Conference Proceedings Paper

Analysis of the Effects of the Thai Power Development Plan 2015 on Air Quality from 2016 to 2036

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Abstract: Air pollution is a serious issue that affects many parts of the world, Southeast Asia in particular. Nitrogen oxides, particulate matter, sulfur dioxide, and other emissions have negative impacts on human health as well as overall environmental quality. The major sources in Thailand are open burning and fossil fuel combustion, i.e. in vehicles, energy use in industries and power generation. Given increasing actual and projected GDP growth, subsequent increases in energy consumption are inevitable. The power generation system must grow and expand as well to meet changes in demand from industrial, commercial, and residential customers. The Ministry of Energy of Thailand has published the Power Development Plan 2015 (PDP 2015) to outline policies and goals of the growing power generation and transmission systems throughout the nation. Notably, the plan involves increasing the use of coal-fired generation. Using both the Greenhouse Gas and Air Pollution Interactions and Synergies Model (GAINS) and the Comprehensive Air Quality Model with Extensions (CAMx), we have compared two different emissions scenarios: one with standard emission control technology, and another with maximum feasible emission controls. The effectiveness of emission control technology varied by region and pollutant. The greatest increase in air quality was located around the Rayong province in central Thailand. For PM_{10} in the northern Thailand, however, emission control technologies did little to improve the air quality because the main source of pollutant, biomass burning, was left unabaited. This forecast of air quality can show possible impacts from future emissions in Thailand and regions that may benefit from added emission control technology in the future.

Keywords: air quality; CAMx; GAINS; Thai Power Development Plan; Thailand; Atmospheric Chemistry; Kinetic Modeling

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1. Introduction

Air emissions from the combustion of fossil fuels at power plants are known to negatively impact human health and contribute to environmental destruction through the release of compounds such as particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and mercury (Hg). With projections of Thai GDP growth averaging 3.94 percent annually, the demand for power and associated emissions will inevitably increase [1]. In order to maintain or improve air quality, sufficient measures must be utilized to control emissions and meet power demand in an efficient way. This study examines the projections of Thailand's power generation growth as published by the

Thailand Ministry of Energy in the Power Development Plan 2015 (PDP) [1]. Changes in fuel consumption and power plant capacity provided the basis of the analysis. Coal, generally considered to be a "dirty" fossil fuel, is a big component in the PDP with increased consumption forecasted as a replacement for natural gas-fired generation. The PDP targets energy security through domestic coal use as well as fuel diversification. Most of the natural gas reduction will occur in the northern regions and the central valley. Coal increases will be primarily in the central valley and southern regions.

2. Methodology

This study was conducted using an atmospheric modeling framework, composed of Greenhouse Gas and Air Pollution Interactions and Synergies Model (GAINS) for emission projection, and Comprehensive Air Quality Model with Extensions (CAMx) for future air quality simulations. The focus of the study was to model the increasing use of coal-fired generation and subsequent changes in the concentrations of NO_x, PM_{10}, SO_2, Hg, and ambient $PM_{2.5}$. An inventory of power plants in Thailand and fuel use data were obtained from an ongoing project under the umbrella of the International Institute for Applied Systems Analysis (IIASA) called **E**valuating the **Cl**imate and Air Quality **I**m**P**acts of **S**hort-liv**E**d Pollutants (ECLIPSE) [2]. Several parameters and scenario inputs were taken from this project, in order to establish a consistent base to build projections upon. In Appendix A, a comparison of emissions is provided to illustrate aforementioned effects. Various assumptions and methodological choices were made throughout the study in order to maintain data consistency and a streamlined methodology.

2.1. GAINS Model

2.1.1. Description

The GAINS model developed by the IIASA is an atmospheric modeling system that provides the basis for analyses of air pollutant and greenhouse gas emissions and reduction strategies. All activities contributing to air pollution (energy production, agriculture, industry, transportation, etc.) are inputted into the model to project emissions over a specified time scale [3]. Created scenarios may be adjusted by selecting control strategies from a GAINS database and altering fuel inputs. The model provides emissions data for the nation, calculated from all sectors and activities. The output emission data is further separated into one of five regions in Thailand: Bangkok Metropolitan Region (BMR), Central Valley (CVAL), Northern Highlands (NHIG), Northeastern Plateau (NEPL), or Southern Peninsula (SPEN). In addition, the GAINS model incorporates projected GDP growth for a given country so that economic analyses can reflect control strategy choices. The forecasted average GDP growth, 3.94 percent, was obtained from the PDP and based upon data published by the National Economic and Social Development Board (NESDB). The method of emissions modeling is shown in the following equation [4]:

$$Ei,p = \sum k \sum m \ Ai,kefi,k,m,pxi,k,m,p \qquad (1)$$

where,

i, k, m, p- Country, activity type, abatement measure, pollutant, respectively.

Ei,p- Emissions of pollutant p (for SO_2, NO_x, VOC, NH_3, $PM_{2.5}$, CO_2, CH_4, N_2O, F-gases) in country i.

Ai,k-Activity level of type k (e.g., coal consumption in power plants) in country i.

efi,k,m,p-Emission factor of pollutant p for activity k in country i after application of control measure m.

xi,k,m,p- Share of total activity of type k in country i to which a control measure m for pollutant p is applied.

2.1.2. Data Input

The data input for the GAINS model can be divided into two major sources. The first source is the ECLIPSE project. Further, a branch of ECLIPSE dubbed Toyota's Clean Air for Asia Project (TCAP) ECLIPSE contributed GAINS initial scenario settings from a similar study analyzing the PDP plan from 2010. The TCAP ECLIPSE project team gathered emission estimates for air pollution contributing sectors through surveys as well as individualized combustion efficiencies and megawatt capacities for all power plants in Thailand. Additionally, the TCAP ECLIPSE data provided a compiled list of the power plants' spatial distribution in Thailand from 2010.

The power plant data was cross referenced with the PDP, the second major source, to create an accurate list of all power plants in Thailand with geographic locations, as of 2015. From 2010 to 2015, 18 power plants were retired and 24 added, though most were small biomass plants under 30 megawatts. Additional 2015 PDP referencing for existing plants resulted in updated megawatt capacities. Beyond 2015, the PDP separates power plant installations into 5 year intervals from 2016 to 2036. Using these fuel projections in the appendix of the PDP, the total fuel consumption, in petajoules, was calculated for each power plant in each five-year interval from 2016 to 2036. Based on the TCAP ECLIPSE results for fuel consumption and net energy output, the conversion ratio for each projected plant was assumed to be equal to that of an existing plant of the same fuel type.

Thailand Ministry of Energy classifies three major power plant types, large power producer, including plants under Electric Generating Authority of Thailand (EGAT) and independent power producers (IPP), small power producers (SPP), and very small power producers (VSPP) based on megawatt capacity. IPPs are plants greater than 90 megawatts, SPPs are between 10 and 90 megawatts, and VSPPs are less than 10 megawatts. While data for a current inventory was available, the PDP's 5-year interval projections were spatially vague for all plants except IPPs. Added SPP and VSPP capacity beyond 2016 was assumed to be installed at existing plants. In order to distribute the additions, the total megawatts for each year was administered proportionally by region and fuel type. This was to ensure realistic growth based on existing spatial and fuel type distribution patterns. This was also coordinated with projected increases in renewables and decreases in natural gas as published in the PDP. The fuel conversion ratio was also assumed to remain constant at these plants based on TCAP ECLIPSE.

2.1.3. Fuel Mix for Power Plants

The fuel input data was formatted for the GAINS model and split into categories by region, fuel type, and power plant type. The following tables provide a summarized view of the totals, by region, and demonstrate the fuel share.

Table 1. Fuel Consumption 2016 [1].

GAINS Region	Natural Gas	Diesel	Fuel Oil	Biomass/Renewable	Hard Coal	Brown Coal	Total
BMR	156.29	-	0.9	0.38	-	-	157.57
CVAL	1010.42	5.13	4.35	78.16	31.5	5.5	1135.06
NHIG	-	0.3	0.01	30.64	-	-	30.95
NEPL	35.69	0.02	-	67.4	-	104.93	208.04
SPEN	124.73	0.05	0.85	9.77	-	-	135.4
Total	1327.13	5.5	6.11	186.35	31.5	110.43	**1667.02**

[1] All values given in petajoules.

Natural gas generation accounts for nearly 75 percent of the total generation capacity in 2016 and coal and biomass account for just over 30 percent combined. In 2036, as seen in Table 2, natural gas will account for approximately 40 percent of the total generation capacity, coal will provide between 20 and 25 percent, and biomass/renewables will account for another 30 percent. Diesel and fuel oil are projected to be phased out, but in this time scale, they remain in use as a transition fuel. The biomass/renewable category encompasses many forms of electricity generation, but only biomass was considered as far as emissions are concerned. These fuel requirements approximately align with PDP's 2036 fuel share goal.

Table 2. Fuel Consumption 2036 [1].

GAINS Region	Natural Gas	Diesel	Fuel Oil	Biomass/Renewable	Hard Coal	Brown Coal	Total
BMR	111.27	-	0.9	0.89	-	-	113.06
CVAL	961.02	96.18	4.35	218.61	179.67	3.61	1463.44
NHIG	-	0.3	-	83.39	-	102.96	186.65
NEPL	-	0.02	-	181.03	-	104.93	285.98
SPEN	72.32	0.05	-	504.1	288.9	-	865.37
Total	1144.61	96.55	5.25	988.02	468.57	211.47	**2914.47**

[1] All values given in petajoules.

2.2. Scenario Development

Fuel projections were modeled in two emission control cases: a current legislation (CLE) scenario, and a maximum feasible reduction (MFR) one. The CLE scenario was based on a previous TCAP ECLIPSE scenario and aimed to establish baseline emissions for the PDP, where the MFR scenario was designed to observe the benefits of the most efficient control technologies. These scenarios were developed in the GAINS model scenario builder. An inventory of emission control technologies, as well as their efficiencies, are available in the model.

2.2.1. Current Legislation (CLE)

The first two scenarios used emission controls derived from the TCAP ECLIPSE project. These controls assumes power plants would continue operations using control technologies based on current legislation goals and emission standards. A CLE case was developed for the year 2016 as well as 2036.

2.2.2. Maximum Feasible Reduction (MFR)

The emission control scenario was created to project the gradual, yet aggressive implementation of emission control technologies for power plants from 2016 to 2036 (Table 3). Controls for coal emission were selected and limited to those that reduce NO_x, PM (2.5 and 10), and SO_2 because of significant hazards to human and environmental health. The results from the scenario, however, are not limited to these chemicals, and co-benefit reductions for greenhouse gas emissions and other harmful pollutants may be observed. The emission controls selected were the most effective based on the GAINS provided technology efficiencies.

Table 3. Control technology scenario outline.

		2016	2021	2026	2031	2036
Emissions	**Technology**	**% Share of Penetration of Emission Control Technology**				
NO_x	PBCCSC	80	100	100	100	100
	PBCSCR	80	100	100	100	100
	PHCCSC	80	100	100	100	100
	PHCSCR	80	100	100	100	100
PM	ESP1	20	0	0	0	0
	ESP2	40	50	50	50	50
	HED	40	50	50	50	50
SO_2	PWFGD	80	100	100	100	100
	RFGD	80	100	100	100	100

When altering emission controls in GAINS for MFR, aggregate share of penetration by emission control technologies can be no greater than 100 percent for each fuel type in each sector. For NO_x, PM, and SO_2 emission control technologies, the most effective, according to the efficiency values provided by GAINS, were utilized throughout the 2016–2036 period to make up the percent share for the respective fuel in each sector.

For NO_x and SO_2, the most effective technologies were implemented at 80 percent penetration in the initial five-year period (2016–2021) of GAINS modeling, and were increased to 100 percent penetration from 2021–2036.

For PM, a similar method was employed. ESP1 (1 electrostatic precipitator) was upgraded to ESP2 (2 electrostatic precipitators), thus decreasing the penetration of ESP1 as it was upgraded. The remaining share of PM emission control penetration is held by HED, another highly effective technology (see Appendix A), which increases its penetration from 40 percent (2016–2021) to 50 percent (2021–2036).

Modern control technologies from the 2012 Energy Technology Perspectives (ETP) were cross referenced with GAINS emission controls while designing the MFR scenario (Table 4). However, to determine the penetration of each, the technologies were adjudged based on their review in the ETP. Existing penetration values previous to 2016 were not taken into account. The MFR did not allocate control technologies based on regional or sector fuel share. The MFR did not allocate different types of control technologies based on regional differences in fuel share. This is because the MFR observed the changes in emissions in response to more efficient control technologies.

The MFR accounted for changes in the PDP that may occur between 2016 and 2036, and provided assumed controls for coal that may not be retired as planned.

Table 4. Emissions control technology descriptions and efficiencies [1].

Emission	Technology	Description	Efficiency (%)
NO_x	PBCCSC	Combustion modification and selective catalytic reduction on existing brown coal power plants	80
	PBCSCR	Selective catalytic reduction on new brown coal power plants	80
	PHCCSC	Combustion modification and selective catalytic reduction on existing hard coal power plants	80
	PHCSCR	Selective catalytic reduction on new hard coal power plants	80
PM	ESP1	Electrostatic precipitator: 1 field—power plants	93
	ESP2	Electrostatic precipitator: 2 fields—power plants	96
	HED	High efficiency deduster—power plants	99
SO_2	PWFGD	Power plant—wet flue gases desulphurisation	95
	RFGD	High efficiency flue gases desulphurisation	98

All values from GAINS provided technology efficiencies [1].

2.3. CAMx Model

2.3.1. Description

CAMx is a gridded, three dimensional photochemical dispersion model that provides projections of tropospheric ozone, particulate matter, and air toxics in a wide range of spatial scales [6]. The model takes into account an array of variables when modeling chemical mechanisms in the atmosphere in addition to background information necessary to runCAMx (meteorology data, regional solar intensity, VOC composition from different sources, etc.). The CAMx model was run in the CLE scenario for March and August in 2016 and 2036 and the same months of 2036 in the MFR scenario. These months, according to TCAP ECLIPSE project findings, have proven to have the highest and lowest concentrations of air pollutants, respectively, in a given year as March represents the driest month and August the wettest one in Thailand. CAMx computes pollutant concentration data on a national scale in four-minute intervals for the duration of each month. Also, CAMx includes international pollution transported by air mass currents. In this study, a special emphasis was on PM_{10}, SO_2, NO_x, and tropospheric ozone as they correlate to emissions of air pollutants from power plant activity. The data flow through CAMx model is presented in Figure 1.

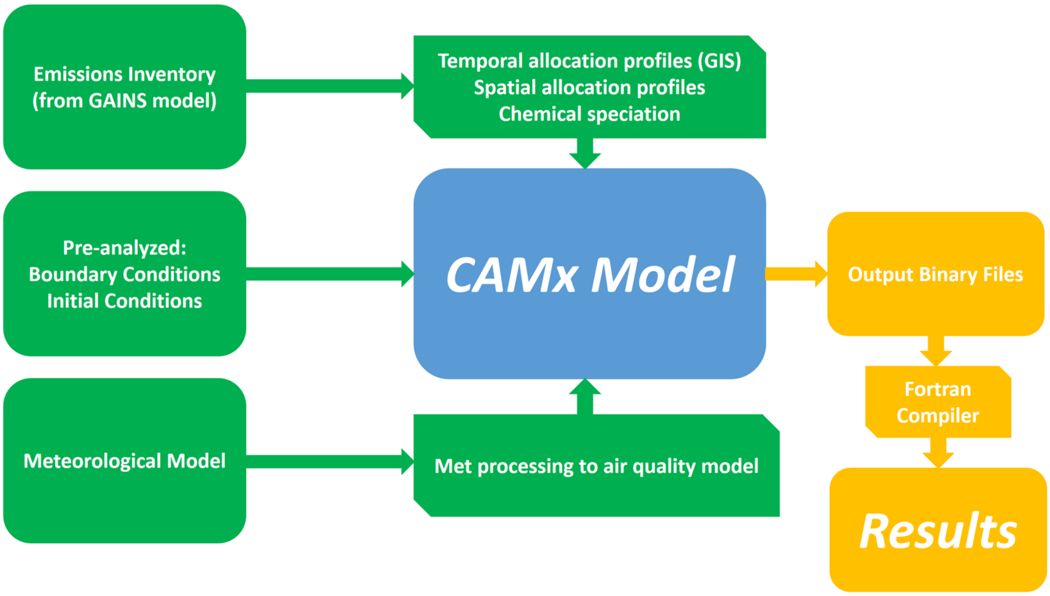


Figure 1. A visual representation of data flow through the CAMx model.

2.3.2. Spatial Profile

The CAMx modeling region was registered using latitude and longitude with gridded cells totaling 115 columns and 171 rows in addition to 22 vertical layers. The grid resolution was 12 km by12 km, and the map projection used was the Lambert Conformal Projection.

2.3.3. Input Requirements

Almost all of the CAMx inputs were set to match the TCAP ECLIPSE 2010 project assuming change in the emission values over a temporal period of five years. Changes in weather patterns due to global climate change were not taken into consideration.

The Weather Research and Forecasting (WRF) meteorological model was used to simulate hourly winds in three dimensions corresponding to each 12 km by 12 km grid. The WRF model manages atmospheric temperature, pressure, rainfall, wind speed and direction, and top modeling region borders. The AHOMAP ozone column data was also utilized.

Thirteen pollutant emissions were processed from GAINS in order to calculate average pollutant concentrations in March and August of each scenario. The pollutants processed were CH_4, CO, CO_2, HG, N_2O, NH_3, NO_x, PMBC, PMOC, PM_{10}, PM_{25}, SO_2, and VOC. For all emissions except for the power plant and shipping sectors, the study used the MEGAN MACC database for biogenic emissions and the GFEDs database for biomass burning at each hour for each gridded cell. Because these two inputs relied heavily on meteorological conditions, their land cover databases were merged with the WRF model predictions, notably radiation intensity and temperature estimates. Shipping projections were calculated from TCAP ECLIPSE survey data.

Since the power plant sector's emissions were tied to point source locations in Thailand's five GAINS regions, power plants were appended spatially to the CAMx 12 km by 12 km grid. To do so, a geographic information systems (GIS) software, ArcGIS 10.3, was utilized.

In order for CAMx to properly assign emissions to a grid cell, horizontal references were calculated for each sector so that each WRF mixing layer began any given scenario with a starting concentration of each pollutant species. Horizontal references were calculated proportionally by petajoule contribution for a plant in a given sector in a given region so that each sector summed to 1.

Initial concentrations of the simulation were compiled hourly in 4-minute time steps using the WRF model. However, for each target month, one week, at minimum, of the previous month was simulated in order for the model to "spin up" and acclimate to existing conditions.

Several models were used for chemical speciation processing including the PPM advection model, the EBI chemistry solver model, and the Wesley89 dry deposition model.

3. Results

3.1. Emission Results from GAINS

3.1.1. NO_x Emissions

Detailed NO_x emissions resulted from GAINS are reported in Figure 2 and Table 5. Levels of NO_x across all sectors increased by a factor of 1.2 between 2016 CLE and 2036 CLE scenarios, going from a total 947 kilotons per year to 1144 kilotons per year. Three of the five regions showed an increase in levels of NO_x emissions, with the BMR and CVAL regions showing a reduction. Though the CVAL region was forecasted to install 40 petajoules of hard coal by 2036 and ranked second highest by region for average five-year biomass additions (27 petajoules), the CVAL region's power plants equated to 19% of the CVAL region's NO_x emissions. Top emitting NO_x sectors like cement production and agricultural transportation using diesel combustion were predicted to be replaced by combined cycle natural gas. The region with the largest NO_x increase, NEPL, was forecasted to install one 105 petajoule lignite plant in 2016 and 32 petajoules of biomass every five years while uninstalling 20 petajoules of natural gas by 2026. The NEPL regions top five NO_x emitting sectors in both 2016 and 2036 CLE are transportation or diesel engine related.

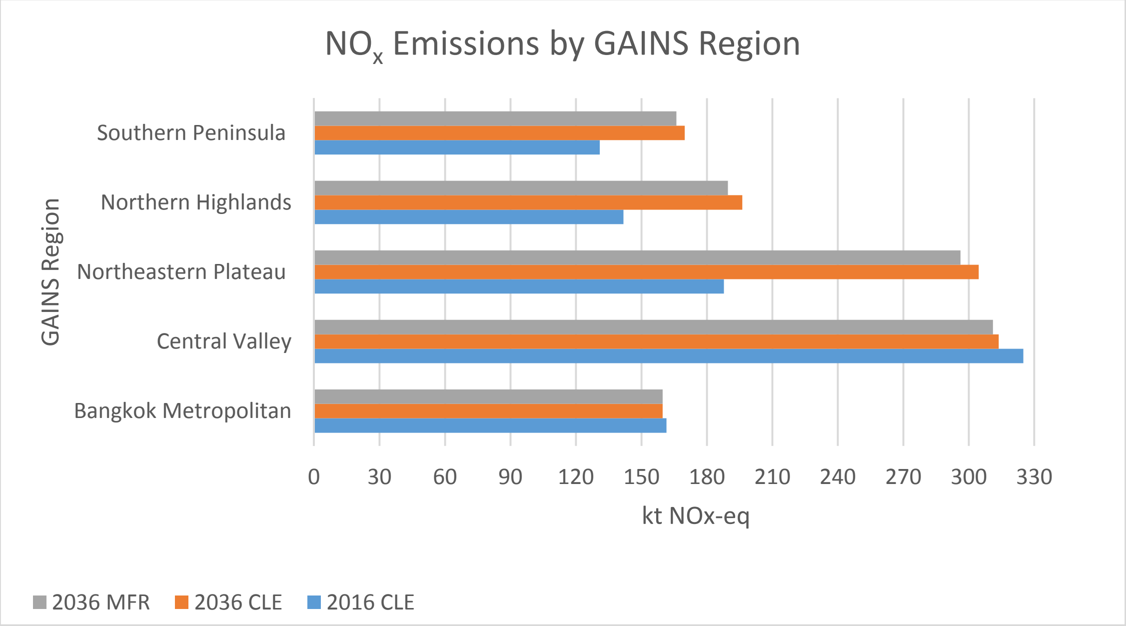


Figure 2. Change in NO_x emissions by region from 2016 to 2036.

Table 5. Power Plant NO_x Emission as a Percent of Total NO_x Emissions.

GAINS Region	NO_x PP CLE 2016 [1]	NO_x PP CLE 2016	NO_x PP CLE 2036	NO_x PP CLE 2036	NO_x PP MFR 2036	NO_x PP MFR 2036
BMR	3.538	2.19%	2.755	1.72%	2.755	1.72%
CVAL	37.242	11.46%	58.731	18.72%	56.097	18.03%
NHIG	19.884	10.59%	34.028	11.17%	25.634	8.66%
NEPL	19.29	13.61%	20.98	10.69%	14.401	7.60%
SPEN	3.685	2.81%	16.411	9.66%	12.597	7.59%
Total	83.639	-	132.905	-	111.484	-

[1] All values given in kilotons per year.

3.1.2. SO_2 Emissions

As shown Figure 3 and Table 6, SO_2 emissions from all sectors in the CLE 2036 were higher than those in the MFR 2036 by a factor of 1.2. However, CLE 2036 SO_2 power plant emissions were higher than the MFR 2036 emissions by a factor of 1.9. Only one GAINS region, NIGH, exhibited a decrease in SO_2. This most likely results from retired coal plants since a decrease from 160 petajoules to 102 petajoules was observed from 2016 to 2036. Two regions, the SPEN and the CVAL responded favorably to the 2036 MFR scenario. 2036 CLE SO_2 emissions were higher in the SPEN region than those of the 2036 MFR emissions by a factor of 14. The NEPL and BMR regions showed no change due to a lack of coal fire power plants in the BMR region, and unchanging coal capacity in the NEPL.

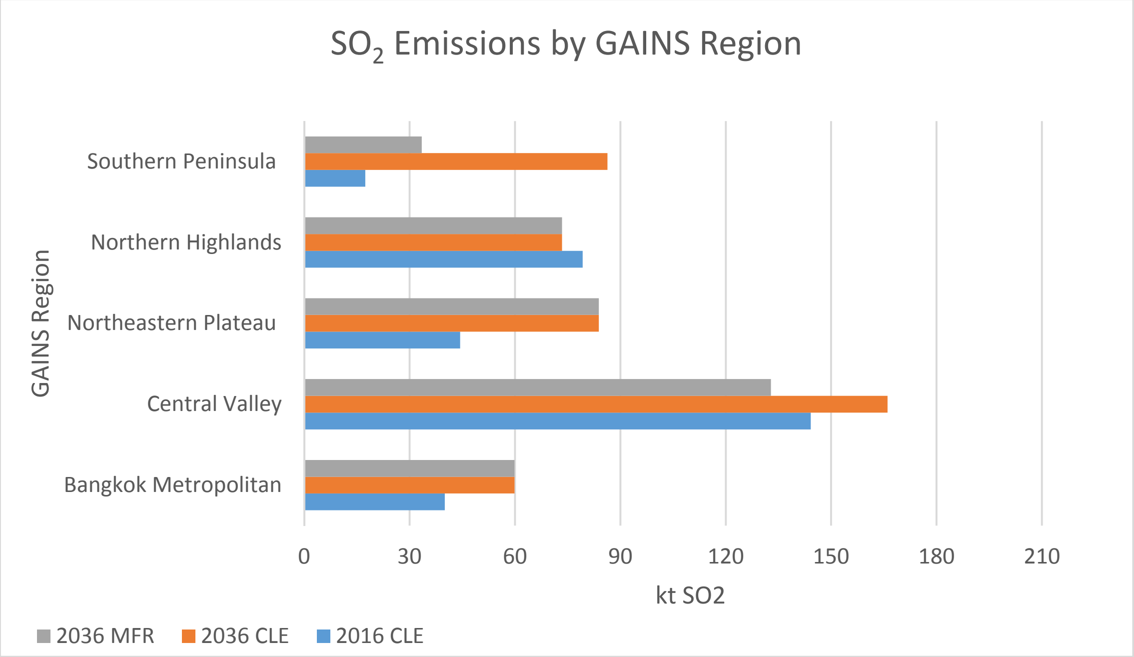


Figure 3. SO_2 emissions by region for 2016 CLE, 2036 CLE, and MFR 2036.

Table 6. Power Plant SO_2 Emission as a Percent of Total SO_2 Emissions

GAINS Region	SO_2 PP CLE2016 [1]	SO_2 PP CLE 2016	SO_2 PP CLE 2036	SO_2 PP CLE 2036	SO_2 PP MFR 2036	NO_x PP MFR 2036
BMR	1.859	4.65%	1.794	3.00%	1.794	2.36%
CVAL	29.219	20.26%	85.601	51.55%	52.434	27.51%
NHIG	22.764	37.69%	19.284	23.00%	19.284	14.87%
NEPL	60.396	76.20%	18.839	25.66%	18.839	12.77%
SPEN	2.16	12.44%	56.965	66.00%	4.111	7.71%
Total	116.398	-	182.483	-	96.462	-

[1] All values given in kilotons per year.

3.1.3. PM_{10} Emissions

Detailed PM_{10} emissions resulted from GAINS are displayed in Figure 4 and Table 7. PM_{10} emissions from all sectors were higher in the CLE 2036 than in the MFR 2036 by a factor of 1.1. However, as seen in Figure 4, CLE 2036 emissions were higher than MFR 2036 emissions by a factor of 2.8 for the power plant sector. The NIGH region had higher PM_{10} emissions in the MFR 2036 as opposed to the CLE 2036 most likely due to the absence of tech controls on biomass. Addtionally, the CVAL region contributed 198 kilotons and 190 kilotons of PM10 in the CLE 2036 and MFR 2036 scenarios, respectively. Though a small difference between the two, CVAL power plant emissions commanded only small percentages of total PM_{10} emissions in the aforementioned scenarios. The main contributor to PM_{10} CVAL emissions was the coal storage and handling sector built around the demand from added coal capacity in the CVAL region. This sector contributed over half of the PM10 emissions in both 2036 scenarios contributing 96 kilotons of PM_{10} in each.

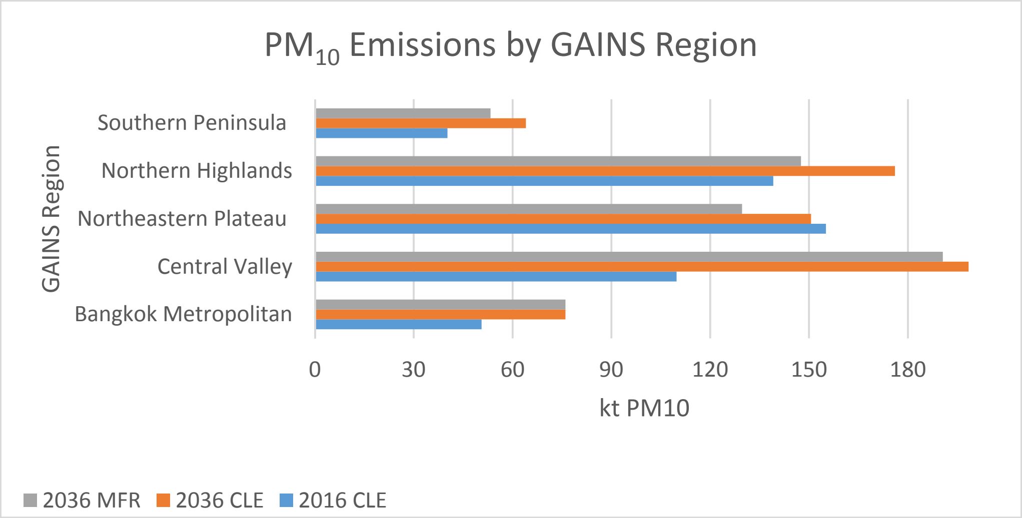


Figure 4. PM_{10} emissions by region for 2016 CLE, 2036 CLE, and MFR 2036.

Table 7. Power Plant PM_{10} Emission as a Percent of Total PM_{10} Emissions.

GAINS Region	PM_{10} PP CLE 2016 [1]	PM_{10} PP CLE 2016	PM_{10} PP CLE 2036	PM_{10} PP CLE 2036	PM_{10} PP MFR 2036	PM_{10} PP MFR 2036
BMR	0.029	0.06%	0.033	0.04%	0.033	0.04%
CVAL	6.6	6.01%	15.457	7.79%	7.661	4.02%
NHIG	44.958	28.98%	34.39	22.83%	13.439	10.36%
NEPL	77.502	55.69%	39.435	22.39%	10.878	7.37%
SPEN	0.252	0.63%	15.666	24.46%	4.948	9.28%
Total	129.341	-	104.981	-	36.959	-

[1] All values given in kilotons per year.

3.2. *CAMx Results*

CAMx post processing simulates pollutant concentrations at know weather monitoring stations in Thailand. The simulated March and August concentrations in each three scenarios were averaged monthly. Seven stations were selected based on apparent changes, areas of high concentration, and locations with new installed capacity. Four stations are located in the CVAL region, Phra Nakhon Si Ayudhya, Saraburi, Rayong and Chonburi. Two stations are located in the NIGH region, Lampang and Nakhon Sawan. One station, Surat Thani, is located in the SPEN region. For fair comparison, hourly pollutant concentrations were compiled into a monthly pollutant average for each station. Four pollutants, NO_x, SO_2, PM_{10}, and Ozone, were analyzed. The obtained results are reported in Figures 6-9.

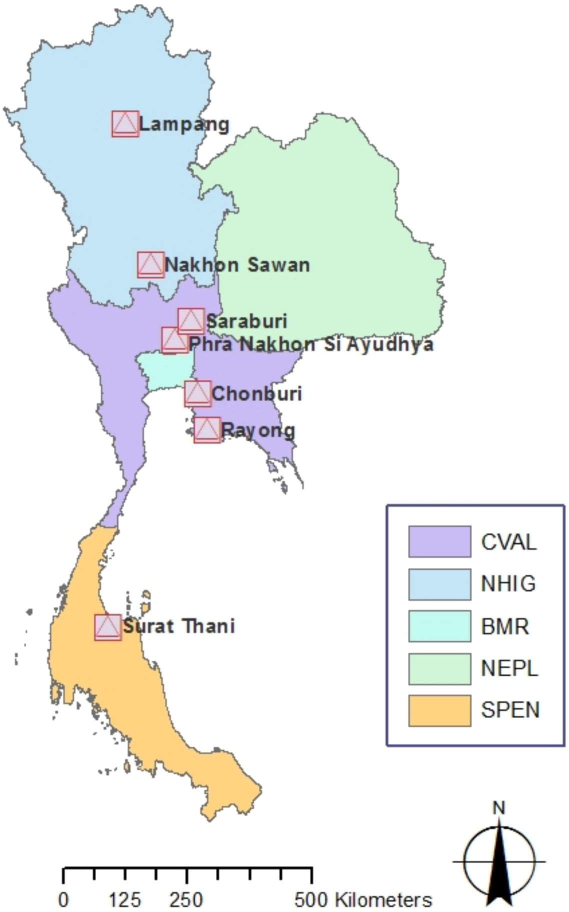
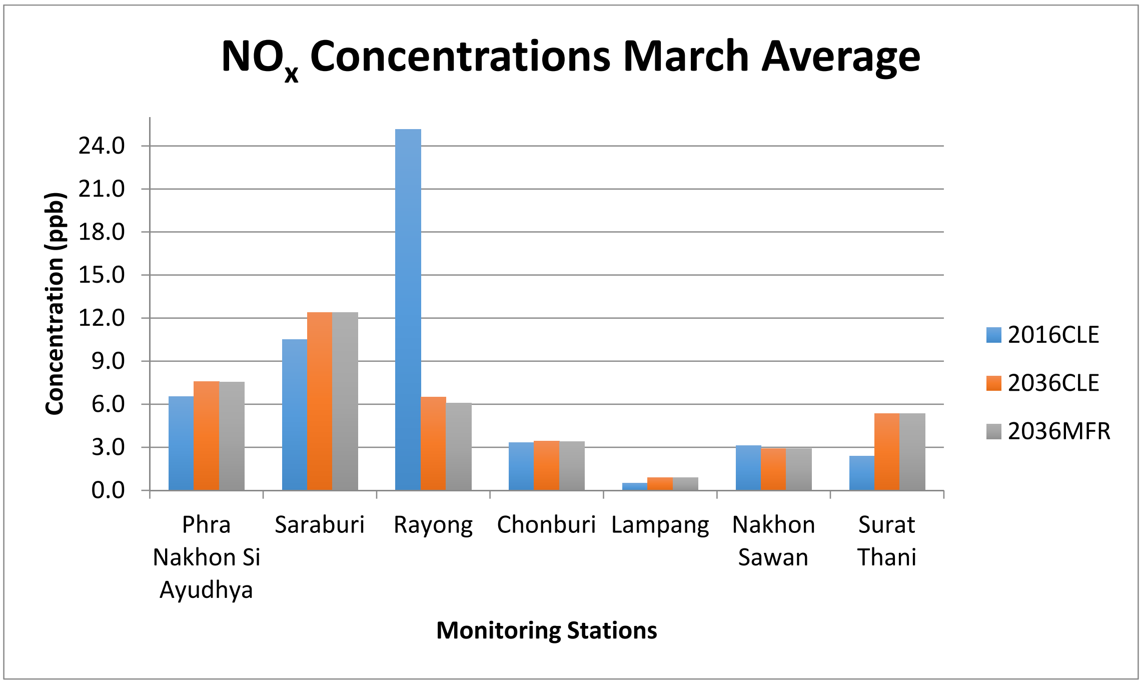


Figure 5. Selected CAMx Monitoring stations.

3.2.1. NO_x Concentrations



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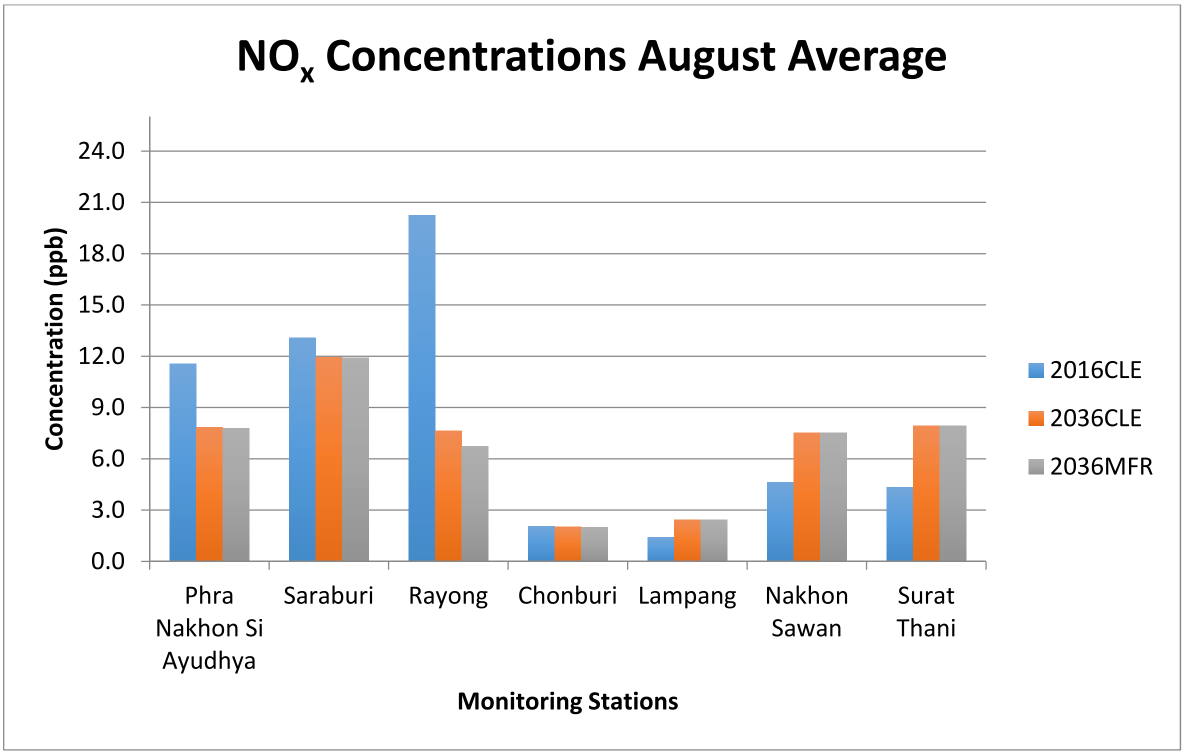
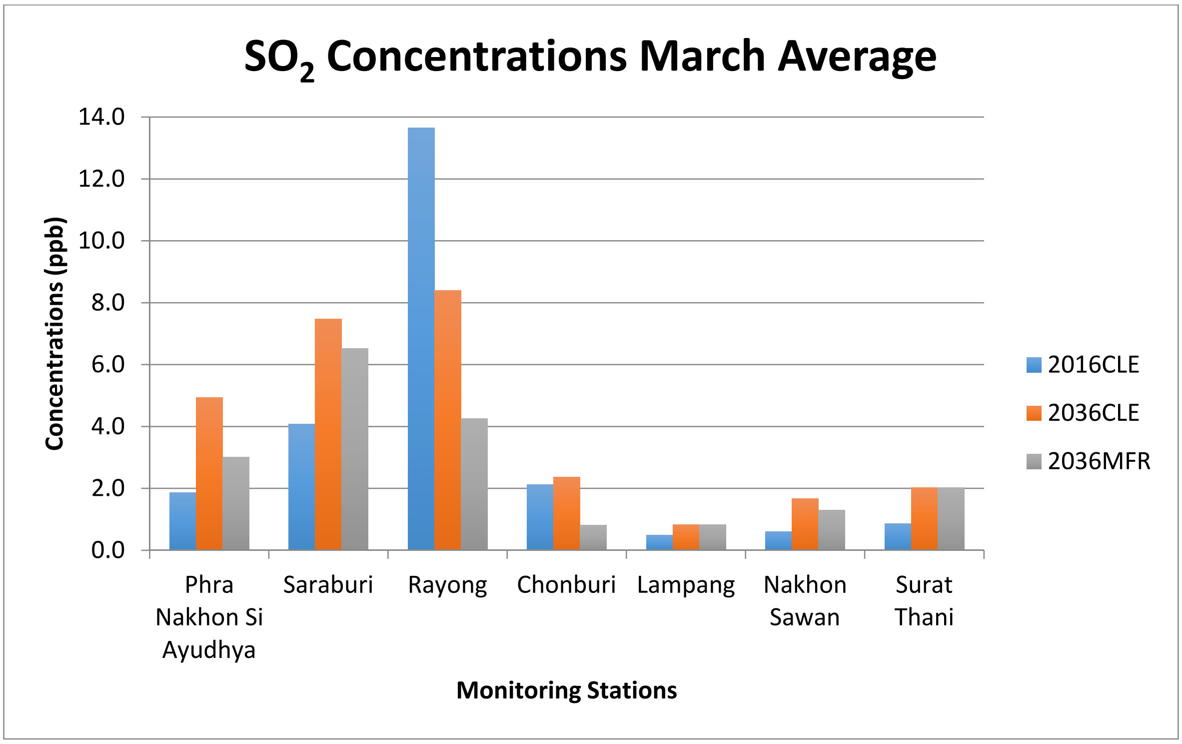


(b)

Figure 6. (a) Monthly average NOx concentrations for each monitoring station in each scenario in March. **(b)** As in Figure 6a, except for August.

3.2.2. SO$_2$ Concentrations



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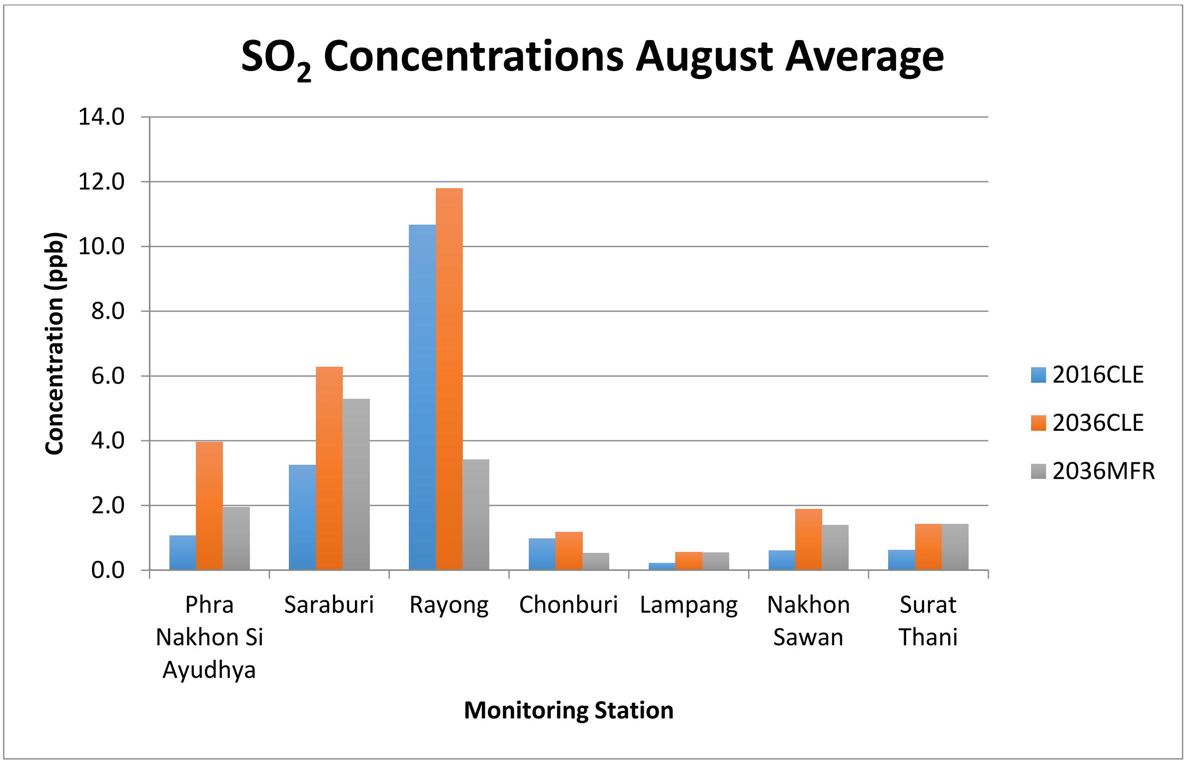
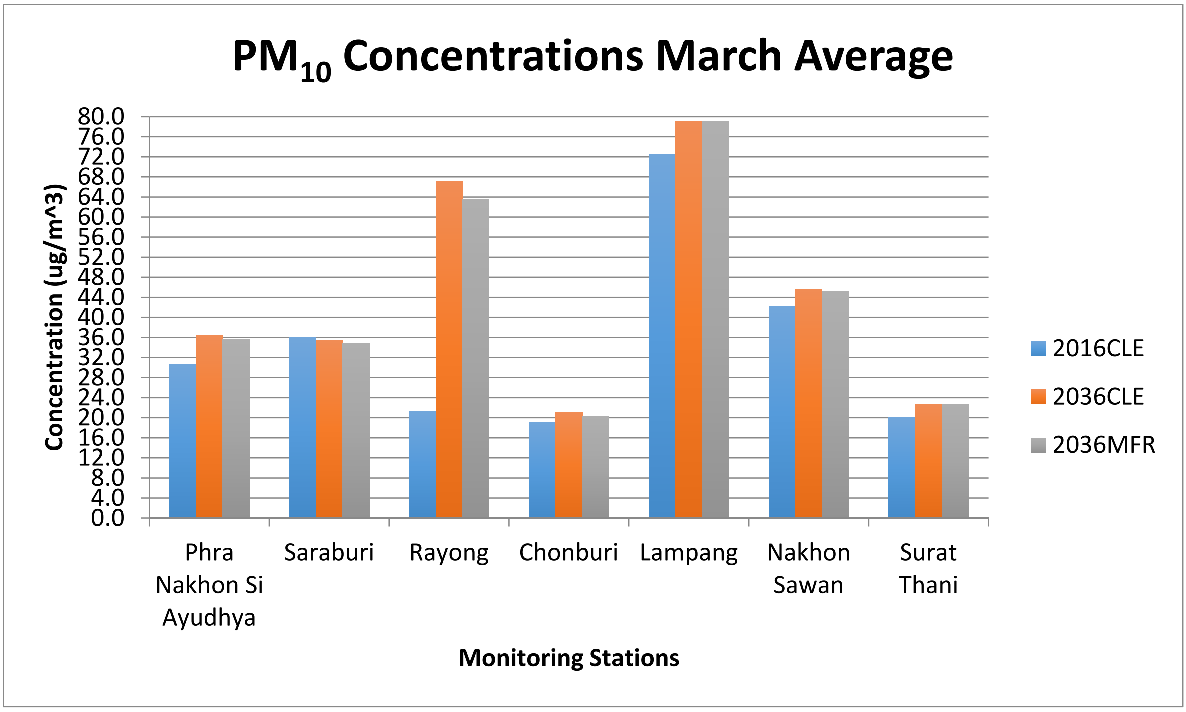


(b)

Figure 7. (a) Monthly average SO$_2$ concentrations for each monitoring station in each scenario in March. **(b)** As in Figure 7a, except for August.

3.2.3. PM$_{10}$ Concentrations



(a)

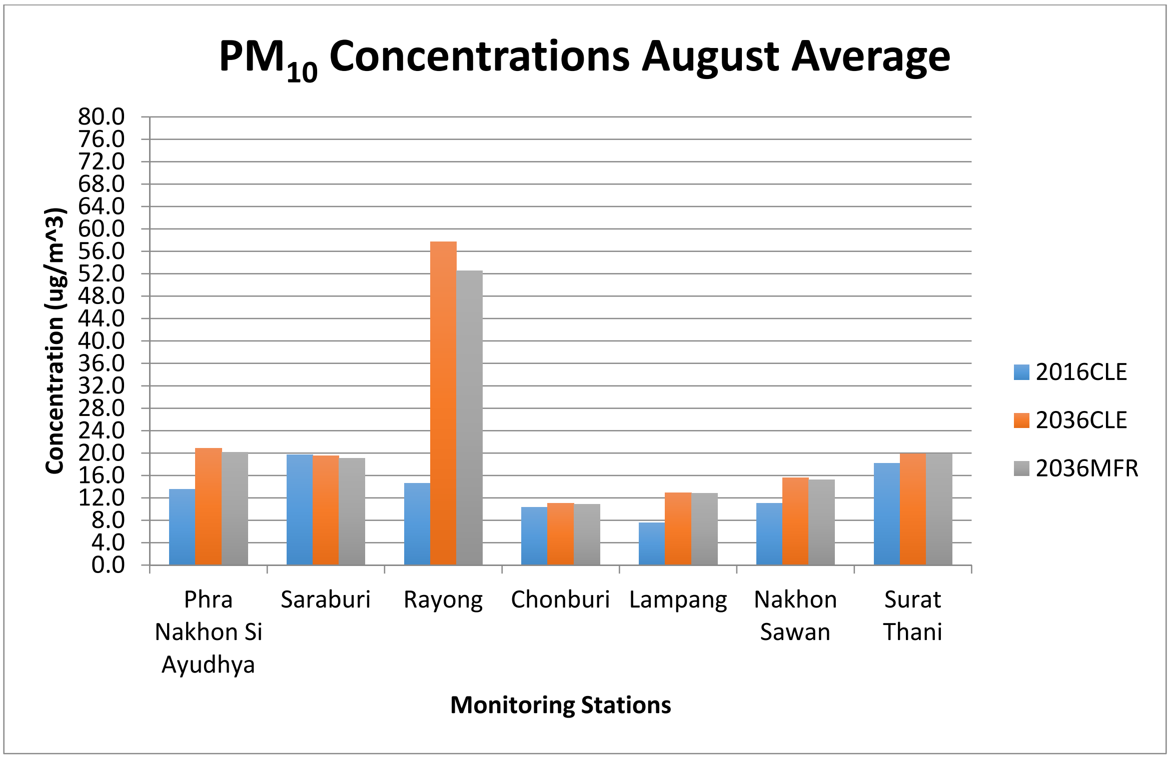
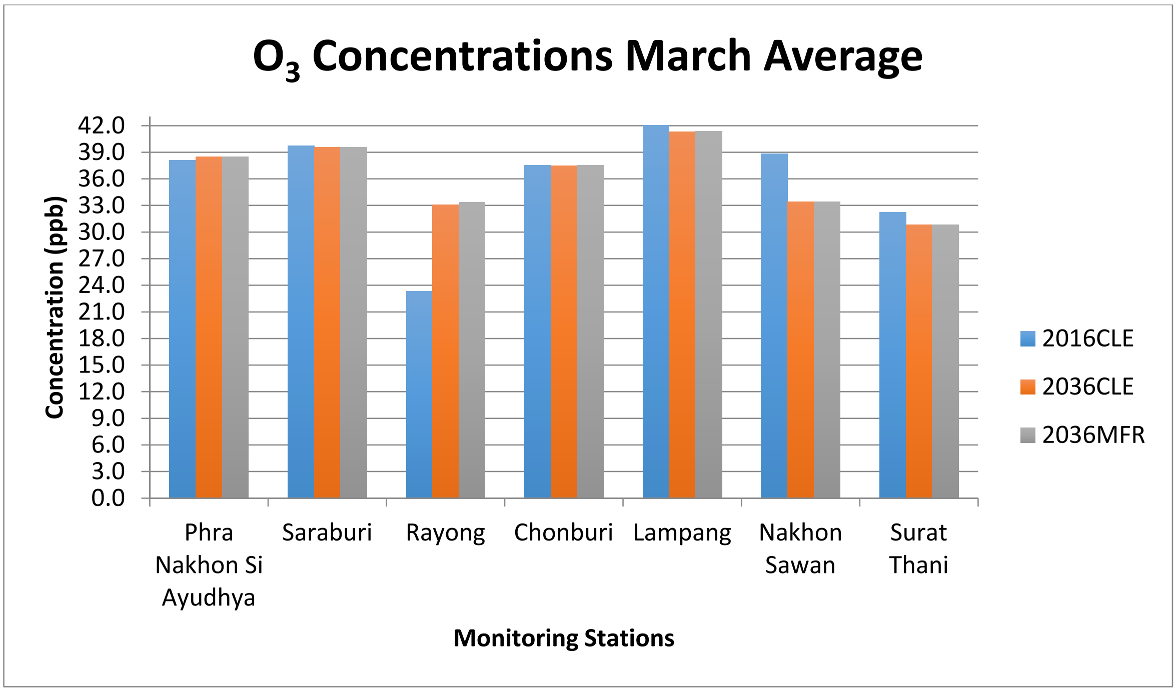


Figure 8. **(a)** Monthly average PM_{10} concentrations for each monitoring station in each scenario in March. **(b)** As in Figure 8a, except for August.

3.2.4. Ozone Concentrations



(a)

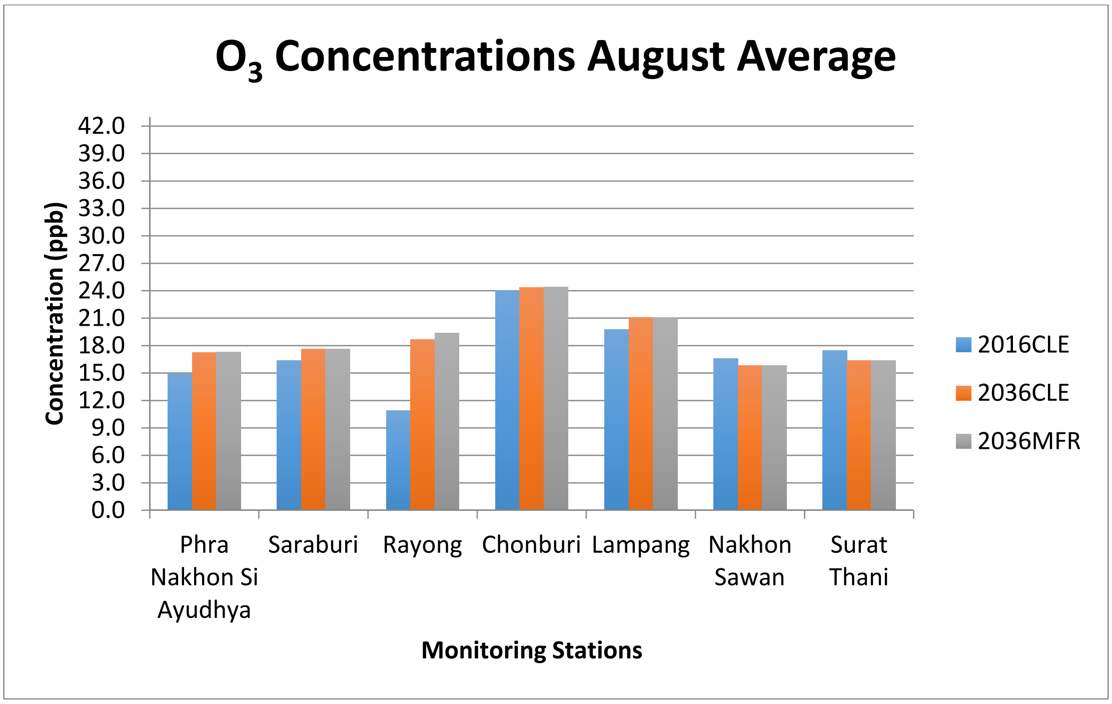


Figure 9. **(a)** Monthly average O_3 concentrations for each monitoring station in each scenario in March. (**b)** As in Figure 9a, except for August.

3.3. Scenario Emissions and Cost Comparison

In addition to the MFR demonstrating more efficient technological controls, the scenario also models the cost of the technologies and the price of increasing emissions. The emissions comparison is shown in Table 8.

Table 8. Emissions comparisons for NO_x, SO_2, and PM_{10}.

GAINS Region	NO_x CLE [1]	NO_x MFR	SO_2 CLE	SO_2 MFR	PM10 CLE	PM10 MFR
BMR	159.729	159.729	59.844	59.844	76.045	76.045
CVAL	313.703	311.069	166.045	132.877	198.429	190.632
NHIG	304.569	296.175	83.856	83.856	150.618	129.666
NEPL	196.181	189.602	73.409	73.409	176.098	147.539
SPEN	169.801	165.988	86.305	33.451	64.053	53.335
Total	1143.983	1122.563	469.459	383.437	665.243	597.217

[1] All values given in kilotons per year, for year 2036.

In all emission categories, pollutant levels were either reduced or remained the same, despite increased fuel consumption. Only the BMR region remained constant because it has no coal fired power plants. A cost of these scenarios, calculated in the GAINS model, is given in Table 9. The cost units are given in million euros per year.

Table 9. Cost Comparison of Control Scenarios.

Region	CLE	MFR
BMR	22.29	22.29
CVAL	429.74	549.56
NHIG	161.42	188.11
NEPL	153.07	171.42
SPEN	203.99	394.38
Total	970.51	1325.76

[1] All values given in million euro per year, for year 2036.

The MFR scenario is more expensive due to the fact that better control technologies are more expensive. Emission totals for all pollutants decreased significantly. NO_x was reduced by 21.41 kilotons, SO_2 was reduced by 86.03 kilotons, and PM_{10} was reduced by 68.03 kilotons. The cost of the control strategy added an additional 355 million euros per year on top of the baseline costs.

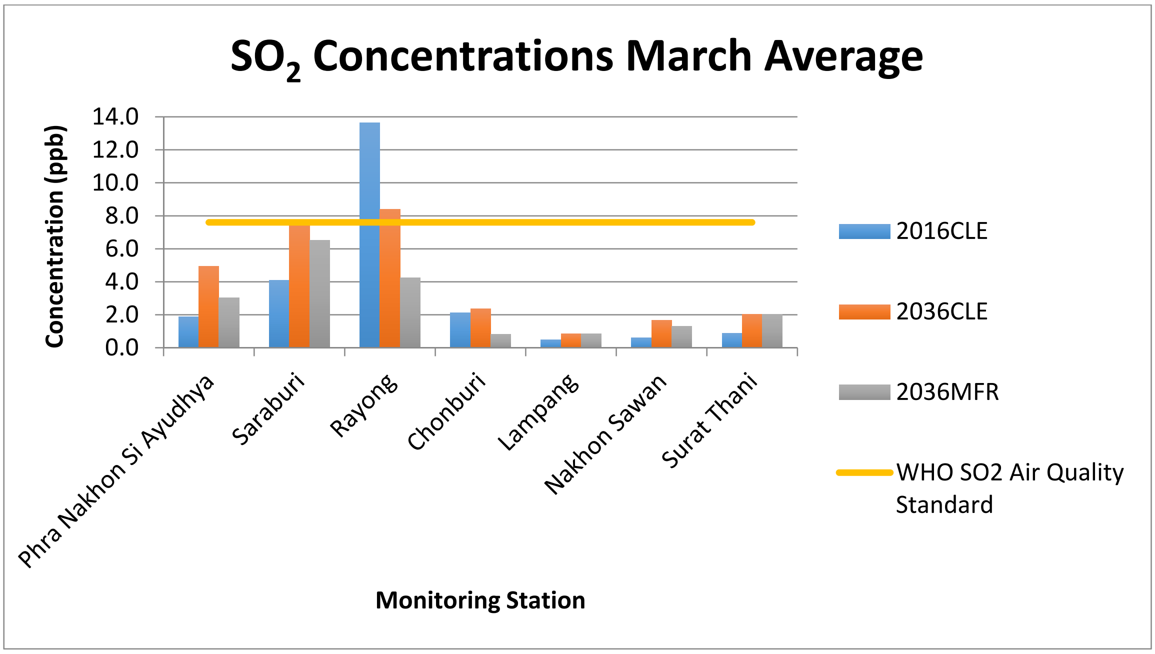
4. Discussion

Judging by the emissions and pollutant concentration results, it is clear that different regions of Thailand can expect varying impacts to air quality if control technologies are maximized for coal power plants. The value of economic and human health benefits resulting from the implementation of such control technology is not consistent throughout the country. The locations with the greatest improvement in air quality in the MFR scenario were closest to coal power plants, which was expected. However, optimal control technologies may not be worth the added cost in certain areas.

4.1. Human Health Impacts

To analyze the human health impacts of each pollutant, this study utilized air quality standards set forth by the World Health Organization (WHO) [7]. Thailand has a series of air quality standards, but they are higher than guidelines set by the WHO. While Thailand is in the process of updating their standards, the WHO guidelines revisited frequently and intended to be applied internationally. For these reasons, this study did not include the Thai air quality guidelines for assessing human health risk.

While CLE and MFR scenarios each showed marked differences between air pollutant concentrations, many of the areas with concentrations over the recommended WHO guidelines did not drastically change with added emission control. However, the most notable change was seen with SO_2 concentrations near the Rayong province station. Figure 10 displays a graph of the average monthly air concentrations of SO_2 at each of the selected monitoring stations. A line representing the WHO air quality standard for the 24-h average of SO_2 is superimposed in yellow. There is no monthly average standard available.



(a)

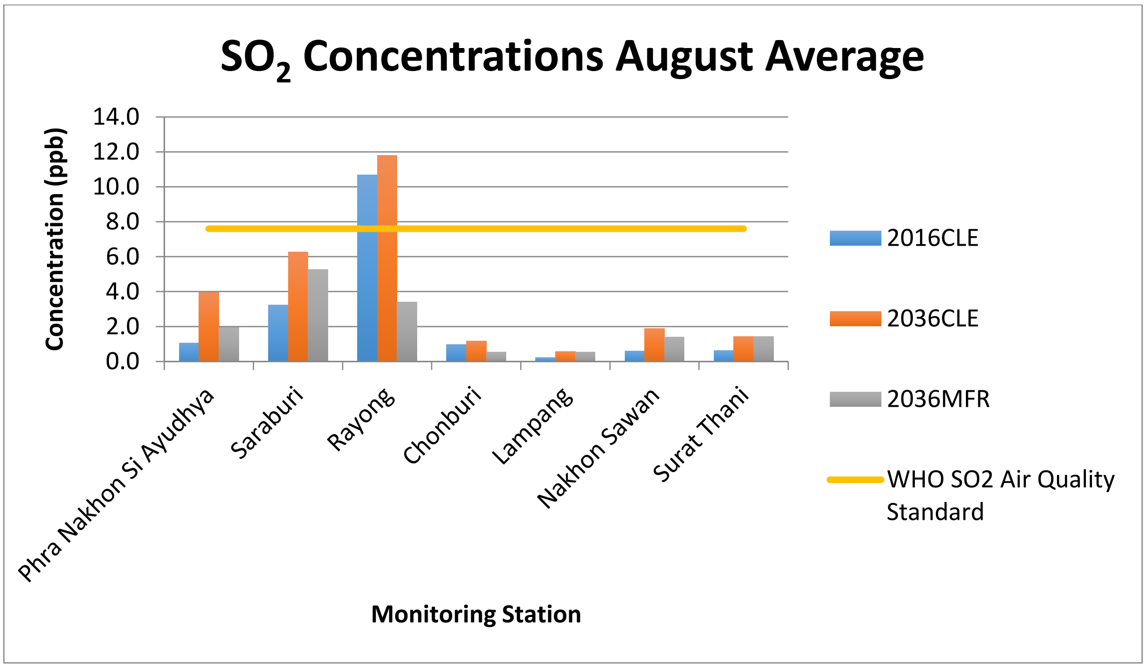
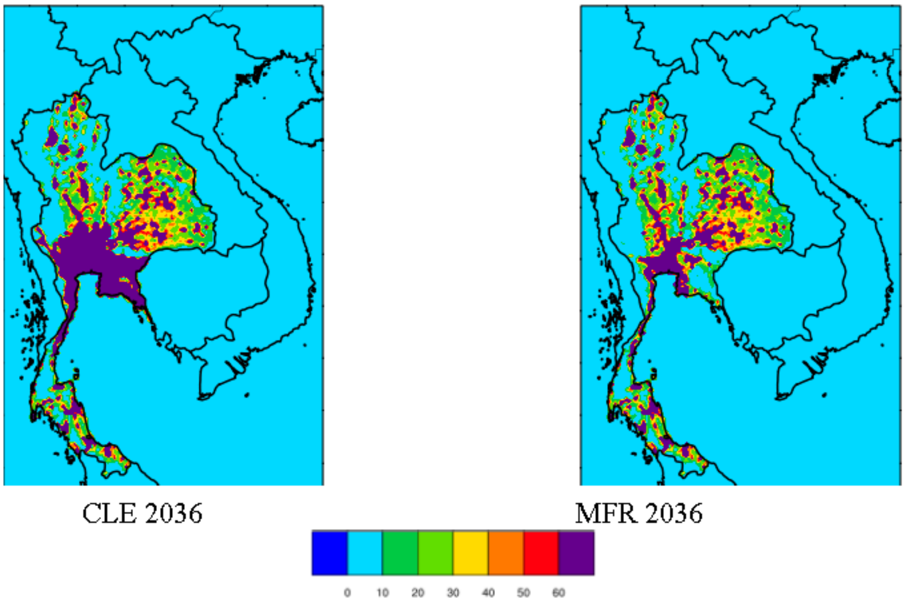


Figure 10. (a) Monthly average SO_2 concentrations compared to WHO standard. (**b)** As in Figure 10a, except for August.

The acceptable average concentration for air pollutants decreases as time span increases. Since this is a comparison of the 24-h WHO air quality standard to the monthly average, the Saraburi station will likely experience unhealthy levels of SO_2 in August. While there is suspected risk to human health near Saraburi, control technologies implemented near Rayong have the greatest potential to positively impact human health. It may also be worthwhile to install SO_2 control technologies at the plant near Saraburi. Since other monitoring stations experienced much lower concentrations of SO_2, it is probably not effective to install costly SO_2 emissions reduction technology in those regions.

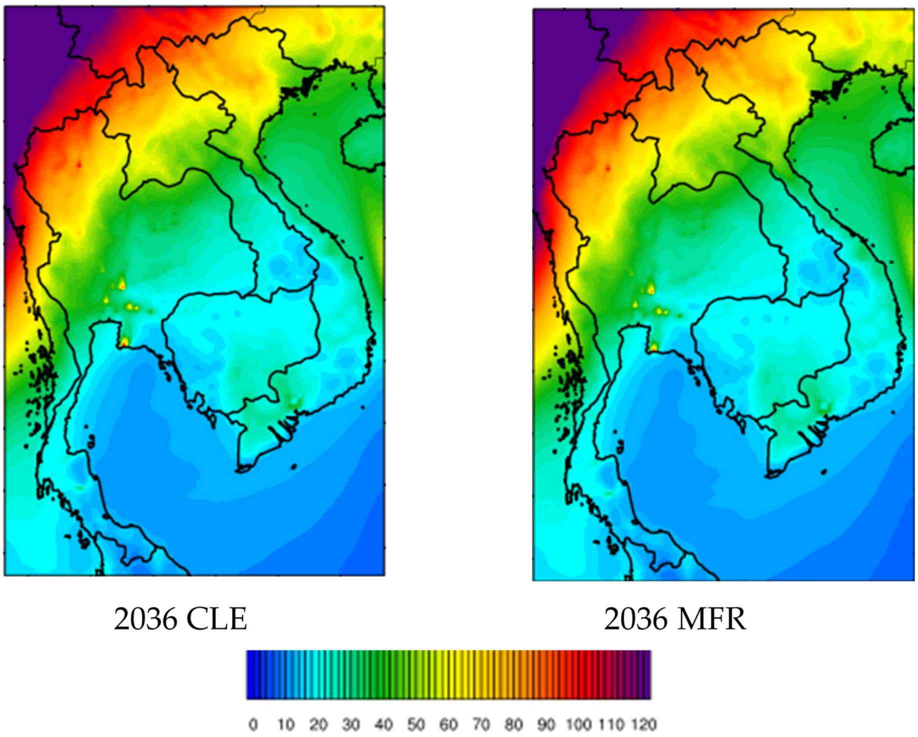
Figure 11 visually displays a snapshot of emissions of SO_2 throughout Thailand in March 2036. The MFR scenario shows drastic reductions near Rayong and the entirety of Thailand. These differences account for the reductions in average monthly SO_2 concentrations.


CLE 2036

MFR 2036

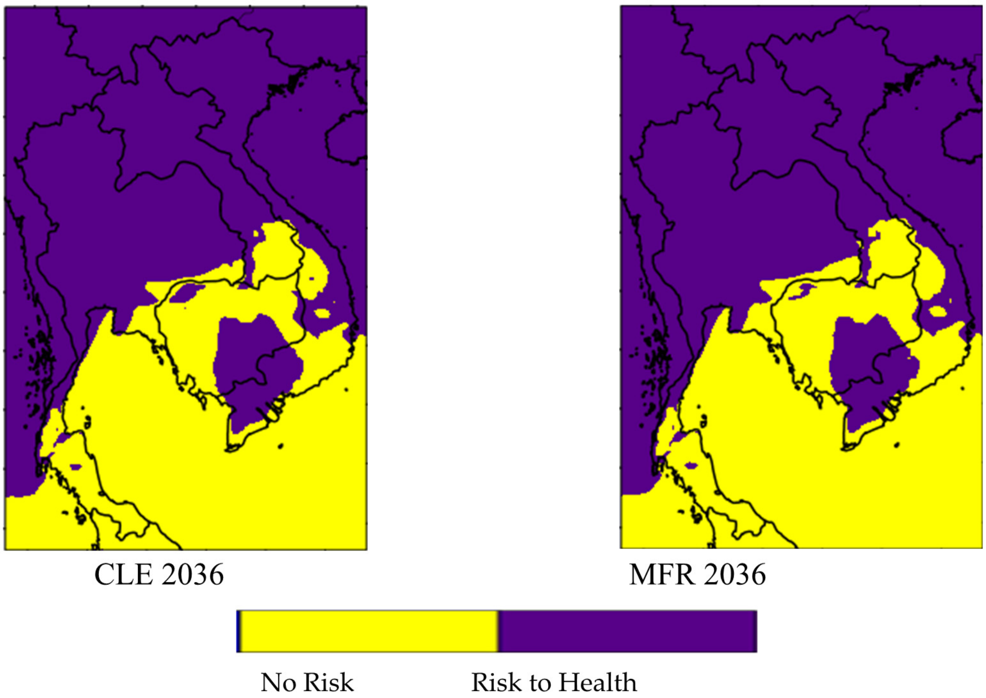
Figure 11. Hourly SO_2 emissions comparison between CLE and MFR for March in kt.

Other than SO_2, the only other pollutant that threatened human health was particulate matter. However, the emissions from power plants did not greatly alter the concentration of PM_{10} in either 2036 CLE or MFR scenarios. Biomass burning proved to be a huge emitter of particulate matter, especially during March. These particulate matter concentrations were high enough that the impact of power plants was barely noticeable. Figure 12 displays the average monthly PM_{10} concentrations across Thailand in 2036 CLE and MFR scenarios for March.


2036 CLE

2036 MFR

Figure 12. Monthy average concentration of PM_{10} for March in each scenario (ug/m^3).


CLE 2036

MFR 2036

Figure 13. Areas of Thailand with average monthly concnetrations of PM_{10} above WHO standard.

Figure 13 depicting areas where the monthly average concentration of PM_{10} in March is higher than the WHO standard clearly shows the extent to which biomass burning, which occurs mainly in the north, drowns out other sources of pollution entirely. Even if emission control technologies were added to new and existing coal power plants, the concentrations of PM_{10} would remain virtually unchanged. Rather than investing in costly control technology, it would be best to address the issue of biomass burning first. Reducing biomass burning has the potential to lower PM_{10} levels more effectively than adding control technology to power plants.

4.2. Results for the Southern Peninsula

The CAMx results displayed little difference between the 2036 CLE and MFR scenarios in the SPEN region, which comes as a surprise. In 2019, a new, 800 MW coal power plant will be installed in Krabi followed by two 1000 MW coal installations in Thepa, a township south of Krabi in the Songkla province. These plans have drawn criticism and concern regarding impacts on air quality. GAINS results demonstrated that there was a large difference between the emissions from this power plant in CLE and MFR scenarios for 2036, but it seems that virtually no changes in concentration were measured by Surat Thani, the closest monitoring station to the plant.

It is unlikely that both scenarios would yield the same pollutant concentrations because there was a large discrepancy in emissions. For example, total SO_2 emissions in the southern peninsula region for MFR proved to be 53 kilotons less than CLE in 2036. There are two possible causes for the lack of emissions showing through in the point-source data: (1) wind patterns; and (2) the influence of the ocean and grid resolution on emissions in the CAMx model.

The meteorology scenario created by meterolological modeling application in Thailand [8] incorporated wind patterns that could push emissions from the new Krabi power plant away from the monitoring station and even out of Thailand. Figure 14 displays a snapshot of wind patterns utilized in the meteorological scenario within CAMx.

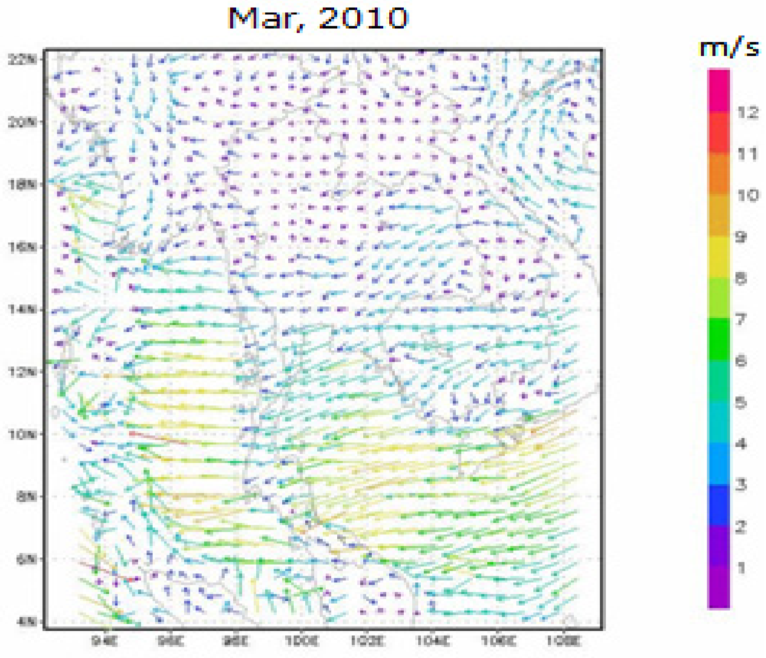


Figure 14. An example of wind patterns in Thailand used in a meteorology model.

As shown in Figure 14, a plume from a power plant located in Krabi would not reach the monitoring station due to wind direction, thus preventing the opportunity to measure the impact of control technologies on air quality.

The ocean could also contribute to these unexpected results since the Krabi plant will be located on the coast. CAMx is split into a 12 km by 12 km grid. Water will have no emissions of pollutants like SO_2 or NO_x. Since the power plant is located adjacent to water, its large emissions are averaged with the low emissions in the surrounding 144 square km area. This could make the otherwise substantial emissions from this power plant appear negligible. To see if the impact of this power plant's proximity to water, another CAMx model run could look at the change in air quality if the power plant were relocated further inland.

5. Conclusions

This study was able to model the possible impacts of the Thai PDP (2015-2036) on future air quality while focusing on the possible benefits of maximum feasible emissions control technology for coal power plants. The benefits provided by an MFR scenario vary for different areas of Thailand in 2036, and the greatest reduction of air pollutants was seen near the Rayong province monitoring station. The results of this study enables to indicate that Rayong area may be the optimal location to invest in emissions control technology.

Considering Figure 7, Rayong, located in the CVAL region, proves to be an optimal choice for MFR related technology that would impact SO_2 emissions significantly. Even so, retrofitting coal plants may prove futile for improving air quality given that the coal transportation sector contributed over 50 percent of PM_{10} emissions in both 2036 scenarios.

Other areas saw little change between CLE and MFR cases. Much of the southern peninsula, for example, may not find worth in investing in costly control technologies. Across the different pollutants considered in this study, maximum feasible control technology provided little impact on air quality.

It is worth noting, however, that the GAINS emissions input for this region did not necessarily match the resulting CAMx output. This could have been caused by weather pushing the plume of a newly installed coal power plant away from the closest monitoring station. Since the Krabi power plant will be located on the coast, the proximity of water could have skewed the results of the CAMx model. In order to conclusively determine the benefits of emission control technologies for the SPEN GAINS region, further study is recommended to model pollutant concentrations in this area.

In Thailand's NHIG and NEPL regions, MFR also did not appear to have a great impact on regional air quality, yet, for a different reason. Biomass in this region dwarfed coal power plants in both emissions and spatial distribution. Even with coal power plant emission reductions in the MFR scenario, the concentration of PM_{10} and NO_x persisted. Coal emission control technology would not greatly improve human and environmental health to justify the technology cost. Therefore, this study recommends that policy makers focus first on reducing emissions from biomass burning. Biomass is a renewable resource, but its encouragement in the 2015 Thai PDP must be coupled with control strategies in areas such as the NHIG, a location already at risk from drifting particulate matter from Myanmar.

To build upon the results of this study, regional modelling with resolution better than 12 km by 12 km could increase the accuracy of air quality forecasts. Such models could also better inform region-specific solutions for improving air quality. In addition, scenarios with wider ranges of emissions control technologies could help identify optimal control strategies across fuel types. Different fuel types could be interchanged to optimize air quality in scenarios, as well. It is imperative to maintain good air quality as power production increases over time. This project provides suggestions and a start to addressing the problems that may arise from air pollutants from the power sector in Thailand in the future.

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Author Contributions: Jared Allard: compiled fuel input and foundational data, helped create emissions control scenarios, ran the GAINS model, and post-processed initial emissions output data; Michael Alleyne: provided assistance with the GAINS model, helped create emission control scenarios; Daniel Day: helped compile the fuel input data, ran the CAMx model, and provided assistance in post-processing of output data; Robert Gourley: ran the CAMx model, provided assistance with UNIX command line, post-processed all output data from CAMx; Thanonphat Boonman: provided assistance with GIS data and software; Pham Thi Bich Thao: provided foundational data and technical guidance for GAINS and CAMx application ; Sebastien Bonnet: provided guidance on the preparation and structuring of the manuscript; and Savitri Garivait: provided research direction, comments and guidance throughout the research process.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BMR	Bangkok Metropolitan Region
CVAL	Central Valley
CLE	Current Legislation
CAMx	Comprehensive Air Quality Model with Extensions
ESP1	1 electrostatic precipitator
ESP2	2 electrostatic precipitator
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies Model
GDP	Gross Domestic Product
HED	High Efficiency Deduster
IPP	Independent Power Producers
MEGAN-MACC	Model of Emissions of Gases and Nature Monitoring Atmospheric Composition and Climate
Hg	mercury
MFR	Maximum Feasible Reduction
NESDB	National Economic and Social Development Board
NO_x	Nitrogen Oxides
NEPL	Northeastern Plateau
NHIG	Northern Highlands
PM	Particulate Matter
PBCCSC	Combustion modification and selective catalytic reduction on existing brown coal power plants
PBCSCR	Selective catalytic reduction on new brown coal power plants
PHCCSC	Combustion modification and selective catalytic reduction on existing hard coal power plants
PDP 2015	Power Development Plan 2015
PPM	Piecewise Parabolic Method
PWFGD	Power plant—wet flue gases desulphurization
RFGD	High efficiency flue gases desulphurization
SPP	Small Power Producers
SPEN	Southern Peninsula
SO_2	Sulfur Oxides
IIASA	International Institute for Applied Systems Analysis
TCAP	Toyota's Clean Air for Asia Project
VSPP	Very Small Power Producers
VOC	Volatile Organic Carbon
WHO	World Health Organization
WRF	Weather Research and Forecasting

Appendix A

Table A1. Emissions comparisons for NO_x and SO_2 from this study and TCAP Eclipse study.

Region	NO_x Base [1]	NO_x TCAP	SO_2 Base	SO_2 TCAP
BMR	3.54	4.11	1.86	1.213
CVAL	37.24	49.93	29.22	29.53
NHIG	19.29	17.88	60.40	34.79
NEPL	19.88	4.95	22.76	2.12
SPEN	3.69	1.65	2.16	2.007

[1] All values given in kilotons per year.

Table A2. Average, min and max concentrations of SO_2 in ppb for each monitoring station.

	Station		Phra Nakhon Si Ayudhya	Saraburi	Rayong	Chonburi	Lampang	Nakhon Sawan	Surat Thani
2015 CLE	**March**	**Max**	20.4	38.7	82.2	9.8	2.1	2.4	3.5
		Ave	1.9	4.1	13.7	2.1	0.5	0.6	0.9
		Min	0.0	1.0	5.6	0.2	0.0	0.1	0.1
	August	**Max**	4.7	16.8	56.3	7.2	1.2	2.7	3.0
		Ave	1.1	3.2	10.7	1.0	0.2	0.6	0.6
		Min	0.0	1.4	5.8	0.1	0.0	0.1	0.1
2035 CLE	**March**	**Max**	32.4	66.5	83.8	12.7	8.7	7.5	8.3
		Ave	4.9	7.5	8.4	2.4	0.8	1.7	2.0
		Min	0.4	2.1	1.9	0.5	0.0	0.2	0.2
	August	**Max**	15.7	30.1	35.2	8.0	5.7	8.4	7.0
		Ave	4.0	6.3	11.8	1.2	0.6	1.9	1.4
		Min	0.4	2.6	2.9	0.3	0.1	0.1	0.2
2035 MFR	**March**	**Max**	29.0	63.7	24.9	5.4	8.7	6.4	8.3
		Ave	3.0	6.5	4.3	0.8	0.8	1.3	2.0
		Min	0.2	2.0	1.8	0.2	0.0	0.1	0.2
	August	**Max**	8.3	27.5	16.9	4.1	5.7	6.8	7.0
		Ave	2.0	5.3	3.4	0.5	0.6	1.4	1.4
		Min	0.1	2.4	1.8	0.2	0.1	0.1	0.2

Table A3. Average, min and max concentrations of NO_x in ppb for each monitoring station.

Station			**Phra Nakhon Si Ayudhya**	**Saraburi**	**Rayong**	**Chonburi**	**Lampang**	**Nakhon Sawan**	**Surat Thani**
2015 CLE	**March**	**Max**	53.2	115.6	156.2	18.0	2.6	20.8	7.1
		Ave	6.5	10.5	25.2	3.3	0.5	3.1	2.4
		Min	0.4	2.2	9.6	0.5	0.1	0.2	0.4
	August	**Max**	43.8	49.8	102.0	8.9	5.9	15.2	20.2
		Ave	11.6	13.1	20.2	2.1	1.4	4.6	4.3
		Min	1.0	4.1	11.2	0.6	0.3	0.6	0.5
2035 CLE	**March**	**Max**	62.8	135.0	46.6	21.8	18.9	12.2	17.7
		Ave	7.6	12.4	6.5	3.5	0.9	2.9	5.3
		Min	0.6	2.8	2.2	0.5	0.2	0.4	0.8
	August	**Max**	42.5	57.2	26.8	7.6	14.8	24.4	36.3
		Ave	7.8	11.9	7.7	2.0	2.4	7.5	7.9
		Min	1.2	4.4	3.6	0.6	0.4	0.9	0.8
2035 MFR	**March**	**Max**	62.8	135.0	40.8	21.8	18.9	12.2	17.7
		Ave	7.6	12.4	6.1	3.4	0.9	2.9	5.3
		Min	0.6	2.8	2.0	0.5	0.2	0.4	0.8
	August	**Max**	42.5	57.2	25.6	7.6	14.8	24.4	36.3
		Ave	7.8	11.9	6.7	2.0	2.4	7.5	7.9
		Min	1.2	4.4	3.3	0.6	0.4	0.9	0.8

Table A4. Average, min and max concentrations of ozone in ppb for each monitoring station.

Station			Phra Nakhon Si Ayudhya	Saraburi	Rayong	Chonburi	Lampang	Nakhon Sawan	Surat Thani
2015 CLE	**March**	**Max**	105.7	99.6	79.8	82.9	79.3	97.3	61.9
		Ave	38.1	39.7	23.3	37.6	42.0	38.8	32.2
		Min	0.0	0.0	0.0	14.2	14.4	4.1	9.7
	August	**Max**	56.0	56.7	36.0	42.8	38.3	43.6	47.1
		Ave	14.9	16.4	10.9	24.0	19.8	16.6	17.5
		Min	0.0	0.0	0.0	8.6	8.4	2.0	5.1
2035 CLE	**March**	**Max**	129.3	110.8	65.3	85.2	81.1	71.9	62.2
		Ave	38.5	39.6	33.1	37.5	41.3	33.4	30.8
		Min	0.0	0.0	1.4	15.2	8.3	3.3	6.9
	August	**Max**	56.2	59.5	42.3	41.9	47.8	43.6	49.7
		Ave	17.3	17.6	18.7	24.4	21.1	15.8	16.4
		Min	0.0	0.0	1.2	11.3	6.7	0.0	0.3
2035 MFR	**March**	**Max**	129.4	110.9	65.5	85.3	81.1	71.9	62.2
		Ave	38.5	39.6	33.4	37.5	41.3	33.4	30.8
		Min	0.0	0.0	1.5	15.4	8.3	3.3	6.9
	August	**Max**	56.2	59.5	42.6	42.1	47.8	43.7	49.7
		Ave	17.3	17.6	19.4	24.4	21.1	15.8	16.4
		Min	0.0	0.0	1.6	11.8	6.7	0.0	0.3

Table A5. Average, min and max concentrations of PM$_{10}$ in ug/m^3 for each monitoring station.

	Station		Phra Nakhon Si Ayudhya	Saraburi	Rayong	Chonburi	Lampang	Nakhon Sawan	Surat Thani
2015 CLE	**March**	**Max**	107.5	190.5	65.4	70.6	170.9	96.8	65.6
		Ave	30.8	36.0	21.2	19.1	72.6	42.1	20.1
		Min	1.5	9.4	6.7	4.0	3.7	2.4	4.1
	August	**Max**	37.7	77.4	41.5	25.8	23.0	34.7	30.5
		Ave	13.5	19.7	14.6	10.3	7.6	11.1	18.2
		Min	2.8	6.9	5.6	1.5	1.1	1.7	2.0
2035 CLE	**March**	**Max**	100.2	164.8	446.2	70.5	173.4	101.9	75.2
		Ave	36.4	35.5	67.1	21.1	79.1	45.7	22.7
		Min	1.8	9.2	22.8	4.5	4.1	3.3	4.3
	August	**Max**	69.9	70.1	226.5	39.4	47.7	47.7	33.7
		Ave	20.9	19.5	57.7	11.1	12.9	15.6	19.9
		Min	2.9	5.7	22.1	1.8	2.2	2.3	2.2
2035 MFR	**March**	**Max**	98.5	164.2	399.5	70.3	173.4	101.8	75.2
		Ave	35.7	35.0	63.6	20.4	79.0	45.3	22.7
		Min	1.7	9.1	22.0	4.5	4.1	3.3	4.3
	August	**Max**	66.3	69.4	218.0	36.1	46.3	46.5	33.7
		Ave	20.2	19.1	52.5	10.9	12.8	15.3	19.9
		Min	2.9	5.7	19.8	1.8	2.1	2.2	2.2

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