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EMISSION INTENSITY AND ABATEMENT COST OF FOSSIL FUEL POWER PLANTS IN THAILAND

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Abstract

Monitoring of air emission and pollution control cost is a key to improve air quality management of electricity generation industry. This research comprehensively evaluates abatement cost of sulfur dioxide (SO_2), nitrogen oxides (NO_x), emission intensity and emission inventory of sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), and carbon dioxide (CO_2) emitted from Thailand's fossil fuel power plants. The research applied bottom-up approach with continuously monitored data from 64 percent of Thailand electricity generation industry. The data was used in an evaluation of emission intensity according to technology, fuel type and pollution control system. The research finding indicates that lignite-fired power plants are the major contributors of air pollution in Thailand. The research results will help in improving performance of emission forecast and monitoring via usage of site-specific emission factors. Air emission factors from power plants were found to be 0.022 – 1.432 g-SO_2/kWh, 0.122 – 5.229 g-NO_x/kWh, 0.031 g-PM/kWh, and 452 – 1,443 g-CO_2/kWh. The cost for SO_2 reduction from fossil fuel-based power plants are estimated to be 0.03-0.26 US$/Kg-$SO_2$ while abatement costs of NO_x are 0.31-9.63 US$/kg-$NO_x$. Flue gas desulfurization with wet lime and dry low-NO_x burner are more efficient and cost-effective in controlling SO_2 and NO_x than the other techniques. The research results were also benchmarked against available international data sources. The findings can be used in policy planning and decision making process of key stakeholders to help improve air quality in the future.

Key words: abatement cost, emission intensity, fossil fuel power plant, primary air pollutant

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1. Introduction

Thailand's electricity generation sector relies heavily on fossil fuels especially natural gas which is a major fuel source and contributes 109,454 GWh of electricity generation (69% of total electricity generation), followed by coal which produces 28,207 GWh (18% of total electricity generation) in 2010. The remaining energy sources include fuel oil, hydropower, diesel, geothermal, solar cell and wind turbine. These energy sources are relatively small in proportional to natural gas and coal (DEDE, 2010). The Royal Thai government has established number of financial and legislative policies aiming at enhancing energy security with increasing fuel diversification and ability to cope with environmental impacts especially global warming in the power sector (Sawangphol and Pharino, 2011).

Combustion of fossil fuels (coal, natural gas, fuel oil etc.) results in emission of sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM) or soot and carbon dioxide (CO_2) to atmosphere (Ja'afar et al., 2016). Prolonged exposure to these pollutants can lead to wide range of serious health problems (USEPA, 2011). Database of emission inventory is an essential part in a development of effective environmental management policy to mitigate adverse effects of air pollution. A few studies have been conducted to investigate emission inventory of Thailand's electricity generation sector. These

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studies focused mainly on different sampling scopes and methodology (Krittayakasem et al., 2011; Thao Pham et al., 2008). Outapa et al. (2017) evaluated average emission factors of air toxic compounds, emitted from motorcycles in Bangkok, Thailand using the IVE (International Vehicle Emission) model. The Department of Alternative Energy Development and Efficiency (DEDE) has also conducted annual surveys on emission inventory of Thailand. This inventory, however, was developed based on top-down approach using emission factors that were recommended by international organizations (EEA, 2009; IPCC, 2006; USEPA, 1995; WHO, 1993) which may not necessarily be applicable to power plants in Thailand.

Emission factors are widely used to estimate amount of pollution emission. An emission factor from power plant represents mass of a pollutant emitted per unit of source activity, i.e., electricity generation or fuel consumption. There are many organizations that develop emission factor databases for evaluation of air pollutant emission including the United States Environmental Protection Agency (USEPA), European Environmental Agency (EEA) and Intergovernmental Panel on Climate Change (IPCC), etc. Emission factors developed by different organizations may differ because they were developed using different assumptions and emission data. Emission intensity depends on many factors such as fuel types, combustion technology, operating condition, pollution control technology, quality of maintenance program, and age of equipment. For instance, in a case of natural gas combined-cycle power plant with gas turbine generators, USEPA recommended an emission factor of NO_x between 43 – 138 g/GJ (USEPA, 1995) and EEA recommended an emission factor of NO_x between 92 – 245 g/GJ (EEA, 2009). The key factor that causes the major difference in recommended emission factor is that the USEPA used emission data from all power plants in the United State while EEA used emission data from all of the European Union's countries. A recent comparative study of dynamic changes of CO_2 emission performance of fossil fuel power plants between China and Korea was done by Zhang and Choi (2012). The results demonstrated that innovation and ability for technological leadership are key factors affecting emission performance of power plants in China and Korea. This example shows clearly that development of site-specific or countrywide emission factor database is essential in improving accuracy of emission estimation in a domestic setting.

An effective mean to evaluate an efficiency of pollution treatment technology is through its emission control cost. Pollution abatement cost is generally expressed in the form of expenses per unit of pollutant reduction. The cost of pollution control is mainly comprised of capital investment (i.e. pollution control equipment and technology costs) and operation and maintenance cost (i.e. cost of energy, chemicals, technicians, etc. that are necessary to keep a plant operational).

Information on abatement cost is very important in monitoring performance of pollution treatment and in planning to help improve treatment efficiency. It can even be used as a basis to set up a policy with right incentives to reduce pollution in the long term.

Abatement cost in conjunction with mitigation options has been evaluated for various pollutants in many countries using different evaluation approaches (Choi et al., 2012; Karvosenoja and Johansson, 2004; Vijay et al., 2010). In China, Choi et al. (2012) used nonparametric efficiency analysis technique to estimate the energy efficiency and marginal abatement costs of energy-related CO_2 emissions. In Mexico, Islas and Grande (2008) assessed abatement costs of several SO_2-control options (including flue-gas desulphurization technologies, hydro treatment of fuel oil, and the substitution of high-sulfur by low-sulfur content fuels) and indicated the best-SO_2 reduction options for future investment. Kwon and Yun (1999) evaluated abatement costs for air pollution (SO_2, NO_x, PM and CO_2) from energy sector in South Korea during 1990-1995 using an Econometric Model. CO_2 abatement cost for cement industry in Thailand was investigated by Hasanbeigi et al. (2010) by comparing CO_2 abatement potentials based on existing technology. It is clear from number of studies and research trend in the last decades that economic performance of pollution control system is a very important fact. The focus is on assessment of various control systems to find cost-effective options that offer great environmental benefits under reasonable and effective investment costs. The objectives of this research include: (1) to evaluate emission inventory and develop emission factors of sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2) and particulate matter (PM) from electricity generation of fossil fuel power plants in Thailand and (2) to estimate costs of controlling pollution based on abatement technology utilized in the power plants in Thailand.

This investigation used a bottom-up approach in conjunction with local-specific data obtained from Continuous Emission Monitoring System (CEMs) from each power plants to determine abatement costs and countrywide emission factors of power plants based on electricity generation technology, fuel type, and air pollution control equipment. The findings from this study can be used to help improve effectiveness of air pollution monitoring and management policies in the electricity generation sector with the ultimate goal of improving national air quality.

2. Material and methods

Fig. 1 illustrates the methods for calculating emission factor and emission inventory of flue gases emitted from Thailand's fossil fuel power plants. The process starts with collection of emission data from CEMs (for SO_2, NO_x and PM) and fuel data (for CO_2) and emission flow rate for each operating unit.

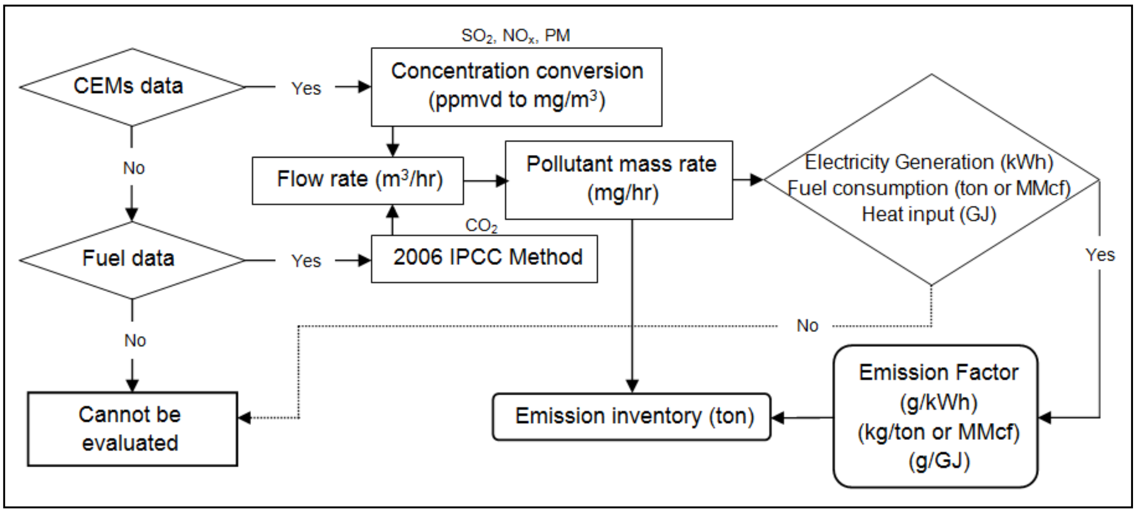

Fig. 1. Stages of emission factor and emission inventory analysis

Pollutant mass rate (PMR) is, then, calculated for each operating unit by multiplying emission concentration with flow rate. The total annual emission of each pollutant is represented by a summation of PMR for a period of one year. The emission factor is calculated by dividing PMR with the associated activity data (for example; electricity generation (kWh), fuel consumption (ton or MMscf) and heat input (GJ)). The results will be presented in three different units of emission factor consisting of g/kWh, kg/ton or MMscf and g/GJ.

2.1. Power plants selection

A large portion of Thailand's electricity (78%) comes from fossil fuel-based power plants. These power plants use mainly natural gas (67% of total capacity) and coal (11% of total capacity) as fuel sources. Very small proportion of power plants uses fuel oil and diesel oil (1% of total capacity) and, thus, is excluded from this investigation. Hydroelectric power plants, renewable power plants, and electricity imported from neighbouring countries contribute only 11%, 5% and 5% of the national installed capacity, respectively. They produced relatively small amount of air pollutants and, therefore, were not included in the research scope.

Fourteen major fossil fuel-based power plants were selected as representatives of the target group in this study. All selected power plants have similar capacity ranging between 500 and 720 MW. This selection criterion is set to help minimize size effect on the study result. The selected power plants consist of thirty-eight (38) electricity-generating units, and can be divided into four (4) main groups according to their fuel types (Bituminous, Lignite and Natural Gas) and electricity generating technology (Thermal and Combined Cycle Power Plant). Details of each group can be described as follow:

1. Lignite coal-fired thermal power plant (LTP) consists of eight (8) units.
2. Bituminous coal-fired thermal power plant (BTP) consists of two (2) units.
3. Natural gas-fired thermal power plant (NTP) consists of six (6) units.
4. Natural gas combined cycle power plant (NCC) consists of twenty two (22) units.

The total installed capacity of the plants in this dataset is 19,711.5 MW which is accounting for 64 percent of total electricity generating capacity of Thailand (30,920 MW as of 31 December 2010) (EGAT, 2010b). Table 1 provides a summary of the proportion of installed capacity of each representative group in relation to total installed capacity of the national grid. It should be noted that this research covered all power plants in BTP, LTP and NTP groups in the national grid. For the NCC group, this research selected the representative power plants to cover approximately 75 percent of the installed capacity of the national grid. Each group of power plant is good representatives of major emission sources of power sector in Thailand.

Table 1. Power generating capacity of fossil fuel-based power plants used in this research compared to the installed capacity of Thailand's national grid

Power Plant Group	*In this research (MW)*	*National Grid (MW)*
LTP	2,180	2,180
BTP	1,346.5	1,346.5
NTP	3,644	3,644
NCC	12,541	16,667
Total	**19,711.5**	**23,837.5** [a]

[a] excluding hydro-electric power plants, renewable power plants and imported from neighboring countries, total capacity of national grid at 31 December 2010 was 30,920 MW (EGAT, 2010b)

2.2. Pollutant mass rate estimation method

A regulation of Thailand's Ministry of Industry requires that all power plants with installed capacity exceeding 29 MW must install Continuous Emissions Monitoring System (CEMs) (Ministry of Industry, Thailand, 2004). The purpose of this regulation is to ensure that environmental parameters (such as concentration of sulfur dioxide (SO_2), nitrogen oxides (NO_x), oxygen (O_2), and particulate matter (PM) discharged from the stacks) are effectively established, monitored and maintained. The CEMs data used in this study was obtained from the Thailand's Pollution Control Department (PCD). CEMs provide continuous records of hourly flue gas emission and flow rates (for the period of one year). The reported concentration of gases is typically in the units of parts per million by volume (ppm) at 25°C, 1 atm, dry basis and 50 percentage of excess air.

Pollutant mass rates (PMR) of NO_x, SO_2, CO_2 and PM emissions on an hourly basis can be determined by multiplying flue gas flow rate (m^3/hr) with pollutant concentration (mg/m^3) as shown in Eq. (1) (USEPA, 1997, 1999):

$$PMRs = C_d \times Q_{d,std} \times 10^{-6} \tag{1}$$

where PMR_s is the pollutant mass rate at standard condition (kg/hr); C_d is dry-basis pollutant concentration (mg/m^3) which is measured by CEMs; $Q_{d,std}$ is the stack gas dry-basis volumetric flow rate corrected to standard conditions (m^3/hr).

Concentration of PM is typically expressed in term of mg/m^3 but NO_x and SO_2 concentrations, which are measured by CEMs instruments, are usually reported in the unit of parts per million, volumetric dry (ppmvd). Concentrations of NO_x and SO_2 emission, then, have to be converted from ppmvd to mg/m^3 using the Eq. (2).

$$C_d\,(mg/m^3) = \frac{C_d\,(ppmvd) \times MW}{V} \tag{2}$$

where MW is the molecular weight in unit of g/mol (46.01 for NO_x and 64.06 for SO_2); V is the volume occupied by 1 mole of ideal gas at 25°C, 1 atm (24.45 L/mol).

To mitigate the issue of lacking in continuous monitoring data of CO_2, emissions of CO_2 are calculated by using fuel analysis and mass balance method according to 2006 IPCC Guidelines (IPCC, 2006). The Energy Regulatory Commission (ERC) and Electricity Generating Authority of Thailand (EGAT) provided data used for the estimation including fuel consumption, fuel composition and calorific values.

2.3. Site-specific emission factors

Site-specific emission factors of NO_x, SO_2, CO_2 and PM emitted from fossil fuel-based power plants can be calculated by dividing pollutant mass rate with source activity at a given time, as shown in the following equation (Eq. 3):

$$Site-specific \quad emission \quad factor = \frac{PMR_s}{Source \quad activity} \tag{3}$$

where PMR_s is the pollutant mass rate at standard condition (kg/unit time); *Source activity* is the related activity of power plant which can be separated into 3 categories including: (1) gross electricity generation (MWh/hr); (2) fuel consumption rate (ton-coal or MMscf-natural gas/hr); and (3) heat input rate (TJ/hr). Site-specific emission factor can also, therefore, be expressed in 3 units: (1) kg/kWh-gross electricity generation; (2) kg/ton-coal or kg/MMscf-natural gas; and (3) kg/TJ-heat input, depending on the application purpose.

Pollution control system can be categorized according to type of controlled pollutant. SO_2 control system such as Flue gas desulfurization (FGD) can be divided into 2 types; (1) using wet limestone and (2) using seawater. NO_x control system includes Water Injection, Low-NO_x Burner (LNB) and Dry Low-NO_x Burner (DLN). As for PM control system, coal-fired power plants are generally equipped with electrostatic precipitator (ESP) used for controlling PM emission. Complete PM monitoring data, however, was available only some types of the power plants. In the case of CO_2 emission, there is no CO_2 control technology (such as carbon capture and storage) currently installed in any power plants in Thailand.

2.4. Abatement cost calculation

Costs of air pollution control consist of 2 main parts: (1) fixed initial cost (capital cost of control system which varies depending on type of control technology) and (2) operating and maintenance costs (cost related to operation and maintenance of control equipment, chemical and fuel, technicians, etc.). This relationship is shown in (Eq. 4). The total annual pollution control cost is a summation of annual capital cost (over lifetime of the power plant) and annual operation and maintenance cost.

$$Total \quad Cost\ (\frac{baht}{year}) = Fixed \quad Cost\ (\frac{baht}{year}) + O\,\&\,M\ (\frac{baht}{year}) \tag{4}$$

All cost data or dataset used in this research were provided by the Energy Regulatory Commission (ERC) of Thailand. In the case that some cost data is not available, capital cost of a power plant is estimated based on data from Thailand power development plan 2010-2030 (PDP2010) as indicated by the Electricity Generating Authority of Thailand (EGAT, 2010a). PDP2010 reports that capital cost of coal-fired power plant is 52,700 baht/kW (1,766.68 US$/kW), whereas the cost for a combined cycle power plant is 24,718 baht/kW (828.63 US$/kW) and that of a gas turbine power plant is 14,808 baht/kW (496.41 US$/kW). Using the published capital costs from the PDP2010, total investment cost of a power plant can be estimated when actual cost data is not available. The PDP2010 also suggests that a pollution control cost of 5% of the total capital investment is a reasonable estimate.

Pollution abatement cost from a power plant is calculated by dividing associated total annual pollution control cost with total annual amount of pollution reduction in the same year of that power plant, as shown in (Eq. 5). The amount of pollution reduction is calculated from an amount of baseline emission (without pollution control implementation) subtracted by an amount of emission from the abatement case (with pollution control measures).

$$Abatement\ Cost\ (\frac{baht}{pollutant\ mass}) = \frac{Total\ Cost\ (\frac{baht}{year})}{Emission\ Reduction\ (\frac{baht}{year})} \quad (5)$$

2.5. Quality assurance and quality control processes

In every steps of analysis, quality assurance processes, such as consistency check and repeated calculation check, are applied to ensure accurate results (USEPA, 1997). Consistency check is used to verify quality of raw data from CEMs. For example, in the case of a power plant shut down, its emission is verified that it is indeed zero. On the other hand, while the boiler is operating, the emissions were also checked that they are above zero and are within a reasonable range. Suspicious data was removed from raw data such as emission that is recorded as below zero. Verification calculations were done at random to check the validity of formula. The emission factors obtained from this research are also compared with the values from standard international sources to ensure that they are within a reasonable range.

3. Results and discussion

3.1. Emission inventory of electricity generation sector of Thailand

Emission inventory in the year 2010 from each power plant group is summarized in Table 2. The table shows total electricity generation and total emission of SO_2, NO_x, PM and CO_2. Among the four groups of power plants in Thailand, LTP generated the highest amounts of SO_2 and PM, while NCC emitted the highest amount of NO_x and CO_2. The following section presents a comparison and discussion of various pollutants emitted from each power plant type. Section 3.3 summarized and highlighted the results in term of emission factors which take into account the amount of electricity generated from each power plant group.

The proportion of electricity generation and amount of air pollution emitted from the LTP, BTP, NTP, and NCC can be directly compared as shown in Fig. 2. The LTP and BTP in combination (so called coal-fired power plants) are the largest emission source of SO_2 which contribute up to 83 percent of total SO_2 emission (LTP: 49 percent and BTP: 34 percent, respectively). The lignite-fired power plants or LTPs, emit approximately 49 percent of total SO_2 emission due to higher sulfur content in lignite coal and higher electricity generation by the LTP.

NCC is the major NO_x emission source (47 percent). The second highest NO_x emission is the LTP with a share of 40 percent of total emission. Even though there is a small difference in electricity generation between LTP and BTP, the difference in NO_x emission is quite significant. This is mainly because NO_x emission is not greatly affected by fuel composition, but rather by combustion process and NO_x control equipment (Bris et al., 2007). High level of NO_x emission from the LTP was, therefore, due to fuel combustion configuration and pollution control system of the power plant itself. The amount of SO_2 emission from the natural gas power production is also relatively high for these types of power plants. This is mainly due to the high sulfur content of the natural gas utilized in Thailand (0.01% by volume) (DEDE, 2010). It should be noted that the data used in the analysis of natural gas power production does not contain the duration that the plants used fuel oil.

The largest emission source of PM is the coal-fired power plants (LTP and BTP) with 60 percent of total PM emission (LTP at 33 percent and BTP at 27 percent, respectively). This is because solid fuel type, in this case coal, when it undergoes combustion process has higher possibility of leaving unburned carbon (ash or PM) than gaseous fuel type. In the case of CO_2 emission, the largest emission source is NCC (43 percent) due to the highest electricity generation from the NCC power plants. The second largest CO_2 emission source is LTP (at 36 percent).

LTP, evidently, is the major source of air pollution emission for fossil fuel-based power plants in Thailand due to high proportion of SO_2, NO_x, PM and CO_2 emissions, as shown in Fig. 2.

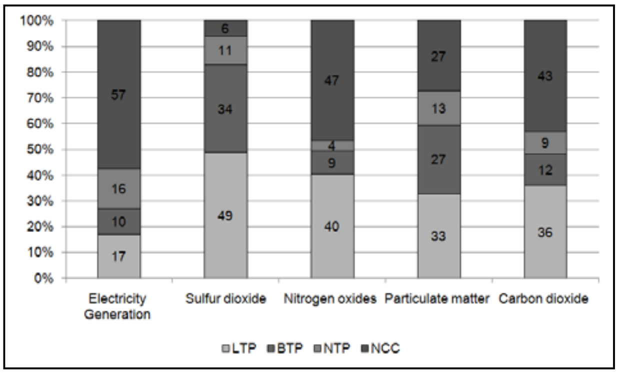

Fig. 2. Proportion of emission and electricity generation from each type of power plant

As Thailand has an abundant resource of lignite coal in some of the Northern Provinces, it is foreseeable that Thailand will continue to use lignite as one of the primary fuels for electricity generation even though it emits higher pollution compared to other energy sources. A recommended solution is to focus on improving the plant's combustion process and emission control technology/system along with installation of effective emission monitoring system to ensure that low emission from these power plants can be accomplished.

Combustion process can be enhanced by improving accuracy in combustion temperature control. This is mainly because NO_x emission is correlated to temperature in combustion chamber (Thermal NO_x generation is limited if combustion temperature is below 1,400°F). To improve SO_2 emission control in lignite coal-fired power plant, both pre-combustion (coal pre-treatment to reduce sulfur content) and post-combustion technology (flue gas desulfurization) must be used to ensure low SO_2 emission. Emission monitoring system must also be accurate and effective through the use of an effective preventive maintenance plan such as regular zero calibration, span/range check and 3rd party verification.

An accurate monitoring system will ensure that amount of pollution released to the environment can be measured correctly. This will create a powerful virtue cycle that results in effective emission management and improvement in air quality.

Table 2. Emission inventory of fossil fuel-based power plants in Thailand for the year 2010

Power Plant Group	***Generation (GWh)***	***SO_2 (ton)***	***NO_x (ton)***	***PM (ton)***	***CO_2 (ton)***
LTP	17,901	22,933	51,164	1,611[a]	25,747,295
BTP	10,533	15,504	11,671	1,306	8,545,144
NTP	16,543	5,247	5,293	649	6,129,862
NCC	60,616	2,830	59,235	1,349	30,047,788
Total	105,593	46,514	127,363	4,915	70,470,089

[a] *evaluated by using emission factor of 0.09 kg/MWh (Krittayakasem et al., 2011)*

Table 3. Site-specific emission factors (mass per electricity output)

Power Plant	***Emission Control***	***Unit: U***	***SO_2 g/U***	***NO_x g/U***	***PM g/U***	***CO_2 g/U***
LTP	FGD (wet limestone)	kWh	1.191	-	-	1,443
	LNB	kWh	-	2.661	-	
BTP	FGD (sea water)	kWh	1.432	-	-	-
	LNB	kWh	-	1.090	-	-
NTP	LNB	kWh	0.022	0.149	-	-
NCC	**Single shaft**					
	DLN	kWh	0.034	0.122	0.031	452
	Multiple shafts					
	No control	kWh	0.034	5.229	0.031	452
	Water Injection	kWh		1.790		
	DLN	kWh		0.824		

Table 4. Site-specific emission factors (mass per fuel consumption)

Power Plant	***Emission Control***	***Unit: U***	***SO_2 kg/U***	***NO_x kg/U***	***PM kg/U***	***CO_2 kg/U***
LTP	FGD (wet limestone)	Ton	1.354	-	-	1,654
	LNB	Ton	-	3.045	-	
BTP	FGD (sea water)	Ton	4.316	-	-	-
	LNB	Ton	-	3.276	-	-
NTP	LNB	MMscf	-	-	-	-
NCC	No control	MMscf	4.267	676.40	4.526	53,918
	Water Injection	MMscf		214.32		
	DLN	MMscf		95.43		

Table 5. Site-specific emission factors (mass per energy input)

Power Plant	***Emission Control***	***Unit: U***	***SO_2 g/U***	***NO_x g/U***	***PM g/U***	***CO_2 kg/U***
LTP	FGD (wet limestone)	GJ	116.54	-	-	141.93
	LNB	GJ	-	263.09	-	
BTP	FGD (sea water)	GJ	172.02	-	-	-
	LNB	GJ	-	130.54	-	-
NTP	LNB	GJ	-	-	-	-
NCC	No control	GJ	4.224	714.42	4.417	61.42
	Water Injection	GJ		243.61		
	DLN	GJ		25.21		

3.2. Site-specific emission factors

Site-specific emission factors developed in this research can be summarized as shown in the Table 3, 4, and 5 based on three main measurement units including: mass per electricity output, mass per fuel consumption, and mass per energy input, respectively. For coal power plants (LTP and BTP), SO_2 emission factor of BTP is higher than that of LTP. This is somewhat surprising at the first glance as the factor from BTP should theoretically be lower due to lower sulfur content in bituminous coal (0.27 – 0.70 percent by weight) than in lignite coal (0.94 – 4.00 percent by weight). This phenomenon can be explained by (1) different in pollution control system installed in the plants and (2) the large gap between capacity and amount of electricity generation. Both LTP and BTP used the same post combustion control technology to reduce SO_2 emission (flue gas desulfurization, FGD) but with different absorbents. The LTP use lime or calcium carbonate ($CaCO_3$) while BTP use alkalinity in seawater as absorbent. Lime has higher absorption capacity (98% efficiency) than seawater (90% efficiency), which leads to lower SO_2 emission factor of LTP. However, in the term of total SO_2 emission, LTP contributes higher annual SO_2 emission than that of BTP (Tables 1 and 2). It should be noted that LTP has 62% more installed capacity than that of BTP and produces 70% electricity more than BTP.

Emission factors of SO_2 from natural gas power plants (NTP and NCC) are slightly different. A key observation in this aspect is that SO_2 emission factors per electricity output from NTP and NCC are much lower than that of BTP and LTP. This is because natural gas has very low sulfur content at approximately 0.01 percent by volume (DEDE, 2010) compared to that in coal. As shown in Tables 3 and 6, the emission factors of NCC group can be divided into two sub-groups including single shaft and multiple shafts. The only difference between these two sub-groups is their electricity generation efficiency which results in different emission factors for both SO_2 and NO_x. In summary, the variations of emission factors between coal and natural gas power plants, are mostly driven by differences in fuel composition, pollution control technology and electricity generation efficiency.

Emission factors developed in this study reflect, in part, the environmental efficiency of controlling equipment/system utilized in the power plants. NO_x emission factors of NCC group were developed based on three different control technologies including: (1) no control, (2) water injection, and (3) dry low-NO_x burner (DLN). Based on the analysis, emission factors of the no-control group and water injection control technology group are higher than that of the DLN. This is because the treatment efficiency of water injection is approximately 66-68%, which is much lower than the efficiency of DLN technology (approximately 84-96%). The estimated pollution control efficiency confirms that the plants with DLN technology have higher pollution control efficiency than that of water injection technology.

Before an emission factor can be used to estimate emission from new emission sources, users should understand its limitations, technologies utilized in the interested power plant, available dataset, etc. Type of emission source, design criteria, pollution control device, raw material and fuel of the power plant of interest should be similar to the underlining assumptions and conditions of the reference sources in order for the emission factors to be applicable. Users should also choose the most relevant and the most up-to-date emission factor for their applications.

3.3. Comparison of emission factors

Table 6 presents a summary and comparison of emission factors developed in this research and those reported from available publications or well-known sources, such as from the European Environmental Agency (EEA, 2009), Intergovernmental Panel on Climate Change (IPCC, 2006), the United States Environmental Protection Agency (USEPA, 1995) and the World Health Organization (WHO, 1993). Information in Table 6 was organized based on power plant group, technology, and unit of emission factor. As shown in the table, emission factors obtained from this study are comparable to that of the studies done by other researchers and international organizations for many parameters. Some parameters, however, are slightly different from that of the other sources. This difference is expected because this study utilizes local-specific data sources in the development of the factor.

For the LTP, the results are comparable to that of other domestic studies for all pollutants with no significant variation observed. The similarity can also be seen when comparing the results with that of international studies. For example; the NO_x emission factor of LTP as developed from this study is 3.045 kg/ton, which is within the range of 2.087 – 3.084 kg/ton (USEPA, 1995). The NO_x emission factor of LTP is 263 g/GJ which is well within the range of 143 – 571 g/GJ as reported by EEA (2009).

For the BTP, SO_2 emission factor is 4.316 kg/ton, which is within an upper range of 1.17 – 5.07 kg/ton as reported by the WHO in its 1993 publication. The SO_2 emission factor, however, is lower than the value suggested by the USEPA (1995) (10.3 – 44.8 kg/ton). This variation may be caused by different sulfur content of the fuel utilized in Thailand and in the US. Bituminous coal in Thailand has sulfur content approximately 0.27 – 0.70 percent by weight while those in the United States have a much higher sulfur content at approximately 0.6 – 2.6 percent by weight. This difference is the major contribution to the difference in the observed SO_2 emission. The NO_x emission factor of BTP is comparable to those reported by other researches (EEA, 2009; USEPA, 1995; WHO, 1993). For the NTP, NO_x emission factor in Thailand is 0.149 g/kWh, which is lower than that in Iran (2.694 ± 0.038 g/kW) as documented by Nazari et al. (2010).

For the NCC, NO_x emission factor is 95.5 – 676.4 kg/MMscf which, while a broad range, is comparable to the 177.4 kg/MMscf as reported by the WHO in 1993. This NO_x emission is, however, higher than the values documented by the USEPA (1995) (14.3 – 57.2 kg/MMscf). In addition, the SO_2 emission factor from the USEPA publication (1995) is 0.272 kg/MMscf which is comparable to 0.257 kg/MMscf as reported by the WHO (1993) but lower than the result found in the research (4.267 kg/MMscf). This variation may be caused by many factors including the differences in generation efficiency, pollution control technology, fuel quality, combustion configuration, age of power plant, emission standard, etc.

There are several reasons that can explain the differences in reported emission factors among various sources. The SO_2 emission factor of LTP as reported by the USEPA (1995) is much greater than that of the WHO (1993) and from this study. This may be due to the difference in pollution control devices and sulfur content in the base fuel utilized in the power plants. The difference in fuel's sulfur content is a major contributing factor. A typical sulfur content of lignite used in LTP in Thailand is in the range of 0.94 to 4.00 percent by weight, which is much higher than the sulphur content as reported in the USEPA's publication (0.8 to 1.1 percent by weight). Similarly, the SO_2 emission factor of NCC in Thailand is higher than that reported by the WHO and USEPA. Typical sulfur content of natural gas used in Thailand's NCC is approximately 0.01 percent by volume (DEDE, 2010), which is much higher than that reported by the WHO (0.000615 percent by volume). Furthermore, the emission factor of LTP as published by the USEPA was from power plants that do not have SO_2 pollution control device while the power plants in the WHO's study had installed flue gas desulfurization (FGD). This has significant impact and causes the SO_2 emission factor from the USEPA to be higher than that of WHO and the factor obtained in this research. The rest of SO_2 parameters are within a comparable range with the results from other reputable sources.

Other parameters (PM and CO_2) are within a close range to the results observed by other researches in all three units and power plant groups (LTP, BTP, NTP and NCC). There are many reasons as to why there are small variations between the results from domestic and international researches. The main reason is because emission intensity are affected by many factors such as fuel properties, pollution control technologies, combustion process configuration, power plant loading, and etc. All these factors can vary significantly between the domestic and international samples. For instance, the international emission factors like those reported by the WHO or IPCC are average values from sources in their sample space which can scatter over vast geographic locations. Some emission factors were developed based on data from specific regions like those reported by the USEPA for the United States or the EEA for the European Union.

In summary, the emission factors developed in this research are within the range reported by other reputable publications. This comparison helps increase confidence of the applicability and accuracy of the developed emission factors especially for Thailand domestic applications. Site-specific emission factors from domestic study should be used when they are available before applying emission factors from international sources because the factors based on site-specific or domestic dataset are typically more applicable and can provide higher accuracy in an evaluation of total emission. It should be noted that the emission factors in this study were evaluated from a one-year dataset. These emission factors should be consistently and continuously updated when new emission dataset from CEMs becomes available in the future.

3.4. Abatement cost of SO_2 and NO_x from fossil fuel power plant in Thailand

3.4.1. Abatement cost of SO_2

Table 7 summarizes the results of SO_2 abatement costs obtained from this study. The costs range between 1.00-6.97 Baht/Kg-SO_2 (0.03-0.26 US$/Kg-$SO_2$) or 46-130 Million Baht per annum (1.54-4.36 MUS$/year) for the power plants in the case studies. These costs depend on the amount of SO_2 treated per year and pollution control system used in the power plants. Abatement cost per unit of SO_2 reduction can be categorized into 2 groups based on control technology including: (1) Flue Gas Desulfurization (FGD) with wet lime and (2) FGD with sea water. Abatement cost of FGD with wet lime is approximately 1.00 – 1.20 Baht/Kg-SO_2 while that of FGD with sea water is higher at approximately 6.97 – 7.87 Baht/Kg-SO_2. The amount of treated SO_2 depends significantly on type of control technology. In these cases studies, FGD with sea water can treat SO_2 approximately 5,834-6,585 ton/year (1.1-1.2 ton/year/kWh) while FGD with wet lime can treat SO_2 at a much higher level at approximately 90,638 – 130,033 ton/year (39-58 ton/year/kWh) despite higher electricity generation in the CP-1 and CP-2. The FGD with wet lime, evidently, is a more efficient and cost-effective SO_2 control technology. Other factors, however, must be considered when adopting control technology such as management of wastes produced from the treatment of SO_2.

3.4.2. Abatement cost of NO_x

The NO_x abatement costs range between 9.19 - 287.25 Baht/kg-NO_x (0.31 - 9.63 US$/kg-$NO_x$) or 34 – 493 Million Baht per year for the cases studies in this research as shown in the Table 8. Similar to the abatement costs of SO_2, the abatement costs of NO_x depend on pollution control system used in the power plants and amount of treated NO_x. The abatement cost per unit of treated NO_x can be categorized into 2 groups including: (1) Dry Low-NO_x Burner and (2) Fuel Ratio Control. Dry Low-NO_x Burner abatement cost is approximately 9.19 – 22.52 Baht/Kg-NO_x which is lower than that of Fuel Ratio Control (221 – 287 Baht/Kg-NO_x). Dry Low-NO_x Burner can treat approximately 2,021 – 4,969 ton/year of NO_x (0.7 – 1.7 ton/year/kWh) whereas using Fuel Ratio Control can reduce NO_x approximately by 1,702 – 1,742 ton/year (0.5 - 0.7 ton/year/kWh). Based on the results, it is clear that the Dry Low-NO_x Burner is a more efficient and cost-effective system in controlling NO_x than the Fuel Ratio Control process.

3.4.3. Comparison with other researches

The SO_2 abatement costs observed in this research is comparable with those reported by international publications. The NO_x abatement cost, however, has a wider range.

Table 6. Emission factors from this research and other published sources

Power Plant	*Source Characteristic*	*Emission Factor*				*Unit*	*References*
		SO_2	*NO_x*	*PM*	*CO_2*		
LTP	Pulverized Coal, FGD, ESP (Thailand)	1.191	2.661	-	1,443	g/kWh	This research
	Pulverized Coal, FGD, ESP (Thailand)	1.333	2.504	-	1,067	g/kWh	Krittayakasem et al. (2004)
	Pulverized Coal, FGD, ESP (Thailand)	1.260	2.830	0.090	1,080	g/kWh	Krittayakasem et al. (2011)
	Pulverized Coal, FGD, LNB	1.354	3.045	-	1,654	kg/ton	This research
	Pulverized Coal, FGD	1.20 -1.65 (1.5 S [a])	6.000	0.273 – 0.296 (0.031 A [b])	-	kg/ton	WHO (1993)
	Pulverized Coal, LNB	56.2	2.087 - 3.084	-	1,487 (32.93 C) [c]	kg/ton	AP-42, USEPA (1995)
	Pulverized Coal, FGD, LNB	116.54	263.09	-	141,930	g/GJ	This research
	Pulverized Coal, FGD, ESP (Thailand)	120	260	10.24	101,300	g/GJ	Krittayakasem et al. (2011)
	Dry bottom boilers	330 - 5000	143 – 571	20 - 80	-	g/GJ	EEA (2009)
	Stationary Combustion	-	-	-	91,000 - 115,000	g/GJ	IPCC (2006)
BTP	Pulverized Coal, FGD, LNB	4.316	3.276	-	-	kg/ton	This research
	Pulverized Coal, FGD	1.17 - 5.07 (1.95 S [a])	10.50	0.145 – 0.455 (0.05 A [b])	-	kg/ton	WHO (1993)
	Pulverized Coal, FGD, LNB	10.3 - 44.8 (17.24 S) [a]	4.40 - 4.99	0.157 - 0.728 (0.054A-0.08A) [b]	-	kg/ton	AP-42, USEPA (1995)
	Pulverized Coal, FGD, LNB	172.02	130.54	-	-	g/GJ	This research
	Dry bottom boilers	330 - 5000	200 – 350	3 - 300	-	g/GJ	EEA (2009)
	Stationary Combustion	-	-	-	90,000 - 100,000	g/GJ	IPCC (2006)
NTP	Thermal power plant (Thailand)	0.022	0.149	-	-	g/kWh	This research
	Thermal power plant (Iran)	-	2.694 ± 0.038	-	633 ± 10	g/kWh	Nazari et al. (2010)
NCC	Combined cycle power plant (Thailand)	0.034	0.824 - 5.229	0.031	452	g/kWh	This research
	Combined cycle power plant (Thailand)	-	0.850 - 1.100	0.034	451.64	g/kWh	Krittayakasem et al. (2011)
	Combined cycle power plant (Iran)	-	2.295 ± 0.033	-	450 ± 7	g/kWh	Nazari et al. (2010)
	Stationary Gas Turbines	4.267	95.43 - 676.40	4.526	53,918	kg/MMscf	This research
	Stationary Gas Turbines	0.257 (15.6 S [a]) [d]	177.4	6.001	-	kg/MMscf	WHO (1993)
	Stationary Gas Turbines	0.272	14.3 - 57.2	3.054	53,524	kg/MMscf	AP-42, USEPA (1995)
	Stationary Gas Turbines	4.224	25.21 – 714.42	4.417	61,420	g/GJ	This research
	Combined cycle power plant (Thailand)	-	110 – 120	4.11	54,790	g/GJ	Krittayakasem et al. (2011)
	Stationary Gas Turbines	4.044	43 – 138	2.839	47,000	g/GJ	AP-42, USEPA (1995)
	Gas Turbines	0.169 - 0.393	92 – 245	0.454 - 1.820	-	g/GJ	EEA (2009)
	Stationary Combustion	-	-	-	54,000 - 58,000	g/GJ	IPCC (2006)

[a] *"S" is the weight percent of Sulfur in the fuel. Typical Sulfur content for lignite is 0.8-1.1%; bituminous are 0.6-2.6%; natural gas are 0.000615%*
[b] *"A" is the weight percent of Ash in the solid fuel. Typical Ash content for lignite is 8.8-9.5%; bituminous are 2.9-9.1%*
[c] *"C" is the weight percent of Carbon is solid fuel. Typical Carbon content for lignite is 45.16%*
[d] *Value in unit of kg/m^3*

Table 7. SO_2 abatement cost of fossil fuel power plants in Thailand

Power Plant	*Pollution Control System*	*Electricity (MWh)*	*Treated SO_2 (ton/year)*	*Abatement Cost*	
				MBaht/year (MUS$/year)[a]	*Baht/kg-SO_2 (US$/ kg-$SO_2$)*[a]
CP-1	FGD (sea water)	5,385,635	6,585	45.91 (1.54)	6.97 (0.23)
CP-2	FGD (sea water)	5,147,121	5,834	45.91 (1.54)	7.87 (0.26)
CP-3	FGD (wet lime)	2,104,123	120,135	126.86 (4.25)	1.06 (0.04)
CP-4	FGD (wet lime)	2,245,422	130,033	130.01 (4.36)	1.00 (0.03)
CP-5	FGD (wet lime)	2,148,626	92,542	111.00 (3.72)	1.20 (0.04)
CP-6	FGD (wet lime)	2,345,234	98,767	108.01 (3.62)	1.09 (0.04)
CP-7	FGD (wet lime)	2,465,768	98,437	103.35 (3.46)	1.05 (0.04)
CP-8	FGD (wet lime)	2,482,390	102,250	104.26 (3.50)	1.02 (0.03)
CP-9	FGD (wet lime)	2,145,544	90,638	92.67 (3.11)	1.02 (0.03)
CP-10	FGD (wet lime)	1,964,246	92,244	92.93 (3.12)	1.01 (0.03)

[a] *Exchange rate* 1 *US. Dollar:* 29.83 *Baht*

Table 8. NO_x abatement cost of fossil fuel power plants in Thailand

Power Plant	*Pollution Control System*	*Electricity (MWh)*	*Treated NO_x (ton/year)*	*Abatement Cost*	
				MBaht/year (MUS$/year)[1]	*Baht/Kg.-NO_x (US$/ Kg.-$NO_x$)*[1]
NGC-1	Dry Low-NOx Burner	4,155,095	3,955	70.22 (2.35)	17.75 (0.60)
NGC-2	Dry Low-NOx Burner	4,259,443	4,185	69.34 (2.32)	16.57 (0.56)
NGC-5	Dry Low-NOx Burner	4,794,712	4,443	68.23 (2.29)	15.36 (0.51)
NGC-6	Dry Low-NOx Burner	5,265,071	4,475	68.28 (2.29)	15.26 (0.51)
NGC-7	Dry Low-NOx Burner	4,358,070	4,969	89.67 (3.01)	18.05 (0.61)
NGC-8	Dry Low-NOx Burner	2,173,244	3,692	33.91 (1.14)	9.19 (0.31)
NGC-9	Dry Low-NOx Burner	2,653,736	3,564	33.91 (1.14)	9.52 (0.32)
NGC-10	Dry Low-NOx Burner	2,856,568	2,021	45.52 (1.53)	22.52 (0.75)
NGT-4	Fuel ratio control	2,553,830	1,702	463.96 (15.55)	272.59 (9.14)
NGT-5	Fuel ratio control	2,360,700	1,742	384.61 (12.89)	220.78 (7.40)
NGT-6	Fuel ratio control	3,393,420	1,717	493.25 (16.54)	287.25 (9.63)

[a] *Exchange rate* 1 *US. Dollar:* 29.83 *Baht*

Table 9. Comparison of emission abatement cost from power plants in various locations

References	*Year*	*Type (Location)*	*Cost (Baht/Kg.-SO_2)*
This research	2010	Coal power plants (Thailand)	1.00 - 7.87
Kwon and Yun	1990-1995	Coal power plants (Korea)	8.6 [a]
Coggins and Swinton	1990-1992	Coal-burning utilities (Wisconsin)	5.24 - 9.75 [b]
Gollop and Roberts	1973-1979	Fossil-fueled electric generation (US)	4.21 - 36.57 [b]
Islas and Grande	2000	Electric power sector (Mexico)	6.71 - 9.37 [b]
References	*Year*	*Type (Location)*	*Cost (Baht/Kg.-NO_x)*
This research	2010	Natural gas power plants (Thailand)	9.19 – 287.25
Kwon and Yun	1990-1995	Coal power plants (Korea)	4.06 [a]
USEPA	2009	CUECost model	7.46 - 67.12 [b]

[a] *Exchange rate 1 Won: 0.73 Baht*
[b] *Exchange rate 1 US Dollar: 29.83 Baht*

This difference may due to (1) difference in evaluation methodology (this research used engineering-cost approach but the others used mathematical model, econometric method, or microeconomic theory-based method), (2) period of evaluation and economic conditions, and (3) difference in pollution control technology.

4. Conclusions

The emission factors of fossil fuel power plants in this study were developed according to power plant type, fuel and pollution control device utilized in the power plants. The emission factors can be summarized as follow: 0.022 – 1.432 g-SO_2/kWh for SO_2, 0.122 – 5.229 g-NO_x/kWh for NO_x, 0.031 g-PM/kWh for PM, and 452 – 1,443 g-CO_2/kWh for CO_2. Abatement costs for SO_2 are approximately 0.03 - 0.26 US$/Kg-$SO_2$ while abatement costs of NO_x range between 0.31 and 9.63 US$/kg-$NO_x$.

The emission factors and abatement costs of fossil fuel power plants obtained from this research become important basis for estimation of air pollution level and control performance from the power plants in various settings and operating conditions. The results can be used as benchmarks for improving efficiency of air pollution management system of power sector in Thailand and other countries that utilized power plants with similar underlying technology and conditions.

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