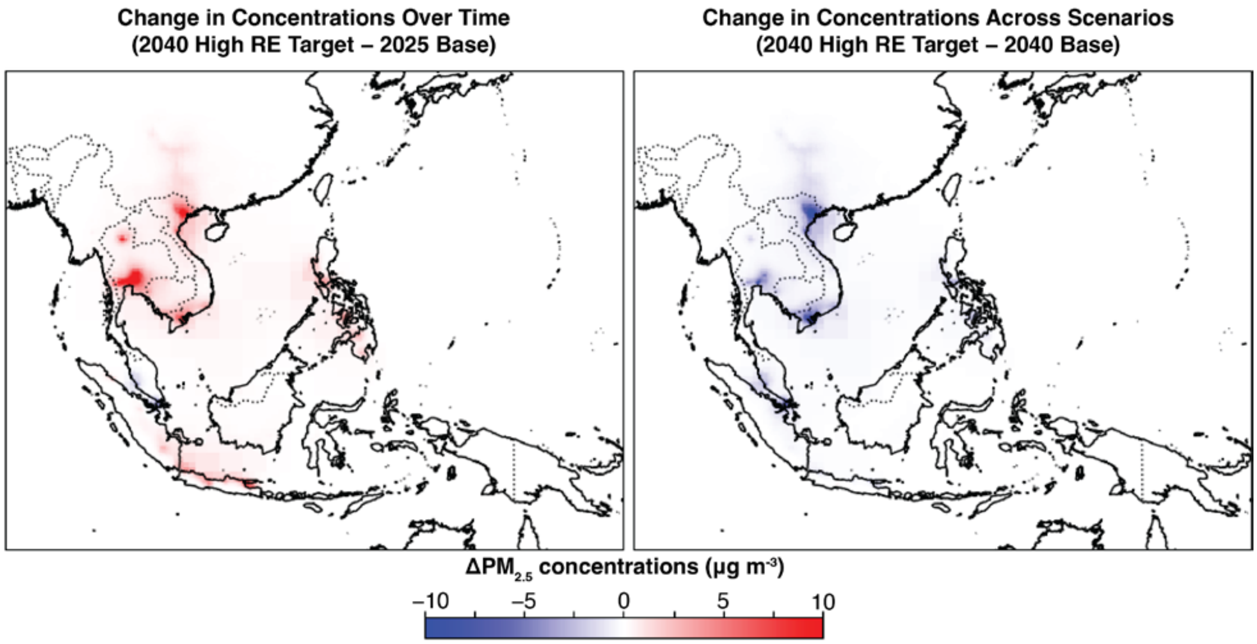

Figure ES-5. $PM_{2.5}$ concentrations change as a result of the changes to the power sector's resource mix and generation levels in the AIMS III scenarios.

The left frame shows the difference between the High RE Target scenario in 2040 and the 2025 Base scenario, which shows that even under the highest renewable penetration scenario, $PM_{2.5}$ concentrations increase, and they increase the most in certain regions in three countries: Thailand, Vietnam, and Indonesia. The right frame shows the difference between the High RE Target scenario compared to the Base scenario, both in 2040. This frame shows that, compared to a business-as-usual scenario (Base), the High RE Target scenario reduces $PM_{2.5}$ concentrations, and it does so in similar areas to those that are increased in the left frame.

Table ES-1 reports comparisons of the alternative AIMS III scenarios to the Base scenario in terms of average $PM_{2.5}$ concentration in Southeast Asia and the fraction of the population living in places with lower $PM_{2.5}$ concentrations (i.e., breathing cleaner air). From this perspective, two trends can be seen. First, air quality attributable to power sector emissions is better for most citizens in ASEAN countries for all three alternative AIMS III scenarios (compared to the Base scenario). This trend increases over time, reflecting greater shares of non-fossil resources in the AIMS III scenarios. Second, the High RE Target scenario achieves the greatest fraction of air quality improvement for ASEAN citizens, resulting in improved air quality for nearly 100% of ASEAN citizens.

Table ES-1. Changes in Population-Weighted Annual Average $PM_{2.5}$ Concentrations Relative to the Base Scenario and Over Time

Note: Also shown is the percentage of the population exposed to reduced annual average $PM_{2.5}$ concentrations (i.e., percentage of people breathing cleaner air) relative to the Base scenario.

Scenario	Year	Population-Weighted Change in $PM_{2.5}$ Concentration Relative to Base Scenario ($\mu g\ m^{-3}$)	% of Population Breathing Cleaner Air (Relative to Base scenario)
Optimum RE	2025	-0.01	15.3%
Optimum RE	2030	0.00	40.4%
Optimum RE	2040	-0.08	91.1%
ASEAN RE Target	2025	-0.08	91.8%
ASEAN RE Target	2030	-0.09	98.8%
ASEAN RE Target	2040	-0.01	33.8%
High RE Target	2025	-0.04	91.9%
High RE Target	2030	-0.18	99.7%
High RE Target	2040	-0.50	99.3%

Because emissions of precursors to $PM_{2.5}$ increase owing to the increase in power demand (and generation to meet it) in all AIMS III scenarios, so, too, do the incidences of excess mortality, as shown in Figure ES-6. The distribution of increases in excess mortality reflects the spatial distribution of emissions increases across ASEAN countries, with the greatest increases in countries such as Thailand, Vietnam, Indonesia, and the Philippines.

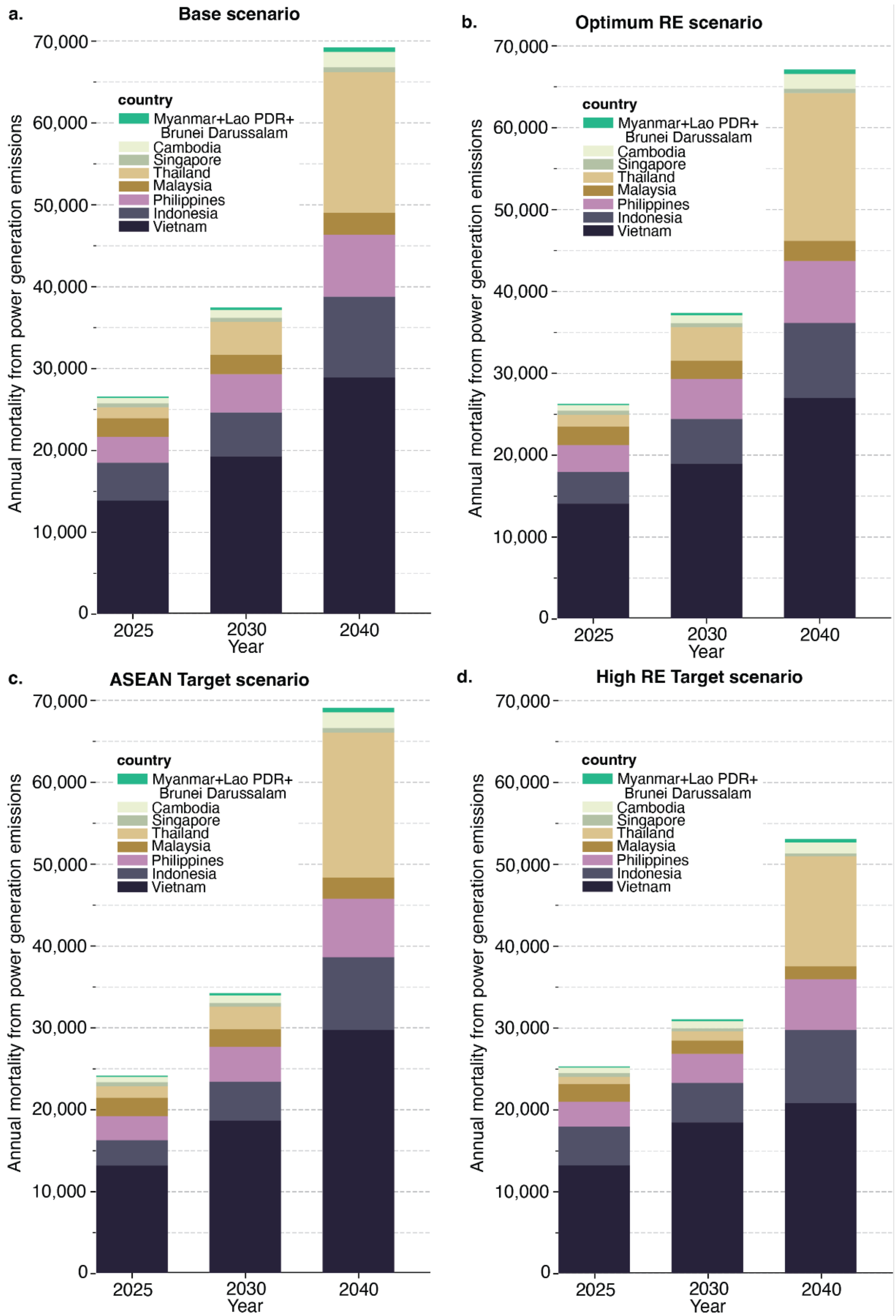

Figure ES-6. Annual mortality attributable to total projected power generation emissions in the (a) Base, (b) Optimum RE, (c) ASEAN RE Target, and (d) High RE Target scenarios, broken down by ASEAN member country in which mortality occurs

We observe net reductions in power sector air quality-related mortality in the ASEAN region for all alternative AIMS III scenarios (compared to the Base scenario) in 2040. For the High RE Target scenario, all countries benefit and experience reductions in excess mortality resulting from the power sector scenarios modeled in AIMS III; however, a few countries experience increases in $PM_{2.5}$-related excess mortality under the Optimum RE (Thailand) and ASEAN RE Target (Thailand and Vietnam) scenarios.

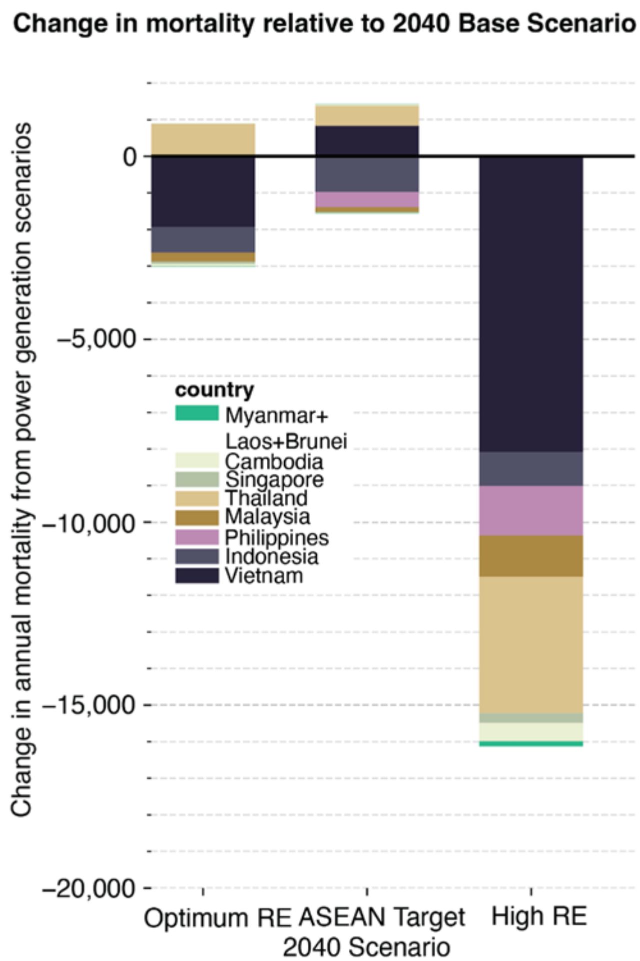

Figure ES-7. Change in annual mortality in 2040 (relative to the Base scenario) for the ASEAN RE Target, High RE Target, and Optimum RE scenarios, broken down by ASEAN member country in which mortality occurs

Conclusions and Key Limitations

Our analysis finds that changing power generation emissions is a crucial lever for improving public health in ASEAN member countries. To meet a doubling of demand for power generation, the AIMS III scenarios all predict an increase in coal power, which will meet the majority of demand by 2040 in all scenarios. As a result, we find that there will be an increase in power sector-related excess mortality over time across all AIMS III scenarios. The High RE Target scenario leads to the greatest reduction in net mortality of the four AIMS III scenarios, associated with a reduction in more than 16,000 excess deaths each year by 2040 compared to the Base scenario. The High RE Target scenario is also the scenario that reduces exposure to $PM_{2.5}$ for the greatest proportion of people living in the ASEAN region, improving air quality for 99.3% of people compared with the Base scenario.

Along with increasing renewable generation and decreasing reliance on coal, we find that there is large potential for technologies to reduce the health impacts of coal plants. Seventy-five percent of the excess mortality from power generation is from emissions of sulfur oxides, suggesting that flue gas desulfurization (a mature technology that is not currently in wide adoption in the region) can reduce health impacts. Improving the efficiency of combustion, reducing NO_x emissions through the installation of control technologies such as selective catalytic reduction or low NO_x burners, and sourcing and burning cleaner coal (e.g., with lower sulfur content) could also reduce health impacts. Demand-side strategies can also be used to reduce electricity demand such that less fuel is combusted.

While this analysis based on the AIMS III scenarios suggests different levels of air quality and public health benefits, there are several limitations associated with this study, which can influence our results; actual realizations in the future could be different from those presented here. Some of these are:

- Our analysis builds on the AIMS III power sector modeling, which considered a very coarse representation of countries. Thus, the resulting spatial details of future scenarios is also coarse. We used the best available data to generate high spatial resolution of future power plant locations for our air quality modeling, but uncertainties remain in the location, and potentially also the magnitude, of air quality and health impacts.
- Within the power sector, our analysis focuses only on thermal generation from coal, gas, and diesel. In some countries, other air pollutant-emitting sources (e.g., power plants combusting solid, liquid, or gaseous biomass-derived fuels) can also substantially contribute to electricity generation. Thus, our results do not represent all power sector-related emissions and associated air quality and health impacts, and they likely underestimate them due to the exclusion of biomass-fueled sources.
- Our analysis focuses only on the power sector. Given the rapid economic expansion and population growth in the region, there will likely be changes in sectors other than the power sector (e.g., transportation, household fuel consumption). Whereas changes in other sectors that alter power demand are captured in the generation projections of the AIMS III scenarios, concomitant changes in those sectors are not quantified. For instance, some portion of the increase in power generation will meet future transportation and/or building (e.g., cooking or heating) electrification, yet those sectors were not included in this study, which thus misses emissions decreases from vehicles and buildings owing to their electrification. Such cross-sector linkages could be explored in future research.

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1 Study Introduction

The Association of Southeast Asian Nations, or ASEAN, was established in 1967 in Bangkok, Thailand. The current member states of ASEAN include Brunei Darussalam Indonesia, Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam. The aims of ASEAN include collaboration and partnership to accelerate economic growth and social and cultural development in the region. One such area of collaboration that the ASEAN countries have explored is the power sector, with particular focuses on multilateral electricity trade, improved grid resiliency, and modernization (ASEAN 2022). The viability of such a partnership in the power sector has been studied through the ASEAN Interconnection Masterplan Studies, the most recent of which is the ASEAN Interconnection Masterplan Study III (AIMS III). AIMS III is a comprehensive analysis that includes an update on the ASEAN cross-border transmission system with higher shares of variable renewable energy (VRE) under the ASEAN Power Grid.

This study augments AIMS III by quantifying the potential air quality and public health effects of AIMS III scenarios. It was performed by the National Renewable Energy Laboratory and the University of Minnesota in partnership with the ASEAN Centre for Energy (ACE). In addition, it was supported by many ACE stakeholders (ASEAN member states) who provided valuable review and data inputs during the development of the emissions inventory, which is the primary input for air quality modeling. This study uses a first-of-its-kind global air quality model—the Global Intervention Model for Air Pollution (Global InMAP)—and it is the first application of this model to extend its results to public health. The results of this study are intended to be used by ACE, ACE's stakeholders in the ASEAN region, and ASEAN country decision makers, including governments and civil society, to help inform decisions about renewable energy integration and regional interconnection of the power sector, especially in terms of the air quality and public health impacts of different scenarios.

2 Background and Motivation

2.1 Air Pollution and Human Health

Exposure to outdoor air pollution is the largest environmental risk factor for death and disease worldwide, associated with millions of cases of excess mortality each year (Burnett et al. 2018; Landrigan et al. 2018; McDuffie et al. 2021). Although there are many pollutants in the air that affect human health, the most important class of pollutants is fine particulate matter, $PM_{2.5}$, which are airborne particles of a diameter ≤2.5 micrometers (μm) (Lim et al. 2012). These particles are small enough to deposit deep inside the respiratory system and penetrate from the alveoli into the bloodstream, where they can travel and cause oxidative damage and inflammation (Miller 2020). These are believed to be some of the main biological pathways by which $PM_{2.5}$ exposure negatively impacts our health, which is characterized as risk from mortality of all causes ("all-cause mortality") and mortality from specific diseases, such as chronic obstructive pulmonary disease, lower respiratory infections, lung cancer, stroke, ischemic heart disease, and diabetes mellitus (Pope et al. 2006; Burnett et al. 2018). $PM_{2.5}$ is found in outdoor (ambient) concentrations in all areas of the world that humans inhabit, including towns, cities, and the countryside (Hammer et al. 2020). Even low concentrations of $PM_{2.5}$ affect human health, and there is no known threshold below which long-term exposure to $PM_{2.5}$ concentrations does not affect health (Pope et al. 2015).

$PM_{2.5}$ particles can be very diverse in their shape, chemical composition, and source. $PM_{2.5}$ can be emitted directly in particulate form ("primary $PM_{2.5}$," e.g., from combustion processes or dust) or can form chemically in the atmosphere from the emissions of precursor pollutants ("secondary $PM_{2.5}$"). The four precursor pollutants that are most responsible for the formation of secondary $PM_{2.5}$ are sulfur oxides (SO_x), nitrogen oxides (NO_x), ammonia (NH_3), and non-methane volatile organic compounds (VOCs). Primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors are emitted from all economic sectors and a wide range of human activities (Thakrar et al. 2020), including in industry, transportation, agriculture, and residential and commercial sectors. $PM_{2.5}$ and precursors also have large biogenic and natural sources, such as soil, lightning, and desert dust (Lelieveld et al. 2015).

Because of the health impacts of $PM_{2.5}$ exposure and its wide-ranging emissions sources, there are many changes to emissions that can lead to changes in population health. Understanding how different decisions, such as regulations for cookstoves or incentives for vehicle electrification, can affect human health is crucial for enhancing human well-being and the environment overall (Thakrar et al. 2020). Designing and implementing effective decisions requires understanding how they are going to affect pollutant emissions sources, modeling how those changes in emissions affect changes in pollutant concentrations across space, and estimating how the resulting changes in human exposure will affect human health. Models that can be used for this purpose are discussed in Section 3.1.

2.1.1 Air Pollution in Southeast Asia

Southeast Asia is one of the most polluted regions worldwide, with population-weighted annual average $PM_{2.5}$ concentrations exceeding 20 μg/m^3 (Hammer et al. 2020), more than three times higher than the guidelines given by the World Health Organization. Pollution has been increasing overall in the region (Shaddick et al. 2020; Hammer et al. 2020). Although emissions from China greatly affect air pollution concentrations in Southeast Asia, the majority of the burden of disease from air pollution in Southeast Asia is from emissions occurring within the region (Zhang et al. 2017).

Exposure to outdoor (ambient) $PM_{2.5}$ is the most important environmental risk factor for mortality in Southeast Asia (Forouzanfar et al. 2016), associated with 130,000–320,000 excess mortalities (i.e., the increase in expected deaths above the counterfactual expected deaths) in ASEAN member countries in

2019 (McDuffie et al. 2021). By contrast, exposure to ozone in 2019 was only associated with around 9,000 excess deaths in the region.

Of the 130,000–320,000 excess deaths, around 10% are from the energy sector (Figure 1), including 6% from coal-sourced power generation and 4% from other power generation sources that emit air pollutants. This amounts to approximately 10,000–40,000 cases of excess mortality each year from total (primary and secondary) $PM_{2.5}$ exposure, which is more than the excess deaths from transportation-related pollution (McDuffie et al. 2021).

Power generation is projected to greatly increase in the region to meet growing demand (Sagbakken et al. 2021), and, in turn, the excess mortality attributable to power generation in the region is also expected to increase (Koplitz et al. 2017). Understanding the effects of different power generation scenarios on air quality and human health in the coming decades is thus a priority for public health, especially under newer scenarios of fuel mixes, regional interconnection, and demand growth.

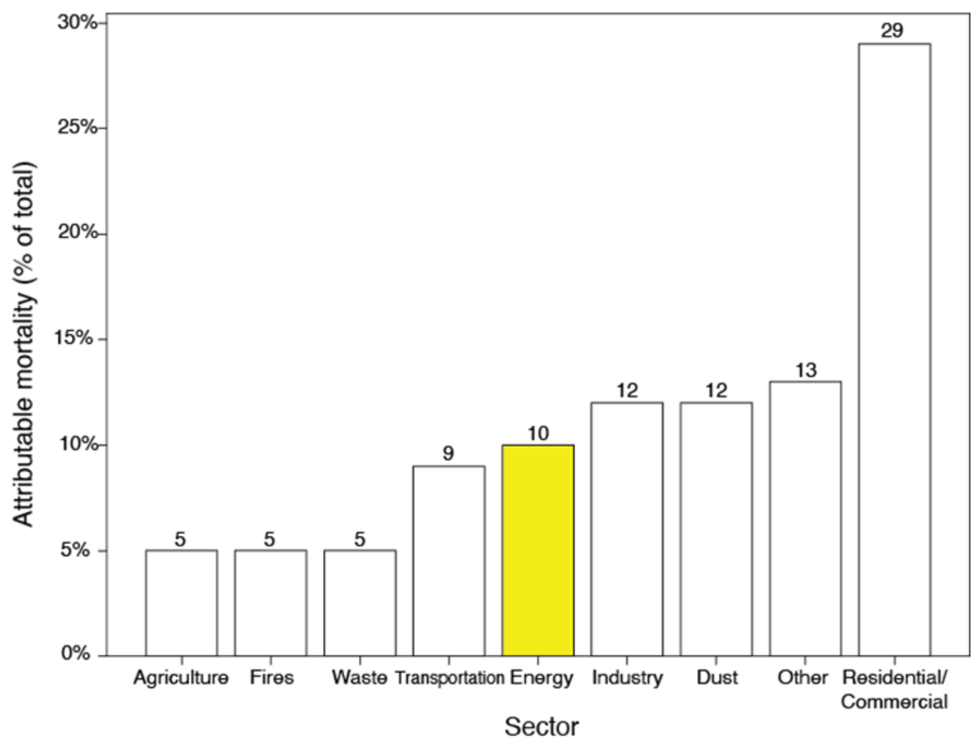

Figure 1. Sectoral contributions to excess mortality from outdoor $PM_{2.5}$ exposure in ASEAN member countries in 2019

Source: McDuffie et al. (2021)

3 Models and Methods

3.1 A Primer on Air Quality Modeling

To estimate the excess mortality associated with $PM_{2.5}$ from power generation, it is important to estimate how pollution travels, reacts, deposits, and leads to human exposure. This involves air quality modeling: simulating the physics and chemistry of the atmosphere to quantify how emitted air pollutants disperse and undergo chemical reactions in the atmosphere, leading to changes in pollutant concentrations. The emissions inputs to air quality models (known as "emissions inventories") specify where, when, and how much of each pollutant is emitted by each source. The inventories report emissions for pollutants relevant to the formation of $PM_{2.5}$ and O_3, such as VOCs, NO_x, NH_3, primary $PM_{2.5}$, and SO_x. Once released into the atmosphere, pollutant transport is governed by meteorological variables, such as wind speed, temperature, and planetary boundary layer height. This transport is calculated using numerical solutions of the laws of physics describing fluid motion in the atmosphere. The transformation of pollutants via atmospheric chemistry is calculated by solving equations that describe known chemical reactions for both gas- and particle-phase species. These chemical reactions can form "secondary" pollutants of interest (e.g., secondary $PM_{2.5}$, O_3) and can also represent the transformation of emitted gas-phase species to particle-phase pollutants.

The treatment of details of atmospheric chemistry and physics can lead to several choices of air quality models, depending on the analysis. Some models that consider detailed treatment include global or regional chemical transport models. Other sets of relatively simple steady-state dispersion models use a simplified treatment of atmospheric boundary layer dynamics and chemistry, examples of which are limited area dispersion models, which are often used for regulatory applications (e.g., AERMOD) (Cimorelli et al. 2005). Chemical transport models have consistently grown in computational complexity, incorporating online emissions, detailed chemistry of the gaseous and aerosol species, loss processes, and feedback to the atmosphere. Some widely used chemical transport models include CMAQ, WRF-Chem, GEOS-Chem, and MOZART, which can be used to model air pollution from local to global scales.

This detailed treatment of the atmospheric physics and chemistry makes these models computationally intensive, requiring very detailed input data (emissions and meteorology) and extensive training and computing resources. To overcome this challenge, several reduced-complexity models have been developed in the last decade, with some covering domains focused only on the United States (EASIUR, InMAP) (Heo et al. 2016; Tessum et al. 2017); however, more recent versions can simulate the air quality anywhere globally (e.g., Global InMAP, which is an expansion of the U.S. version of InMAP) or for regions outside the United States (e.g., for China) (Wu et al. 2021; Thakrar et al. 2022). These reduced-complexity models require fewer and less detailed inputs and fewer computing resources than chemical transport models, and thus they are very attractive for policy-related scenario assessments similar to the AIMS III scenarios.

For this analysis, we use Global InMAP (Thakrar et al. 2022), a global reduced-complexity air quality model that estimates both primary and secondary $PM_{2.5}$ concentrations arising from changes in emissions. Global InMAP has a variable-resolution computational grid, ranging from ~500 km in less populated places to ~4 km in urban areas. The grid and underlying population are based on 2020 projections from the Gridded Population of the World at 0.01° resolution (Gridded Population of the World 2022). InMAP directly estimates annual average $PM_{2.5}$ concentrations, which can be used to estimate changes in excess mortality using a concentration-response relationship. Here, we use the Global Exposure Mortality Model (GEMM) concentration-response relationship (Burnett et al. 2018), which estimates the expected excess mortality from five causes: lower respiratory infections, cardio-obstructive pulmonary disease, stroke, ischemic heart disease, and lung cancer.

3.2 AIMS III Power Generation Scenarios

AIMS III capacity expansion planning considers four different scenarios for the simulated years 2018–2040 that account for different levels of renewable energy (RE) and fossil-based power generation. For this analysis, three capacity expansion solution years (2025, 2030, and 2040) are considered for all modeled scenarios (called "Base," "Optimum RE," "ASEAN RE Target," and "High RE Target"). The primary differences between the scenarios are their assumptions regarding renewable (specifically VRE, which herein is defined as wind and solar) generation shares and parameters to be optimized in the capacity expansion modeling. Table 1 presents a brief description of the scenario assumptions, which are detailed in the following text.

Table 1. Summary of Scenarios Based on VRE Generation, Optimization Assumptions, and the Key Parameters Optimized in the Capacity Expansion Modeling

Note: PDP = power development plan, RE = renewable energy, VRE = variable renewable energy

Scenario	Is VRE Optimized or Exogenous?	Source of VRE Generation Levels	What Is Optimized/Minimized in Capacity Expansion Modeling?
Base	Exogenous (firm input)	Based on country PDP	Thermal generation Cost minimization
Optimum RE	Optimized	Optimized in the model	All capacity including thermal generation (except hydropower) VRE Interconnection capacity Cost minimization
ASEAN RE Target	Exogenous	RE targets of ASEAN member states	Thermal generation (except existing and committed) Interconnection capacity Cost minimization
High RE Target	Exogenous	Inputs from ASEAN member states, assumes much higher VRE than other scenarios	Thermal generation Interconnection capacity Cost minimization

Base Scenario: This scenario forms the baseline for the subsequent scenarios. The scenario starts with current installed capacity, the firm (committed) capacity additions for generation and transmission assets as per the power development plans (PDPs) for each ASEAN member state and any planned retirements. Some of the key assumptions for this scenario include:

- Committed projects are treated as fixed plans, but noncommitted thermal power plants in PDPs are re-optimized.
- VRE (wind and solar) is treated per the country-level PDP, beyond which VRE is increased based on inputs from the ASEAN member states.
- No new transmission capacity is added to the existing network.

Optimum RE Scenario: This scenario develops an optimized generation mix by re-optimizing all capacity (thermal, VRE, and transmission) beyond each country's PDP (except hydropower). The noncommitted thermal plants under each PDP—namely, those for which construction has not commenced or where the power purchase agreement has not been signed—are also re-optimized. Thus, this scenario reflects the co-optimization of thermal and VRE generation and transmission requirements.

ASEAN RE Target Scenario: This scenario differs from the Optimum RE scenario in its treatment of VRE capacity additions, which are determined based on the RE target in the ASEAN Progressive scenario (APS) of the 6th ASEAN Energy Outlook (AEO6).[2] Thermal generation and transmission capacity expansions are co-optimized, with VRE capacity as exogenous input to the power sector modeling. VRE capacity up to 2025 was based on AEO6 and based on an enhanced projection of AEO6 for years beyond 2025.

High RE Target Scenario: This scenario assumes much higher VRE capacity additions in future years to understand the resulting impacts on national-level grids and cross-border transmission. Assumed country-specific renewable energy generation shares in the High RE Target scenario were determined through consultations with ASEAN member states. VRE generation shares in the ASEAN region are assumed to be much higher (25%–30% in the generation mix by 2040) than in the ASEAN RE Target scenario.

We note that the AIMS III scenarios were developed in 2018–2019. Many countries have since updated their PDPs, and these updates are not included in our analyses. The results of this study could be updated to reflect more recent PDPs in future work.

To meet growing energy demand, power generation in ASEAN countries is expected to double from 2025 to 2040 for all scenarios (Figure 2). Under Base scenario assumptions, the majority of power generation (64%) in 2040 is met by coal. Electricity generation from non-fossil (i.e., not from coal, gas, or oil) sources is expected to increase by 40% from 2025 to 2040, but this is not enough to meet the growing energy demand. As a result, the fractional contribution of non-fossil sources to power generation is projected to fall, from 23% in 2025 to 16% in 2040. Among fossil-based sources, the Base scenario indicates that coal generation grows to 693 TWh in 2025, 974 TWh in 2030, and 1,803 TWh in 2040, the latter of which corresponds to an increase by a factor of 2.6 (relative to 2025).

A similar trend is observed in other scenarios. For example, in the High RE Target scenario, 694 TWh generation in 2025 is from coal in the region, which increases to 850 TWh in 2030 and 1,461 TWh in 2040. Region-wide, gas-based generation (including both combined cycle and open cycle), which generally is a much less polluting energy source compared to coal, decreases from the Base scenario to the High RE Target scenario in all three analysis years; however, the longitudinal change shows an increasing trend from 408 TWh in 2025, to 465 TWh in 2035, and 534 TWh in 2040 in the Base scenario. Diesel-based generation generally decreases, but it has a much smaller share as an electricity source in the region (e.g., in the High RE Target scenario, diesel accounts for only 5 TWh in 2040, which is <1% of the total required generation).

All three alternative (non-Base) AIMS III scenarios follow a similar story as the Base scenario (Figure 2 and Figure A-1 and Figure A-2 in the appendix): Coal is projected to meet the majority (53%–62%) of power generation by 2040, and although non-fossil generation is projected to increase for all the scenarios, its fractional contribution in both the Optimum RE and ASEAN RE Target scenarios decreases. Only in the High RE Target scenario does the fractional contribution of non-fossil generation increase, but it does so largely at the expense of natural gas (which goes from 16% to 10% of the contribution) rather than coal (which, like all other scenarios, increases its share).

The region-wide share of renewable energy (including VRE) and fossil-based sources of generation for the four scenarios and three modeling years is shown in Figure 2. Notably, despite an increase in net generation from renewable energy sources, their share in the generation mix decreases in all scenarios

[2] The APS, also known as the ASEAN Plan of Action for Energy Cooperation (APAEC) Target scenario, is a scenario in AEO6. It implies the acceleration of renewable energy by accounting for the APAEC's aspirational 23% renewable energy share target in the total energy mix.

from 2025 to 2030 and 2040 except for the High RE Target scenario. The Base and Optimum RE scenarios have similar renewable energy and fossil-based source contributions to the generation mix. The share of renewable energy sources in the ASEAN RE Target scenario shows the largest decrease from 2025 to 2040. Although the VRE (wind and solar) generation share consistently increases from 2025 to 2030 and 2040 in the High RE Target scenario, this is at the expense of natural gas and other renewable energy (geothermal, hydro). The share of coal-based generation increases in most scenarios even when the VRE share is increasing.

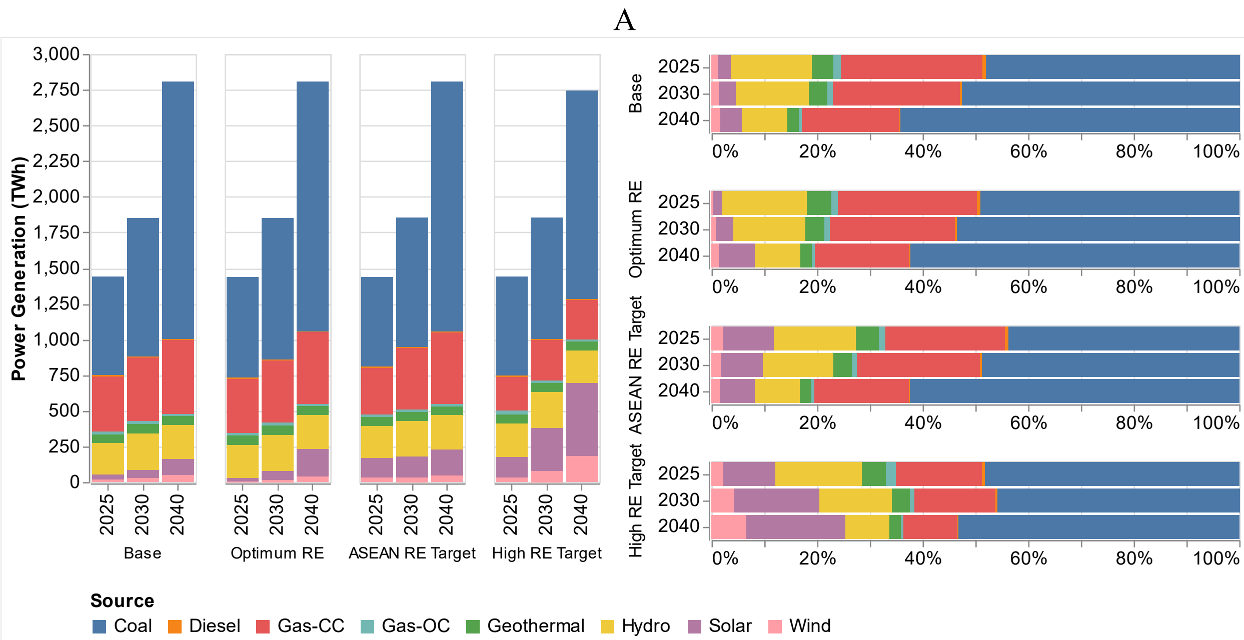

Figure 2. Power generation (in TWh) by different sources, including renewable (geothermal, hydropower, solar, and wind) and fossil (coal, natural gas [both open cycle (OC) and closed cycle (CC)], and oil), is shown for the four scenarios and three modeling years (left)

Note: The right-hand panel shows the relative contribution from each source (power generation mix).

3.3 Emissions Inventory Development

In this section, we focus on the methods we followed for developing the emissions inventory, which are the inputs to the Global InMAP air quality model. An emissions inventory is an accounting of different sources of emissions, including pollutant-specific mass release rates over a given time interval and their locations.[3] The following subsections describe in more detail our approach for estimating emissions for selected sources in the power generation sector in Southeast Asia.

Generation Technologies: The AIMS III scenarios model generation from several different technologies. These are: coal, diesel, gas (open-cycle and combined-cycle combustion turbines), geothermal, hydropower, pumped storage, solar, and wind. In this study, we consider only fossil-based generation technologies (i.e., coal, diesel, and gas turbines). Other technologies that are used for electricity

[3] In a more complex chemical transport model-based analysis, one needs to account for all possible sources of emissions (e.g., emissions from different sectors, such as power generation, industry, domestic, agriculture, fires, as well as natural and biogenic emissions); however, as explained in Section 3.1, Global InMAP only requires incremental emissions changes. Thus, for this analysis, we only needed to create an emissions inventory for the power generation sector.

generation in the region (e.g., biomass, waste-to-energy) can also emit primary particulate matter and gaseous pollutants, but they are not included in this analysis because AIMS III did not consider them.

Activity: Activity refers to the amount of a fuel, energy service, or good that is used for the time period and geographic region within the project scope. In this study, *activity* refers to the amount of fossil fuel-based electricity generation that was available at an hourly time resolution from the AIMS III modeling. Activity data were available for three fuel types (coal, natural gas, and diesel) either at the country level (Brunei Darussalam, Cambodia, Lao PDR, Myanmar, Philippines, Singapore, Thailand, and Vietnam were modeled at a single node in AIMS III) or sub-country level (Indonesia and Malaysia each were represented as three nodes in the AIMS III modeling). Because Global InMAP requires annual emissions rates, hourly generation from AIMS III is aggregated to the annual total generation in units of MWh.

Emissions Factors: *Emissions factors* refer to the mass of a pollutant of interest released per unit of activity data. For example, for electricity generation, this can be expressed as kilograms of SO_x per unit of fuel consumed (metric tons of coal) or kilograms of SO_x per unit of electricity generated (MWh). Emissions factors can be based on several different methods: direct measurement over specified time periods (e.g., based on grab-sampled test data or real-time measurements), mass balance analysis, or indirect approaches based on emissions limits imposed by source-type specific emissions standards. In the absence of availability of country-specific emissions factors (from test measurements or real-time measurements such as those from continuous emissions monitoring systems), we estimated emissions factors based on a review of current emissions standards in each ASEAN country. The review of current emissions standards was performed with the support of in-region experts and in consultation with ACE and ASEAN member state representatives. Emissions standards were only available for a select set of pollutants (PM, NO_x, SO_x) and left out some pollutants required as input to the air quality model (VOC, NH_3, $PM_{2.5}$). The following paragraph describes the approach followed to derive the emissions factors based on emissions standards. Fuel- and country-specific emissions factors for all the pollutants are included as a spreadsheet. See “Emission Standards Based EFs” sheet of the spreadsheet: AIMS-III-Air-Quality-Study-Data-Sheet.xlsx.” A more detailed description of our approach is provided in the appendix (Section A.2).

An emissions factor based on electricity generation can be referred to as output-based or input-based. An input-based emissions factor primarily rely on the properties of the fuel or material input that is being consumed and generating the emissions, such as U.S. reporting of criteria pollutants in pounds per million British thermal units (lb/MMBtu). This emissions factor lists the emissions of pollutants in pounds while depending on the heating value of the fuel in MMBtu. Other input-based emissions factors may depend on mass or volume, which are also inherent properties of the input fuel. An output-based emissions factor can have units of pounds per MWh (lb/MWh), which relies on the output unit of MWh of electricity generated through the input of a given fuel. The conversion factor between these two types of emissions factors is referred to as the heat rate, which is typically listed in units of Btu/kWh. The heat rate is a conversion that accounts for the energy input of a fuel (in Btu) required to generate 1 kilowatt hour (kWh) of electricity. A lower heat rate indicates greater efficiency (i.e., 1 kWh of electricity can be generated with less energy input and therefore wastes less fuel in the conversion to a new form of energy). Output-based emissions factors reflect efficiency in combustion and electricity generation, whereas input-based emissions factors only account for fuel characteristics such as volume, mass, or energy content.

Plant Stack Characteristics: Stack characteristics include physical parameters of a power plant stack or chimney. These include stack height above the ground level, stack diameter, flue gas exit velocity, and temperature at the stack top. Stack parameters can influence the pollutant dispersion: A shorter stack can increase near-field pollutant concentration, whereas a taller stack can reduce the near-field concentration but can disperse pollutants over longer distances. Detailed data on stack parameters are not available for all the plants in the regions. We reviewed the literature and worked with the country representatives to obtain as many parameters as possible. For the specific plants for which stack parameters were available, we used available parameters. In addition, a regression model was developed that predicted stack height as a function of the unit capacity. Such a relation was developed for both coal and gas plants (Figure 3). Note that this relationship is not well defined and is used as a gap-filling exercise. We include a sensitivity analysis to check the impacts of stack height assumptions on subsequent analysis, as explained in Section 3.4. For diesel plants, we used constant stack parameters based on mean estimates of data we collected for diesel generators. Details on the stack parameters used on the study are shown in Table 2.

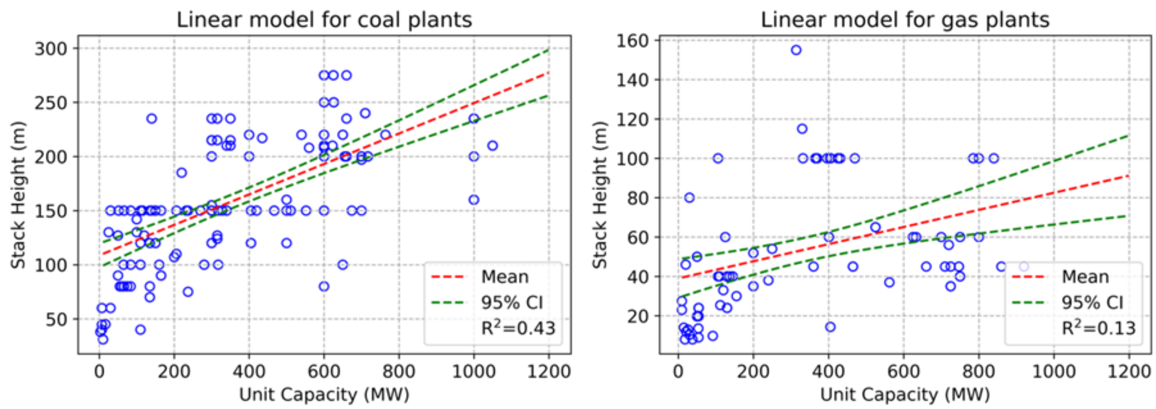

Figure 3. Stack height distribution relative to the unit capacity for coal and gas plants and the corresponding regression fit used for estimating stack height for plants lacking these data

Table 2. Stack Parameters Used in This Analysis

Note: These parameters are derived from data collected in the region for different plant types. Stack height is either plant-specific stack (where available) or regressed to the capacity (MW) for coal and gas plants (Figure 3). Other parameters are either plant-specific or default values based on the average of data collected in the region with the help of ACE. Distributional statistics (5th percentile, median, and 95th percentile) of stack heights by country and fuel types (for coal and gas) are included in the appendix. Stack heights used for individual generation units in the region are included on a separate data sheet ("AIMS-III-Air-Quality-Study-Data-Sheet.xlsx").

Parameter	Units	Coal	Gas	Diesel (Default Values Listed Are Used for All Generators)
Stack Height	m	Plant-specific data or regressed to capacity	Plant-specific data or regressed to capacity	11.1
Stack Diameter	m	Plant-specific data or default value of 4.79	Plant-specific data or default value of 4.58	1.02
Exit Gas Velocity	m/s	Plant-specific data or default value of 21.1	Plant-specific data or default value of 23.6	18.9
Exit Gas Temperature	Degrees C	Plant-specific data or default value of 124	Plant-specific data or default value of 213	398

Power Plant Locations: Power plant locations are one of the most influential factors when assessing their exposure impacts. We compiled data from several different sources, which are listed in Table 3. Country-level maps for power plant locations are included in the appendix (see Section A.3).

Table 3. Data Sources Used for Power Plant Locations

Data Source	Fuel Type	Data up to	Reference
ASEAN Center for Energy (ACE)	Coal, gas, diesel	2020	ACE (2021)
Global Coal Plant Tracker	Coal	2021	Global Coal Plant Tracker, Global Energy Monitor, July 2021
Global Gas Plant Tracker	Gas	2021	Global Gas Plant Tracker, Global Energy Monitor, August 2021

We reconciled the data (location, power plant capacity) from the three power plant databases where possible, but preference was given to the data contained in the ACE database; however, given the rapid increase in the new coal, gas, and diesel builds in the ASEAN region, generation from the existing plants is lower than the generation from the AIMS III scenarios. Having some estimates of future plant locations is critical and a required input to model the air quality impacts from the AIMS III scenarios. This can be achieved by a detailed siting analysis, capacity planning models at a finer spatial resolution, or using some surrogates (such as population density, resource availability). A detailed siting analysis was outside the scope of this analysis, and the capacity expansion modeling was an exogenous input to our analysis and was conducted at a very coarse resolution (one to three nodes per country). Thus, we relied on the third approach for locating any new builds. We collected data on power demand projection where possible and used the relative fraction of demand in a region to distribute country-level generation for each AIMS III modeling scenario. Specific details on the countries where the power demand projection data were used are listed in Table 4.

Table 4. PDPs or Other Spatial Surrogates Used by Different Countries for Distributing the Node-Level Data from AIMS III Modeling to Finer Spatial Resolution

Country	Nodal Representation in Capacity Expansion Modeling	Surrogate Definition Used for Nodal-to-Regional Generation Distribution	Source
Brunei Darussalam	One node (country level)	Existing plant distribution	Plant locations based on Table 3
Cambodia	One node (country level)	PDP data at 24 province levels	Power Development Master Plan in Kingdom of Cambodia, 2015
Indonesia	Three nodes (three regions: Java, Kalimantan, Sumatra)	Existing plant distribution in each node region	Plant locations based on Table 3
Lao PDR	One node (country level)	Existing plant distribution	Plant locations based on Table 3
Malaysia	Three nodes (three regions: Peninsular Malaysia, Sabah, Sarawak)	Existing plant distribution in each node region	Plant locations based on Table 3
Myanmar	One node (country level)	Existing plant distribution	Plant locations based on Table 3
Philippines	One node (country level)	PDP data for three island groups (Mindanao, Luzon, Visayas)	Philippines PDP 2016–2040
Singapore	One node (country level)	Existing plant distribution	Plant locations based on Table 3
Thailand	One node (country level)	PDP data for seven regions (defined as Central, Eastern, Metropolitan area, Northeastern, Northern, Southern, Western)	Thailand PDP 2018
Vietnam	One node (country level)	Existing plant distribution	Plant locations based on Table 3

Specific plant locations used in our analysis are shown in Figure 4, and this spatial pattern is almost consistent between different years and scenarios, although a few additional plants are created depending on the need to equal generation data from AIMS III modeling.

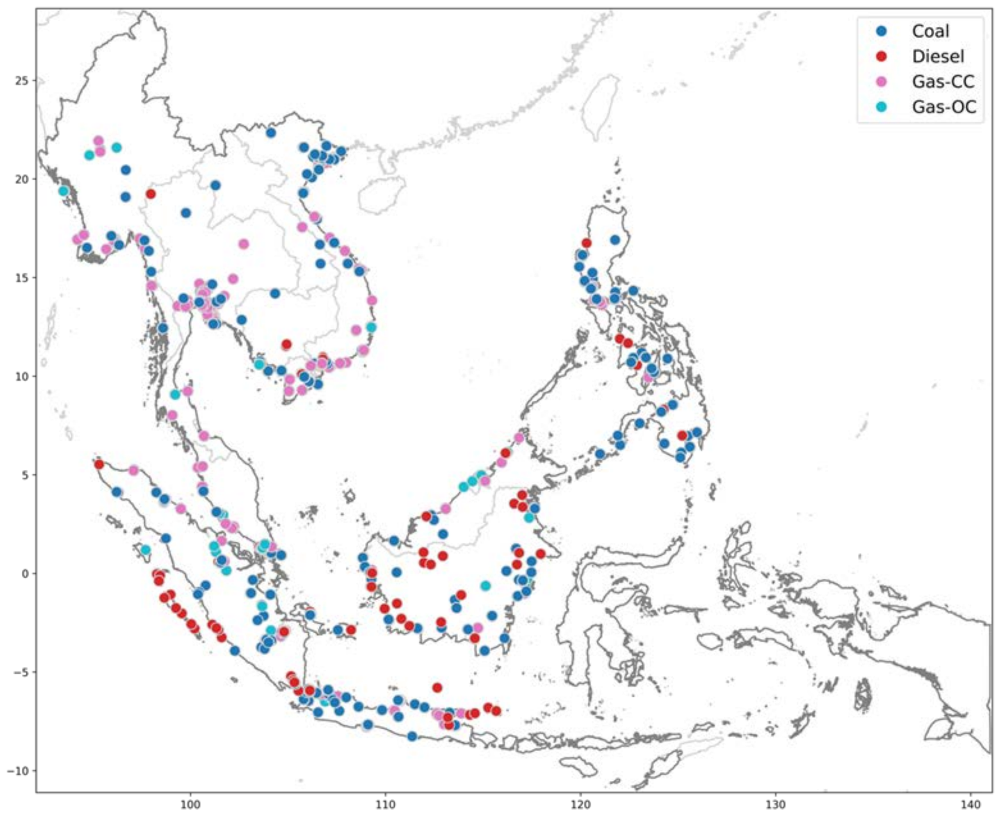

Figure 4. Location of various coal, oil, and gas plants used in the study

Note: These locations were taken from various sources, including data from ACE and global data sets such as the Global Coal Plant Tracker and Global Gas Plant Tracker. Eastern Indonesia was not included in AIMS III, so no thermal plants in Eastern Indonesia were used in our analysis. Maps showing the plant locations for individual ASEAN countries are included in the appendix (Section A.3).

3.4 Sensitivity Scenarios

To assess the range of potential air quality and health impacts in the region arising from the AIMS III scenarios, we studied the sensitivity of our model outputs by using a different set of select model inputs. The two model inputs used for the sensitivity analysis are pollutant emissions factors and stack height. The methods listed previously in this section served as one estimate of emissions inventory based on a country-specific emissions standard for each pollutant. Emissions standards are the maximum allowable concentration for each fuel and plant type set forth by regulations in each ASEAN country; however, these standards-based emissions estimates could be different from prevalent emissions factors in each country. This set of emissions factors is used to show the range of possible emissions based on available activity data. Emissions factors used for the sensitivity scenarios were based on the reported values in literature for ASEAN countries (first preference), regional values (second preference), or the U.S. Environmental Protection Agency-reported values (last preference). Publicly available emissions factors are not listed for criteria pollutants in most ASEAN countries. Through a review of the literature, we found emissions factors for criteria pollutants related to electricity generation for Vietnam and Thailand (Krittayakasem et al. 2011), though no specific literature could be located for the remaining countries. The emissions factors used for the remaining ASEAN countries are from the Regional Emission Inventory in Asia (REAS) Version 2 (v2) (Kurokawa and Ohara 2019). The relevant region is listed as Asian countries that do not include China, Japan, Taiwan, South Korea, or South Asia.

Emissions factors in each case reference the input-based value in lb/MMBtu and then refer to the heat rate previously assigned to each set of standards. Emissions factors for Thailand do not include VOC, so values from REAS v2 were used as the closest approximation. None of the available references provided emissions factors for ammonia, so the existing emissions factors were used for this table as well. In cases where emissions factors referred to $PM_{2.5}$ emissions directly, no scaling factor was needed to convert from PM to uncontrolled $PM_{2.5}$ emissions. In cases where emissions factors are only provided for a single type of coal, those values are used for each coal and combustion type in that country. SO_2 emissions factors in Vietnam vary depending on the sulfur content of the fuel: for coal, the lower value of 0.6% is selected, and for fuel oil, the sulfur content is used based on locally sourced oil. When the coal type for a location is not known, the value for subbituminous coal is used, following the methods reported by the Global Energy Monitor (GEM) and in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Fuel- and country-specific emissions factors for all the pollutants are included as a spreadsheet; see "Sensitivity Case EFs" sheet of the attached "AIMS-III-Air-Quality-Study-Data-Sheet.xlsx" file.

The other set of sensitivities is based on stack parameters, specifically stack height since ground-level concentrations can vary with stack height. We used a 95% confidence interval for the stack height and created an input data set that varies stack height while keeping all other inputs (emissions and other stack characteristics) constant. This stack height sensitivity was applied to both "emissions standards" and "literature"-based emissions inventories. Thus, we conducted a total of six sensitivity runs for each country. The sensitivity runs are described in Table 5.

Table 5. Different Sensitivity Types Used in the Study

Note: Two different sets of emissions factors are used, with three stack height variations from low to high (based on 95% confidence interval) derived from a regression model fitted to the data (see Figure 3) for a total of six sensitivities for each country.

Source of Emissions Factor	Stack Height Variation		
Emissions Standard	Lower bound of stack height (based on 95% confidence interval)	Mean stack height	Upper bound of stack height (based on 95% confidence interval)
Literature	Lower bound of stack height (based on 95% confidence interval)	Mean stack height	Upper bound of stack height (based on 95% confidence interval)

4 Results and Discussion

In this section, we present the results on the power sector emissions inventory developed for the three future years and the four power sector scenarios. Note that most of the results and analysis presented should be considered for the ASEAN region, although we do provide country-specific details where possible. Analysis of changes to emissions, concentrations, and health is possible at the country level, and also within countries, with additional data, which could be the subject of future research.

4.1 Emissions Estimates of AIMS III Scenarios

As pointed out before in the Methods section, emissions are dependent on the activity data, which in the case of the power sector modeled here is generation, and emissions factors. Thus, the emissions can significantly vary from one country to another and from one year to another. Annual total emissions of criteria air pollutants or the precursor gases are dominated by coal combustion for all countries, as shown in Figure 5 for NO_x and $PM_{2.5}$ for the Base scenario, except for the countries where there is little or no coal combustion (e.g., Brunei Darussalam or Singapore).

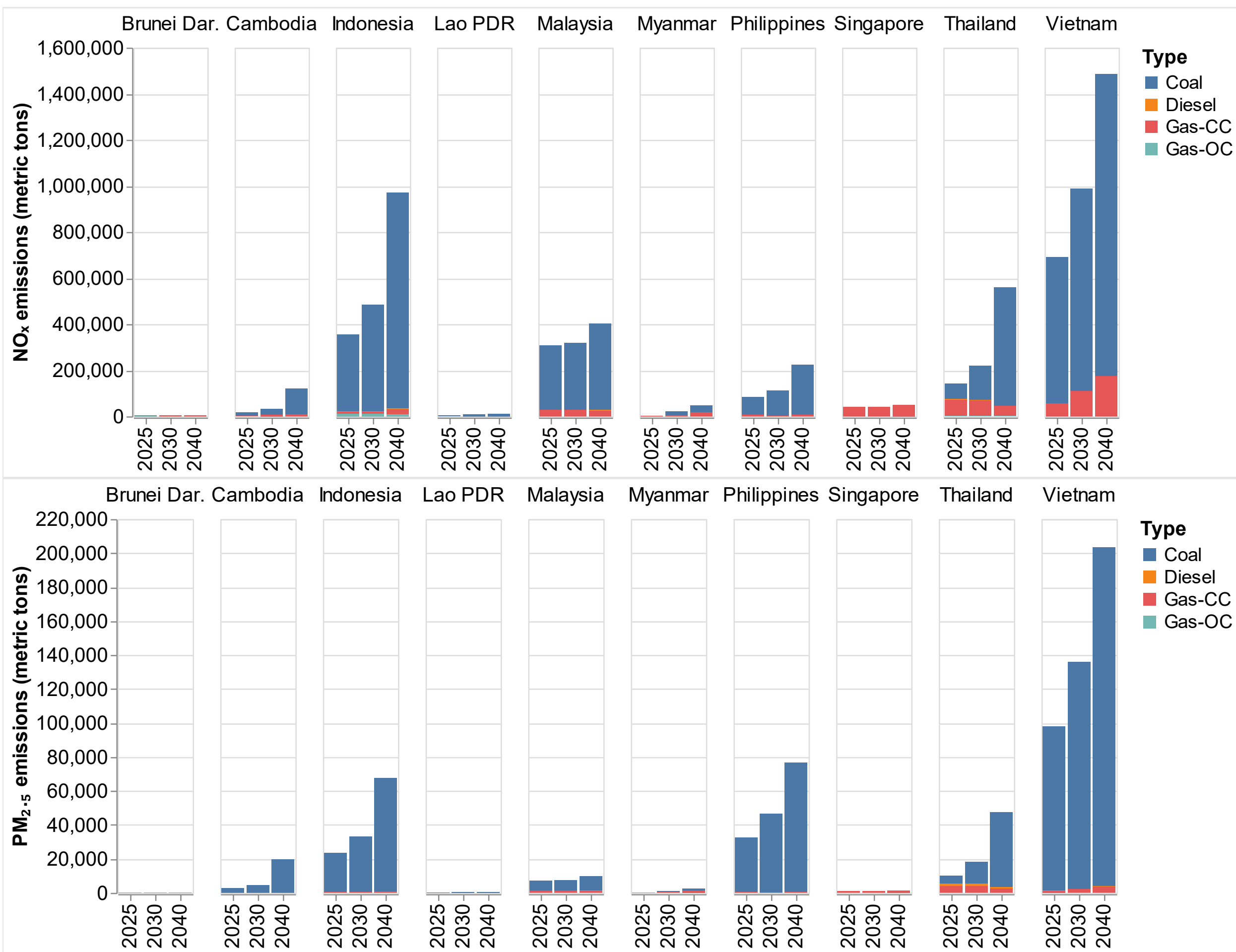

Figure 5. Estimated emissions of NO_x and $PM_{2.5}$ by country and by unit type in the three AIMS III modeling years for the Base scenario

Emissions in the region increase from 2025 to 2030 and 2040 in all the scenarios. Total power sector emissions in the High RE Target and ASEAN RE Target scenarios are always lower than in the Base scenario, whereas regional total emissions in the Optimum RE scenario can be slightly higher relative to the Base scenario, depending on the pollutant, and are lower only in 2040 for all pollutants. More pollutant-specific details on emissions reduction in these scenarios relative to the Base scenario are shown in Figure 6. Note that these are regional total emissions from the power sector, and country-specific changes relative to the Base scenario could be different.

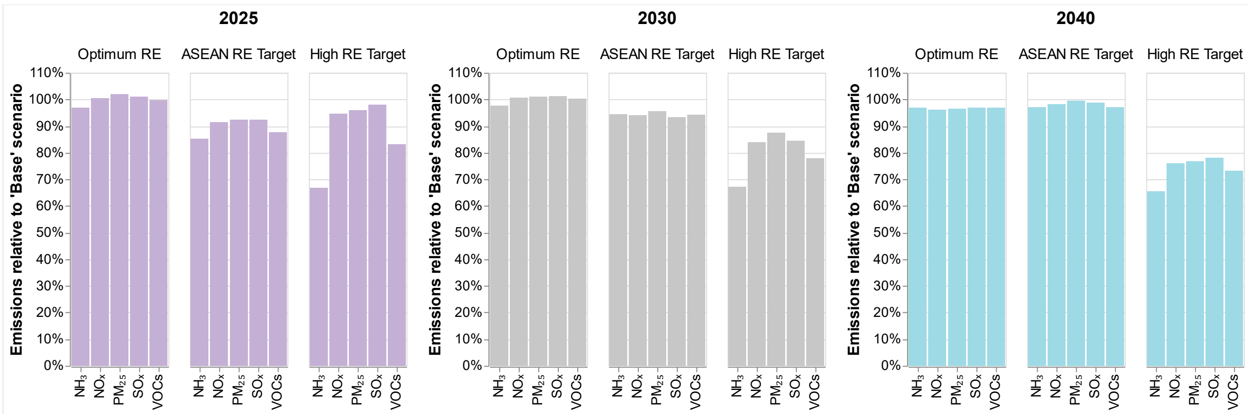

Figure 6. Emissions in the Optimum RE, ASEAN RE Target, and High RE Target scenarios relative to the Base scenario for the three AIMS III modeling years

Note: These are regional total emissions for the respective years, and country-specific changes could be different than shown here.

Table 6 gives the annual emissions totals of $PM_{2.5}$ and precursor pollutants for each scenario in 2025, 2030, and 2040 for both standards-derived emissions estimates and literature-derived emissions estimates.

Table 6. Projected Emissions for Each Scenario in Each Year Using Standards-Derived Emissions Estimates

Note: Emissions are reported in teragrams (Tg) per year (1 Tg = 1 million metric tons)

Scenario	Year	Emissions (Tg/year)				
		SO_x	NO_x	Primary $PM_{2.5}$	NH_3	VOC
Base	2025	1.820	1.650	0.176	0.005	0.020
Base	2030	2.550	2.230	0.249	0.005	0.025
Base	2040	4.620	3.880	0.429	0.007	0.039
Optimum RE	2025	1.680	1.510	0.162	0.004	0.018
Optimum RE	2030	2.380	2.100	0.238	0.005	0.024
Optimum RE	2040	4.560	3.810	0.428	0.006	0.038
ASEAN RE Target	2025	1.780	1.560	0.168	0.003	0.017
ASEAN RE Target	2030	2.160	1.870	0.218	0.004	0.020
ASEAN RE Target	2040	3.610	2.950	0.330	0.004	0.029
High RE Target	2025	1.840	1.660	0.179	0.004	0.020
High RE Target	2030	2.580	2.250	0.252	0.005	0.026
High RE Target	2040	4.480	3.730	0.414	0.006	0.038

4.1.1 Emissions Inventory for the Sensitivity Runs

Country-level emissions estimates for different pollutants in the sensitivity runs are given in Table 7. We observe large variations in estimated emissions based on emissions factors from the literature (compared to those based on emissions standards in the base runs). The heat map in Figure 7 shows emissions in the sensitivity run compared to the base run for 2040 for the Base scenario. NH_3 emissions did not differ because the same emissions factor is used to estimate its emissions between the sensitivity and base runs. $PM_{2.5}$ emissions are larger in the sensitivity runs in the two countries with largest generation in the region: Vietnam (3.3 times) and Indonesia (1.1 times), and also in Lao PDR (1.3 times) and Malaysia (1.1 times), which have relatively smaller shares of the total regional generation. VOC emissions in the sensitivity runs are always higher (by 60%–150%) compared to the base emissions. NO_x emissions are also higher in the sensitivity runs in all countries (except Brunei Darussalam and Vietnam).

The largest differences in the two emissions factor approaches are found for SO_x, where the annual total emissions in the Base scenario in 2040 are 5.5 times higher for Indonesia in the sensitivity runs relative to the base runs. SO_x emissions estimates in the sensitivity runs are higher (by 1.1–4.1 times) for most other countries in the region, except for Brunei Darussalam, Singapore, and Thailand. Note that another set of sensitivity runs where stack height was varied was also conducted, but the emissions are kept constant in these runs. These comparisons show that the emissions inventory is a large source of uncertainty in our analysis, and the results presented in our health impact analysis should only be considered in a relative sense (i.e., potential air quality and health benefits in one scenario relative to another scenario, as in the High RE Target scenario relative to the Base scenario).

Table 7. Projected Emissions for Each Scenario in Each Year Using Literature-Derived Emissions Estimates

Note: Note that emissions are reported in teragrams (Tg) per year (1 Tg = 1 million metric tons)

Scenario	Year	Emissions (Tg/year)				
		SO_x	NO_x	Primary $PM_{2.5}$	NH_3	VOC
Base	2025	4.190	2.220	0.377	0.005	0.039
Base	2030	5.720	3.000	0.518	0.005	0.051
Base	2040	10.300	5.250	0.794	0.007	0.080
Optimum RE	2025	4.280	2.250	0.384	0.005	0.040
Optimum RE	2030	5.840	3.040	0.514	0.005	0.051
Optimum RE	2040	9.970	5.090	0.747	0.006	0.078
ASEAN RE Target	2025	3.770	2.000	0.353	0.004	0.035
ASEAN RE Target	2030	5.330	2.810	0.501	0.005	0.048
ASEAN RE Target	2040	9.860	5.100	0.810	0.006	0.079
High RE Target	2025	4.250	2.100	0.360	0.003	0.034
High RE Target	2030	5.070	2.550	0.494	0.004	0.041
High RE Target	2040	8.470	4.140	0.585	0.004	0.059

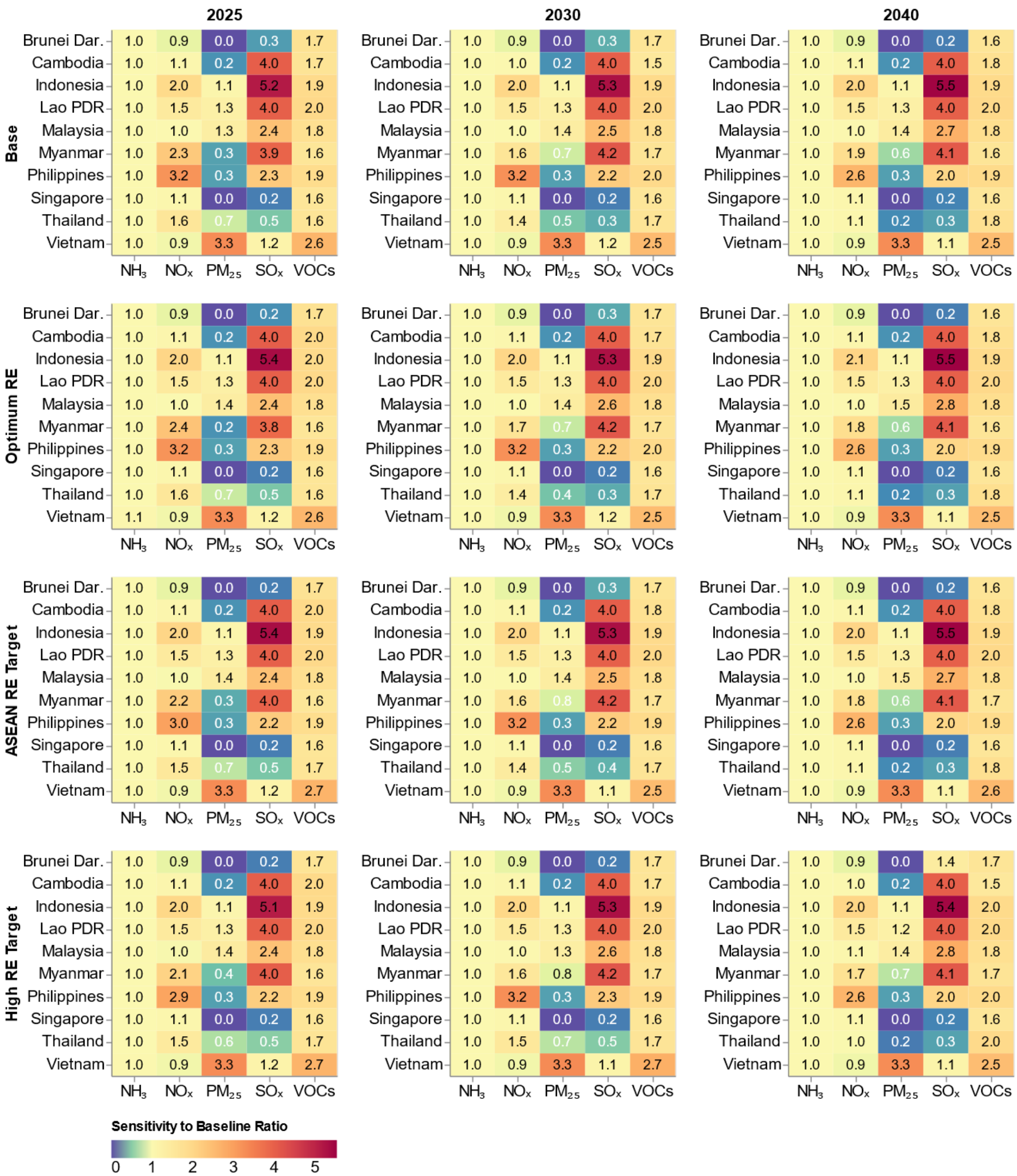

Figure 7. Emissions in the sensitivity run (based on emissions factors from the literature) relative to the emissions in the Base run (based on emissions factors from standards-derived emissions estimates)

4.2 AIMS III Scenario Impacts on $PM_{2.5}$ Concentration

Figure 8 shows the total $PM_{2.5}$ concentrations associated with power generation in the Base scenario for 2025, 2030, and 2040. As can be seen, pollutant concentrations from power generation are increasing over time and retain a similar spatial pattern because the largest pollution sources are expected to be in similar locations.

By 2040, relative to the Base scenario, all three policy scenarios (ASEAN RE Target, High RE Target, and Optimum RE) reduce population-weighted pollutant concentrations (see Table 7), with the High RE Target scenario giving rise to the greatest reduction; however, the spatial variations in pollutant reduction vary across the scenarios (see Figures 9, 10, and 11). Whereas the High RE Target scenario gives rise to almost all of the population in the ASEAN member countries breathing cleaner air relative to the Base scenario, the ASEAN RE Target scenario gives rise to only 33.8% of the population breathing cleaner air, with air quality worsening in several locations, including parts of Thailand and Vietnam (see Table 7).

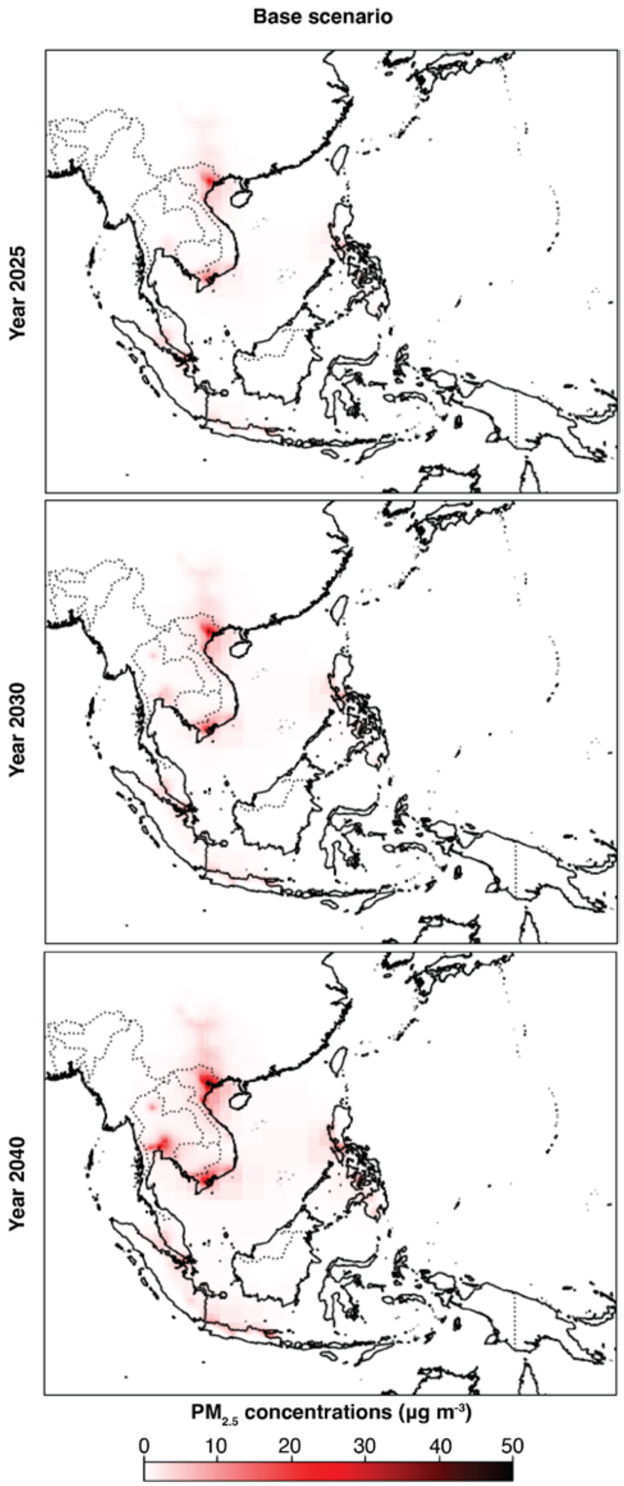

Figure 8. $PM_{2.5}$ concentrations across the ASEAN region attributable to projected power generation in the Base scenario for 2025, 2030, and 2040

Table 8. Changes in Population-Weighted Annual Average $PM_{2.5}$ Concentrations (Relative to the Base Scenario) for the ASEAN RE Target, High RE Target, and Optimum RE Scenarios

Note: Also shown is the percentage of the population exposed to reduced annual average $PM_{2.5}$ concentrations (i.e., percentage of people breathing cleaner air) relative to the Base scenario.

Scenario	Year	Pop-Wtd. Change in $PM_{2.5}$ Concentration Relative to Base Scenario ($\mu g\ m^{-3}$)	% of Population Breathing Cleaner Air (Relative to Base Scenario)
Optimum RE	2025	−0.01	15.3%
Optimum RE	2030	0.00	40.4%
Optimum RE	2040	-0.08	91.1%
ASEAN RE Target	2025	-0.08	91.8%
ASEAN RE Target	2030	-0.09	98.8%
ASEAN RE Target	2040	-0.01	33.8%
High RE Target	2025	-0.04	91.9%
High RE Target	2030	-0.18	99.7%
High RE Target	2040	-0.50	99.3%

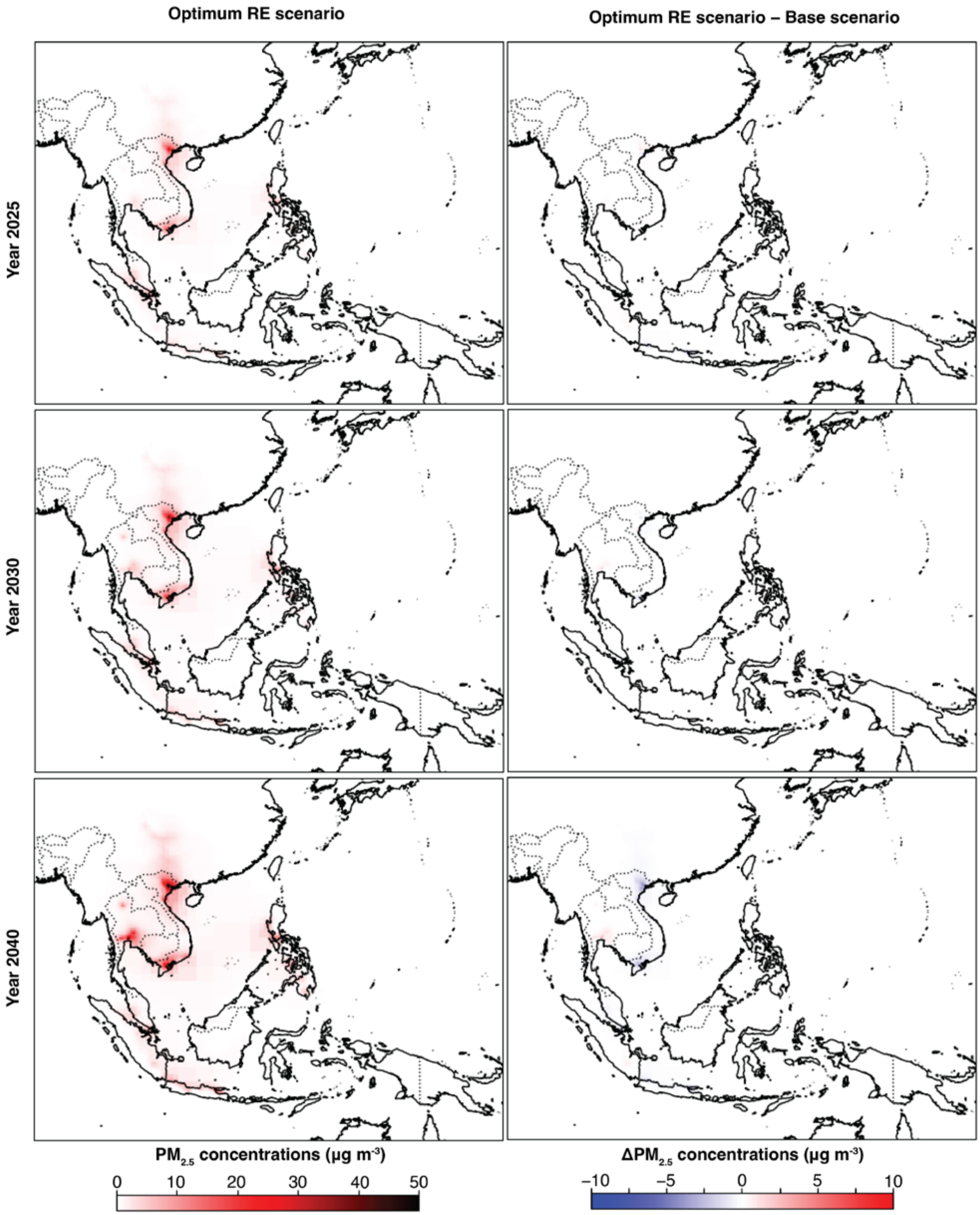

Figure 9. $PM_{2.5}$ concentrations across the ASEAN region attributable to projected power generation in the Optimum RE scenario for 2025, 2030, and 2040

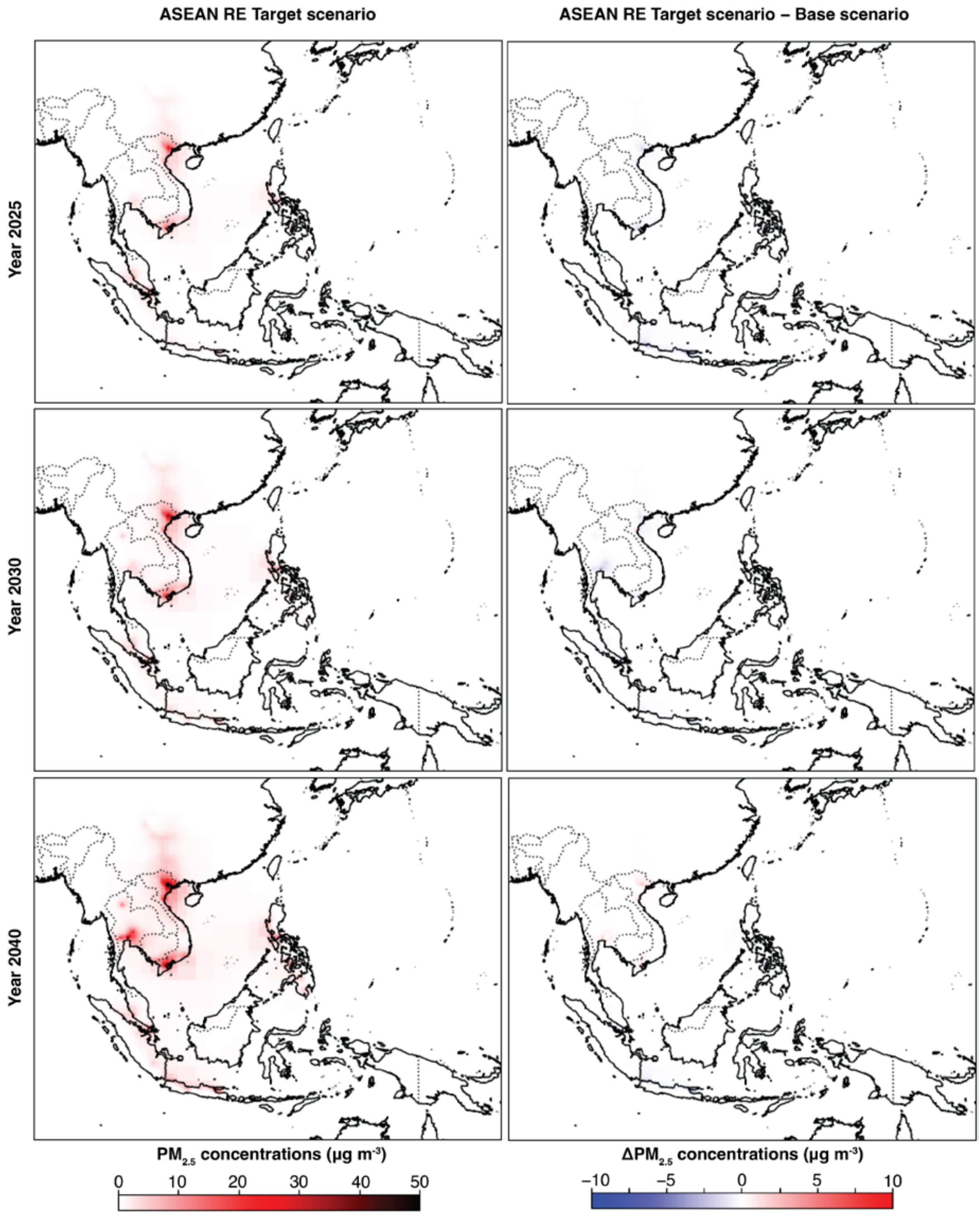

Figure 10. $PM_{2.5}$ concentrations across the ASEAN region attributable to projected power generation in the ASEAN RE Target scenario for 2025, 2030, and 2040

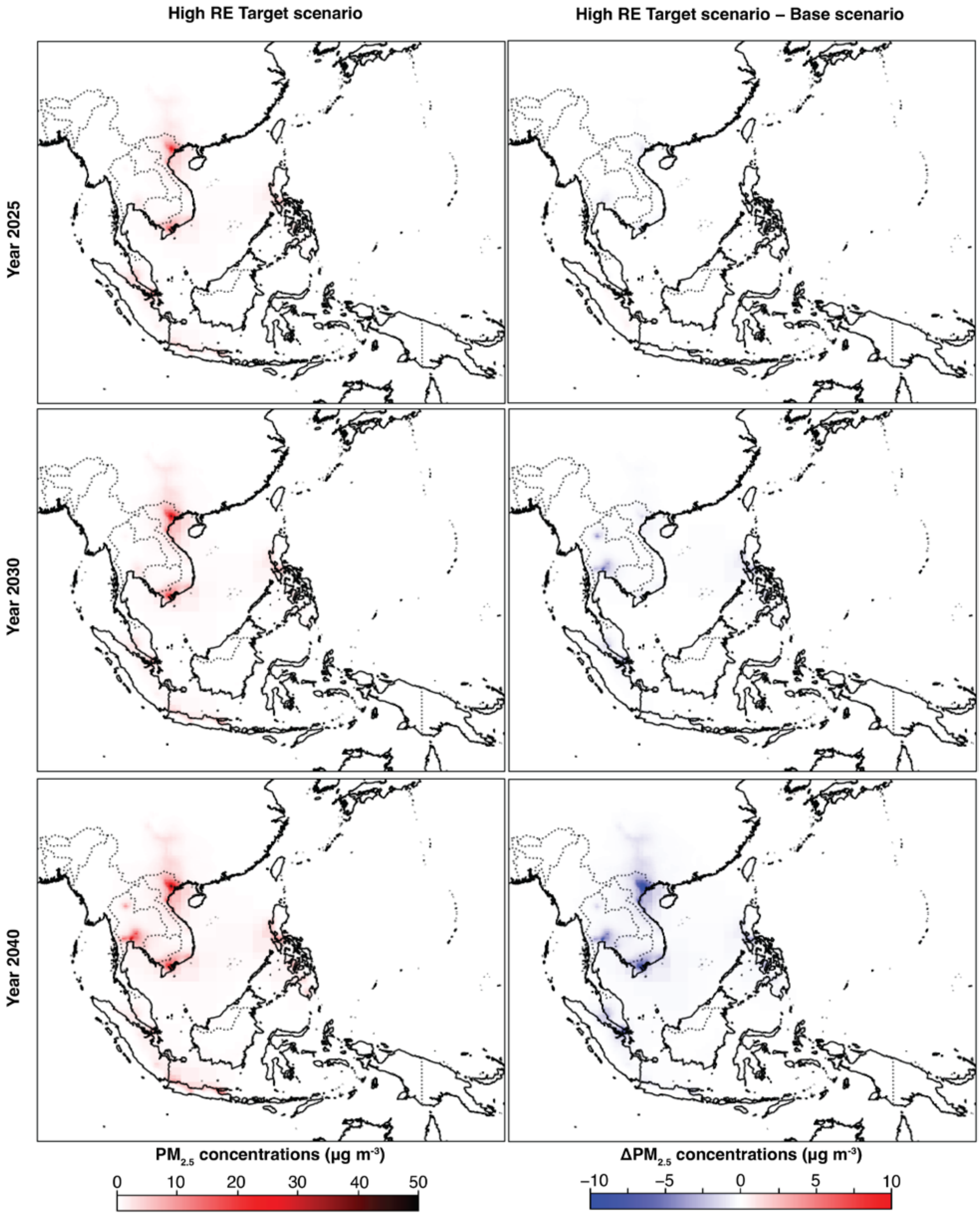

Figure 11. $PM_{2.5}$ concentrations across the ASEAN region attributable to projected power generation in the High RE Target scenario for 2025, 2030, and 2040

4.3 AIMS III Scenario Impacts on Excess Mortality

Our analysis indicates that annual excess mortality attributable to power generation in the ASEAN region increases by 161% between 2025 and 2040 in the Base scenario (from 26,500 annual deaths in 2025 to 69,200 annual deaths in 2040) (see Figure 12a). Mortality increases over time for all countries in the Base scenario but at different rates, with Malaysia experiencing only one-fifth more deaths (+400 annual deaths) and Thailand experiencing almost a twelvefold increase (+15,800 annual deaths).

In 2040, the Optimum RE, ASEAN RE Target, and High RE Target scenarios all indicate reduced mortality relative to the Base scenario (see Figure 12b and Table 9). The High RE Target scenario indicates the largest impact, reducing annual mortality from power generation by more than 16,000 deaths in 2040 compared to the Base scenario. The Optimum RE scenario has more modest reductions (−2,000 annual deaths) by 2040 relative to the Base scenario. The ASEAN RE Target scenario reduces mortality more than the Optimum RE scenario in 2025 and 2030, but by 2040, the Optimum RE scenario reduces mortality more than the ASEAN RE Target scenario.

Only the High RE Target scenario reduces mortality relative to the Base scenario for all ASEAN member countries in 2040 (see Figure 12b), whereas the ASEAN RE Target and Optimum RE scenarios are projected to increase mortality in some member countries, even though they reduce mortality overall, relative to the Base scenario. (Note that the magnitude and direction of change in mortality varies by scenario and year for a specific ASEAN country and is shown in Figure A-14 for 2025 and 2030.) The increase in mortality in Vietnam for the ASEAN RE Target scenario in 2040 relative to the Base scenario is due to a higher share of coal in the generation mix.[4] In Vietnam, coal is used to meet 62% of the demand in the ASEAN RE Target scenario, whereas its share is only 59% in the Base scenario.

The ASEAN RE Target, High RE Target, and Optimum RE scenarios all project increases in excess mortality from power generation emissions over time (see Figure 13), even though they all reduce mortality relative to the Base scenario (in 2040). Projected increases in excess mortality over time are explained by increases in coal-powered energy generation for each scenario, as shown in Figure 2. The High RE Target scenario is the only scenario where some countries experience a reduction in mortality attributable to power generation in 2040 relative to 2025. In the High RE Target scenario, both Malaysia and Singapore experience an absolute reduction in annual excess mortality attributable to power generation (by 26% and 34%, respectively); in the Base scenario, these countries experience an increase in excess mortality attributable to power generation by 18% and 20%, respectively, in 2040, compared to 2025.

The resulting excess mortality arises from several causes of death (Figure 14). By pollutant, the excess mortality is mostly driven by $PM_{2.5}$ formed by SO_x emissions (75% of total excess mortality attributable to power generation in the 2030 Base scenario), followed by $PM_{2.5}$ formed by NO_x (19%) and primary $PM_{2.5}$ (6%) (Figure 14). Mortality from $PM_{2.5}$ formed by NH_3 and VOC emissions is negligible (<0.1%).

[4] We note that Vietnam has updated their PDP since 2018–2019, with a different outlook on renewables and thermal power plants. Because our analyses are based on the AIMS III scenarios, we do not incorporate these updates.

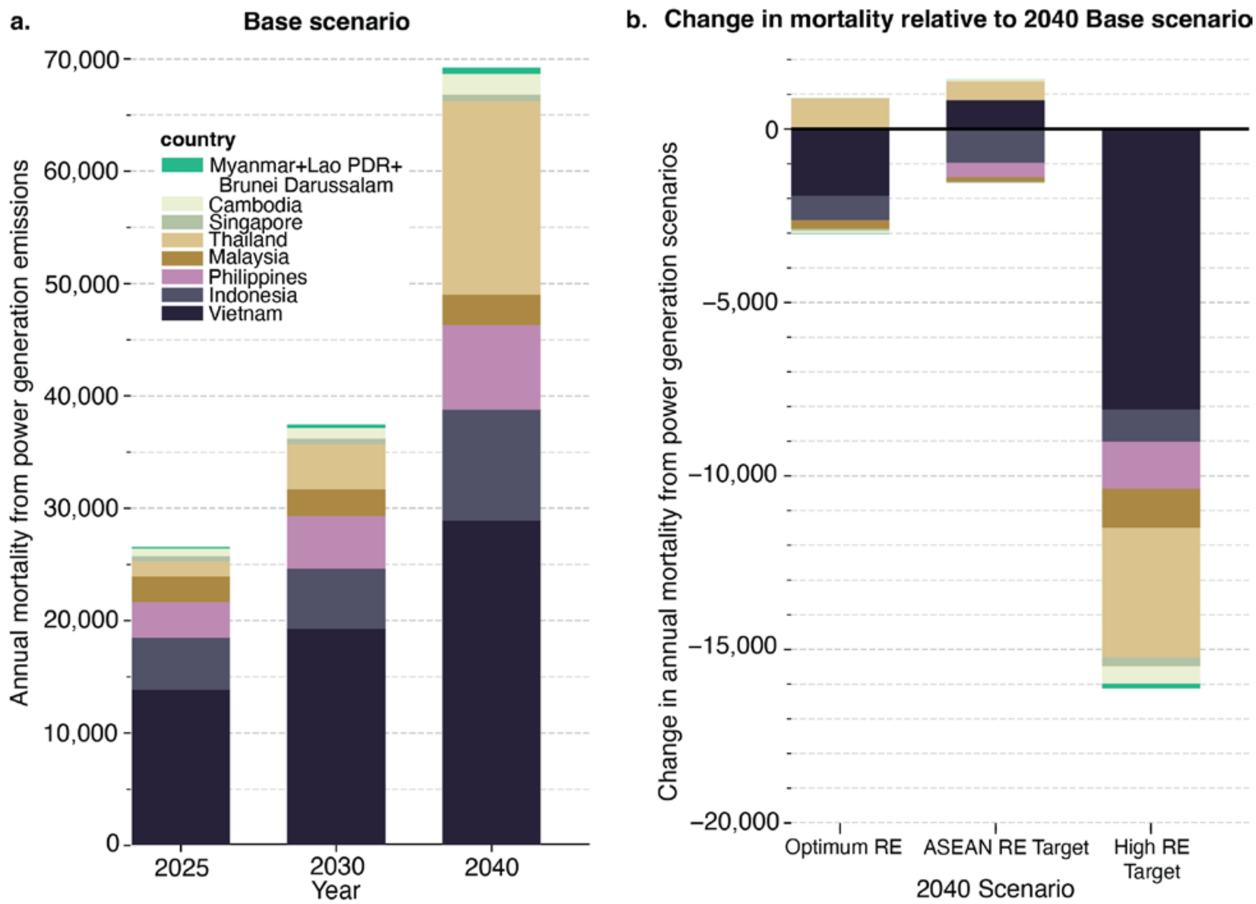

Figure 12. (a) Annual excess mortality attributable to total projected power generation emissions in the Base scenario, broken down by ASEAN member country in which mortality occurs, and (b) change in excess mortality in 2040 (relative to the Base scenario) for the ASEAN RE Target, High RE Target, and Optimum RE scenarios, broken down by ASEAN member country in which mortality occurs

Note: See Figure 13 for scenario-specific excess mortality and Figure A-14 for changes relative to the Base scenario in 2025 and 2030.

Table 9. Annual Mortality Attributable to Total Projected Power Generation Emissions in Each Scenario, Broken Down by ASEAN Member Country Where Mortality Occurs

Annual mortality for each country is expressed relative to the Base scenario. Positive values indicate that the scenario results in more deaths than the Base scenario in that country; negative values indicate that the scenario results in fewer deaths than the Base scenario in that country.

	Year 2025			**Year 2030**			**Year 2040**		
Country	Optimum RE	ASEAN RE Target	High RE Target	Optimum RE	ASEAN RE Target	High RE Target	Optimum RE	ASEAN RE Target	High RE Target
Brunei Darussalam	0	0	0	0	0	0	0	0	0
Cambodia	27	−15	−10	11	−17	−103	−68	41	−506
Indonesia	−752	−1,527	107	112	−615	−530	-703	−973	−936
Lao PDR	2	−5	−3	−1	−8	−18	−9	6	−63
Malaysia	−19	−60	−113	−135	−208	−753	−248	−131	−1,126
Myanmar	5	−1	−4	7	−10	−38	−4	−2	−75
Philippines	115	−198	−111	212	−394	−1,108	24	−416	−1,353
Singapore	7	−5	0	−11	−45	−141	-58	−34	−265
Thailand	98	81	−484	65	−1301	−2885	868	545	−3729
Vietnam	214	−684	−637	−329	−602	−805	−1,932	836	−8,077
Total	−305	−2,413	−1,254	-70	−3,200	−6,381	−2,130	−127	−16,130

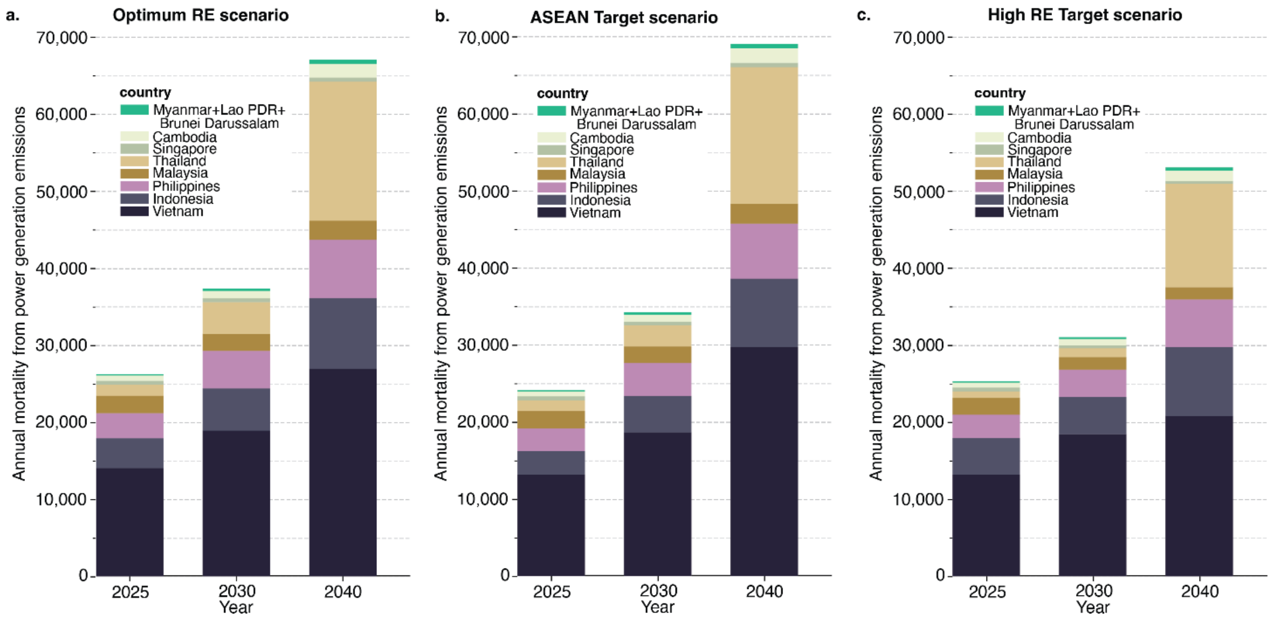

Figure 13. Annual mortality attributable to total projected power generation emissions in the (a) ASEAN RE Target, (b) High RE Target, and (c) Optimum RE scenarios, broken down by ASEAN member country where mortality occurs

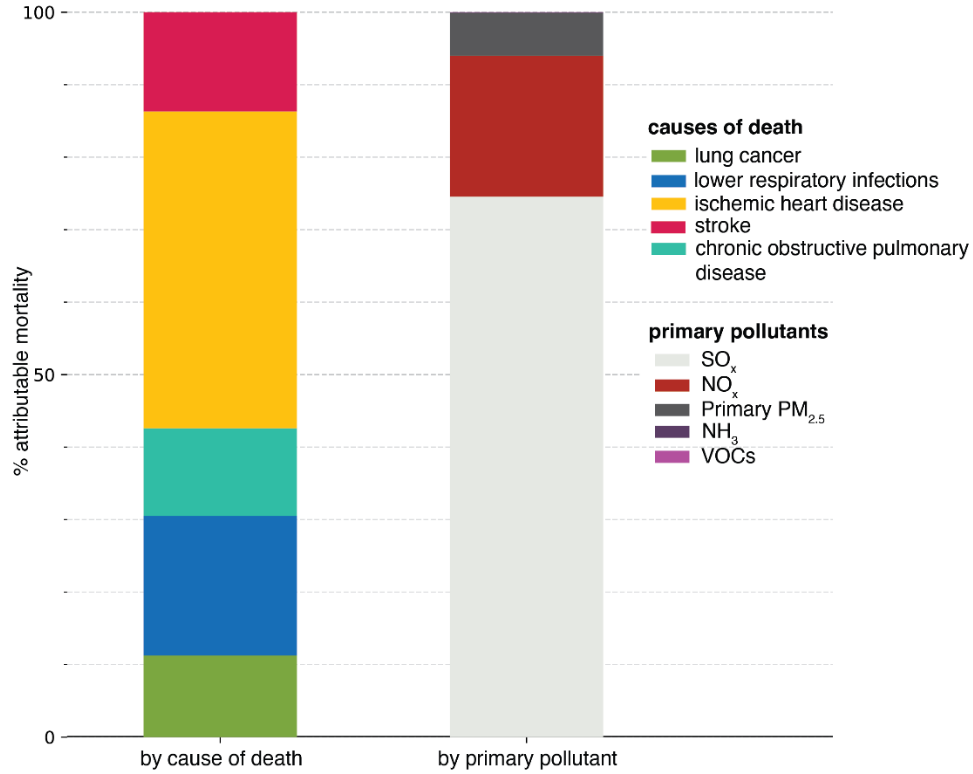

Figure 14. Fractional contributions to mortality attributable to total power generation in the Base scenario, 2030, attributable to the five causes of death and five primary pollutants considered in this study

Note: NH_3 and VOCs are associated with a very small percentage (<0.1%) of mortality.

4.3.1 Mortality Intensity

The increase in mortality attributable to power generation across scenarios is partly explained by the increase in power generation, but there are also changes in mortality intensity (excess deaths per unit of energy generated). We found that mortality intensity increases for the Base, ASEAN RE Target, and Optimum RE scenarios over time for the ASEAN region as a whole, but it decreases in the High RE Target scenario in 2030 (compared to 2025) and then increases in 2040 (Figure 15). This means that the per-unit mortality-related social cost of power generation is increasing for these scenarios regardless of how much power generation overall is increasing.

Figure 16 through Figure 19 show that the mortality intensity varies by country and that the country-level trends vary across scenarios. These results suggest that there is potential to reduce mortality in the ASEAN region if more electricity is generated in countries with lower mortality intensity and less energy is produced in countries with higher mortality intensity. Overall, the country-level mortality intensity is influenced by how much emitting (often coal-powered) generation increases in that country, the emissions intensity of power generation in that country (the level of emissions per unit power generated), and the extent to which the coal-fired power plants and other emitting plants are located upwind of population centers.

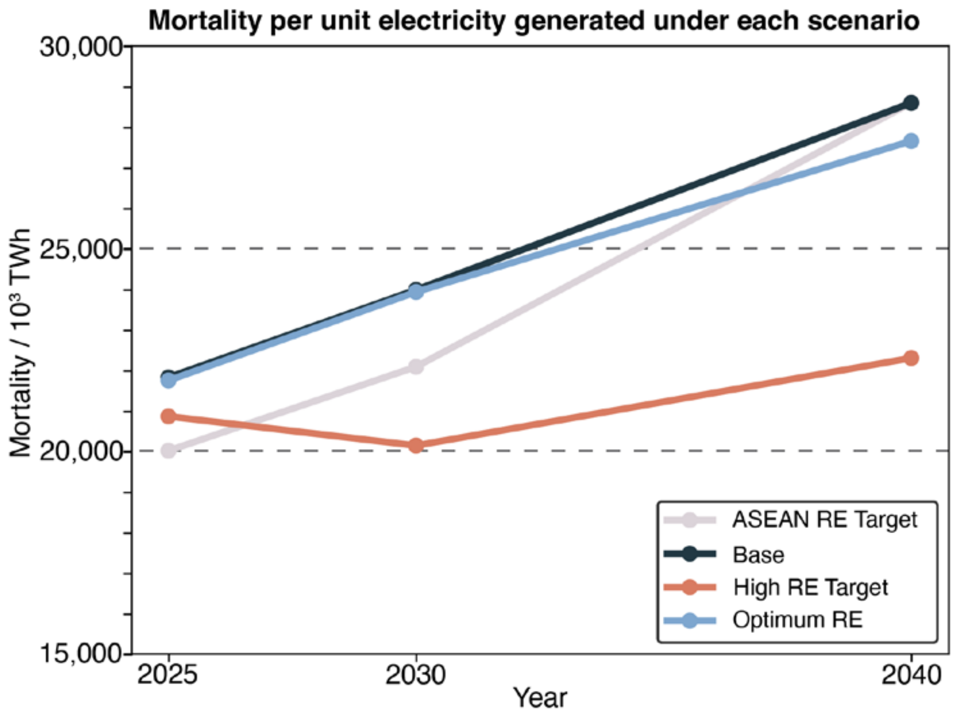

Figure 15. Excess mortality in the ASEAN region attributable to 10^3 TWh of energy generation for 2025, 2030, and 2040 under each scenario

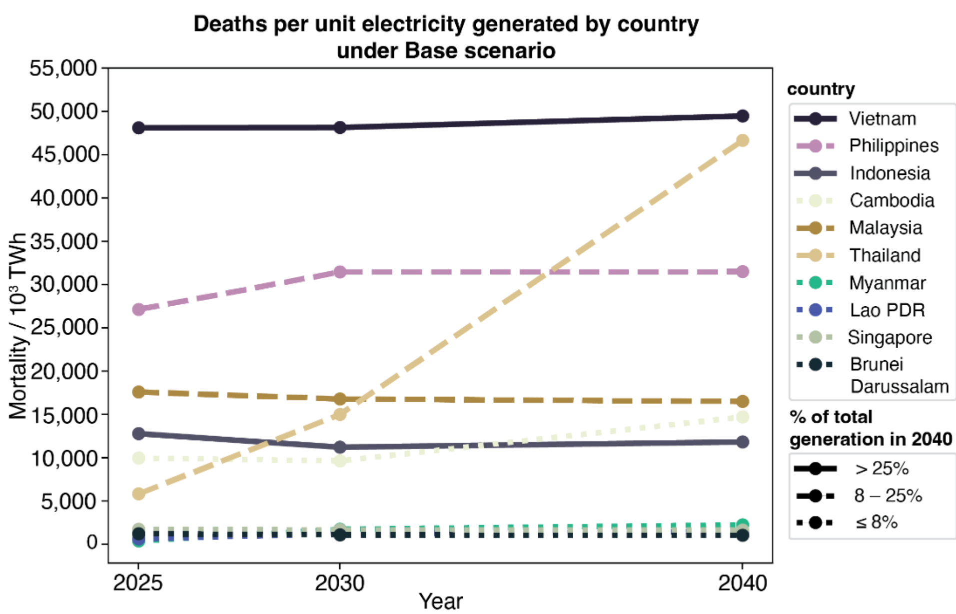

Figure 16. Excess mortality in the ASEAN region attributable per 1,000 TWh of energy generated in each ASEAN member country for 2025, 2030, and 2040 in the Base scenario

Note: Solid lines denote countries that generate >25% of total energy in the Base scenario in 2040, dashed lines denote countries that generate 8%–25%, and dotted lines denote countries that generate ≤8%.

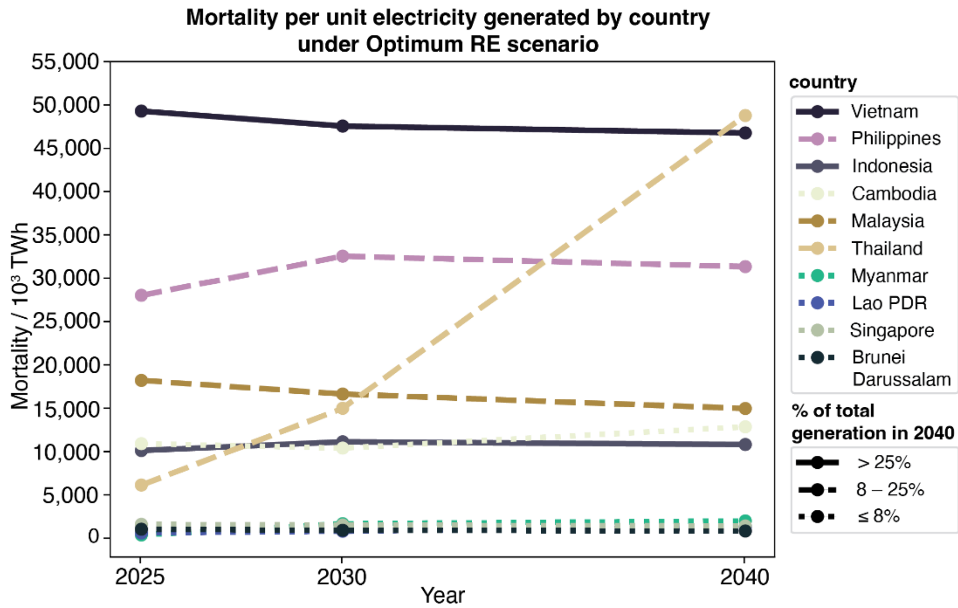

Figure 17. Excess mortality in the ASEAN region attributable to 10^3 TWh of energy generated in each ASEAN member country for 2025, 2030, and 2040 in the Optimum RE scenario

Note: Solid lines denote countries that generate >25% of total energy in the Base scenario in 2040, dashed lines denote countries that generate 8%–25%, and dotted lines denote countries that generate ≤8%.

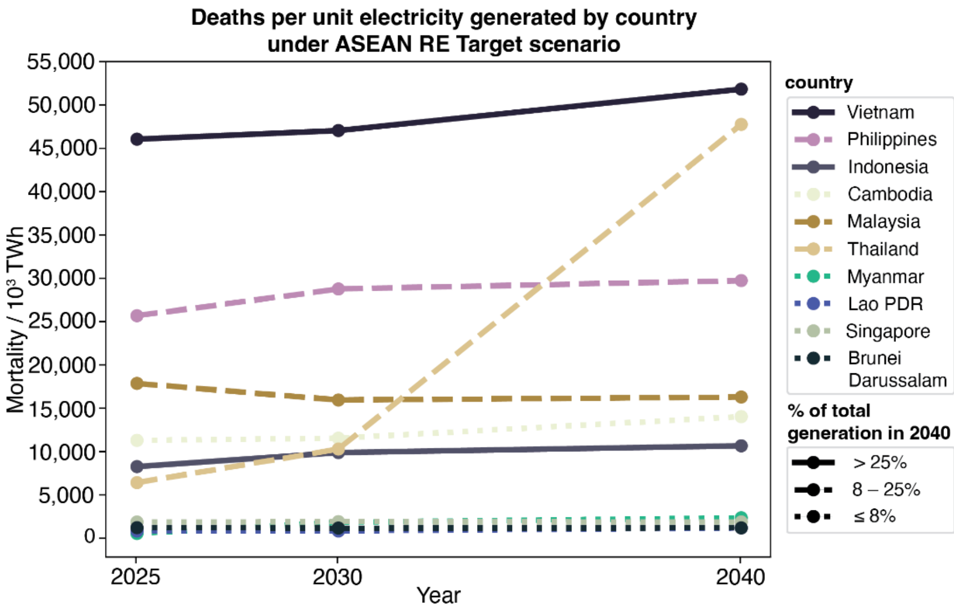

Figure 18. Excess mortality in the ASEAN region attributable to 10^3 TWh of energy generated in each ASEAN member country for 2025, 2030, and 2040 in the ASEAN RE Target scenario

Note: Solid lines denote countries that generate >25% of total energy in the Base scenario in 2040, dashed lines denote countries that generate 8%–25%, and dotted lines denote countries that generate ≤8%.

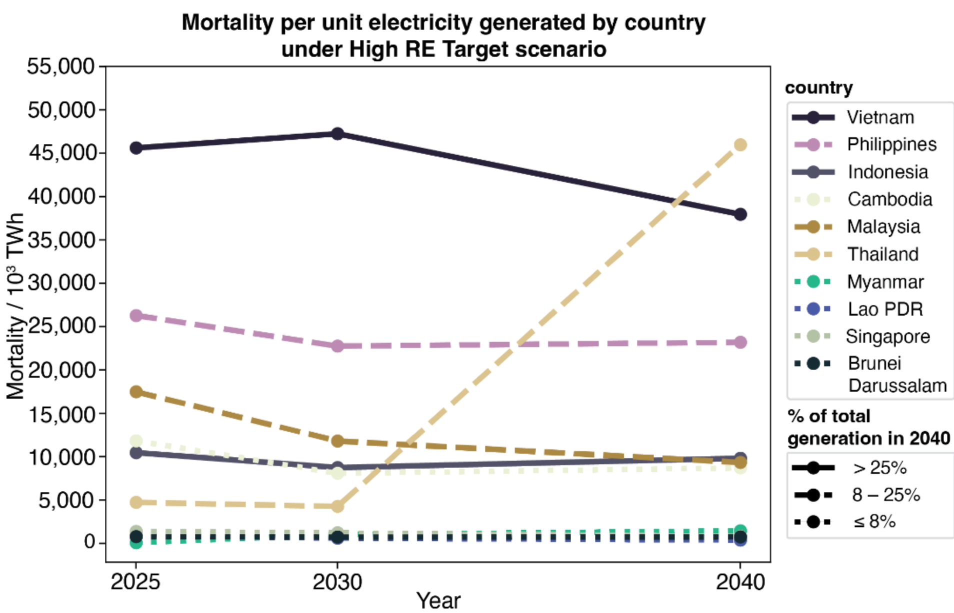

Figure 19. Excess mortality in the ASEAN region attributable to 10^3 TWh of energy generated in each ASEAN member country for 2025, 2030, and 2040 in the High RE Target scenario

Note: Solid lines denote countries that generate >25% of total energy in the Base scenario in 2040, dashed lines denote countries that generate 8%–25%, and dotted lines denote countries that generate ≤8%.

4.3.2 Sensitivity Analyses

The emissions sensitivities show that the choice of emissions inventory makes a large difference in estimates of the overall health impacts. Across scenarios and years, the literature-derived emissions estimates give rise to a projected additional 18,000–37,000 annual deaths compared to the standards-derived emissions estimates (Figure 20). Constraining the uncertainty in emissions, including through understanding the role of future enforcement in achieving permitted emissions levels, would be important to getting a better understanding of the future health impacts; however, some qualitative results from the analyses, including comparisons between scenarios, are fairly robust to the emissions sensitivities. For example, the trend in mortality change across scenarios and modeling years is similar. Similarly, the relative magnitude of change in mortality between scenarios is also robust to the emissions sensitivities. For example, the High RE Target scenario reduces annual excess mortality in 2040 relative to the Base scenario by 16,100 deaths when using the standards-derived emissions estimates and 22,100 deaths when using the literature-derived emissions estimates. For both sets of emissions, the High RE Target scenario has the greatest reduction in annual excess mortality relative to the Base scenario, and it reduces annual mortality in 2040 across all countries (whereas the other scenarios increase annual mortality in at least one country).

Estimates of total mortality vary greatly between choices of emissions factors, but the overall findings presented here are robust to the choice of stack height. For the standards-derived emissions estimates, the range of stack heights considered leads to annual excess mortality that varies by fewer than 10 deaths in 2040 for all scenarios considered. For the literature-derived emissions estimates, the results were somewhat more sensitive to stack height, but they still varied by less than ±1% (500 deaths) depending on the choice of stack height (within the 95% confidence interval) across all scenarios and years. Therefore, although stack height was a key unknown model input for several power plants in the region, the results presented here are robust to the assumed stack height.

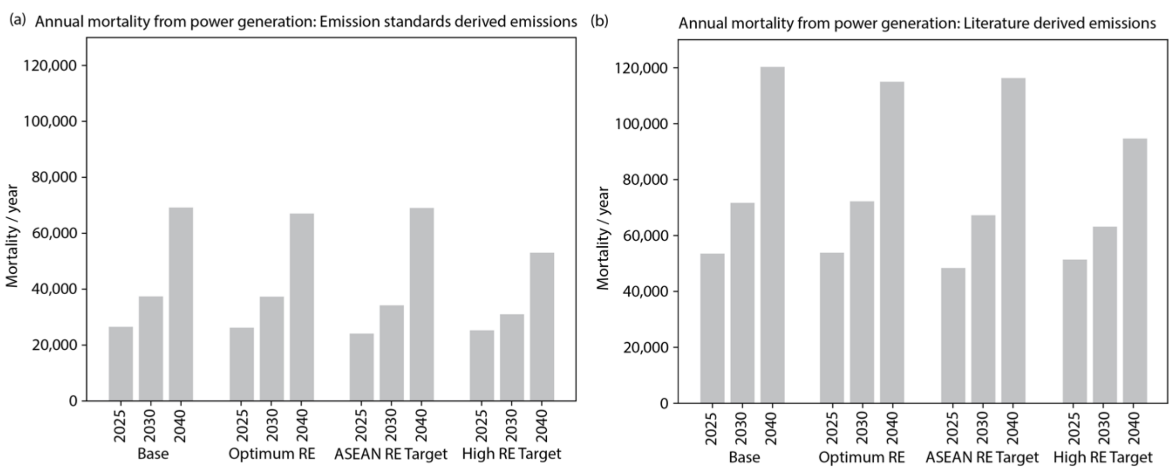

Figure 20. Total excess mortality per year from all scenarios in 2025, 2030, and 2040 using (a) standards-derived emissions estimates and (b) literature-derived emissions estimates

5 Limitations

While we have tried to represent the emissions from electricity generating units as accurately as possible, this section acknowledges several limitations of this study. In this analysis, we represent countries as a single node (or three nodes for two countries) in the capacity expansion modeling. The coarse geographic resolution in the power sector analysis leads us to make assumptions on the locations of any new builds of thermal power plants. Our analysis uses a geospatial distribution of future nodal generation to subregions that are based on existing or projected country-specific PDPs, which, in turn, are available at a variety of geospatial resolutions. Location can be one of the most influential inputs in assessing exposure and mortality from emissions sources, but given the limited scope of our analysis, we did not carry out any uncertainty assessment that accounts for different plant locations. Mortality rates and population are assumed to be static in this analysis, when in reality the population is projected to increase in the region, which would make the mortality estimates higher than presented here.

In addition, the PDPs used for some of the countries have changed since the AIMS III analysis was conducted, which formed the basis of this study. The new PDPs for these countries suggest a decreasing reliance on coal, which is likely to lead to greater reductions in excess mortality compared to the AIMS III scenarios analyzed.

Our analysis follows the scope boundaries of the AIMS III analysis and therefore focuses only on fossil fuel-based power generation units, i.e., it excludes any biomass-based generation (biofuel or waste-to-energy). Our results here should not be construed as representing all power sector-related emissions and associated air quality and health impacts; in fact, our results underestimate them with regard to the exclusion of biomass-fueled sources. As a first-order approximation, the magnitude of underestimation is likely proportional to the fraction of generation from biomass-based sources in each country. For example, for some countries, such as Thailand, biomass could be a large fraction of the power generation mix.

Another important limitation is our sole focus on the power sector and the complete exclusion of expected emissions changes in other sectors even when related to increases in power generation. For instance, some portion of the increase in power generation will meet future transportation and/or building electrification, which is arguably related to the power sector changes. Southeast Asia is a rapidly growing region, and if the trend of growth in population, affluence, and economic activity continues, there would be expected increases in emissions. Our study does not consider any of these changes, but such changes are likely to lead to significant changes to emissions, concentration, and resultant health effects. Thus, the results reported here should not be interpreted as estimates of future $PM_{2.5}$ concentrations and health effects in general for the ASEAN member countries. This study solely analyzes the air quality and public health impacts from the four power sector scenarios as modeled by AIMS III.

6 Study Conclusions

Air pollution can be caused by emissions from various human activities as well as emissions from natural sources, such as wildfires or airborne dust. Exposure to air pollution has been shown to lead to excess mortality, the majority of which is caused by the inhalation of $PM_{2.5}$, tiny aerosol particles directly emitted by various sources or chemically formed in the atmosphere. In the ASEAN region, $PM_{2.5}$ concentrations are high compared to standards set by health agencies, such as the World Health Organization. Previous studies indicate that 130,000–320,000 excess deaths occur from exposure to outdoor $PM_{2.5}$ pollution in the ASEAN region, about 10% of which are attributed to the energy sector (McDuffie et al. 2021), and the excess mortality attributable to power generation is expected to greatly increase in the coming decades (Koplitz et al. 2017). Thus, interventions to reduce air pollutant emissions from the energy sector could yield significant public health benefits.

The AIMS III analysis projects the power generation in the ASEAN region to double from 2025–2040. The AIMS III scenarios all involve an increase in coal-powered generation, which accounts for more than 50% of total generation in all scenarios explored. Using power generation data from the AIMS III scenarios and power sector emissions standards for the ASEAN countries, our analysis projects an increase in the emissions of all estimated pollutants because the generation is still coal-driven in 2040. Our air quality modeling indicates that the majority of excess mortality from power generation is associated with secondary $PM_{2.5}$ from SO_x emissions, followed by secondary $PM_{2.5}$ from NO_x, and primary $PM_{2.5}$ emissions.

There is less coal-powered generation in 2040 in the High RE Target, ASEAN RE Target, and Optimum RE scenarios than in the Base scenario. These scenarios involve reductions in excess mortality relative to the Base scenario. Of all the scenarios considered, the High RE Target scenario is estimated to yield the highest mortality reductions through reducing exposure to outdoor air pollution: more than 16,000 lives each year by 2040. The High RE Target scenario is also the scenario that is estimated to reduce exposure to $PM_{2.5}$ for the greatest proportion of people living in the ASEAN region, improving air quality for 99.3% of the ASEAN population compared with the Base scenario. Whereas the High RE Target scenario improves air quality and reduces mortality overall in every ASEAN member country, the ASEAN RE Target and Optimum RE scenarios increase mortality relative to the Base scenario in a few countries, even though they reduce mortality overall in the region relative to the Base scenario.

Public health impacts are estimated to increase from 2025–2040 if the ASEAN nations were to follow the power sector transition based on any of the four AIMS III scenarios. This is largely because the AIMS III scenarios project that coal will still be central to the electricity sector in 2040. Switching to more efficient emissions control technologies is one way to reduce health impacts. For example, as shown in the results, the emissions of sulfur gases cause about 75% of excess mortality. Technologies such as flue gas desulfurization—which are mature but not widely used in the region—can be used to reduce the impacts of coal-powered plants. Other strategies could include improving the efficiency of combustion, reducing NO_x emissions through the installation of control technologies such as selective catalytic reduction or low NO_x burners, or sourcing and burning cleaner coal (e.g., with lower sulfur content). Demand-side strategies can also be used to reduce electricity demand such that less fuel is combusted. Finally, further increasing the deployment of renewable electricity generation technologies to substitute for combustion-based power generation should also further reduce health impacts, and it has been contemplated in more recent PDPs than those that the AIMS III scenarios were based on.

This study was designed for a country-level analysis of the region; however, future analyses informed by this study can be used to conduct country-specific analyses, such as power plant siting optimization to minimize public health impacts. Any such analysis could further benefit from the availability of more comprehensive data sets on power plant characteristics and improved emissions estimates (e.g., data from continuous emissions monitoring systems), which can reduce the uncertainty of the emissions estimates.

Overall, our findings suggest that the air quality-related health effects of power generation are substantial in the ASEAN region. Excess mortality will only become a more pressing challenge by 2040, but the choice of AIMS III scenario can influence the level of this challenge. The High RE Target scenario has been found to provide the greatest benefits in terms of reduced excess mortality compared to the other AIMS III scenarios because it reduces the utilization of fossil fuels. The public health benefits we estimate herein are experienced throughout the ASEAN region. Given the trans-boundary nature of air pollution, where pollutants emitted in one country could have health impacts in another ASEAN country, the countries could create regional strategies to follow a trajectory that reduces mortality as more investments are made in the power sector. These strategic power sector investments can consider the utilization of renewable power, partnerships to locate plants in lower mortality intensity regions, and the prioritization of emissions control equipment as measures to reduce public health impacts.

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Appendix

A.1 Power Generation by Different Fuel Types in the ASEAN Region in the Different Scenarios and Years Modeled

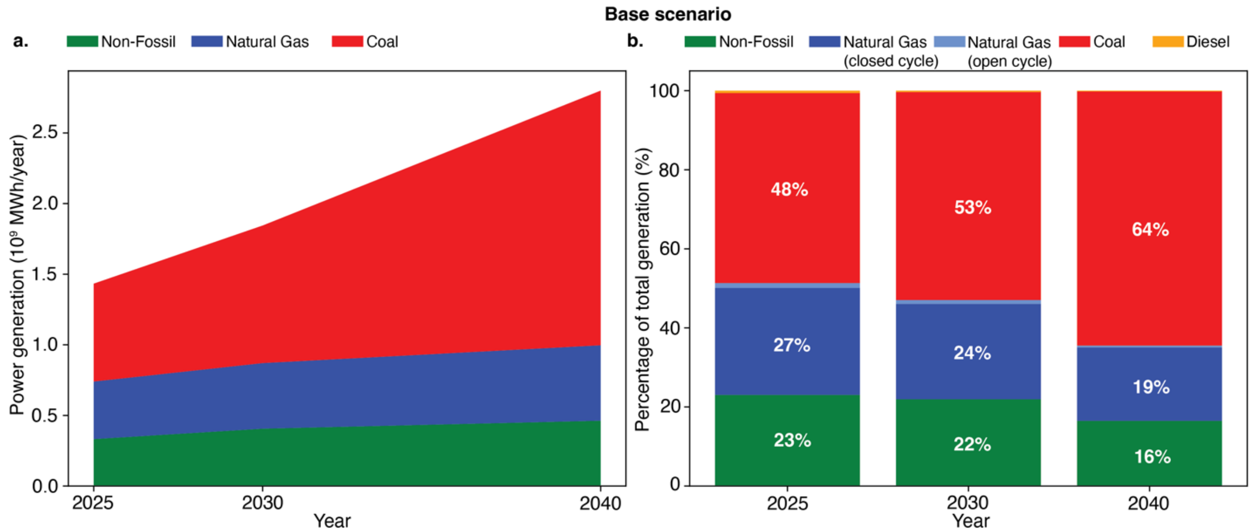


Figure A-1. (a) Changes in projected power generation over time in the Base scenario, broken down by power source

Diesel power generation is negligible and not included here. Natural gas generation includes both closed-cycle and open-cycle generating units. (b) Changes in projected fractional contribution of power sources to total power generation in the Base scenario.

Note: Here, diesel is included (yellow), and natural gas generation is broken down into closed-cycle and open-cycle generation. Percentages of the total generation by source are given for coal generation, natural gas (closed-cycle) generation, and non-fossil generation.

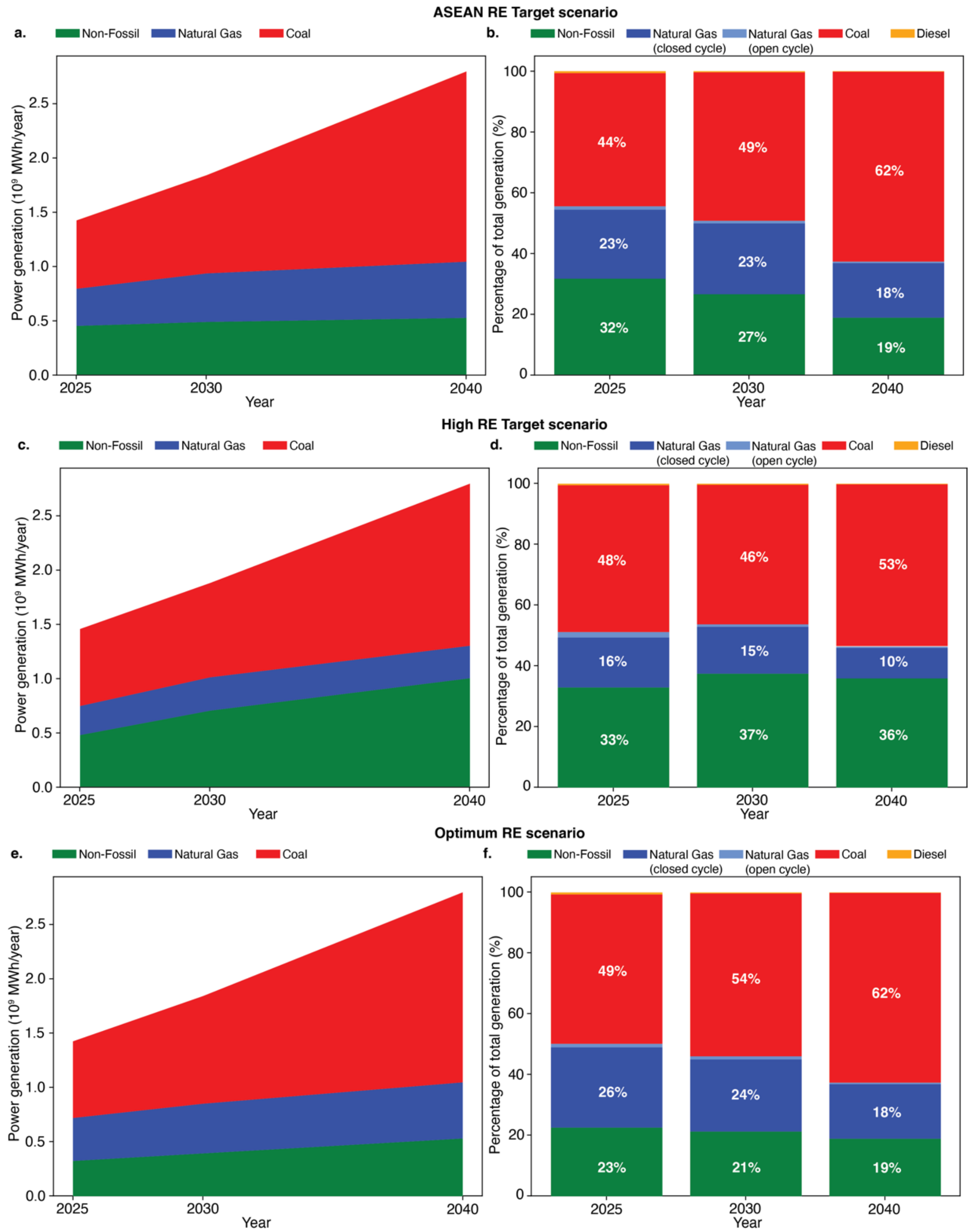


Figure A-2. Changes in projected power generation over time in the ASEAN RE Target (a), High RE Target (c), and Optimum RE I scenarios, broken down by power source

Diesel power generation is negligible and not included in the left-hand column. Natural gas generation includes both closed-cycle and open-cycle generating units. Alongside are shown changes in projected fractional contribution of power sources to total power generation in the ASEAN RE Target (b), High RE Target (d), and Optimum RE (f) scenarios.

Note: Here, diesel is included (yellow), and natural gas generation is broken down into closed-cycle and open-cycle generation. Percentages of the total generation by source are given for coal generation, natural gas (closed-cycle) generation, and non-fossil generation.

A.2 Emissions Factors Used in the Study

Total emissions for a region are typically determined through a localized activity factor and an emissions factor. Activity refers to the amount of a fuel, energy service, or good that is used for the time and geographic period in the project scope. The activity level for each country and smaller region in this study is provided as total megawatt hours (MWh) of electricity generated in a given hour, day, month, or year. The emissions factor should correspond with the units of the activity factor, yielding a numerator of pollutant output and a denominator of MWh. The species of interest are criteria pollutants that contribute to either primary or secondary particulate matter ($PM_{2.5}$), the latter of which include ammonia (NH_3), nitrogen oxides (NO_x), sulfur dioxides (SO_x), and non-methane volatile organic compounds (VOCs). Including $PM_{2.5}$, these are the five pollutants that require emissions factors to be developed. Emissions factors for these pollutants are restricted to the combustion of fossil fuels, biomass, and waste because the scope of this work includes emissions formed during the operational stage of electricity generation. Renewable energy technologies (other than biomass) and nuclear energy do not generate criteria pollutants during operation, and for this study, emissions generated during other stages of the life cycle are not included.

An emissions factor based on electricity generation can be referred to as output-based rather than input-base (ERG 2014). An input-based emissions factor primarily relies on the properties of the fuel or material input that is being consumed and generating the emissions, such as U.S. reporting of criteria pollutants in pounds per million British thermal units (lb/MMBtu). This emissions factor lists the emissions of pollutants in pounds while depending on the heating value of the fuel in MMBtu. Other input-based emissions factors may depend on mass or volume, which are also inherent properties of the input fuel. An output-based emissions factor can have units of pounds per MWh (lb/MWh), which relies on the output unit of MWh of electricity generated through the input of a given fuel. The conversion factor between these two types of emissions factors is referred to as the heat rate, which is typically listed in units of Btu/kWh. The heat rate is a conversion that accounts for the energy input of a fuel (in Btu) required to generate 1 kilowatt hour (kWh) of electricity. A lower heat rate indicates greater efficiency (i.e., 1 kWh of electricity can be generated with less energy input and therefore wastes less fuel in the conversion to a new form of energy). Output-based emissions factors reward greater efficiency in combustion and electricity generation compared to input-based emissions factors that may only account for fuel characteristics such as volume, mass, or energy content.

Country-Specific Emissions Factors

The initial data set for generating emissions factors is in the form of concentration standards for each country. These standards list the maximum concentration of a pollutant that can be detected in the flue gas generated when a specific fuel is combusted. Standards are provided for several pollutants in concentrations of either parts per million (ppm) or milligrams per normal meter cubed (mg/Nm^3). For countries and standards where the emissions limit is provided in units of milligrams per meter cubed (mg/m^3), it is assumed that the concentration is measured at standard reference conditions, and the units of measurement would be equivalent to mg/Nm^3. Standards that list particulate matter as either “total suspended particulate,” “unspecified/all sizes,” or “something else” are also assumed to refer to total particulate matter because these are alternate methods of indicating the same type of particulate matter. Total suspended particulate refers to the largest category of airborne particulate matter, which includes all smaller sizes as well (European Environment Agency 2020). The list of standards used to calculate emissions factors was compiled from data collected by the ASEAN Center for Energy and Koplitz et al. (2017) (see Table A-1). In many cases, the same set of standards is applied to multiple fuel types. For instance, in Thailand, there are two sets of standards for natural gas, depending on if the generating unit was commissioned before or after January 31, 1996. Each of these fuels will generate multiple sets of emissions factors, rather than a single set for each fuel and date of commissioning. Natural gas can generate electricity in either a gas turbine, steam turbine, or with a combined cycle. These fuels have different heat rates or dry fuel factors, respectively, and they are used in Thailand, so multiple values are generated. Instead of 4 sets of emissions factors (2 fuels with 2 date ranges), there are now 12 sets of emissions factors because each set of fuels also has three variations that apply to each range of dates. This is one example for calculating emissions factors from a single set of standards that is also applied to the multiple types of coal, standards that apply to a broad range of solid and gaseous fuels, or standards that apply to all combustion fuels equally. An example of the latter case is in Brunei, which has a single set of concentration standards that serve as the starting point to determine emissions factors for both coal and natural gas.

Table A-1. Regulatory Standards Applicable to the Power Sector That Are Used to Derive Output-Based Emissions Factors for the Standards-Based Emissions Estimates Case

Country	Applicable Regulatory Standard
Brunei Darussalam	Pollution Control Guidelines for Industrial Development, 2003. Department of Environment, Parks and Recreation, Ministry of Development. Available at: http://www.env.gov.bn/SitePages/Pollution%20Control%20Guidelines%20for%20Industrial%20Development.aspx (last accessed September 16, 2022)
Cambodia	Sub-Decree on Air Pollution and Noise Control, 2001. Ministry of Environment. Available at: https://openjicareport.jica.go.jp/pdf/11675097_06.pdf (last accessed September 16, 2022)
Indonesia	Indonesia's national regulatory legislations of air pollution control are ruled under several laws/acts and government regulations as follows: a. Law No. 32/2009 Regarding the Protection and Management of Environment b. Government Regulation No. 41/1999 Regarding Air Emission Control c. Ministry of Environment Decree No. 21/2008 Regarding Static Emission Sources Quality Standard for Business and/or Activities of a Thermal Power Plan Ministry of Environment and Forestry Regulation No. P.15/MENLHK/SETJEN/KUM.1/4/2019 on Emissions Standard of Thermal Power Plant ("PermenLHK 15/2019") Available at: https://allin.or.id/permenlhk-no15-2019-baku-mutu-emisi-pembangkit-listrik-termal/ (last accessed September 16, 2022)
Lao PDR	Permitted emissions value for thermal power plants is regulated in Lao PDR's National Pollution Control Strategy and Action Plan 2018-2025, with Vision to 2030. Available at: http://www.gms-eoc.org/uploads/resources/922/attachment/Laos-Pollution-Strategy-Plan-2018-2025-draft.pdf (last accessed September 16, 2022)
Malaysia	Emissions standards for Malaysia are set by the Department of Environment under the authority of the Environmental Quality Act 1974, amended in 2007 and 2012. Emissions standards for industrial processes, including power generation, are covered in the Environmental Quality (Clean Air) Regulations 2014. Available at: https://eswis.doe.gov.my/helpDocs/No.5%20-%202014/Peraturan-peraturan_kualiti_alam_sekeliling_udara_bersih_2014_EN.pdf (last accessed September 16, 2022)
Myanmar	The applicable regulation is the National Environmental Quality (Emission) Guideline (2015). This guideline applies to combustion processes fueled by gaseous, liquid, and solid fuels and biomass and designed to deliver electrical or mechanical power, steam, heat, or any combination of these. Available at: https://www.myanmar-responsiblebusiness.org/pdf/2015-12-29-National-Environmental-Quality_Emission_Guidelines_en.pdf (last accessed September 16, 2022)
Philippines	The Philippines Clean Air Act of 1999 (Republic Act No. 8749) outlines the government's measures to reduce air pollution and incorporate environmental protection into its development plans. The emissions limit values for the Philippines are laid down by the Department of Environment and Natural Resources (DENR) in Administrative order no. 2000-81, Implementing rules and regulations for RA 8749. These rules

Country	Applicable Regulatory Standard
	and regulations apply to all industrial emissions and other establishments that are potential sources of air pollution. Available at: https://pab.emb.gov.ph/wp-content/uploads/2017/07/RA-8749-IRR-DAO-2000-81.pdf (last accessed September 16, 2022)
Singapore	Power plant emissions in Singapore are regulated by the Environmental Protection and Management Act (Chapter 94A, Section 77). Available at: https://sso.agc.gov.sg/SL/EPMA1999-RG8 (last accessed September 16, 2022)
Thailand	The emissions standard for thermal power plants in Thailand is regulated by the Ministry of Industry (2004), issued under Factory Act B.E.2535 (1992). Available at: http://www.secot.co.th/secot_ww/StandardSECOT/standard.pdf
Vietnam	Emissions standards are set by the Ministry of Natural Resources and Environment, and the most recent version of the applicable emissions standard is NTR 22: 2009/BTNMT Emissions standards for thermal power industry. Available at: http://enidc.com.vn/Client/upload/News/User_2/2010/07/04/emission_standard.docx (last accessed September 16, 2022)

Calculating Emissions Factors

The first step in converting the standards for each fuel type to an output-based emissions factor is to determine the input-based emissions factor. For standards provided in parts per million (ppm) (NO_x and SO_x), an equation provided in Appendix A of the U.S. Environmental Protection Agency (EPA) Combined Heat and Power program report *Output-Based Regulations: A Handbook for Air Regulators* (ICF International and ERG Inc. 2014) lists the method for converting a mass-based concentration to an input-based emissions factor:

$$^{lb}/_{MMBtu} = ppm * k * F_d * \frac{20.9}{20.9 - \%O_2} \tag{1}$$

In Equation 1, *k* refers to a conversion factor specific to each pollutant species. This converts the concentration of a pollutant species to a mass per standard volume basis. K-factors are provided for NO_x and SO_x in Appendix A of the EPA report (*Output-Based Regulations: A Handbook for Air Regulators*) in units of (lb/standard cubic foot (scf))/ppm and are specific to the molecular weight of each pollutant. F_d refers to a dry fuel factor specific to each fuel type and is the ratio of the gas volume from combustion products to the heat content of the fuel (U.S. EPA 2017). The dry fuel factor is provided in Appendix A of the U.S. EPA report (*Output-Based Regulations: A Handbook for Air Regulators*) for several fuels, with additional EPA sources or the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model being used to determine the dry fuel factors for the remaining fuels used in ASEAN countries (ICF International and ERG Inc. 2014). Dry fuel factors are provided in units of dry cubic feet per million Btu (dcf/MMBtu). The last term in the equation is a correction factor that adjusts the oxygen content of the flue gas (where pollutant concentration is recorded) to the oxygen content of clean air, which is the oxygen content of air used in combustion. Several pollutant concentration standards list the oxygen percentage that should be used in the measurement; if an oxygen percentage is not provided, then a value of 9% O_2 is used as a median between the high and low values of 15% and 3% O_2, which is the range of oxygen content listed in the standards from ASEAN countries.[5]

If the concentration standard is provided in units of mg/Nm^3 or mg/m^3, then the k-factor in Equation 1 is replaced with a direct unit conversion from mg/m^3 to lb/scf. This conversion yields the same units as the original form of the equation [ppm * (lb/scf)/ppm = lb/scf].

Converting From Input-Based to Output-Based Emissions Factors

Once the input-based emissions factors for each fuel type and pollutant have been calculated, Equation 2 can be used to find the output-based emissions factor:

$$^{lb}/_{MWh} = {}^{lb}/_{MMBtu} * \frac{heat\ rate\ (^{Btu}/_{kWh})}{1000} \tag{2}$$

An output-based emissions factor is directly reliant on the heat rate, which itself depends on the fuel, method of combustion (turbine, boiler, engine, or combined cycle), and the overall efficiency of the combustion unit. The same fuel and combustion method can have a higher efficiency if the unit is maintained, repaired, and kept in good working condition, which results in a lower heat rate. Therefore, finding accurate heat rates that are as specific as possible to each set of standards is the most important step to calculate an accurate output-based emissions factor. A specific heat rate is used for each fuel and combustion method; if a heat rate is provided for a specific generating unit, then that value is used instead. The heat rate for several fuels is provided in a study of the social welfare impact from the Trans-Asian electricity trade (Purvins et al. 2021). The heat rates for bituminous, subbituminous, and lignite coal are provided by the Global Energy Monitor (GEM) (Global Energy Monitor 2021) using the Lower Heating Value (LHV) method that is more common outside the United States. Heat rates from GEM are

[5] See https://gaslab.com/blogs/articles/flue-gas-oxygen-measurement.

used, as opposed to values reported in ASEAN countries, because GEM also accounts for the coal combustion method. The heat rate varies depending on if each coal type is combusted using subcritical, supercritical, ultra-supercritical, or integrated gasification combined-cycle combustion. Anthracite coal is found only in Vietnam (among ASEAN countries), so the average heat rate for anthracite coal reported in the Global Coal Tracker (from GEM) is used as a representative value. The heat rate for natural gas steam turbine combustion is taken from EIA-reported values for years 2010–2020 (EIA 2022). The heat rate for 2020 is used and varies by 0.3% over the 10-year period. Heat rates for natural gas combined-cycle and gas turbine use, as well as a diesel internal combustion engine, are taken from sources more specific to ASEAN countries (Powerphase LLC, 2021; Zhang and Alvarez 2021) These sources include a report on new energy production in Vietnam and Indonesia as well as values reported by recent gas turbines installed in Southeast Asia. Overall, heat rates for U.S. sources do not differ greatly compared to those listed for ASEAN countries.

Ensuring Emissions Factors Are Realistic

While the method listed here is useful for determining emissions factors for the pollutants of concern, we must also ensure that the calculated values are physically possible for each pollutant. There can be cases where the emissions factor derived from a standard is more than 10 times larger than other sources might list, which is an indicator that emissions based solely on that standard are not possible. Regardless of the standard, emissions factors will not be used that are not possible for each fuel. To prevent this occurrence, an additional check is built into the calculations for each set of factors. If the input-based emissions factor is larger than the emissions factor for that pollutant and combustion method as listed in AP-42, then AP-42 values are used (U.S. EPA 2016). If the input-based emissions factor is smaller than AP-42, the value based on the concentration standard is used. Emissions factors from AP-42 to compare against are taken from the following sections for NO_x, SO_2, and particulate matter:

- Section 1.4 for natural gas combusted in a boiler
- Section 3.1 for natural gas combusted in a turbine (default if method not listed)
- Section 3.2 for natural gas combusted in an engine
- Section 3.3 for diesel or fuel oil combusted in an engine or turbine
- Section 1.2 for anthracite coal
- Section 1.1 for bituminous and subbituminous coal
- Section 1.7 for lignite coal.

In determining coal emissions factors, some additional steps are required. The sulfur content is assumed to be 0.8% when determining an SO_2 emissions factor as a conservative estimate and using methods described in AP-42. Total particulate matter values are calculated using the average ash content for each type of coal (Bowen and Irwin 2008). NO_x emissions factors vary depending on the furnace type, so multiple values are available. Anthracite coal is assumed to use a pulverized coal boiler, whereas lignite is pulverized coal with dry-bottom and pre-New Source Performance Standards (if these boilers are older or less efficient than New Source Performance Standards). Bituminous and subbituminous coals use pulverized coal dry-bottom wall-fired boilers, pre-New Source Performance Standards. Dry-bottom boilers are more common than wet-bottom, and wall-fired is one of the more common firing methods for coal combustion. The selected values are also on the higher end of those available to represent a potential maximum value, rather than an actual assumed value (which is being calculated with standards-based emissions estimates). The heating value for each coal type is assumed to be on the lower range of the values listed in AP-42, again because this calculation is setting a potential maximum value for each emissions factor.

Pollutants Without an Emissions Standard in Country Regulations

In several cases, an emissions standard is not available for a fuel used in an ASEAN country. This occurs for several fuels where a concentration standard is provided for NO_x but not SO_x or particulate matter, many instances where biomass is the fuel used to generate electricity, and for all fuels regarding NH_3 or VOC (both of which do not have a maximum detectable concentration standard in the available data sets). Alternate methods are used to determine the emissions factors for these pollutants and fuels. There are also several instances where an emissions standard is provided for NO_x from natural gas combustion without a standard listed for SO_x or particulate matter. In these cases, SO_x emissions factors are taken from AP-42 sections 1.4, 3.1, and 3.2 for boilers, turbines, or engines, respectively. Particulate matter emissions are taken from a spreadsheet developed by the U.S. EPA as a newer source of particulate matter emissions factors for natural gas, process gas, and liquefied petroleum gas (LPG) (Huntley 2006). The spreadsheet was created to serve as an update to AP-42 for particulate matter emissions factors for gaseous fuel because the existing values in AP-42 do not always account for updated combustion or particulate testing methods. The spreadsheet includes the results from EPA tests that were performed for $PM_{2.5}$ from natural gas combustion, aggregated into a single location, and in some cases, emissions factors differ from those in AP-42 by a factor of 10 or more.

Volatile Organic Compound Emissions Factors

There is not an output concentration standard listed for ozone or non-methane VOCs; proxy values for VOC emissions factors for combustion fuels are taken from Wei et al. (2008). The emissions factors used in the referenced publication are designed for use in China, which is chosen due to its proximity to the ASEAN countries because emissions factors for these countries are not directly available for VOCs (Roy et al. 2021).[6] These emissions factors use averages from several sources, including AP-42, the European Environmental Agency, and studies examining China specifically, to arrive at an average value that is not based solely on measurements from the United States. Emissions factors are provided for natural gas, coal, and diesel/fuel oil in units of grams per kilogram and converted using the heating value for each fuel.

Ammonia Emissions Factors

Because there is not a concentration limit provided for ammonia, substitute values are taken from the 1994 U.S. EPA report *Development and Selection of Ammonia Emissions Factors* (U.S. EPA 1994). Table 5 and Table 6 in this report lists the ammonia emissions factors for natural gas, coal, and diesel/fuel oil, both uncontrolled and when selective catalytic or non-catalytic reduction (SCR or SNCR) is employed as a NO_x control method. SCR involves the injection of ammonia into the flue gas stream and passing through a catalyst bed so that the NO_x will react with NH_3 to form nitrogen gas and water. There is a degree of slip from unreacted ammonia when this control method is used that increases the ammonia emissions factor. Emissions factors are provided as lb/ton for coal, lb/1000 gallon for fuel oil/diesel, and lb/MMscf for natural gas. The heating value and density of each fuel was used to convert the emissions factors to the input-based emissions factor of lb/MMBtu. SCR was only listed as a control method for Thailand and Vietnam in the data sets available; if SCR is determined to be present in other countries, then the same emissions factors can be used because they are not dependent on inputs other than fuel type.

[6] VOC emissions factors are listed for Vietnam in Roy et al. (2021). The sources for this article for NMVOC are IPCC, AP-42, and a European air pollutant inventory guidebook. The sources for NMVOC in Wei et al. (2018) are AP-42, a report on coal VOC emissions from the European Commission, and the same European air pollutant emissions inventory guidebook. The values are selected from Wei et al. (2018) because the final value for each fuel is an average rather than a single value and the emissions factors are more conservative (higher) than those from Roy et al. (2021) to account for uncertainties that may exist with fuel combustion in ASEAN countries.

Determination of $PM_{2.5}$ Fraction of Total Particulate Matter Mass Release Rates

The country emissions standards often only include particulate matter, which includes all particulate matter sizes, whereas inputs to Global-InMAP require $PM_{2.5}$, the fraction of particulate matter that has an aerodynamic diameter smaller than 2.5 µm. The following sources (Table A-2) were used to determine the fraction of particulate matter that is $PM_{2.5}$ for each fuel used in ASEAN countries.

Table A-2. Data Source for Converting Emissions Factors of Particulate Matter to $PM_{2.5}$ Fraction That Is Used as Input to Global InMAP

Fuel Type	Source
Anthracite Coal	AP-42 Section 1.2 Anthracite Coal Combustion
Bituminous/ Subbituminous Coal	AP-42 Section 1.1 Bituminous and Subbituminous Coal Combustion
Lignite Coal	AP-42 Section 1.7 Lignite Coal Combustion
Diesel/Fuel Oil	AP-42 Section 3.4 Large Stationary Diesel and All Stationary Dual-fuel Engines
Natural Gas	Development of Fine Particulate Emissions Factors and Speciation Profiles for Oil and Gas-fired Combustion Systems, Topical Report: Test Results for a Combined Cycle Power Plant with Oxidation Catalyst and SCR at Site Echo. 2004 (England 2004)

The percentage of total particulate matter attributed to $PM_{2.5}$ is available in AP-42 for all coal types for uncontrolled emissions as well as when any of three particulate matter control methods is used: scrubber, electrostatic precipitation, or a baghouse/fabric filter. The percentage of particulate matter attributed to $PM_{2.5}$ is only available for uncontrolled emissions for diesel, fuel oil, and natural gas. For natural gas, most particulate matter emissions (assumed 99%) are $PM_{2.5}$, which is confirmed in AP-42 for natural gas boilers and engines. The particulate matter emissions factor is multiplied by the percentage of $PM_{2.5}$ for each fuel to calculate the $PM_{2.5}$ emissions factor. Myanmar and the Philippines have particulate matter emissions standards in units of PM_{10} rather than total particulate matter. To determine the amount of $PM_{2.5}$, the same sources and method were used when the standard refers to total particulate matter, but the fraction applied to the calculated particulate matter emissions factor is (% $PM_{2.5}$ / % PM_{10}).

Sensitivity Emissions Factors

The methods listed previously in this section serve as one estimate of the emissions factors for each country and standard. In this study, we also consider another source of emissions factors, which is based on published (in peer-reviewed literature, reports, etc.; not through government enforced programs, such as the continuous emissions monitoring system) emissions factors for each country or the region as a whole. Publicly available emissions factors are not listed for criteria pollutants in most ASEAN countries; emissions factors for greenhouse gases in each country are prevalent but irrelevant to the current study. Vietnam and Thailand have emissions factors for criteria pollutants related to electricity generation that can be used here, though for the remaining countries, an average for the region must be used (Krittayakasem et al. 2011; Roy et al. 2021). The emissions factors used for the remaining ASEAN countries are from the Regional Emissions Inventory in Asia (REAS) Version 2, as listed in Kurokawa and Ohara (2019). The relevant region is listed as Asian countries that that do not include China, Japan, Taiwan, South Korea, or southern Asia. Emissions factors in each case reference the input-based value in lb/MMBtu and then refer to the heat rate previously assigned to each set of standards. Emissions factors for Thailand do not include VOC, so values from REAS v2 were used as the closest approximation. None of the available references provided emissions factors for ammonia, so the existing emissions factors were used for this table as well. In cases where emissions factors referred to $PM_{2.5}$ emissions directly, no scaling factor was needed to convert from particulate matter to uncontrolled $PM_{2.5}$ emissions. In cases where emissions factors are provided for only a single type of coal, those values are used for each coal and combustion type in that country. SO_2 emissions factors in Vietnam vary depending on the sulfur content of the fuel: For coal, the lower value of 0.6% is selected, and for fuel oil, the “local” sulfur content is used. When the coal type for a location is listed as “unknown,” the value for subbituminous coal is used, following the methods reported by GEM and in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

A.3 Location of Thermal Power Plants Used in the Study

The following maps provide locations of the coal, diesel, and gas (both open-cycle and closed-cycle) units for each ASEAN country. The maps here are based on the Base scenario for the year 2040; however, the exact units used in each scenario-year combination can be slightly different from those shown here depending on the generation in those scenario and years for the individual countries.

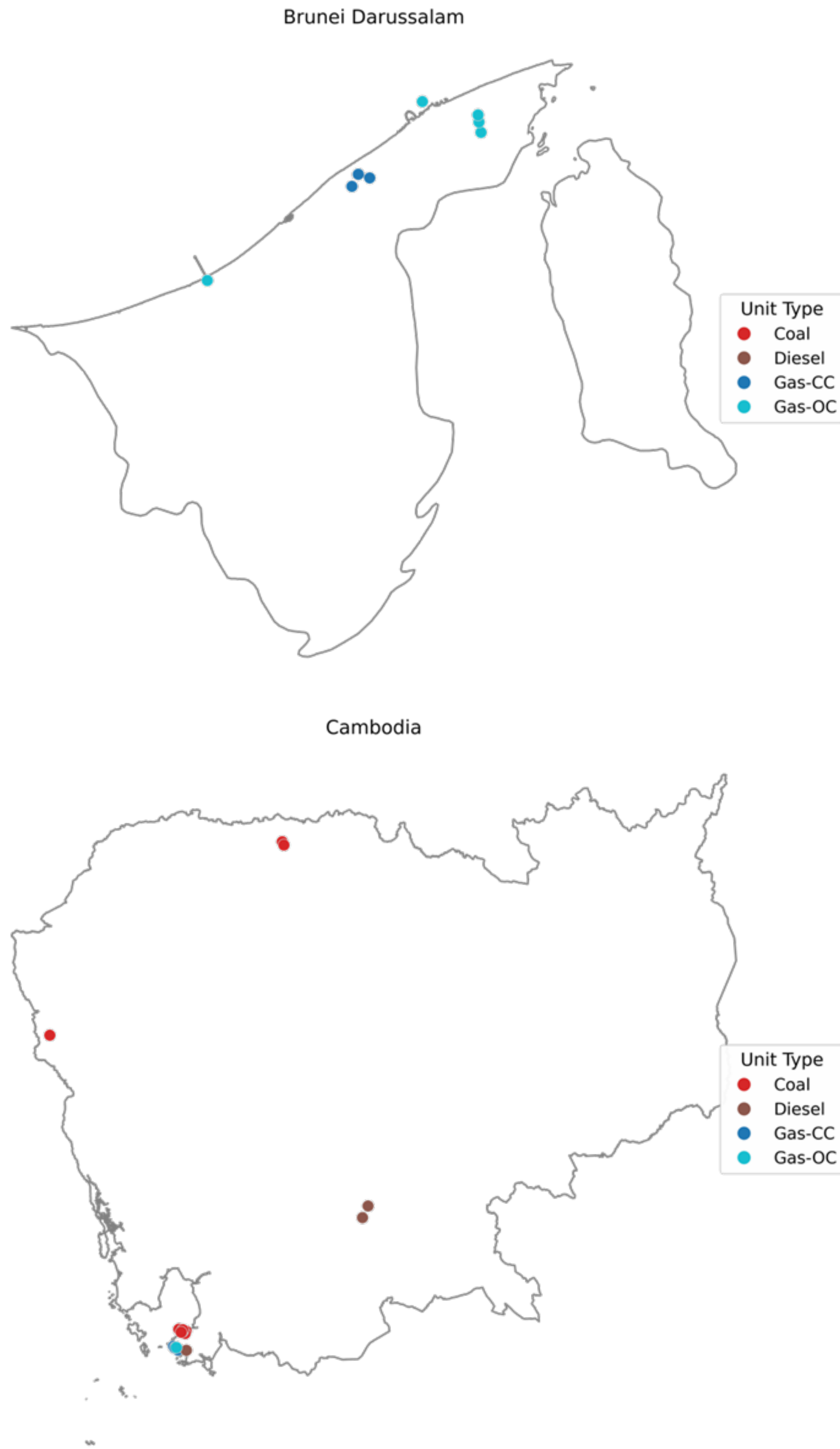


Figure A-3. Locations of power plants in Brunei Darussalam and Cambodia in 2040 for the Base scenario

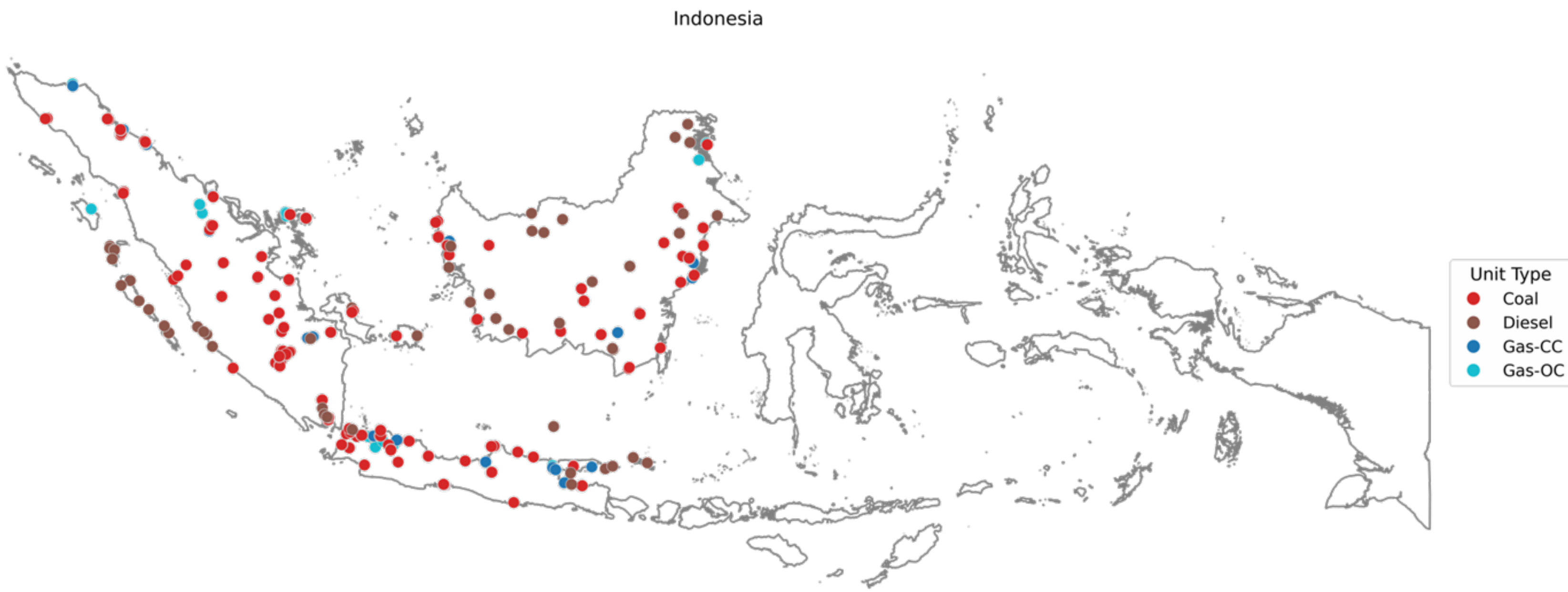
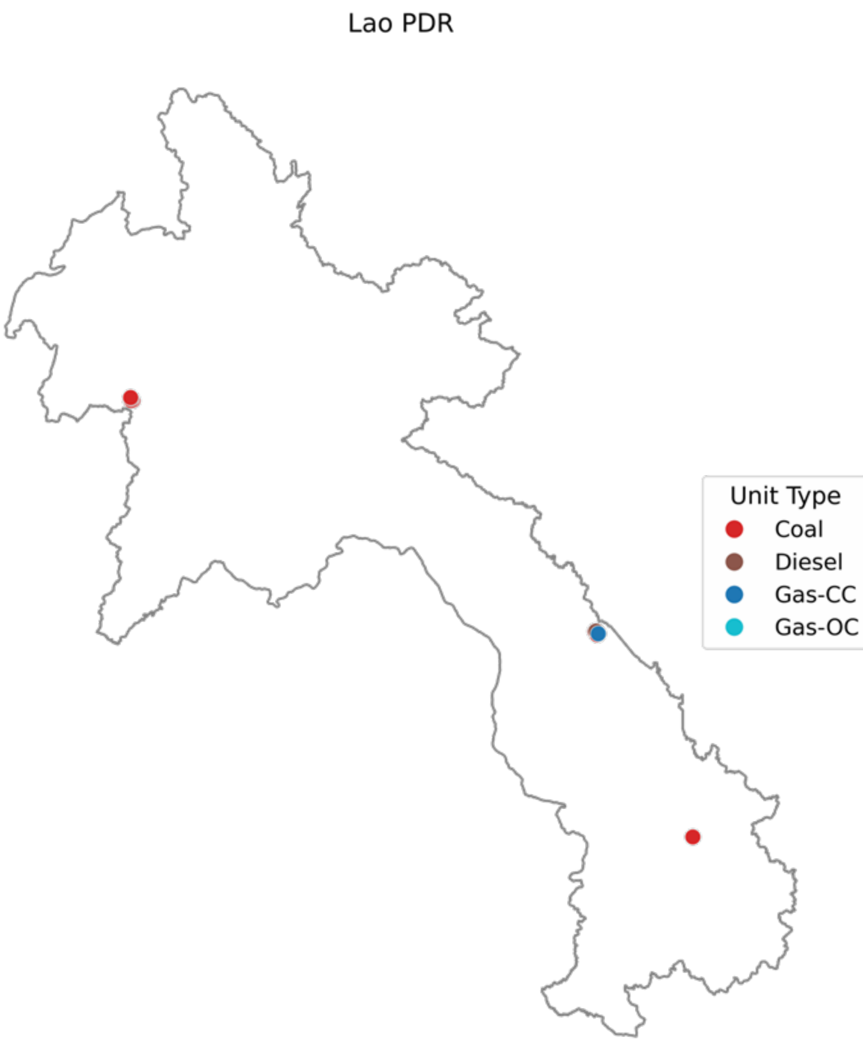


Figure A-4. Locations of power plants in Indonesia in 2040 for the Base scenarios



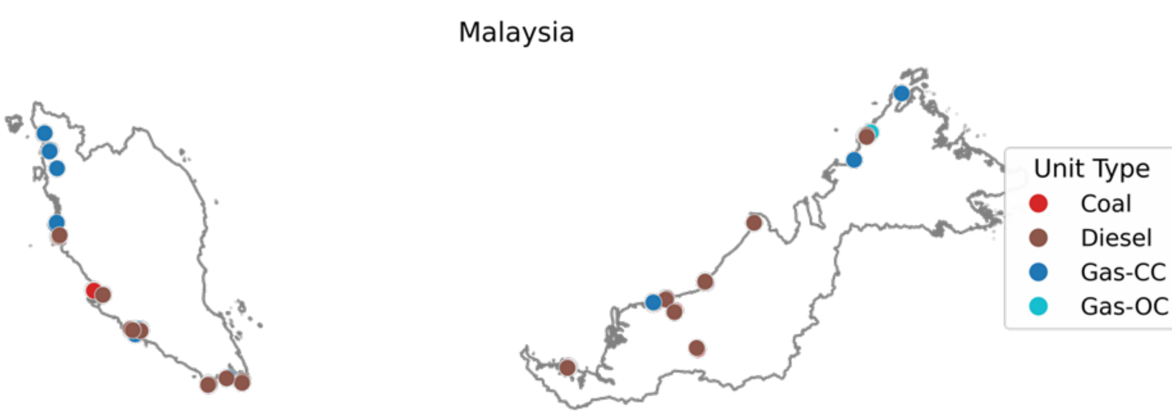


Figure A-5. Locations of power plants in Lao PDR and Malaysia in 2040 for the Base scenario

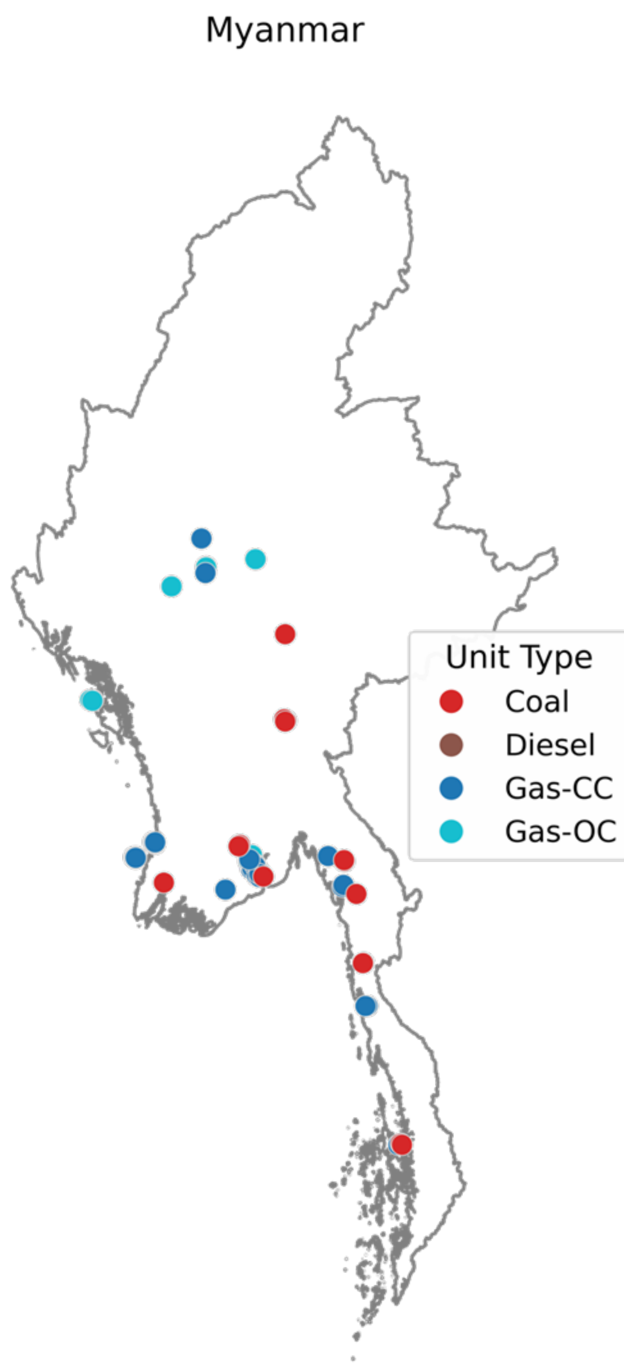


Figure A-6. Locations of power plants in Myanmar in 2040 for the Base scenario

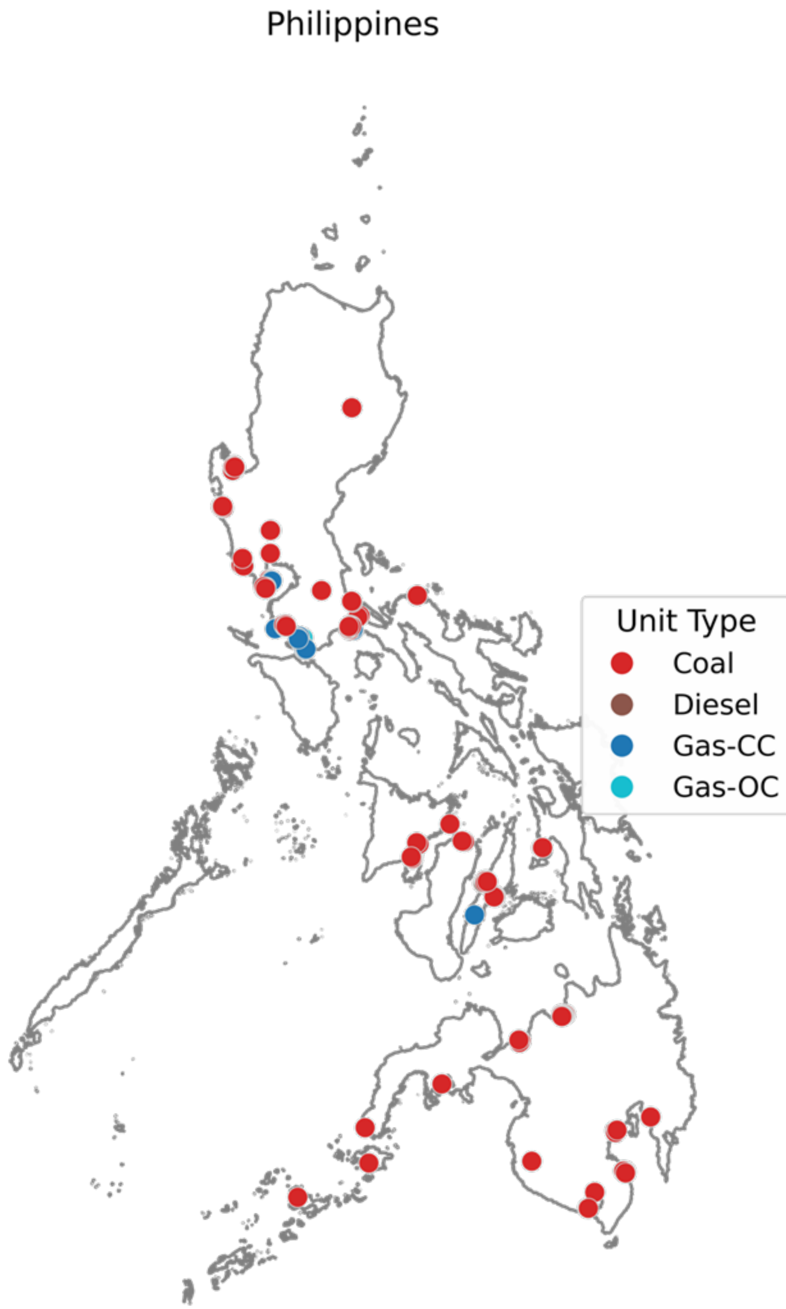


Figure A-7. Locations of power plants in the Philippines in 2040 for the Base scenario

Figure A-8. Locations of power plants in Singapore in 2040 for the Base scenario

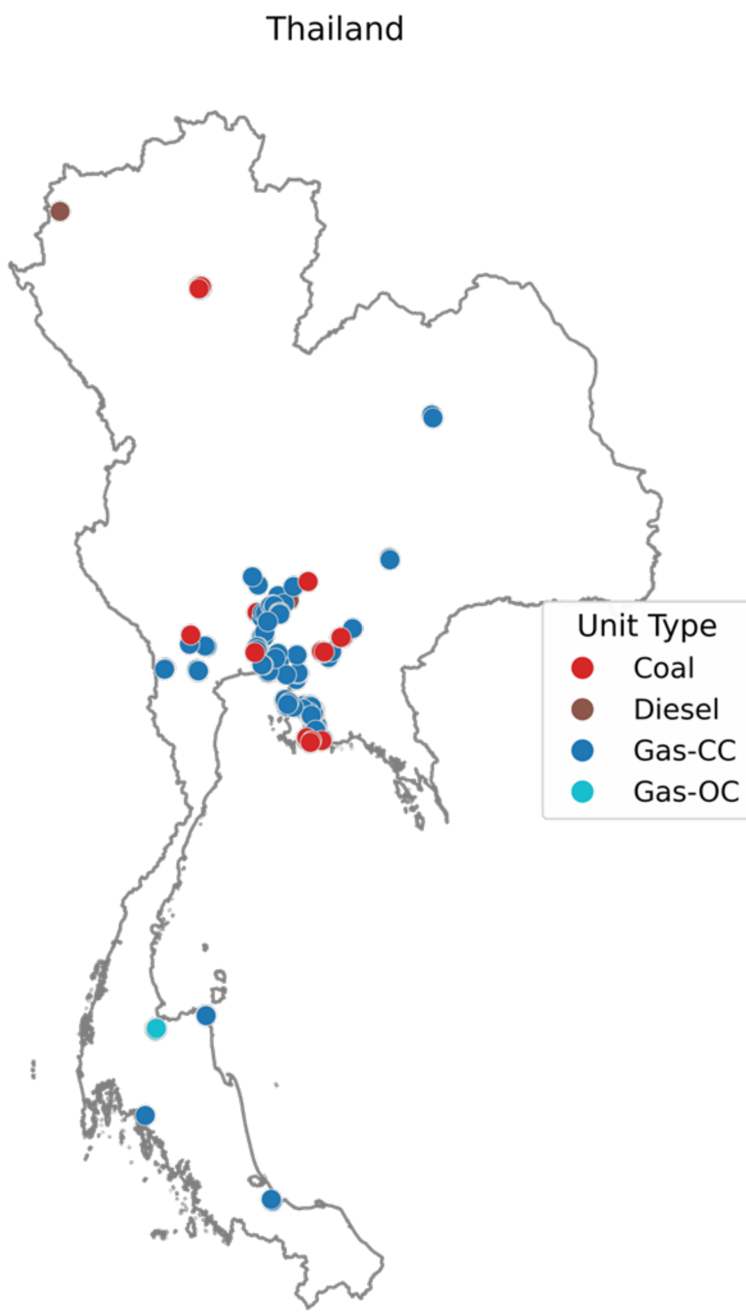


Figure A-9. Locations of power plants in Thailand in 2040 for the Base scenario

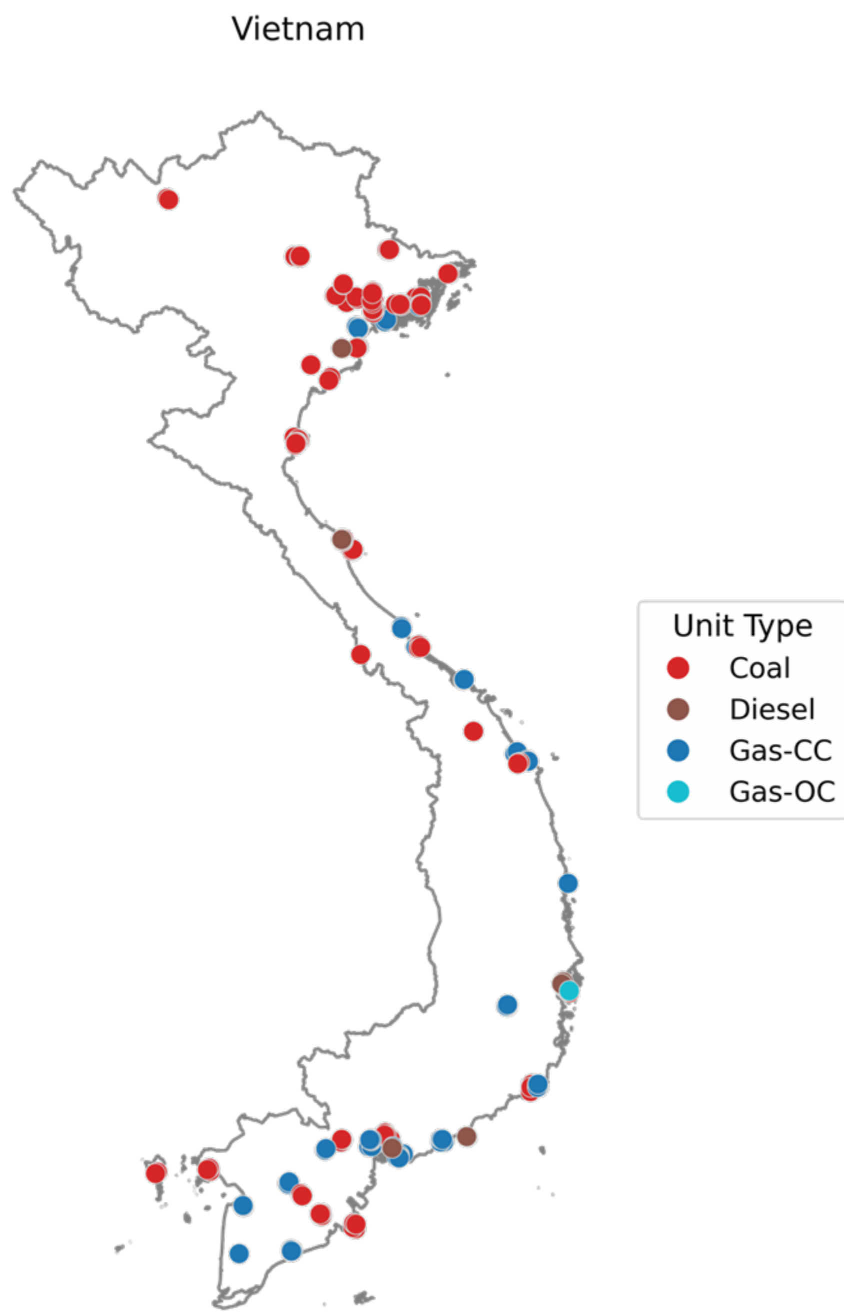


Figure A-10. Locations of power plants in Vietnam in 2040 for the Base scenario

A.4 Distributional Statistics of Stack Heights

Stacks heights were based on multiple sources, as outlined in the report. Based on available stack height data, a regression model was used to obtain stack height as a function of capacity (MW). Distributional statistics containing 5th, 50th (median), and 95th percentiles of the stack heights for each country are given in Table A-3 for coal plants and Table A-4 for natural gas plants (given the lack of data points, constant stack heights for diesel plants were used, as shown in Table 2).

Table A-3. Stack Height Distributional Statistics for Coal Plants in ASEAN Countries

Note that there are no coal plants in Brunei Darussalam and Singapore.

Country	Stack Height 5th Percentile (meters)	Stack Height Median (meters)	Stack Height 95th Percentile (meters)
Cambodia	131	140	163
Indonesia	129	147	234
Lao PDR	135	193	234
Malaysia	131	190	229
Myanmar	130	147	234
Philippines	131	140	190
Thailand	129	143	203
Vietnam	131	185	212

Table A-4. Stack Height Distributional Statistics for Gas Plants in ASEAN Countries

Country	Stack Height 5th Percentile (meters)	Stack Height Median (meters)	Stack Height 95th Percentile (meters)
Brunei Darussalam	44	47	62
Cambodia	82	82	82
Indonesia	44	50	74
Lao PDR	9	46	82
Malaysia	44	54	80
Myanmar	43	48	67
Philippines	43	67	82
Singapore	45	58	61
Thailand	46	47	74
Vietnam	47	74	82

A.5 Contribution of Different Fuel Types to Emissions of NO_x, SO_x, and $PM_{2.5}$

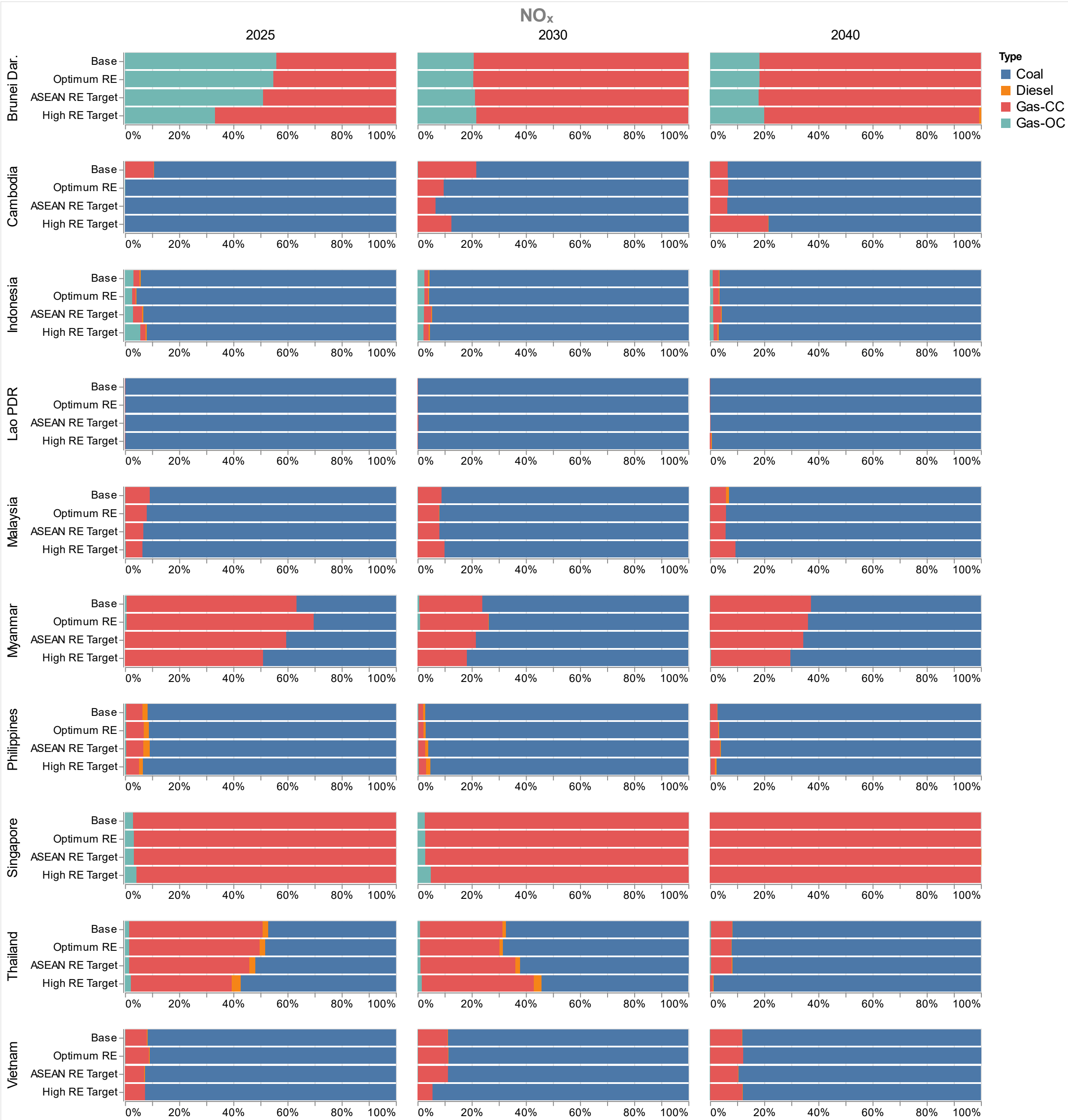


Figure A-11. Emissions share of the three generation unit types for NO_x in the Base emissions inventory

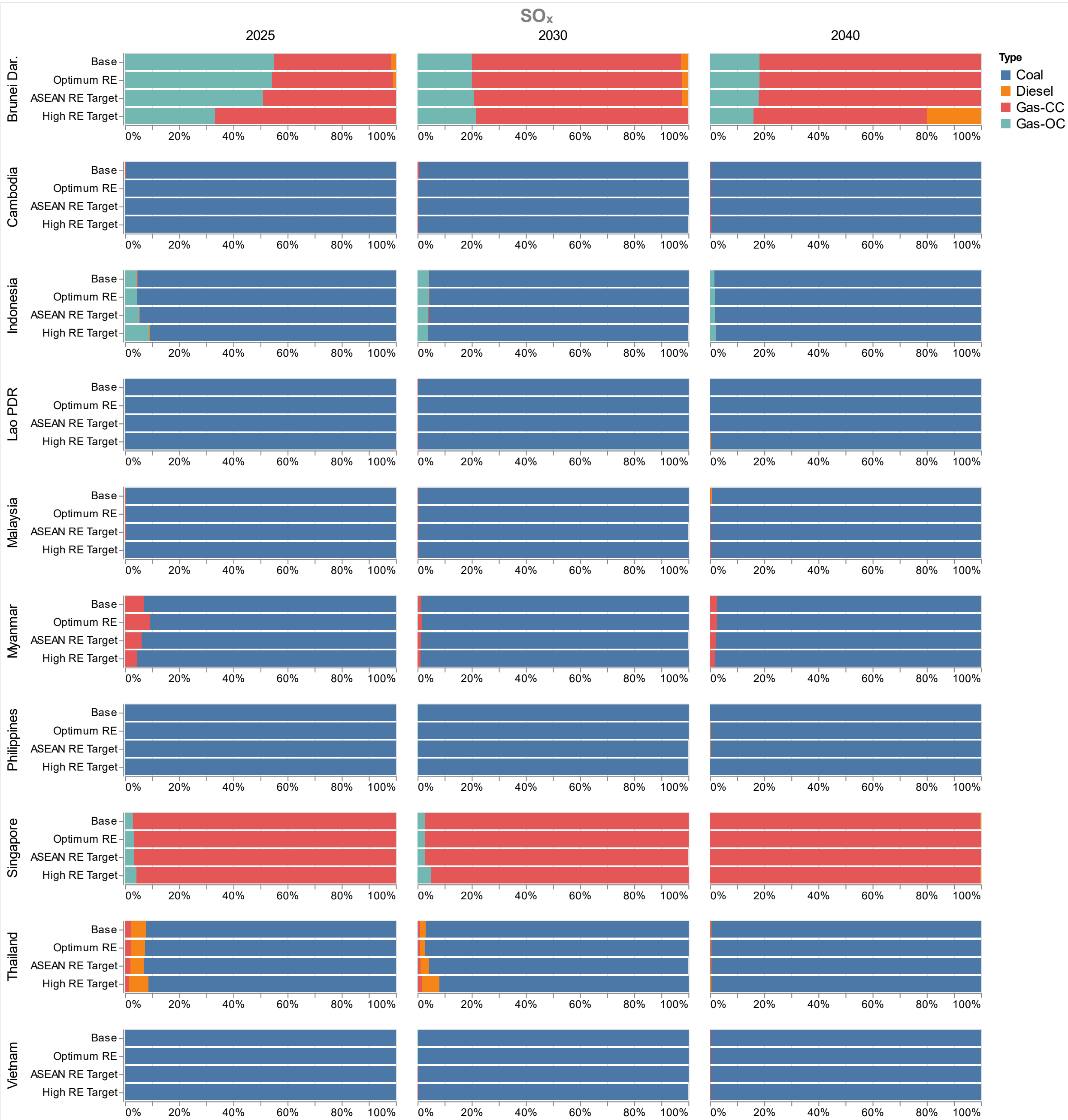


Figure A-12. Emissions share of the three generation unit types for SO_x in the Base emissions inventory

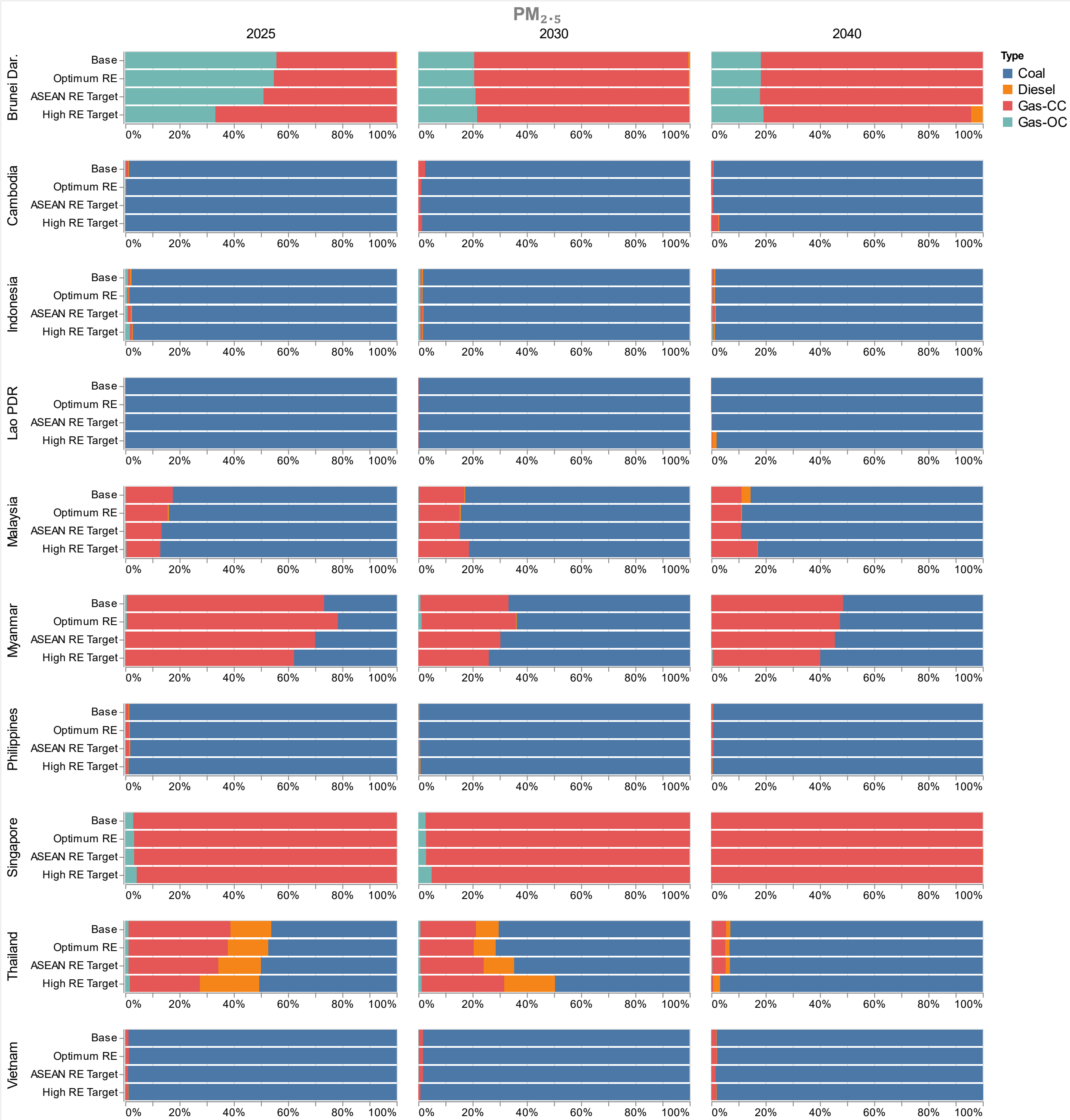


Figure A-13. Emissions share of the three generation unit types for $PM_{2.5}$ in the Base emissions inventory

A.6 Additional Mortality Results

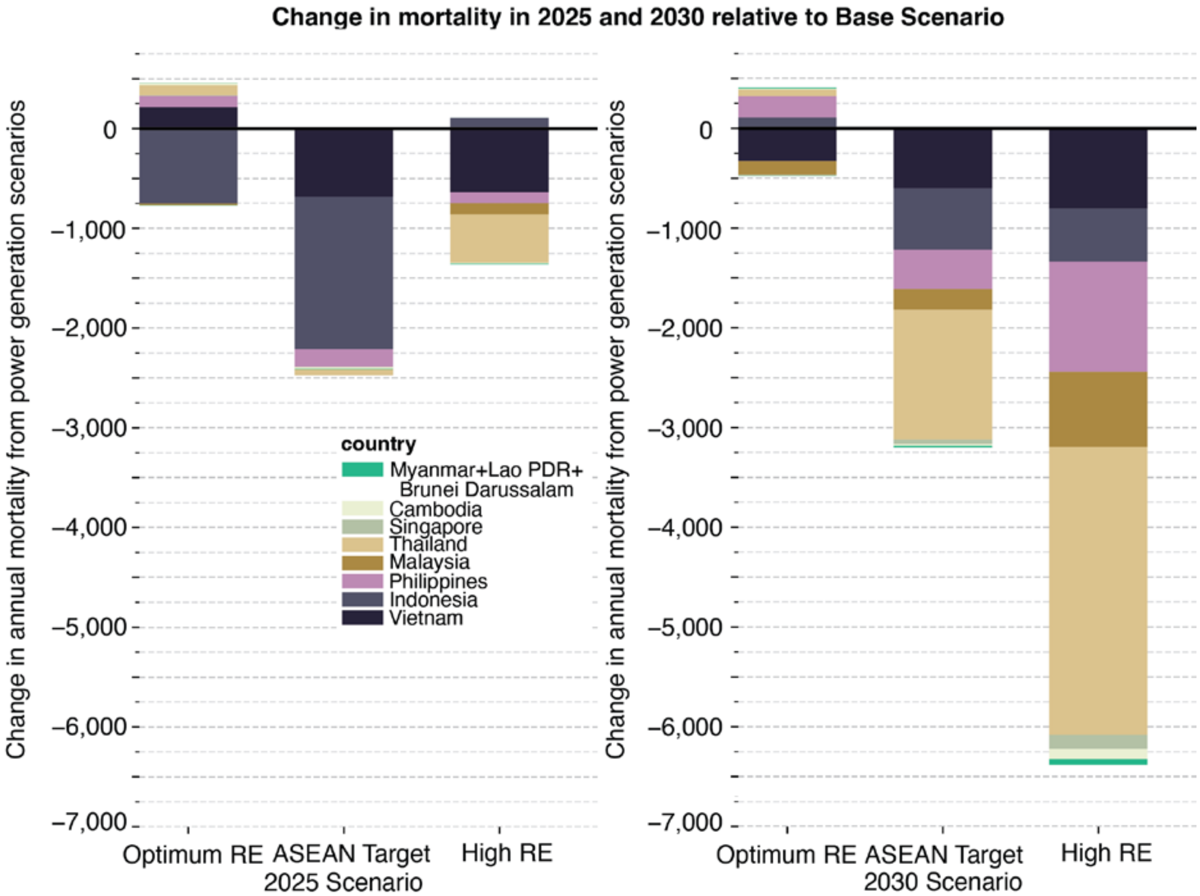


Figure A-14. Change in excess mortality in 2025 and 2030 (relative to the Base scenario) for the Optimum RE, ASEAN RE Target, and High RE Target scenarios, broken down by ASEAN member country in which mortality occurs

A.7 Comparison of Emissions Estimates to Earlier Studies

Some earlier studies have assessed emissions from the energy sector and quantified their impacts on air quality and public health. For example, Koplitz et al. (2017) estimated the disease burden from coal combustion in Southeast Asia in 2030, accounting for emissions increase from any existing, under construction, and planned coal power plants. They estimate that coal plants in ASEAN countries emit 2.3 million metric tons (MT) of SO_x, 2.3 million MT of NO_x, and 75,000 MT of $PM_{2.5}$ emissions. Compared to this, our emissions estimates for the Base scenario in 2030 are 2.5 million MT of SO_x, 1.9 million MT of NO_x, and 238,000 MT of $PM_{2.5}$ emissions. Total generation from coal plants in ASEAN countries in Koplitz et al. is assumed to be 1,177 TWh, whereas the Base scenario in this study assumes 930 TWh from coal plants. These differences in emissions estimates between this study and Koplitz et al. can be attributed to assumptions related to emissions factors and activity data (generation).

While work by Koplitz et al. focused only on coal plants, other estimates are also available from different studies. Here, we compared our emissions estimates for the 2025 Base scenario with those from the Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants (ECLIPSE, Version 5) global inventory (Stohl et al. 2015), shown in Figure A-15. Gridded global ECLIPSE v5 emissions clipped to the ASEAN countries from its Baseline scenario (which assumes that any current or proposed environmental regulations are enforced) for the energy sector are used for the comparison. Note that the ECLIPSE energy sector is broader than the power generation sector and also includes emissions associated with energy conversion and extraction, in addition to those directly from activities at power plants. Given that the ECLIPSE v5 sector definition is wider than power generation, ECLIPSE v5 emissions are expected to be higher than the AIMS III estimates; however, ECLIPSE v5 estimates use 2015 energy projections from the International Energy Agency, and the region has seen considerable growth in its energy hunger and reliance on coal since then. Among specific pollutants, estimates of SO_x are closest to those from ECLIPSE v5 (note that SO_x in ECLIPSE is in fact SO_2), NO_x estimates in AIMS III are higher than ECLIPSE v5, and $PM_{2.5}$ estimates are very similar.

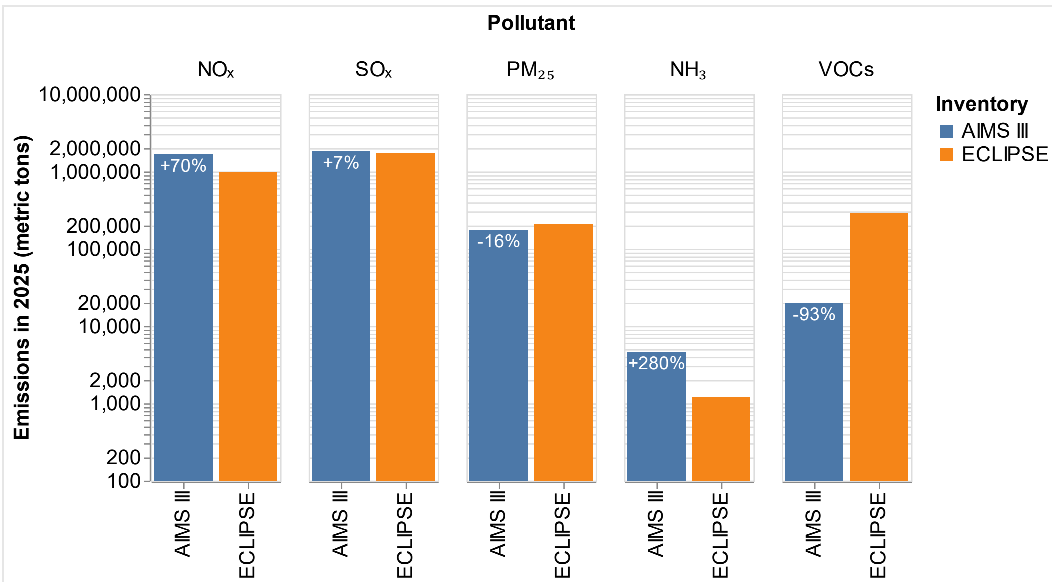


Figure A-15. Comparison of emissions from the AIMS III Base scenario for 2025 with those from the ECLIPSE Baseline scenario energy sector for the same year

Note: Also shown is the difference of the AIMS III inventory relative to the ECLIPSE inventory (annotated as a percentage difference on bars labeled AIMS III). Note that the ECLIPSE SO_x emissions are of SO_2.

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