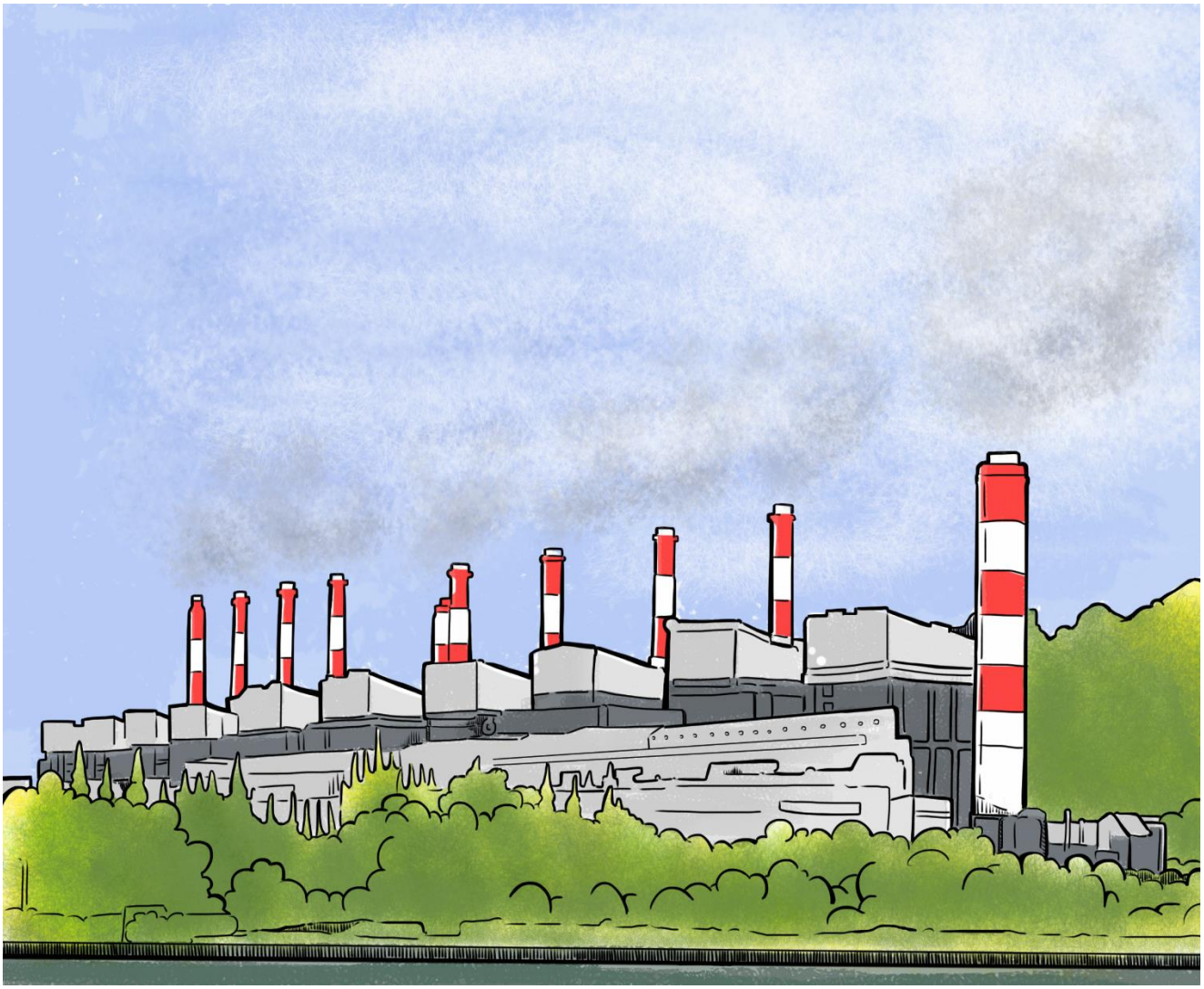
Final Report

Reducing Mercury Emission from Coal Combustion in the Energy Sector in Thailand



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Reducing Mercury Emission from Coal Combustion in the Energy Sector in Thailand

A UN Environment Report

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Acronyms &Abbreviations

AAQMS	Ambient Air Quality Monitoring System
ACI	Activated carbon
AEDP	Alternative Energy Development Plan
APCDs	Air pollution control devices
AQNIS	Air Quality and Noise Management Bureau
ASTM	American Society for Testing and Materials
ASTMD	Standard Practices for Collection of Channel Samples of Coal in a Mine
BAT	Best Available Techniques
BIG/GT	Biomass integrated gasification /gas turbines
BEP	Best Environmental Practices
CCV	Continuing Calibration Verification
CEMS	Continuous emission monitoring system
CHP	Combined heat and power plants
CS-ESP	Cold-side ESP
DIW	Department of Industrial Works
GDP	Gross domestic product
Gwh	Gigawatt hours
DQI	Data quality indicators
EF	Emission factor
EGAT	Electricity Generating Authority of Thailand
EPPO	Energy Policy and Planning Office
ERC	Energy Regulatory Commission
ESP	Electrostatic precipitator
FF	Ffabric filter
Hg	Mercury
HI	Halogen injection
ICV	Initial calibration verification standard

Acronyms &Abbreviations

IEA	International Energy Agency
INC	Intergovernmental negotiating committee
IPPs	Independent power producers
LFB	Laboratory Fortified Blank
LFM	Laboratory Fortified Matrix
LNB	Low NOx burner
MW	Megawatt
OFA	Over fired air
PC	Pulverized coal boiler
PCD	Pollution Control Department
POG	Process Optimization Guidance
QA/QC	Quality assurance and quality control
RCM	Certified reference materials
SCR	Selective catalytic reduction
SPPs	Small power producers
SSCV	Second source calibration verification standard
SW-FGD	Seawater flue gas desulfurization
VSPPs	Very Small Power Producers
W-FGD	Wet flue gas desulfurization

Executive Summary

Mercury (Hg) emission from anthropogenic sources is a global environmental pollution problem and a global threat to human health. The United Nations Environment Programme (UNEP) estimates that coal combustion contributes about 24% of global anthropogenic Hg emissions, and coal-fired power plants are thought to be the largest mercury emission source in the world. On an individual country basis, the largest emitters from this category are China, India, and the United States of America. Meanwhile, the Arctic Council has found that within the eight Arctic countries, the Russian Federation (Russia) and the U.S. contribute the bulk of Hg emissions from power plants. According to the recent global inventory, about 65% of emission came from stationary fuel combustion in 2000. Geographically, Asia accounts for about 54% of the emission, and China is the largest Hg emitting country.

As reported by the Energy Policy and Planning office (EPPO) of Thailand in 2016, around 64% of coal and lignite consumption was for electricity generation. Most of domestic lignite (97%) was used in electricity generation, whereas only 35% of imported coal was fed into independent power producers (IPPs) and small power producers (SPPs). Currently, there are 23 coal-fired power plants in Thailand. These plants were equipped with various types of the co-benefit air pollution control devices (APCDs) (i.e., electrostatic precipitator (ESP), wet flue gas desulfurization (W-FGD), seawater flue gas desulfurization (SW-FGD). At present, either the mercury inventory or the mercury emission standard has not been comprehensively established. Although, in 2010, emission standards for new power plants and existing power plants were announced by the Ministry of Natural Resources and Environment under the authority of the Enhancement and Conservation of National Environmental Act, B.E. 2535 (1992), these standards only impose limits on the quantity and concentrations of sulfur dioxide, nitrogen oxides (as nitrogen dioxide) and particulate matter.

Methodology

As a part of the project supported by The UN environment and the PCD (Pollution Control Department, Thailand), *"Reducing mercury emissions from coal combustion in the energy sector"*, this study, focusing on emissions of mercury from coal combustion so as to generate electricity, is a contribution to international efforts to reduce mercury pollution. It aims to establish mercury emission factor and then to estimate future trend emission of mercury from a coal-fired power plant sector in Thailand. The expected outcomes include the action plan on reducing mercury emission from coal combustion and capacity building for stakeholders.

In this study, the sampling protocol was conducted from May to June, 2017. There were two steps of sample collection, one is for coal samples from coal stockpiles; and another is for feed coal, combustion products and untreated flue gas at each electricity generation unit. For step 1, fifty coal and lignite samples were collected from 10 coal stockpiles of the four coal-fired power plants in three provinces. Of these samples, about 10 samples were lignite and 40 samples were bituminous. For mercury measurement during combustion process, feed coal, combustion products and untreated flue gas were obtained from two selected coal-fired power plants as a representative for bituminous (named Plant 1) and lignite (named Plant 2 with three operation units, which are Unit 6,10 and 13) power plants, respectively. At each power plant, five sampling cycles were repeatedly conducted for five consecutive days. Thus, the sample size for each sample type is five (i.e. 5 feed coal samples, 5 fly ash-samples). Of each sampling cycle, feed coal, combustion products and untreated flue gases were collected and analyzed following the Standard Practices for Collection of Channel Samples of Coal in a Mine (ASTMD series). All analysis methods and procedures complied with the project quality assurance and quality control (QA/QC) criteria.

The mercury mass balance, emission factors and future trend of mercury emissions from coal-fired power plants were then calculated. Recommendations for options on possible control measures for reducing mercury emissions from the coal-fired power sector were

proposed and presented in the workshop, which was held on 7th November 2017 at Thammasat University, Thailand. In the workshop, Process Optimization Guidance (POG) and Best Available Techniques (BAT)/Best Environmental Practices (BEP) were also addressed by Dr. Wojciech Jozewicz and Lesley Sloss, respectively. In addition, the research team openly shared and discussed with participants to obtain the opinions and suggestions on the project. Finally, the draft action plan on reducing mercury emission from coal-fired power plants was anticipated.

Results of the project

1. Coal characteristics

Bituminous had higher carbon and fixed carbon content, but lower content of sulfur, chlorine, mercury and arsenic than lignite. Both bituminous and lignite had very low concentrations of bromine.

2. Mercury concentrations and speciation in samples from coal combustion process

At combustion process, bituminous feed coal contained mercury content less than lignite around 50%. Mercury content in fly ash was found to be higher than that in bottom ash, except for the Plant 2/Unit 10. The oxidized mercury form (Hg^{2+}) was most likely bound to gypsum slurry with concentration about 140.69 ± 8.79-168.92±38.92 µg/kg. However, it was found in SW-FGD with very low concentration (0.09±0.02 µg/kg). The flue gases at stack of the Plant 1 contained all three forms with a similar portion about 32-36%, whereas in the Plant 2, the flue gases contained a significant quantity of Hg^0 over other two forms, possessing 67-81% of the total mercury. It is to note that actually, approximate Hg speciation could be estimated from samples directly measured as three forms (Hg^0, Hg^{2+} and Hg_p); however, in this study its speciation was assumed from the Hg behavior in flue gas at downstream of APCDs.

3. Mercury mass balance

The Hg mass balances across the entire combustion process and across each of the air pollution control devices were calculated in accordance with the Hg mass flow rates entering and leaving the plants. The overall Hg balance for each plant was around 38.6%

for the Plant 1, 82.2% for the Plant 2/Unit 6, 109% for Plant 2/Unit 10, and 64.8% for Plant 2/Unit 13. Only the result of the Plant 2 was within the acceptable error range of ±30 as proposed in Takahisa et al. (2000) and Yu et al. (2014).

4. **Future mercury emission estimates from coal-fired power plants in Thailand: Scenarios of estimation for 2025**

To generate the most likely estimation of future trend of mercury emission, two approaches were applied, which were (1) using the measured data from this study and (2) using the existing Hg removal efficiency of relevant APCDs in literatures.

- In approach 1, the calculation was based on the emission factors, which were considered by two scenarios. Scenario 1 assumed that the mercury mass balance was within the acceptable error range. Therefore, the Hg emission factors were estimated from the direct stack emissions of mercury (actual concentrations). Scenario 2 assumed that the uncaptured fractions of a combustion process were thought to be the emission. Therefore, Hg emission factors were estimated from the uncaptured emissions.
- In approach 2, the calculation was based on the existing Hg removal efficiency of relevant APCDs in literatures. The selected Hg removal efficiencies were relevant to the APCDs installed in 23 existing coal fired power plants in Thailand. Then the mercury removal efficiencies for the pulverized coal in boiler (PC), selective catalytic reduction (SCR), cold-side ESP (CS-ESP), and SW-FGD were assumingly used to estimate the mercury emission for these 23 plants and other new expected power plants in future. Due to lack of information about the types of APCD installed in small and new expected coal-fired power plants, we assumed that these plants will operate without APCDs (as uncontrolled system).

For the approach 1, it was found that emission factors of Hg from the scenario 2 were higher than that from scenario 1. In addition, no matter what scenario applied, the Plant 2 emitted higher Hg concentrations than the Plant 1. In associated with scenarios, the emission factors of Hg for the Plant 1 were 8.59$\pm$4.86 and 44.31$\pm$11.40 mg per ton coal

(mg/t), respectively. Likewise, for the Plant 2, the emission factors of Hg were 69.67±30.07 and 85.76±9.91 mg/t, respectively. Considering the future mercury emissions, in both scenarios, the plant 2 showed higher emission rate than that estimated for the plant 1.

When using the existing mercury removal efficiencies of the co-benefit APCDs to predict the future trend of mercury emission from 23 existing and new expected power plants from 2017 to 2025, a lignite power plant still plays the significant source of Hg emission. However, by 2025 the total Hg emission is expected to decrease and collectively the Hg emission from a lignite power plant will be reduced around 66 %. On the other hand, it is expected that Hg emission from bituminous power plants may slightly increase after 2020. Apparently, the new expected bituminous power plants will be the significant source of increasing mercury emission, whereas the emissions from the existing bituminous power plants remain steadily. It is to note that the estimation for new power plants, which are not yet developed, was based on the worst-case assumption that these plants would be operated without APCDs. The most important factors affecting mercury emissions are the mercury content of coal and the mercury removal efficiency of APCDs (air pollutant control devices).

5. Recommendation

The recommendations are proposed as follows:

1) Mercury emission inventory must be applied in both the existing and expected new power plants; and must be regularly performed and reviewed. It is therefore the emission factors appropriated for Thailand will be established;
2) promoting technology capacity building and research on the efficiency of power plants and APCDs relevant to the system installed in Thailand;
3) applying Best Available Techniques/Best Environmental Practices (BAT/BEP) for all industries using coal and lignite as fuels. The implementation should consider these conditions as follows:
    - The actions include full range of options of BAT/BEP, where feasible and applicable, to control the emission;

- The performance and effectiveness of selective control technique options are taken into account in order to ensure the high level of protection of human health and the environment as a whole;
- Furthermore, cost and benefits of each control technique option need to be assessed. The need should also be taken into account for sound maintenance and operational control of the techniques, so as to maintain the achieved performance over time.

4) establishing the emission standard imposed limits on the concentration of mercury emitted from coal-fired power plant;
5) supporting a capacity building program for researchers, technicians and national coordinators of the mercury inventory and monitoring.

Recognizing the need to allow both the existing and expected new coal-fired power plants sufficient time to test, plan, and implement actions, including technology optimization as well as the control policies, the action plan is necessary and should be implemented in phases. Proposed action plan for reducing mercury emission from coal-fired power plant is presented in table below:

Action plan for reducing mercury emission from coal-fired power plants

Task	Action	Time-frame	Responsible/Involvement*
1	Capacity building programs of mercury emission inventory	1 years	PCD
2	Mercury emission inventory	2-3 years	PCD, EPPO,DIW, ERC and power plants
3	Capacity building programs of mercury monitoring	5 years	PCD,EPPO,DIW,ERC and power plants
4	Review of law and regulation at national and international levels	1 year	PCD, DIW,ERC
5	Establishment of Hg emission standard applied for power plants in Thailand	5 years	PCD,EPPO,DIW,ERC and power plants

Action plan for reducing mercury emission from coal-fired power plants

Task	Action	Time-frame	Responsible/Involvement*
6	Implementation of BAT/BEP, which are appropriated for power plants in Thailand	5 years	PCD,EPPO,DIW,ERC and power plants

PCD: Pollution Control Department; EPPO: Energy Policy and Planning Office, Ministry of Energy; DIW: Department of Industrial Works, Ministry of Industry; ERC: Energy Regulatory Commission; BAT/BEP: Best available techniques /Best environmental practices.

*These organizations/departments are expected to be a focal point or to involve with each action plan. However, in future, they can be changed according to appropriate situation.

6. Outcome of the workshop for capacity building

The participants proposed suggestions and recommendations as follows:

6.1) Participants made some questions and concerns related to the methodology and results of this project. The key issues can be summarized as follows:

- Information from this project is little comparing to the whole situation of mercury emission from coal-fired power plants in Thailand due to uncertainties and limitations (see section 5.6 and 5.7). It is necessary to be careful about what may be disseminated to public;
- Development of mercury emission factor which was based on the mass balance and limitation;
- Uncertainty of scenarios for estimating mercury emission, which involved projected coal consumption, emission factor and removal efficiency of co-benefit APCDs;
- Impact of this project on the decision-making about the mercury emission standard in Thailand

6.2) Participants proposed their opinions and recommendations related to the reduction of mercury emission and establishment of mercury emission standard as follows:

- Government should organize the roadmap for reducing mercury emission from coal fired-power plants in Thailand;

- Cost-benefit analysis should be taken into consideration for selecting the dedicated APCDs for removing mercury;
- It is necessary to expand this study to more coal-fired power plants. Further study for other types of power plants that also contribute mercury emitted to environment is needed;
- Mercury emission factor should be set specific to situation in Thailand rather than that uses in other countries;
- If the mass balance method would be recommended for establishing emission factor, sample size and collection period should cover the full range of processes in order to ensure the result with statistical significance;
- The PCD (Pollution Control Department) should be the focal point for conducting the meeting to inform stakeholders about the policy, procedure and clear direction of how to follow the national plan.
- Other suggestions include:
    - controlling the mercury import;
    - totally assessing all sources of mercury emission

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1. Introduction

1.1. Background

Mercury occurs naturally in the earth's crust. It is released into the environment from volcanic activity, weathering of rocks and as a result of human activity. Human activity is the main cause of mercury releases, particularly artisanal and small-scale gold mining and coal combustion (all uses). Coal-fired power plants are one of the main sources of mercury emission to the environment. During combustion, the mercury in the coal is transformed into three species: particle-bound mercury (Hg_p), vapor-phase elemental mercury (Hg_0), and vapor-phase oxidized mercury (Hg^{2+}). Vapor-phase elemental mercury is extremely volatile and insoluble. Therefore, the conversion of mercury from one form to another is important for selecting the appropriate mercury removal technology (UNEP, 2017).

Mercury is a dangerous heavy metal to both humans and animals. Since it is an element, it cannot be degraded. It is highly toxic to the central nervous system and it has the ability to both bioaccumulation and bio-magnification in food webs. Living organisms readily take up mercury from their surroundings with levels generally increasing with each step up the food chain (Dabrowski, et. al., 2008).

There are many sources of natural and anthropogenic mercury emissions, but coal combustion is known to be the major anthropogenic source of mercury (Hg) emissions in many countries Hsi, et.al, 2010). Pirrone et al. (2010) suggested that summing up the contributions from anthropogenic sources, nearly 2320 Mg of mercury is released annually to the global atmosphere (31% GEb). The emissions still increase in Asia because of increased burning of coal and increased industrialization. Asia has the largest average emission inventory compared to the other continents in the world. Wu, et.al, (2015) summarized that the largest emissions occur from combustion of fossil fuels, mainly coal in utility, industrial, and residential boilers. As much as two-thirds of the total emission of ca. 2,190 ton of Hg came from combustion of fossil fuels. Asian countries contributed about 54 % (1,179 tons) to the global Hg emission from all anthropogenic sources worldwide in 2000. China contributes about 28 % to the global emissions of mercury, and

is followed by other four Asian countries including India, Japan, Kazakhstan, Korea Democratic Republic.

The Governing Council (GC) of the United Nations Environment Programme initiated a global assessment of mercury in 2001. The report was presented to the GC in 2003, and key findings of the Global Mercury Assessment were: (1) Mercury is present in various environmental media and food all over the world; (2) mercury is persistent, (3) undergoes long-range transport and cycles globally; and (4) Mercury is highly toxic and has caused adverse impacts on human health and the environment (UNEP 2003). The findings were acknowledged as sufficient evidence of adverse global impacts to warrant international action and the GC endorsed the need for global action in 2003. This GC decision resulted in formation of the UNEP Mercury Programme. At its twenty-fifth session, in 2009, the GC decided on a number of matters that would influence the future path of global work on mercury. It established an intergovernmental negotiating committee (INC) to develop the globally binding instrument to control emissions and releases of mercury.

The project entitled "Reducing mercury emissions from coal combustion in the energy sector" was conducted in China, India, Russia and South Africa. As part of this work, the Process Optimization Guidance (POG) Document was developed. This guidance addresses the process that can reduce mercury emissions from coal combustion, and improve mercury emission inventories and related information.

Reduction in mercury emissions from the coal combustion can be addressed by pre-combustion and/or post combustion techniques. The pre-combustion techniques include coal cleaning, coal blending, thermal treatment of coal. Senoir et, al. (2000) explained that the post-combustion region of the boiler is divided into three parts: (1) convective section to air heater (AH), (2) ESPs, and (3) flue gas desulfurization unit (FGD).Post combustion techniques involve the existing APCDs (Air pollution control devices) combinations, which are designed to capture conventional pollutants such as sulfur dioxides (SO_2), nitrogen oxides (NO_x) and particulate matters (PM). These APCDs can also remove mercury from flue gases in two ways: removal of Hgp in particulate control devices and

removal of Hg^{2+} in FGD scrubbers. Thus, the mercury removed from the flue gas may be found in fly ash and in the scrubber solids (gypsum for WFGD) or liquid effluent (sea water for SW-FGD). Dedicated mercury control technologies can be applied to plants to increase the efficiency of the existing APCDs combinations. The most widely applied mercury control technology at coal-fired power plants is additional chemical injection at various stages of the process, which is usually called co-benefit enhancement technologies (Ancora, 2015). Chemical injections include halogen (HI) and activated carbon (ACI), however, a better understanding of the oxidation of elemental mercury is needed; as well as ACI is still expensive for developing countries including Thailand.

With a view to reduce mercury emission from coal based power plants, the essential pre-requisite is to have a proper inventory structured data bank on the mercury content of the coals from the major sources. In Thailand, there are few studies focusing on mercury emissions from coal-fired power plants, which were estimated by using adopted mercury removal efficiencies from literatures (Thao and Garivait, 2012; EGAT, 2017). Mercury emission inventory has not yet systemically implemented. Although, in 2010, emission standards for new power plants and existing power plants were announced by the Ministry of Natural Resources and Environment under the authority of the Enhancement and Conservation of National Environmental Act, B.E. 2535 (1992), these standards impose limits on the quantity and concentrations of sulphur dioxide, nitrogen oxides (as nitrogen dioxide) and particulate matter (IEA, 2016).

Hence, with the support from the UN environment and the PCD (Pollution Control Department, Thailand), this study aims to conduct an inventory of mercury emissions from selected coal-fired power plants in Thailand as a case study. To the extent estimation of future mercury emissions, additional information on coal used; status of existing co-benefit APCDs and statistic profile of coal and lignite will be taken into consideration.

1.2 Objectives

1. Assessment of mercury content of coals fed to coal fired power plants; this includes in-country coals as well as imported coals;
2. Development of projections of coal consumption (2025);
3. Characterization of existing power plants with regard to capacity and air pollutants control technologies installed;
4. Direct measurements of the emissions of mercury from selected power plants based on their capacity, vintage, fuel types, emission control systems, including speciation of mercury in flue gas and partitioning of mercury in the combustion products; .
5. Estimation of the mercury emission factors based on the information gained during this project and comparison with relevant published emission factors.

1.3 Major tasks

The major tasks of this project are as follows;

Task 1: Coal information

1. Information will be collected on the amount of coal consumed, (for electricity production) by coal source; available information on coal analysis on dry basis (including Hg, As, Se, CI, Br, Ca, Na content);
2. Information will be collected or estimated on the coal consumption (projected coal use) for electricity generation for the target year 2025;
3. Analyses of untreated Thai coal samples following relevant International Accepted Standards. Coal sample analysis will include proximate and ultimate analyses, including determination of Hg, As, Se, CI, Br, Ca, Na content of coal;
4. Inter-calibration of Hg analysis will be carried out on 10 selected coal samples as a quality control of analysis results.

Task 2: Power plant information

1. Available national and provincial information will be collected on installed power plant capacity and electricity generation by coal combustion as of 2016, including the approximate locations of power plants;
2. Available national and provincial information will be collected on the installed configuration of any air-pollution control equipment and its typical operational efficiency;
3. Available national and provincial information will be collected on any available results of measurements of Hg emissions from coal-fired power plants;
4. Hg emission measurements at selected power plants. Direct Hg measurements in minimum three coal based power plants adopting standard procedures for solid and gaseous sampling according to international accredited methods (recommended flue gas measurement method: US EPA Method 30B utilizing US EPA Mercury Measurement Toolkit). However other international scientifically recognized methods can be used. The selection of at least three power plants for measurements will reflect the distribution of power plants by their size and age. The sample collection and analysis can be adjusted for the most benefit of the project upon the consultation between UN Environment Programme and Faculty of Public Health, Thammasat University.

Task 3: Mercury emission inventories and future estimates

1. Develop mercury emission factors based on data sets from selected power plants and the analysis of coals used in Thailand;
2. The emission inventories will be shared by a network of experts and stakeholders for comments;
3. Develop future mercury emission estimates (scenario for 2025).

Task 4: Report preparation

A fully referenced and reviewed technical report presenting results will be prepared for publication on UN Environment's website. Methods will be described in the report and raw data will be attached in annexes.

Task 5: Capacity building

1. Capacity building activities will be carried out to inform stakeholders about the goals, progress, and intended outcome of the project in the context of developing options to reduce mercury emissions and releases from coal-fired power plants in Thailand;
2. Capacity building activities may include, for example, visits to institutions participating in the program, production of informational materials, etc.;
3. An information seminar, including a workshop on the "Process Optimization Guidance for Reducing Mercury Emissions from Coal Combustion in Power Plants (POG)" and the INC guidance on Best Available Techniques and Best Environmental Practices (BAT/BEP) will be organized to disseminate information to relevant stakeholders (policymakers, administrative staff in the power plant sector);
4. Options on how to reduce mercury emissions and releases from the coal-fired power sector will be developed. The task will account for growth projections for coal consumption, installed capacity, and electricity generation. The task will discuss approaches that may be utilized to reduce future Hg emissions from the sector.

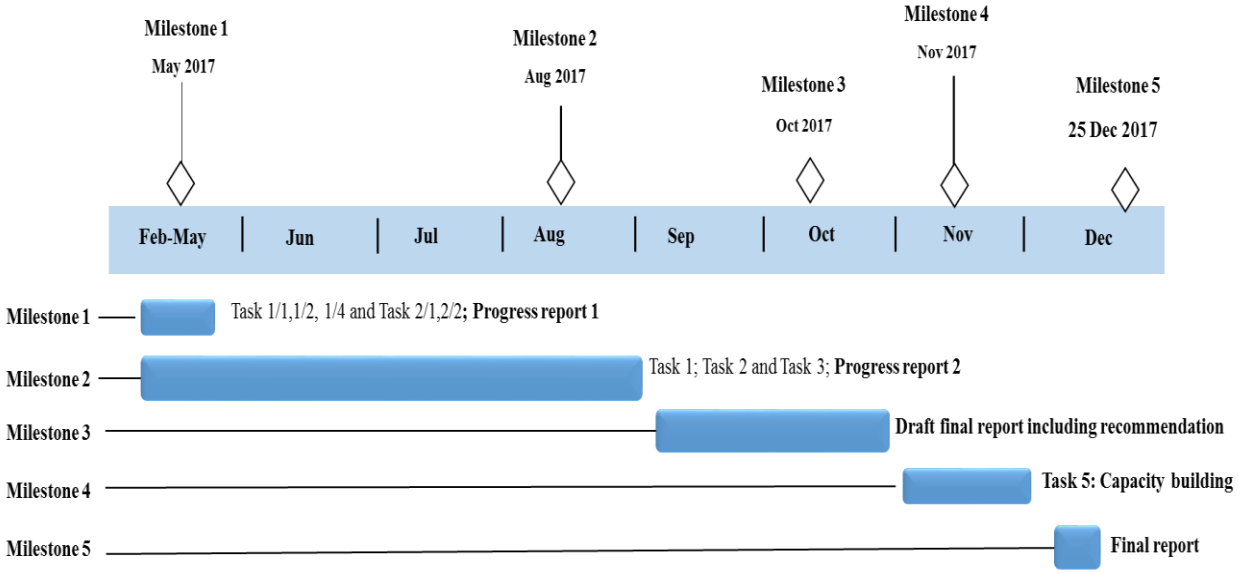
1.4 Deliverables

1. Improved basis for the quantification of current and projected mercury emissions from the coal-fired power plant section.
2. Inventory of mercury emissions from coal-fired power plants in Thailand and speciation of mercury in the flue gas at power plants from Task 2 above.

3. Mercury concentrations in other combustion products (fly ash and bottom ash) of the power plants from Task 2 above.
4. Updated information on the coal power sector, overview and characterization of power plants and projections of installed capacity and electricity production through 2025.
5. Quarterly progress reports including actions completed in the reporting period and actions planned for the following reporting period.
6. A fully referenced and reviewed technical report presenting results for publication on UN Environment's website.
7. Options to reduce mercury emissions and releases from the coal-fired power sector.
8. Information seminar for stakeholders to present the results of the project, including a training workshop on the POG and the BAT/BEP

1.5 Work plan

Project will be completed in Approximately 11 Months, from 22 February 2017 to 25 December 2017. The time frame of project is illustrated below:



2. Coal and lignite information

This part provides the coal information of Thailand such as the amount of coal consumption, electricity production by coal source, and available information on coal analysis. Actually, in Thailand the word coal and lignite are officially named for a power plant that uses anthracite, bituminous, or sub-bituminous as its fuel; and that uses lignite as its fuel, respectively. Thus, in this report, coal refers to bituminous, sub-bituminous and anthracite, excluding lignite.

2.1 Type of coal and its utilization in Thailand

The American Society for Testing and Materials (ASTM) categorizes coals by ranking in the natural series from lignite to anthracite. The method of ranking is based on levels of geological metamorphosis, fixed carbon, and calorific value. This method classified coal into four types: anthracite, bituminous, sub-bituminous, and lignite. Anthracite, the hardest coal with the highest energy, is classified in rank I, bituminous in rank II, sub-bituminous in rank III, and lignite, the lowest coal quality, in rank IV (Table 2.1).

Table 2. 1 *Classification of coal by rank, ASTM system*

Rank	Type of coal	Fixed Carbon (%)		Volatile Matter (%)		Energy (MJ/kg)
		Dry	*Moist*	*Dry*	*Moist*	*Moist*
I	Anthracite	> 98–86	> 92–81	< 2–14	< 2–15	35.5–31.4
II	Bituminous	86–54	81–45	14–57	13–40	35.8–24.4
III	Sub-bituminous	55–53	45-37	53–55	36–38	26.7–19.3
IV	Lignite	52	32–26	32–35	38–50	< 19.3

Sources: ASTM D388-15, Standard Classification of Coals by Rank, ASTM International, West Conshohocken, PA. (2015)

All types of coal are used in Thailand, especially lignite, bituminous, and sub-bituminous. Lignite is the most common coal produced in Thailand. It is commonly used for electricity generation, but not widely used in industry because it contains lower energy and higher pollution comparing with other coal types. Anthracite, bituminous, and sub-bituminous which are used in industrial processes and electricity generation are mainly imported from Indonesia and Australia (Thai Custom Department, 2017).

2.1.1 Lignite production

Thailand has around two Gt of lignite reserves located in Northern Thailand. It is estimated that 1400 Mt is economically recoverable. This would generate power for up to 100 years at present rates (IEA, 2010). There are plans to keep Mae Moh (the largest coal-fired power station owned by EGAT) operational for a further 40 years, and perhaps longer. The Government policy of diversification for coal is based primarily on using low sulphur imported coals in future coal-fired power stations.

Figure 2.1 shows that the amount of lignite production in Thailand has been significantly increased from 1986 to 2016 (around +204%). Over 80% of Thailand's total annual production comes from the Mae Moh surface mine in northern Thailand and the rest from private sectors. Considering the production during the last decades, lignite from Mae Moh was slightly increased (around +3%) but from private sector was dramatically decreased.

All of Mae Moh's production is consumed by the adjacent power plant (2625 MW). On the other hand, most of the lignite produced by other Thai mines is used by industry, mainly in cement manufacture. Imports of bituminous coal are mostly destined for consumption in the iron and steel sector. Table 2.2 presents characteristics of lignite produced in Thailand (Pintana and Tippayawong, 2013).

Figure 2. 1 *Lignite production in Thailand between 1986 and 2016 (EPPO, 2017)*

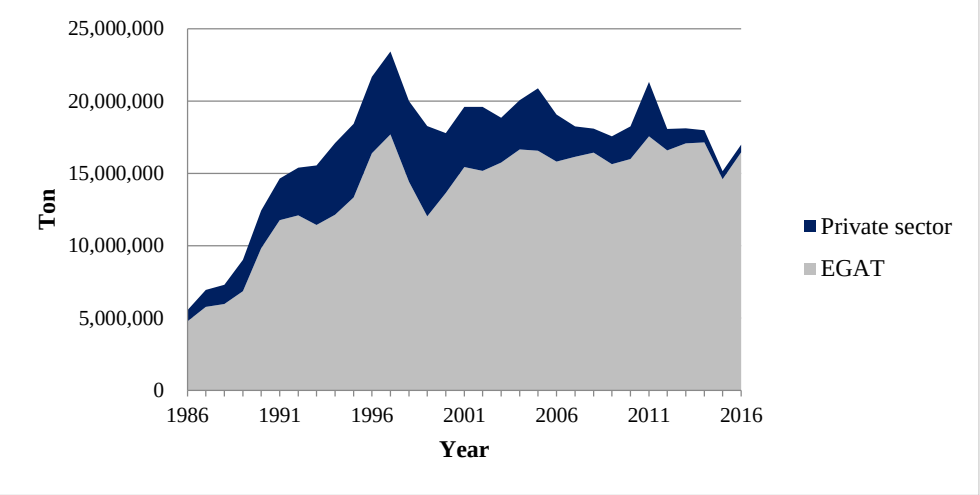


Table 2. 2 *Analysis results of Thai lignite samples in 2013*

Characterization	Low CaO lignite	High CaO lignite
Proximate analysis (% w/w, as-received basis)		
Moisture content	35.1	39.6
Volatile matter	28.2	27.6
Fixed carbon	25.8	20.9
Ash	10.9	11.8
Ultimate analysis (% w/w, dry basis)		
C	58.5	58.4
H	3.0	2.4
N	1.9	1.8
O	12.9	12.6
S	5.5	3.3
Ash compositions		
Na_2O	1.9	0.7
MgO	4.2	3.4
Al_2O_3	13.4	1.4

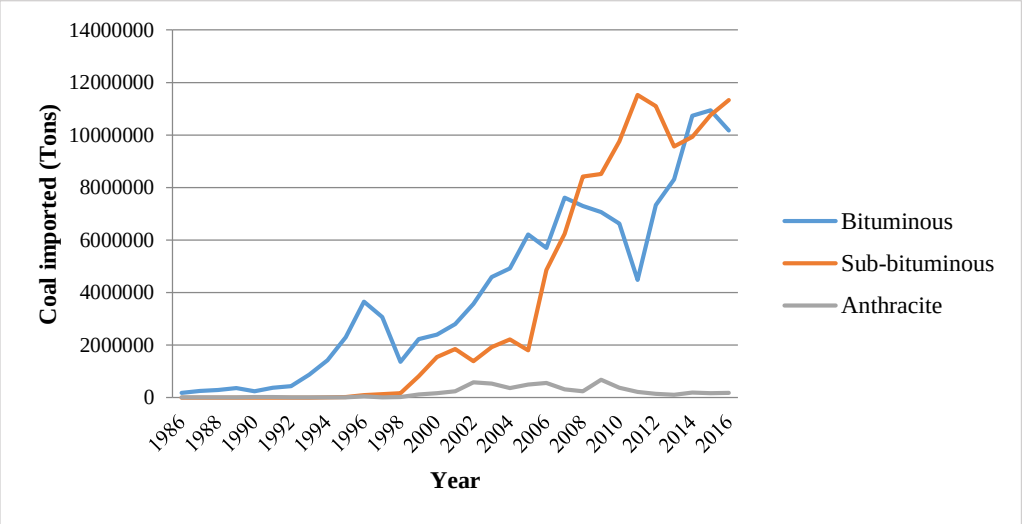
Table 2. 2 *Analysis results of Thai lignite samples in 2013*

Characterization	Low CaO lignite	High CaO lignite
SiO_2	21.1	16.6
P_2O_5	0.1	0.2
SO_3	17.4	33.4
K_2O	1.3	0.2
TiO_2	0.3	0.1
Fe_2O_3	28.9	15.9
MnO_2	0.1	0.1
CaO	11.4	28.2
CaO (SO_3-free basis)	13.8	42.3

2.1.2 Coal import

Anthracite, bituminous, and sub-bituminous coal have been imported to Thailand for both industrial processes and electricity generation. Sub-bituminous is imported with the largest amount comparing with bituminous and anthracite. Sub-bituminous has been rapidly increased since 2006, with more than 130% growth rate in 2016 and still increasing (Figure 2.2). Thailand imported sub-bituminous, bituminous, and anthracite around 11,335,870, 10,172,070, and 181,670 tons, respectively. They came mainly from Indonesia (around 75%) and about 14% from Australia (DPIM, 2014). Of these, in 2010, about 35% were used for electricity generation by IPP (an independent power producer) and SPP (a small power producer).

Figure 2. 2 *Coal imported to Thailand between 1986 and 2016 (EPPO, 2017)*



2.2 Coal and lignite consumption in Thailand

According to EPPO (2015), Coals and lignite are consumed in Thailand for electricity generation and industrial processes and the use of lignite and coal in Thailand are increasing in both sector. In 2016, coal and lignite were consumed around 38,457,405 tons, with 64% for electricity, and the rest for industry (Figure 2.3). Most of domestic lignite (97%) was used in electricity generation, whereas only 35% of imported coal was fed into an independent power producer (IPP) and a small power producers (SPP).

According to coal and lignite consumption for electricity in Thailand, lignite has been used by EGAT (the Electricity Generating Authority of Thailand). In addition, coal was also utilized by IPPs and SPPs. Lignite has been used in electricity generating for long time, whereas bituminous and sub-bituminous just have been used in Thailand since 1995 and 2016 by SPPs and IPPs. Although the share of coal consumption for electricity generation, comparing to lignite, was significantly increased to 35% in 2016, lignite is still the main fuel for Thai coal power plant (around 65%). However, the amount of lignite used in coal-

fired power plant is stable within around 16,000,000 to 18,000,000 tons per year during the last decades as shown in Figure 2.4.

Figure 2. 3 *Coal and lignite consumption of Thailand between 1986 and 2016 (EPPO, 2017)*

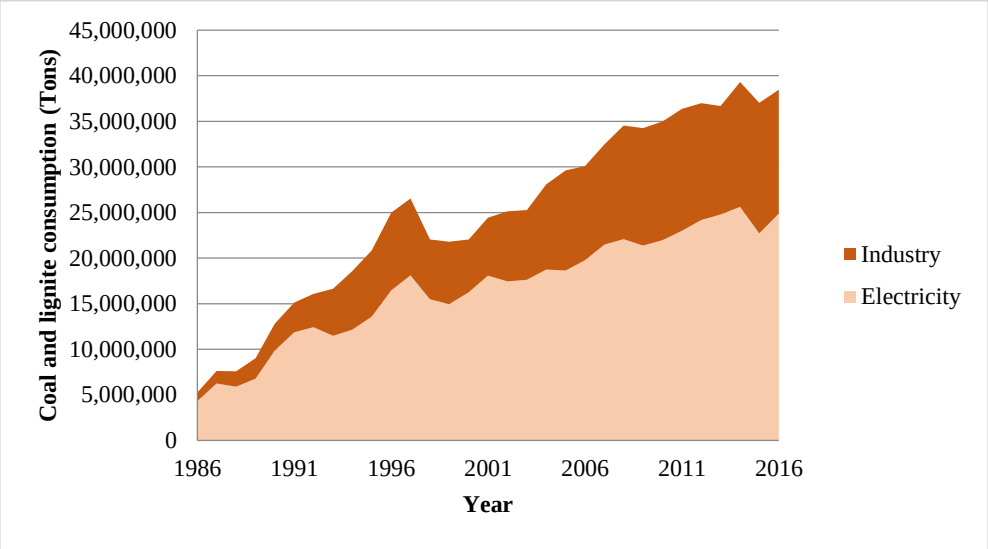
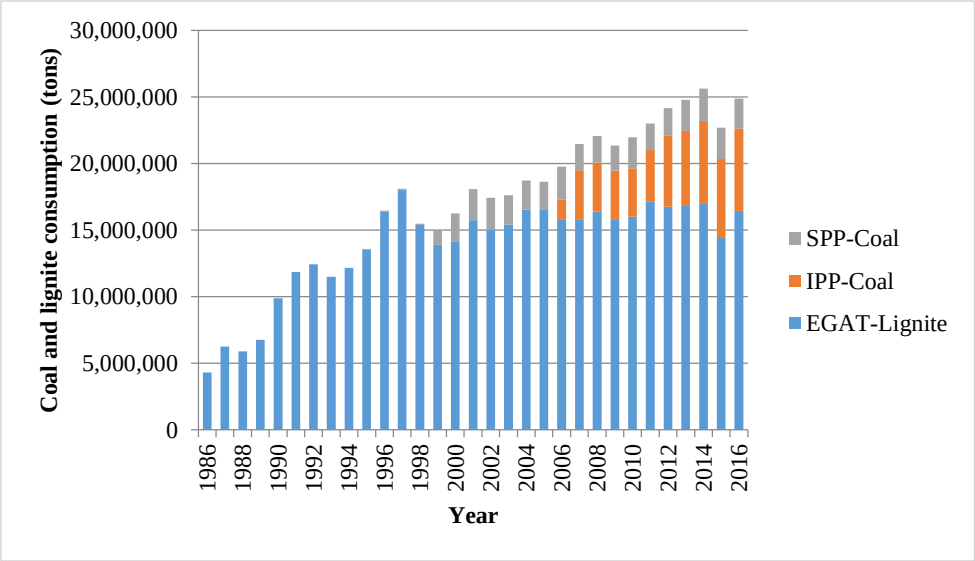


Figure 2. 4 *Coal and lignite consumption of Thailand between 1986 and 2016 classified by types of power plant (EPPO, 2017)*



EGAT- the Electricity Generating Authority of Thailand; IPP- an independent power producer; SPP- a small power producer

2.3 Existing information on analysis of coal and lignite used in Thailand

The average energy content of lignite from Mae-Moh mine is around 11.76 MJ/kg which is lower than that in coals imported from Indonesia and Australia. Most of Indonesian coal is currently produced from Kalimantan mines and less than 4% of coal is produced from Sumatran mines (Ewart and Vaughn, 2009). Australian coal export is from coal mines in New South Wales and Queensland. Australian coal has energy content around 25 – 29.7 MJ/kg which is higher than Indonesian coal (17 – 28 MJ/kg). Characteristics of lignite (Thailand) and bituminous and sub-bituminous (Indonesia and Australia) are shown in Table 2.3 to Table 2.5.

Table 2. 3 *Characteristic of lignite from Mae-Moh mine (Unit: % by Mass)*

Parameter	Value	Range
Proximate Analysis		
Volatile matter	27.44	25.95 – 28.60
Ash content	16.46	11.74 – 21.57
Moisture content	31.98	30.15 – 37.77
Fixed carbon	23.04	16.09 – 28.68
Total sulfur	2.39	2.19 – 3.00
Ultimate Analysis		
Carbon	67.36	32.31 – 88.95
Hydrogen	5.99	0.04 – 13.17
Oxygen	20.25	0.18 – 55.07
Nitrogen	1.05	0.12 – 2.67
Chlorine	0.03	0.00 – 0.20
Sulfur	5.35	2.43 – 10.72
Mercury	$5.1x10^{-7}$	$(10x10^{-7})$-$(10x10^{-4})$
	0.0051 mg/kg	0.001 – 0.01 mg/kg

Source: TEAM Consulting Engineering and Management *Co. Ltd.* (2016).

Table 2. 4 *Characteristic of Indonesian coal (Unit: % by Mass)*

Parameter	Bituminous coal	Sub-bituminous coal
Volatile matter	31 – 42	28 – 37
Ash content	2 – 12	1.5 – 7.5
Moisture content	10 – 12	24 – 38
Sulfur content	0.10 – 0.95	0.07 – 0.90
Energy (MJ/kg)	23.18 – 28.04	17.16 – 21.77

Source: Ewart and Vaughn (2009)

Table 2. 5 *Characteristic of Australian coal (Unit: % by Mass)*

Parameter	Bituminous and Sub-bituminous coal
Volatile matter	20 – 44.5
Ash content	8 – 20.5
Moisture content	3.5 – 16
Sulfur content	0.3 – 5
Energy (MJ/kg)	25 – 29.7

Source: Australia's Export Coal Industry (1996)

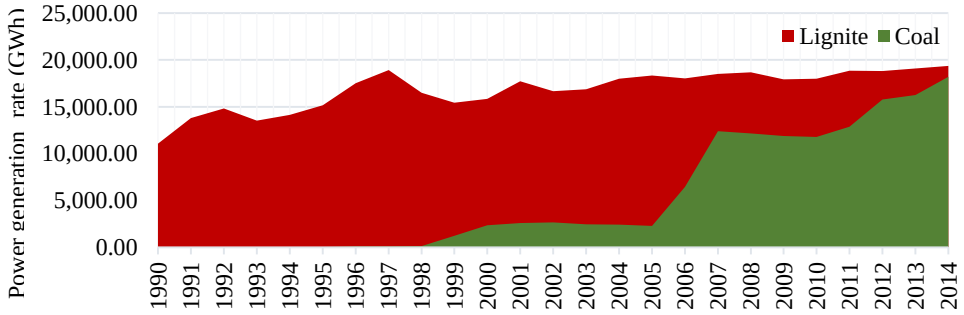
3. Coal-fired power plant information

This part aims to provide the general information and situation of the electricity generation and the coal-fired power plants in Thailand. There are three main topics described in this section: a) the situation of electricity generation in Thailand; b) list of the electricity power plants in Thailand, which bases on fuel sources, its location and installed capacity; and c) national and provincial information of air pollution control and operational efficiency.

3.1 Situation of electricity generation in Thailand

According to the report of the Energy Policy and Planning Office (EPPO, 2015) under the Ministry of Energy, power generation from 1990 to 2014 has mainly associated with various types of fuels including natural gas, coal and lignite; and oil. The largest two sources of fuel are natural gas and coal and lignite, which account for 66% and 20%, respectively. Lignite was first fuel introduced to be used for generating power in the country. After that, bituminous and sub-Bituminous were imported as an alternative source of fuel. Power generation rates from these two sources are illustrated in Figure 3.1.

Figure 3. 1 *Power generation rate by coal and lignite in Thailand*



3.2 Coal-fired power plants in Thailand

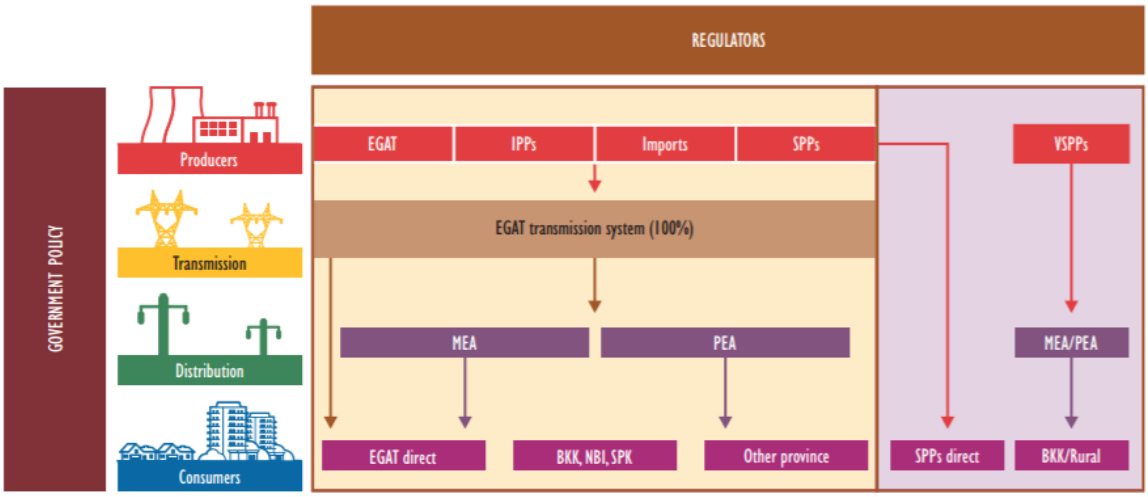
3.2.1 Electricity demand

Electricity consumption rate (GWh) is influenced by many factors: population, gross domestic product (GDP), stock index (SET index) and total revenue from exporting

industrial products (export). Electricity generation tends to steadily increase so as to meet the country's rapidly increasing demand. Thailand's economic success story has resulted in a steady and steep increase in its energy consumption and, as a consequence, a rising dependency on imported fuels and associated exposure to international commodity prices. As a recent example, average gross domestic product (GDP) growth of 3.6% per year between 2005 and 2010 translated into an increase in primary energy demand of 4.1% per year (ADB, 2015).

Currently, main electricity producers are the EGAT (Electricity Generating Authority of Thailand), the IPPs (Independent Power Producers), the Small Power Producers (SPPs); and the Very Small Power Producers (VSPPs). As implemented in Thailand, the enhanced single buyer model consists of a single vertically integrated utility, EGAT, owning and managing a portion of the generation fleet, the entirety of the transmission network, and a portion of the retail market (Figure 3.2). In addition to its own generation fleet, EGAT purchases electricity from IPPs, SPPs, and imports from other countries (which are generally structured as IPPs).

Figure 3. 2 *Single buyer model consists of a single vertically integrated utility*



Note: BKK - Bangkok; NBI - Nonthaburi; SPK - Samut Prakan; these three provinces make up the service area of MEA (Metropolitan Electricity Authority). Source: IEA (International Energy Agency), Thailand Questionnaire, 2015

3.2.2 Type, capacity and its location

As reported by the International Energy Agency (IEA, 2016), coal-fired power generation accounts for 19.9% of total power production in Thailand. In 2014, demand for coal amounted to 25.6 million tonnes of coal-equivalent (Mtce), and was evenly split between industrial and electricity generation uses (Table 3.1). Thailand expects demand for coal to increase at an average annual rate of 1.8% per year, reaching 36.1 Mtce by 2036. While increasing industrial demand accounts for some of this growth, the majority is due to increases in coal used for power generation, which usually depends on domestic electricity demand. On average, electricity demand typically grows approximately 0.9-1.1 times of the GDP growth (Tunpaiboon, 2016). The business sector (30% of total consumption), and the industrial sector (45%) altogether make the largest proportion of 75%, while the rest are demands from households (22%) and others (3%).

Table 3. 1 *Thai coal consumption by sector (Mtce)(IEA, 2016)*

Sector	2012	2013	2014	2015*
Electricity generation	12.9	12.9	13.6	10.3
Industry	10.6	9.7	12.0	10.3
Total	23.4	22.6	25.6	20.7

*January through October

Twenty three coal-fired power plants that use of the combustion of coal in order to generate electricity have been installed and operated in 10 provinces of Thailand (Figure 3.3). Available data on power plant type, capacity and location installed in the country are summarized in Table 3.2.

Table 3.2 shows the total capacity of coal-fired power plants in Thailand with the rate of 8,704 MW. Of which 58% of this capacity was shared by EGAT while the remaining 30%, 10%, and 2% of the total capacity were gained from the IPPs, SPPs, and VSPPs, respectively. The two largest power plants operated in the country belong to the Mae Moh power plant and the BCLP power plant with the total installed capacities of 2,180 and 1,434 MW, respectively. Bituminous is widely used for the combustion process to generate heat and electricity while lignite is only utilized in the Mae Moh power plant (EPPO, 2017).

Table 3. 2 *Summary of coal-fired power plants in Thailand*

	Power Plant (Group)	Location	Main/alternative fuel type[1]	Capacity (MW)
1	Nanyang Energy	Krathum Baen, Samut Sakhon	B	1.8
2	Ekarat Pattana	Takhli, Nakhon Sawan	B	3.0
3	TPI Polene	Kaeng Koei, Saraburi	B	6.0
4	Ajinomoto (Thailand)	Lat Lum Kaeo District, Pathum Thani	B/Diesel oil	8.6
5	Inter Pacific Paper	Bangsang, Prachinburi	B	9.5
6	United Paper	Mueang, Prachinburi	B	9.5
7	Elite-KraftPaper	Mueang, Sa Kaeo	B	9.8
8	Thai Cane Paper PLC	Kabinburi, Prachinburi	B	26.0
9	Thai Acrylic Fibre	KaengKhoi, Saraburi	B	27.3
10	Environment pulp and paper	Takhli, Nakhon Sawan	B/Hydro power	32.0
11	Panjapol Pulp Industry	Bangsai, Ayutthaya	B	40.0
12	Siam Kraft Industry	Banpong, Ratchaburi	B/Biomass	53.4
13	TPT Petrochemicals	MTP IE[2], Rayong	B	55.0
14	Siam Kraft Industry	Thamuang, Kanchanaburi	B	85.0
15	IRPC public company limited	Mueang, Rayong	B	108.0
16	Glow SPP 3 (Project 1)	MTP IE[2], Rayong	B	160.0
17	Glow SPP 3 (Project 2)	MTP IE[2], Rayong	B	160.0
18	National Power Supply (P1)	SrimahaphotPrachinburi	B	164.0
19	National Power Supply (P2)	SrimahaphotPrachinburi	B	164.0

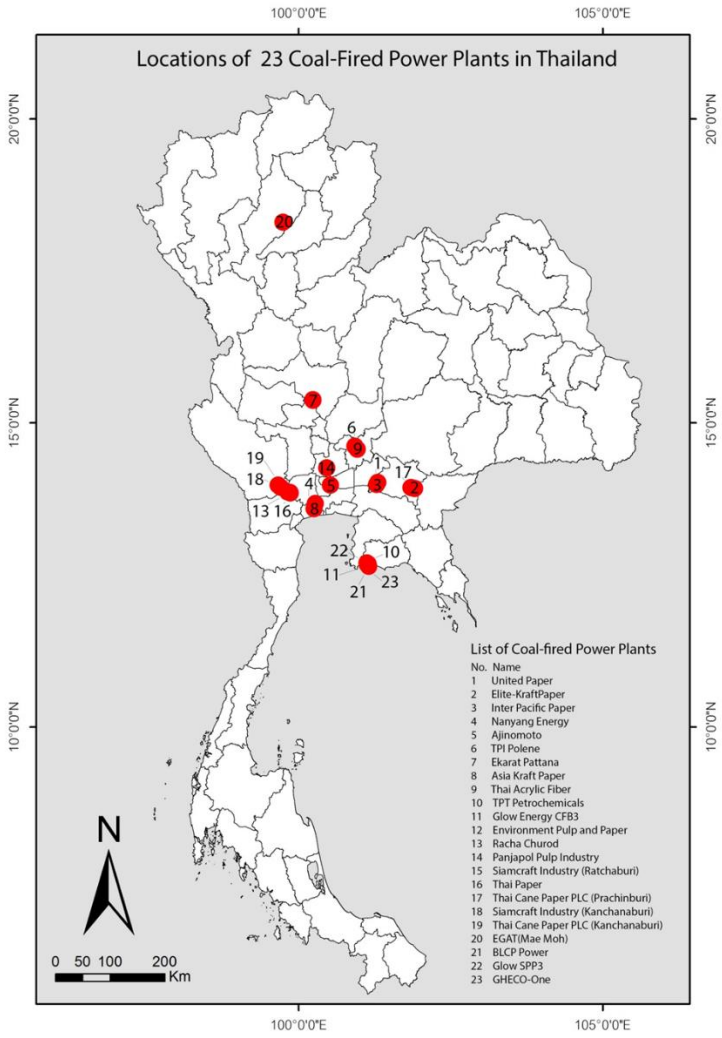
***Table 3. 2** Summary of coal-fired power plants in Thailand*

	Power Plant (Group)	Location	Main/alternative fuel type[1]	Capacity (MW)
20	National Power Supply	PhanomSarakham, Chachoengsao	B	540.0
21	GHECO-One	MTP IE[2], Rayong	B	660.0
22	BLCP Power	MTP IE[2], Rayong	B	1,434.0
23	Mae Moh	Mae-Moh, Lampang	L	2,180.0

Notes: [1] Fuel type B and L represent Bituminous and Lignite, respectively;

[2] MTP IE represents Map Ta Phut Industrial Estate

Figure 3. 3 Locations of 23 coal fired power plants in 10 provinces of Thailand (illustrated as a red spot)



3.3 National and provincial air pollution control and operational efficiency

Coal and lignite are used for production of heat and electricity in different sectors with varying combustion technology. Natural raw materials, including coal and lignite, contain trace amounts of mercury, which is thermally released during the combustion. Most of the

mercury in the coal and lignite is thermally released in gaseous form during the combustion process. The burning of coal releases many pollutants such as oxides of nitrogen (NOx) and sulfur (SOx); and particulate matter and mercury. They also emit greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4), which are known to contribute to global warming and climate change. To help the emission of these, power plants require technology to reduce the output of these harmful substances. Available data on national and provincial policy of air pollution control and operational efficiency, particularly for NOx, SOx and particulate matter, of all coal-fired power plants installed in Thailand are summarized in Table 3.3.

Overall, technologies that are widely equipped at the coal-fired power plant in Thailand for reducing the oxide of nitrogen compound are the applications of Low NOx burner, Over Fired Air and Selective Catalytic Reduction (denoted as LNB, OFA, and SCR, respectively) with the operational efficiency in the range of 63.6%-95%. For sulfur dioxide (SO_2), the Flue Gas Desulfurization using lime stone (W-FGD) and sea water (SW-FGD) are equipped in Plants with installed capacity >90 MW with the operational efficiency in the range of 77.5%-95.2%. For the particulate matter, an Electro Static Precipitator (ESP) device is usually applied to remove this pollutant with the operational efficiency in the range of 99.0%-99.9%.

Moreover, these coal-fired power plant producers also implement a number of monitoring programs to monitor the emissions of air pollution. These include the installations of the Continuous Emission Monitoring System (CEMS), the Ambient Air Quality Monitoring System (AAQMS), the policy for utilize high quality coal that contain sulfur content less than 1%.

Table 3. 3 *Air pollution control devices of coal-fired power plants installed in Thailand*

Power plant	Installed devices (%Efficiency)		
	NOx	SOx	TSP
(1) Nanyang Energy	NR	NR	NR
(2) Ekarat Pattana	NR	NR	NR
(3) TPI Polene	LNB	LS-FGD (95.0%)	Bag Filter (99.9%)
(4) Ajinomoto (Thailand)	NR	NR	NR
(5) Inter Pacific Paper	NR	NR	ESP (99.9%)
(6) United Paper	NR	NR	ESP
(7) Elite-Kraft Paper	NR	NR	NR
(8) Thai Cane Paper PLC	NR	NR	NR
(9) Thai Acrylic Fibre	NR	NR	ESP
(10) Environment pulp and paper	NR	NR	NR
(11) Panjapol Pulp Industry	NR	NR	NR
(12) Siamcraft Industry (Ratchaburi)	NR	NR	NR
(13) TPT Petrochemicals	NR	NR	NR
(14) Siamcraft Industry (Kanchanaburi)	NR	NR	NR
(15) IRPC public co.limited	NR	NR	NR
(16) Glow SPP 3 (Project 1)	LNB+SCR (63.6%)	W-FGD(77.5%-78.7%)	ESP (99.3%)
(17) Glow SPP 3 (Project 2)	LNB+SCR (63.6%)	W-FGD(77.5%-78.7%)	ESP (99.3%)
(18) National Power Supply (P1)	NR	W-FGD	ESP (99.5%)
(19) National Power Supply (P2)	NR	W-FGD	ESP (99.5%)
(20) National Power Supply	NR	W-FGD	ESP (99.5%)
(21) GHECO-One	LNB+OFA+SCR (76.7%)	SW-FGD (95.2%)	ESP (99.5%)
(22) BLCP Power	LNB (85%-95%)	SW-FGD (84.0%)	ESP (99.7%)
(23) Mae Moh	LNB+OFA+SCR (71.3%)	W-FGD (97%)	ESP (99.5%)

Remarks: ESP = Electro Static Precipitator, LNB = Low NOx Burner, W-FGD = Wet-Flue Gas Desulfurization, NR = No Report, OFA = Over Fired Air, SCR = Selective Catalytic Reduction, and SW-FGD = Sea Water- Flue Gas Desulfurization

3.4 Status of air pollution control

As reported by the International Energy Agency (IEA, 2016), the limits of concentration of particulate matter 2.5 (PM 2.5) for Thailand is the same as the EU's; but the standards for NOx

(320 μg/m^3 for 1 hour and 57 μg/m^3 for annual) and SO_2 (780 μg/m^3 for 1 hour and 300 μg/m^3 for 24 hours) are weaker (AQNIS, 2016). In Thailand, emission standards are set by the Pollution Control Department (PCD) of the Ministry of Natural Resources and Environment under the authority of the Enhancement and Conservation of National Environmental Act, B.E. 2535 (1992). Emission limits for new power plants operating after 5 January 2010 were published in the Royal Thai Government Gazette (volume 127, section 7D on 15 Jan 2010). New power plants refer to plants generating, transmitting or distributing electricity that acquired a permit for operation or expansion after 15 January 2010. Emission standards for existing power plants are also covered in the Royal Thai Government Gazette (volume 121, section 113D, 7 Oct 2004), with special mention of the Mae Moh power plant (Table 3.4). Units 4-7 of the Mae Moh power plant are going to be replaced by a single ultra-supercritical unit, which is planned to be operational in 2019.

Table 3. 4 *Emission standard for NOx, SO_2 and PM for coal-fired power plants in Thailand*

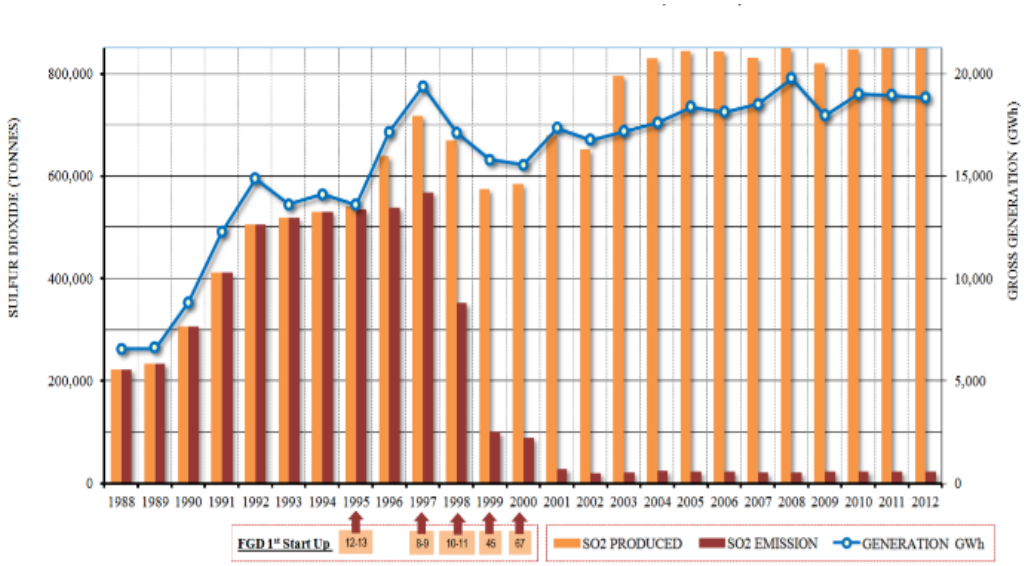
Power plant (MW)	**NO_2(mg/m^3)**		**SO_2(mg/m^3)**		**PM (mg/m^3)**	
	Existing	**New**	**Existing**	**New**	**Existing**	**New**
Existing power plants						
Mae Moh units 4–7 (4 x 150), units 8–13 (6 x 300)	1025	410	915	1030	180	80
Other coal-fired plants of any size	820	410	2002	515	180	80

Source: IEA, 2016,

3.4.1 SO_2 Control

Control of SO_2 emissions from coal-fired power plants is one of the priorities of air pollution control in Thailand. In 1995, the Mae Moh power plant installed the units with flue gas desulfurization devices (FGDs). After that the total SO_2 emissions have been reduced dramatically. This was shown by results from a 25-year monitoring programme conducted at the Mae Moh power plant (Figure 3.4).

Figure 3. 4 *Sulfur dioxide emission rate of the Mae Moh coal fired power plant from 1988 to 2012*

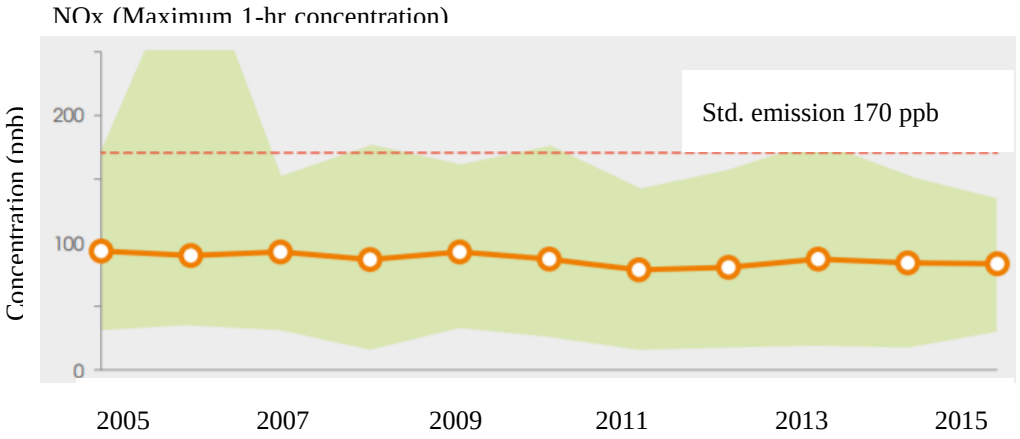


Source: EGAT (2015)

3.4.2 NOx Control

The Pollution Control Department (AQNIS, 2016) reported the 10-year NOx emission concentration in Thailand. It was found that the maximum 1-hr concentration of NOx did not exceed the standard line (Figure 3.5).

Figure 3. 5 *Nitrogen dioxide emission rate in Thailand from 2005 to 2015*



Source: Situation and management of air and noise pollution in Thailand (AQNIS, 2016)

3.4.3 Situation of ambient mercury concentration

In 2015, the Air Quality and Noise Management Bureau (AQNIS) of PCD conducted the monitoring programme to measure Hg concentration in the ambient air in six provinces, the hotspots included power stations, petrochemical plants and municipal solid waste incinerators (AQNIS, 2016). The results are presented in Table 3.5.

Table 3. 5 *Mercury levels (ambient air) in six hotspots of Thailand*

Hot spot sites (province)	**Hg concentration (ng/m^3)**		
	Min	Average	Max
Prachinburi (coal fired PP/Biomass PP)	1.24	2.12	4.42
Rayong (Refinery plant)	1.12	3.08	9.26
(Refinery plant/coal fired PP)	0.72	1.94	8.02
(refinery plant)	0.76	1.53	2.91
Lumpang (Mae Moh PP)	0.83	1.55	8.23
Nan (Hongsa PP, Lao)	0.85	1.66	3.39
Songkla (MSW incinerator)	0.90	1.92	2.97
Phuket (MSW incinerator)	0.42	1.15	3.70
Reference site			
Karnchanaburi (Dam)	0.36	0.77	1.14

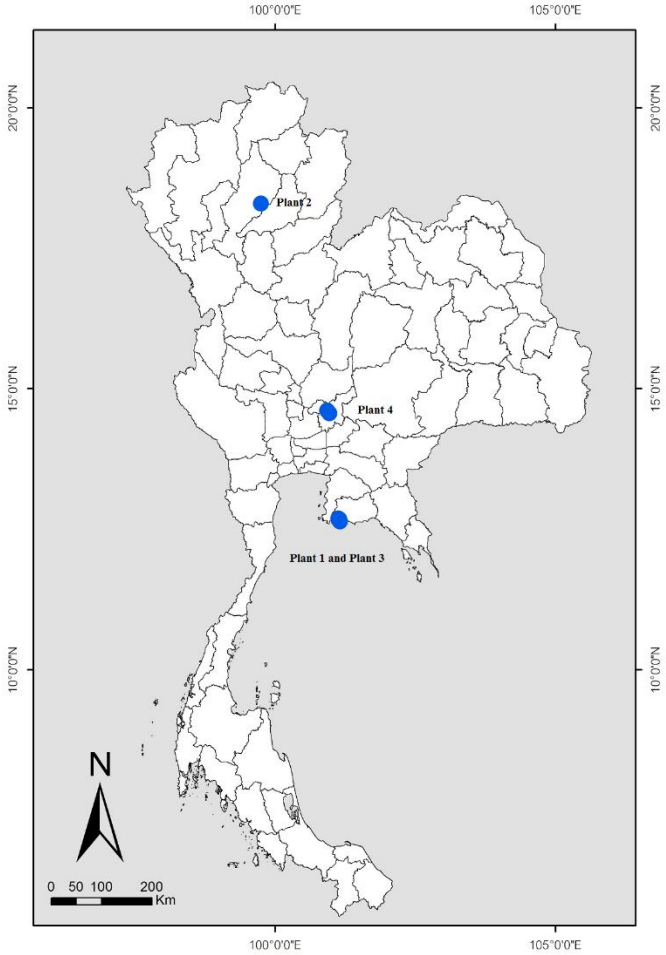
4. Methodology

In this study, the bituminous and lignite power plants were selected as a representative to be a case study. Herein, from now on, a bituminous power plant is named as the Plant 1 and the Plant 2 refers to a lignite power plant. The Plant 1 is located in the phase 2 of the Map Ta Phut Industrial Estate. This power station is a privately-own company which has been incorporated in accordance with the national policy for greater access and participation of private sector in the electricity generation business under the scheme of the independent power producer (IPP). Its fuel source is a top-grade bituminous coal imported from Australia and Indonesia. The plant 2 is located in the mountains of Mae Moh district in Lampang province, Northern Thailand. The fuel source of this plant is lignite. The plant consists of 13 generating units and only three units were selected as study areas.

4.1 Distribution of coal samples

In this study, the sampling was conducted from May to June 2017. Fifty coal and lignite samples were collected from 10 coal stockpiles of the four coal-fired power plants in three provinces, including Rayoug (2 bituminous plants, named Plant1 and Plant 3), Saraburi (1 bituminous plant: named Plant 4) and Lumpang (1 lignite plant: named Plant 2). Figure 4.1 shows the locations of sampled coal stockpiles (blue dots).

Figure 4. 1 *Locations of all sampled coal stockpiles in this study*



4.2 Sampling protocol

The ASTM D 4596-09 procedure (Standard Practice for Collection of Channel Samples of Coal in a Mine) were modified for coal and lignite sampling in this study.

4.2.1 Plant 1 power plant

In the Plant 1, 15 bituminous samples were randomly collected from three coal sources, namely Bee Creek (BC), Hunter Valley (HV) and Suek (SU), thus, collecting five samples for each coal source. At each sampling point, 0.5 kg of coal was collected, which came from two sampling spots and these sampling spots were at least 10 meters away from each other. Of these, five samples were taken for inter-laboratory comparison. Two subsamples were blended to make one valid sample for proximate, ultimate and chemical analysis.

4.2.2 Plant 2 power plant

In Plant 2, 10 coal samples were randomly collected from the two coal yards of Mae Moh mine, namely CS 1 and CS 2, thus, collecting five samples for each coal yard. At each sampling point, 0.5 kg of coal was collected, which came from two sampling spots and these sampling spots were at least 10 meters away from each other. Of these, five samples were taken for inter-laboratory comparison. Two subsamples were blended to make one valid sample for proximate, ultimate and chemical analysis.

In addition, about 15 and 10 coal samples were randomly collected from Plant 3 and 4, respectively. The sources of coal of Plant 3 are PT Jembayan muarabara, PT Kaltim Pruma coal and PT Khotia Makmur insan Abidi. The sources of coal of Plant 4 are Indominco and Lanna Harita. Descriptions of the tested power plants; sources and types of coal; and sample size are presented in Table 4.1.

Table 4. 1 *Coal samples*

Plant/Source	Type of coal	Number of sample
Plant 1 (3 sources)		**15 samples**
Bee Creek (BC), Australia	Bituminous	5
Hunter Valley (HV), Australia		5
Suek (SU), Russia		5
Plant 2		**10 samples**
CS 1, Thailand	Lignite	5
CS 2, Thailand		5
Plant 3		**15 samples**
JM (PT Jembayan muarabara), Indonesia	Bituminous	5
KP (PT Kaltim Pruma coal), Indonesia		5
KM (PT Khotia Makmur insan Abidi), Indonesia		5
Plant 4		**10 samples**
BP, Indominco, Indonesia	Bituminous	5
LH, Indonesia		5
Total		**50**

4.3 Coal analysis method

Sample preparation is referred to ASTM D2013-03 (Standard Practice for Preparing Coal Samples for Analysis). The samples were first air dried to constant weight, and then pulverized

into 80 meshes (200 μm in diameter). Proximate analysis (moisture, volatile matter, fixed carbon and ash), ultimate analysis (carbon, hydrogen, nitrogen, oxygen, and sulfur) and chemical composition (mercury, arsenic, selenium, sodium, calcium, chlorine, barium and bromine) were analyzed by using a method of American Society for Testing and Material (ASTM). The coal analysis methods are shown in Table 4.2.

Table 4. 2 *Analysis Methods for Coal Sample*

Parameter	Analysis Method
1) Proximate Analysis	
Total Moisture	ASTM D3302/D3302M-12
- Inherent Moisture	ASTM D7582-15
- Volatile Matter	ASTM D7582-15
- Fixed Carbon	ASTM D7582-15
- Ash	ASTM D7582-15
2) Ultimate Analysis	
Carbon(C)	ASTM D5373-16
Hydrogen(H)	ASTM D5373-16
Nitrogen(N)	ASTM D5373-16
Sulfur(S)	ASTM D4239-14
Oxygen(O)	Calculation -
3) Chemical Composition	
Heavy Metal	
Mercury (Hg)	ASTM D6722-11
Arsenic (As)	ASTM D6357-11
Selenium (Se)	ASTM D6357-11
Sodium (Na)	ASTM D6357-11
Calcium (Ca)	ASTM D6357-11
Barium (Ba)	ASTM D6357-11
Halogen	
Chlorine (Cl)	ASTM D4208-13
Bromine (Br)	Oxygen Bomb Combustion/Ion Chromatographic Method

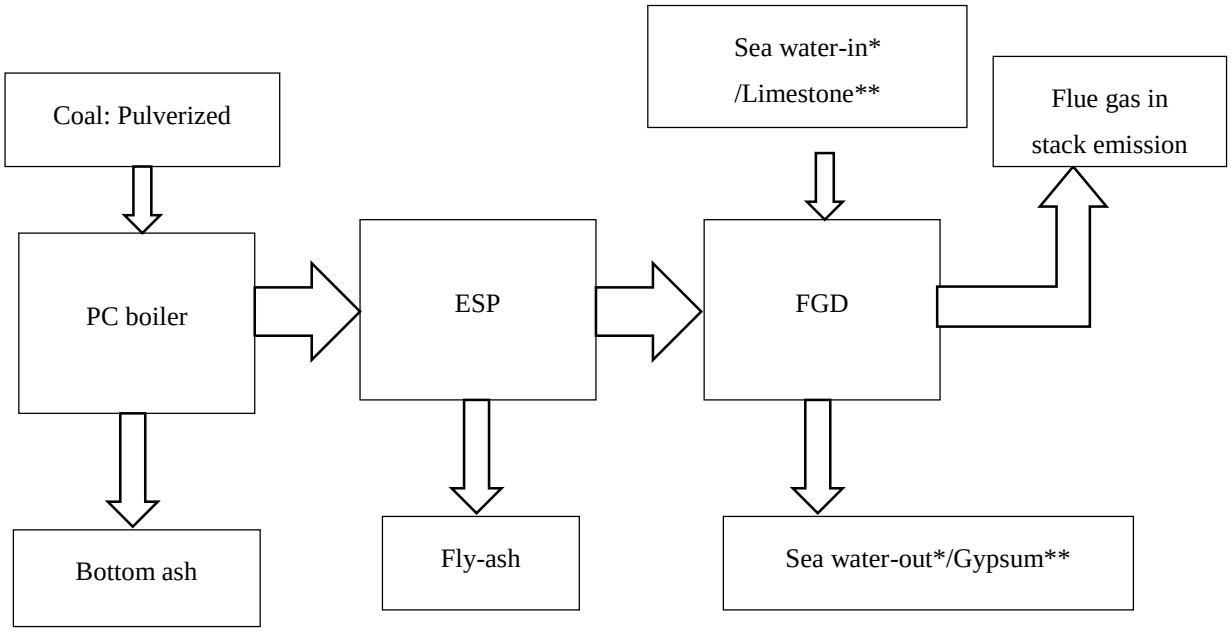
4.4 Sample collection and analysis for mercury in coal combustion process

During the combustion process, coarse particles (bottom ash and boiler slag) settle to the bottom of the combustion chamber, and the fine portion (fly ash) is removed from the flue gas by electrostatic precipitators. In addition, flue gas desulfurization (FGD) is a chemical process to remove gases, especially sulfur oxides. The principle of the FGD process is to chemically

combine the reactive form released in coal combustion by reacting them with limestone for wet-FGD or with seawater for seawater FGD. Untreated flue gas is typically emitted through a chimney stack.

In order to calculate the mass balance of mercury from coal combustion, of each sampling cycle, feed coal, combustion products and untreated flue gases were collected and analyzed. Figure 4.2 shows the one sampling cycle which delineates each collection point of the sample from feed coal, bottom ash, fly ash, limestone/seawater-in, gypsum/seawater-out and stack gas emission. At each power plant unit, five sampling cycles were repeatedly conducted for five consecutive days. Thus, the sample size for each sample type is five (i.e. 5 feed coal samples, 5 fly ash-samples). The samples for mercury determination was obtained simultaneously at the inlet of the dust collector, inlet of the Wet-FGD/SW-FGD (outlet of the dust collector) and outlet of the Wet-FGD/SW-FGD and the stack air, which was sampled over a period of 2 hours. At the same time, the feed coal was collected about 500g. In one sampling cycle, we calculate the mercury mass distribution after the different APCD to get the mercury transform regulation. Analysis methods used in this study are presented in Table 4.3. Figure 4.3 illustrates the sampling train for collecting the untreated flue gases emitted through stack.

Figure 4. 2 *A simplified schematic flowchart of sampling cycle which portrays the sampling points for mercury measurement.*



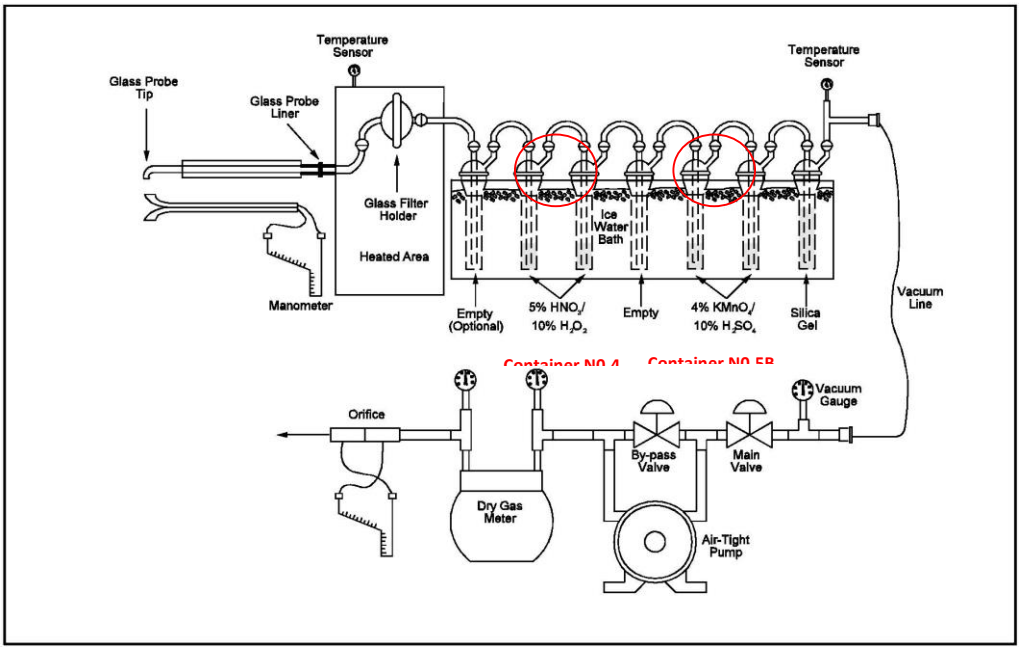
Note * Seawater FGD using seawater as the absorber

** Wet-FGD using limestone as the absorber and gypsum is a by-product

Table 4. 3 Analysis methods for mercury in coal and coal combustion product

Substance	Method
Pulverized coal	ASTM D6722-11
Bottom ash	ASTM D6722-11
Fly ash	ASTM D6722-11
Limestone and gypsum	U.S.EPA 1631
Stack emission	U.S. EPA Method 29

Figure 4. 3 Schematic of the sampling train (U.S. EPA Method 29)



4.5 Type and quality of data

There were two types of data, which were collected. Primary data were obtained by measuring the emission of mercury from two power plants in Thailand. Direct measurement data need to meet the project QA/QC criteria. Secondary data included the installed capacity, electricity generation, amount of coal consumption of existing coal-fired power plants, the installed configuration of air pollution control devices (APCDs) and its typical operational efficiency, mercury emission factors and reviewed mercury removal efficiency of APCDs from literatures.

These data were collected through literature review and mainly cited from statistical yearbooks, annual reports of power sector in Thailand, and published journal articles. All secondary data were from a reliable sources and organizations and can be rechecked for correctness.

4.6 Quality Assurance (QA) and Quality Control (QC)

To ensure quality of data gathered in this project, the Quality Program is planned.

4.6.1 Quality Assurance (QA)

This approach is a routine practice which carried out from sampling through laboratory analysis. The quality assurance will ensure the precision and accuracy of the results by

- the use of appropriate equipment in the analysis
- the correct and appropriate analysis methods
- the reliability of staff and technicians

The quality assurance includes quality control (QC) and quality assessment activities. Quality Control (QC) is a set of measures within a sample analysis methodology to assure that the process is in control. Quality Assessment is a process to determine the quality of the laboratory measurements through internal and external QC evaluations. It includes performance evaluation samples, laboratory inter-comparison samples and performance audits.

4.6.2 Quality control (QC)

In order to obtain reliable results, both sampling technician and analysts are trained and experienced with the test procedures, including sample container and sampler preparation; sampling procedure; reagent preparation and handling; sample handling; safety equipment and procedures; analytical calculations; reporting; and the specific procedural descriptions throughout the method. The quality control activities are separated into QC in the field and QC in the laboratory.

1) QC in the field

Sampling is performed by qualified, trained and experienced personnel according to the specified sampling methods.

a) *Preparation of sample containers and samplers:* the initial step to minimize any contamination that could occur during sampling. All sample containers and

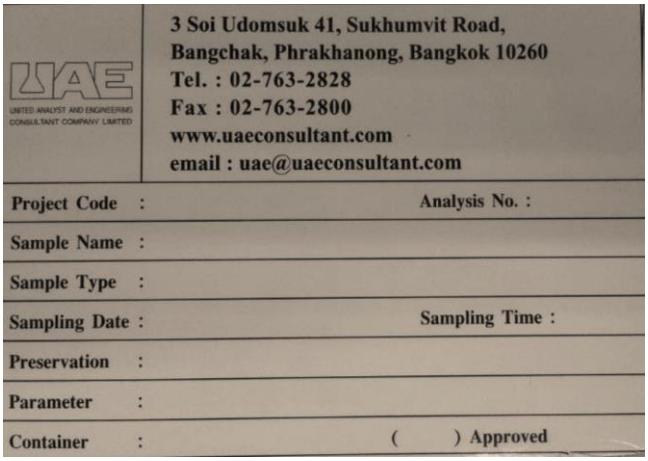
samplers are washed with detergent, cleaned with water and rinsed with distilled water and let dry in a dust-free room to prevent from dirt. The procedures used for sample containers and samplers cleaning are as follows:

- Water sample container: washing procedures for Teflon container are
  - Wash Teflon sampler with detergent
  - Fill up glass sampler with 20 % HNO_3
  - Let stand for 24 hours
    - Discarding the acid, wash the container with distilled water and wrap with a plastic bag
- Coal sample container (for proximate and ultimate coal analysis): washing procedure are
  - Wash plastic container with detergent and water
  - Rinse with distilled water at least 3-5 times
  - Let the container dry in the dustless room
- Coal, ash and gypsum sample container (heavy metal analysis): Washing procedures for polyethylene container are
  - Wash plastic container with detergent and water
  - Rinse with 1+1 HCl and wash with water
  - Rinse with 1+1 HNO_3 and wash with water
  - Rinse with distilled water at least 3-5 times
  - Let the container dry in the dustless room
- Seawater sample container: Washing procedure of fluoropolymer container are
  - Wash container with detergent and water
  - Heat container at 65–75 °C in 4 N HCl (trace-metal purified reagent-grade HCl) or concentrated HNO_3 for 6-12 h.
  - Let container cool, rinse three times with reagent water and fill with reagent water containing 1% HCl
  - Cap and place in a clean oven at 60-70°C overnight

- After cooling, rinse three more times with reagent water, filled with reagent water containing 0.4% (v/v) HCl, and placed in a mercury-free clean bench until the outside surfaces are dry.
- Tightly cap the container (with a wrench), double bagged in new polyethylene zip-type bags until needed, and stored in wooden or plastic boxes until use

b) *Sample labeling*: samples are labeled using a given label. A label is placed on a sample container immediately before sampling. All information must be filled including project code; sample name; sample number; sample type; sampling date; sampling time; sampling duration; preservation; analytical parameters. Example of the label is shown in Figure 4.4.

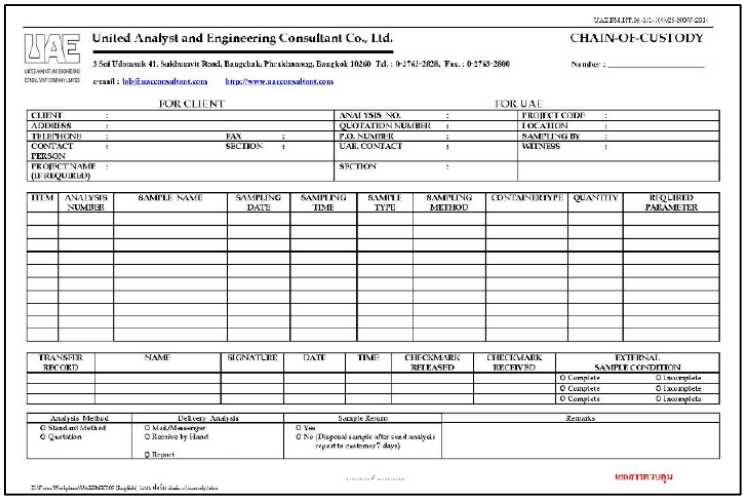
Figure 4. 4 *Label form*



c) *Field Records*: Field records are quality controlled by a filed log sheet and chain of custody form.

- Log sheet includes the detail on name and location of sampling site, sampling date, sampling time and observation around sampling area.
- Chain of custody form includes the detail on sampling date, sampling time, person in charge, analysis number and details of preservation and sample containers. The chain of custody form are shown in Figure 4.5.

Figure 4. 5 *Chain of custody form*



United Analyst and Engineering Consultant Co., Ltd.

CHAIN-OF-CUSTODY

3 Soi Udomsuk 41, Sukhumvit Road, Bangchak, Phrakhanong, Bangkok 10260 Tel. : 0-2763-2828, Fax. : 0-2763-2800

Number : _____

e-mail : lab@uaeconsultant.com http://www.uaeconsultant.com

FOR CLIENT				FOR UAE	
CLIENT :			ANALYSIS NO. :	PROJECT CODE :	
ADDRESS :			QUOTATION NUMBER :	LOCATION :	
TELEPHONE :	FAX :		P.O. NUMBER :	SAMPLING BY :	
CONTACT PERSON :	SECTION :		UAE CONTACT :	WITNESS :	
PROJECT NAME (IF REQUIRED) :			SECTION :		

ITEM	ANALYSIS NUMBER	SAMPLE NAME	SAMPLING DATE	SAMPLING TIME	SAMPLE TYPE	SAMPLING METHOD	CONTAINER TYPE	QUANTITY	REQUIRED PARAMETER

TRANSFER RECORD	NAME	SIGNATURE	DATE	TIME	CHECKMARK RELEASED	CHECKMARK RECEIVED	EXTERNAL SAMPLE CONDITION
							O Complete O Incomplete
							O Complete O Incomplete
							O Complete O Incomplete

Analysis Method	Delivery Analysis	Sample Return	Remarks
O Standard Method O Quotation	O Mail/Messenger O Receive by Hand O Report	O Yes O No (Disposal sample after end of analysis request to customer 7 days)	

d) *Sample transportation:* Coal, ash and gypsum samples will be kept in tightly closed container at ambient temperature during transportation. Seawater samples will be kept cool at > 0 ˚C, ≤ 6 °C. All containers will be placed in plastic zip lock bags to prevent any contamination from the ice box and daily delivered to the laboratory for analysis with label. An example of sample transportation form is shown in Figure 4.6.

Figure 4. 6 *Sample transportation form*

To

Laboratory Department

United Analyst and Engineering Consultant Co.,Ltd.

3 Soi Udomsuk 41 Sukhumvit Rd., Bangchak, Phrakhanong, Bangkok

Tel. 0-2763-2828

Send by .....

Tel. .....

e) *Blank*: Field blank and trip blank will be prepared and sent to laboratory for analysis together with samples.

- Field Blank: aimed to determine any contamination occur during field sampling. This is carried out by exposing distilled water (container) in the field during sampling and preserve at the same way as samples. Field blank is performed at every 20 samples.
- Trip Blank: aimed for container contamination check. The contamination may occur during sample transportation. The container filled with distilled water are transported to the sampling site (without opening the lid while performing the sampling) and brought back to laboratory for analysis. This trip blank is performed for every trip to the field.
- Equipment Blank: aimed to detect any contamination from sampling equipment. At least one equipment blank should be collected for every 20 samples per parameter group and per each matrix. Each type of equipment used in sampling must be accompanied with equipment blank. This blank is prepared in the field before sampling begins, by using the pre-cleaned equipment and filling the appropriate container with analyte-free water. Preservation and documentation of these blanks should be the same as for the collected samples. If equipment is cleaned on site, then additional equipment blanks should be collected for each equipment group.

f) *Air Sampling equipment calibration*:

- Sampling equipment for mercury in air emission are calibrated before every sampling. The leak check, dry gas meter (Yc), % isokinetic and temperature control (filter holder) are calibrated as described in the U.S. EPA Method 1-4 and 29. A log of all calibrations must be maintained. Summary sampling equipment calibration are shown in Table 3.

g) *Replication of samples*: In order to assess precision of the data, 5 replicate samples will be obtained.

2) QC in the laboratory

All laboratory works are performed by qualified, trained and experienced personnel according to the specified analytical methods. A laboratory log of all calibrations must be maintained. Data and laboratory results are recorded using a given form.

a) *Sample receiving:* upon sample arrival, samples and chain of custody form will be checked by an assigned person; sample analysis number will be assigned, and sample will then be registered in laboratory Information Management System (LIMS) and transferred for further analysis.

b) Quality control for air sample analysis

- Method Blank: Blank will be simultaneously analyzed with samples. Blank value should be lower than limit of detection. The blank value of no greater than 5-fold of detection limit is accepted.
- Laboratory Replicate: The analysis result is rechecking by running the replicate sample. This replicate sample is performed for every 10 samples or as specified in the analytical method. The relative percent difference (% RPD) of the two replicates should not be more than 10% or follow the criteria of each parameter.
- Calibration with standard: The equipment used in the analysis should be calibrated with standard solution prior to analyze. The Correlation coefficient (r) of calibration curve should be more than 0.995 or follow the criteria of each parameter.
- Initial calibration verification standard (ICV): ICV is used to assure calibration accuracy during each analytical run. It represents the value of the mid-point initial calibration standard, and used to assure calibration accuracy during each analytical run. It must run immediately after the standard curve was established, and during the analytical batch analysis at the frequency of 5% and after the last sample was analyzed. The deviation from the original value should be within $\pm$5%.
- Second source calibration verification standard (SSCV): SSCV is a known value standard from different source of ICV, used to verify that the standards and the calibrations are accurate and also confirm the calibration curve. The value is accepted within $\pm$ 10% deviation from the 100% recovery.

c) *Quality control* for coal, ash, gypsum and seawater analysis

- Method blank: aimed to check reagent and glassware contamination. Method blanks will be analyzed by the same analytical method as the sample analysis.

The result of the test will evaluate if there is any contamination occurs during the preparation and analysis in laboratory. Method blank is performing for every 10 samples or as specified in the method. The obtained blank values should be lower than the detection limit. If blank value is greater than the detection limit, the value should not greater than 10 times of the average blank value and should not greater than the lowest concentration of the analyzed samples or as specified in the method.

- Laboratory Replicate: analysis results are rechecked by running the replicate samples. This replicate sample is performing for every 10 samples or as specified in the method. The relative percent difference (% RPD) between two replicates should not be more than 20% or follow the criteria of each parameter.
- Initial Calibration Verification (ICV): ICV is the confirmation that calibration was performed correctly. Calibration confirmed by analyzing a solution containing the analytes of interest at concentrations within the calibration range. It must be run immediately after the standard curve was established. The deviation from the original value should be within $\pm$5% or as method specification.
- Continuing Calibration Verification (CCV): CCV is the confirmation that instrument response has not changed significantly from the response at initial calibration. Calibration is verified by analyzing the calibration check solution after every tenth sample. The deviation from the original value should be within $\pm$10% or as method specification.
- Second Source Calibration Verification (SSCV): SSCV is prepared from a stock solution of different source. SSCV is used to determine if the stock and working standards are accurate. SSCV is performed every time that a new calibration standard is used. The value is accepted within $\pm$ 10% deviation from the 100% recovery or as method specification.
- Laboratory fortified blank (LFB): LFB is a method blank that has been fortified with a known concentration of analyst. It is used to evaluate ongoing laboratory performance and analytes recovery in clean matrix. Fortified concentrations are prepared at approximately midpoint of the calibration curve. Include a

minimum of one LFB with each batch of sample prepared. The value is accepted within ± 15 % deviation from the 100% recovery or as method specification.

- Laboratory fortified matrix (LFM): used to evaluate the accuracy of the method as influenced by a specific matrix. LFM is prepared by adding a known concentration of analytes to the sample. Process fortified samples independently through the entire sample preparation procedure and analytical process. Include a minimum of one LFM for every 20 samples in an analytical batch. The value is accepted within ± 15 % deviation from the 100% recovery or as method specification.
- Certified reference materials (RCM) or Reference materials (RM): CRM or RM or QC Standard certified from standard institution are analyzed every 20 samples or as specified in the method. The measured CRM values should be in tolerance interval or within ± 20% deviation from 100% recovery or as method specification.

3) Instrument calibration

All instruments used in the analysis will be calibrated with standard solution prior to analyzing and maintained routinely, which are as follows:

a) Result comparison during laboratory rooms: UAE laboratory participated project of result comparison during laboratory rooms and skill testing with reliable institute such as Department of Science Service, Department of Medical Sciences, Proficiency Testing Australia, Proficiency Testing Canada, etc. in order to monitor of testing and verify within laboratory for improvement of laboratory room.

b) Certification of operator competence: Staff is the most important factor of data quality. Many staff enough for sampling and testing cover all parameters from equipment preparation staff, sampling and testing staff, specialist and result analysis staff in this company. Training course for each position will cover assignment and responsibility and follow as annual training plan. Staff must pass training in part of technique and administer system and gather experience for working.

4.6.3 Quality assessment

Quality assessment is the process used to ensure that quality control measures are being performed as required and to determine the quality of data produced by the laboratory. It includes such items as proficiency samples, laboratory inter-comparison samples, and performance audits. These are applied to test the precision, accuracy and detection limits of methods in use, and to assess adherence to standard operating procedure.

4.6.4 Data Validation

The primary method of validation will be to compare data quality indicators (DQI) with DQI goals. DQI goals have been developed based on reference methods, experience, and project objectives. The DQI goals for mercury measurements are listed in Table 4.4.

Table 4. 4 *Quality assurance/Quality control criteria for mercury analysis*

Parameter	DQI	Frequency of quality control	Acceptance criteria
QC in air sample analysis			
Mercury Emission	Method Blank	Every 10% of all samples	Method Blank < Detection Limit
Mercury Emission	Duplicate	Every 10% of all samples	RPD ≤ 10%
Mercury Emission	Initial Calibration Verification (ICV)	Every 10% of all samples	Recovery 95-105%
Mercury Emission	Second Source Calibration Verification standard (SSCV)	Every 10% of all samples	Recovery 90-110%
QC in Coal, Ash and Gypsum Analysis			
Proximate Analysis (Moisture, Volatile Matter, Fixed Carbon and Ash)	Duplicate	All Samples	RPD ≤ 10%
Ultimate Analysis (Carbon, Hydrogen, Nitrogen and Oxygen)	- Duplicate - QC standard	- Every 10% of all samples - Every 10% of all samples	- RPD ≤ 10% - As certificate of analysis

Table 4. 4 *Quality assurance/Quality control criteria for mercury analysis*

Parameter	DQI	Frequency of quality control	Acceptance criteria
Ultimate Analysis (Sulfur)	- Duplicate - Reference material (RM)	- All samples - Every 10% of all samples	- RPD ≤ 10% - As certificate of analysis
Chemical Composition (Arsenic, Selenium, Sodium, Calcium, Barium)	- Method Blank - Duplicate -Continuing Calibration Verification (CCV) -Laboratory Fortified Blank (LFB) -Second Source Calibration Verification (SSCV) -Laboratory Fortified Matrix (LFM)	- Every 10% of all samples - Every 10% of all samples - Every 10% of all samples - Every 10% of all samples - Every 10% of all samples - Every 10% of all samples	- < Detection Limit - RPD ≤ 10% - Recovery 90-110% - Recovery 85-115% - Recovery 90-110% - Recovery 80-120%
Chemical Composition (Chlorine)	- Method Blank - Duplicate	- Every 10% of all samples - Every 10% of all samples	- < Detection Limit - RPD ≤10%
Chemical Composition (Bromine)	- Method Blank - Duplicate -Continuing Calibration Verification (CCV)	- Every 10% of all samples - Every 10% of all samples - Every 10% of all samples	- < Detection Limit - RPD ≤ 10% - Recovery 90-110%
Chemical Composition (Mercury)	- Method Blank - Duplicate - QC Check Standard	- Every 10% of all samples - Every 10% of all samples - Every 10% of all samples	- < Detection Limit - RPD ≤ 20% - Recovery 90-110%
QC in Seawater Analysis			
Mercury	- Method Blank - Duplicate	- Every 10% of all samples	- < Detection Limit - RPD ≤ 10%

Table 4. 4 *Quality assurance/Quality control criteria for mercury analysis*

Parameter	DQI	Frequency of quality control	Acceptance criteria
	- Initial Calibration Verification (ICV) -Continuing Calibration Verification (CCV) -Laboratory Fortified Blank (LFB) -Laboratory Fortified Matrix (LFM)	- Every 10% of all samples - Every 10% of all samples - Every 10% of all samples - Every 10% of all samples - Every 5% of all samples	- Recovery 95-105% - Recovery 90-110% - Recovery 85-115% - Recovery 85-115 %

5. Results

5.1 Properties of feed coal

Table 5.1 shows the results of proximate analysis for coal and lignite sampls from two power plants. The dominant coal type of these samples is bituminous imported from other countries. Bituminous had higher carbon and fixed carbon content, but lower content of sulfur, chlorine, mercury and arsenic than lignite. Both bituminous and lignite had very low concentration of bromine. (Table 5.1 to Table 5.3). The bituminous coal from the Plant 1 has a lower sulfur content than that from the Plant 3 and 4. Lignite from the Plant 2 contains Hg around 132.31±36.33 - 198.78±25.43 µg/kg. It is to note that lignite also has a higher content of As than that of bituminous coal (Table 5.3). Details of the results are described in Annex-3

Table 5. 1 *Proximate analysis of feed coals*

Coal source	% Content (Mean ± SD)				
	Inherent moisture	**Total moisture**	**Volatile Matter**	**Ash**	**Fixed Carbon**
Plant 1[a] *(Bituminous coal; n= 15)*					
BC (*n=5*)	1.37± 0.07	6.60±0.67	20.30±0.76	20.99±0.67	58.72±0.82
HV *(n=5)*	3.15±0.23	7.74±1.10	35.04±1.98	11.27±1.95	53.69±0.48
SU (*n=5*)	5.21±0.38	13.27±1.65	37.30±1.23	14.11±0.74	48.60±1.17
Plant 2[b] *(Lignite; n=10)*					
CS1 *(n=5*)	15.83±0.44	30.57±1.52	42.58±1.44	32.18±2.57	25.24±2.37
CS2 *(n=5*)	19.06±1.42	32.49±1.47	43.06±2.06	31.45±4.97	25.49±3.47
Plant 3[c] *(Bituminous coal; n=15)*					
JM *(n=5)*	12.10±0.44	19.25±1.53	46.08±0.31	5.20±0.73	48.72±0.61
KP *(n=5)*	11.32±0.77	19.14±1.40	44.43±0.31	7.62±0.68	47.96±0.64
KM *(n=5)*	12.38±0.62	22.22±2.60	45.94±0.24	6.40±1.49	47.67±1.35
Plant 4[d] *(Bituminous coal; n=10)*					
BP *(n=5)*	11.78±1.06	21.62±1.82	44.34±0.35	7.16±1.23	48.50±0.94
LN (n=5)	15.34±0.91	35.45±1.21	47.36±0.40	8.44±1.84	44.20±1.94

Note: *[a,c,d] represent the power plant that uses bituminous as its fuel; [b] represents the power plant that uses lignite as its fuel.*

Table 5. 2 Ultimate analysis of feed coals

Coal source	% Content (Mean ± SD)				
	Carbon (C)	**Hydrogen (H)**	**Nitrogen (N)**	**Sulfur (S)**	**Oxygen (O)**
Plant 1 *(n= 15)*					
BC (*n=5*)	56.72±2.25	4.14±0.07	0.76±0.05	0.34±0.01	17.05±2.16
HV *(n=5)*	64.92±5.16	5.19±0.21	1.40±0.23	0.51±0.02	16.71±4.36
SU (*n=5*)	63.76±2.62	5.24±0.21	1.32±0.16	0.41+0.02	15.16±2.82
Plant 2 *(n=10)*					
CS1 *(n=5*)	47.55±2.31	5.67±0.08	1.78±0.08	4.70±1.03	8.12±1.21
CS2 *(n=5*)	48.86±3.27	6.28±0.41	1.77±0.10	4.46±1.51	7.17±2.34
Plant 3 *(n=15)*					
JM *(n=5)*	68.04±0.84	6.57±0.19	1.40±0.06	0.14±0.02	18.65±0.56
KP *(n=5)*	67.01±1.02	6.28±0.19	1.37±0.02	0.74±0.08	16.99±0.96
KM *(n=5)*	66.95±1.01	6.50±0.13	1.35±0.02	0.63±0.09	18.31±1.36
Plant 4 *(n=10)*					
BP *(n=5)*	67.33±0.87	6.36±0.23	1.39±0.02	2.06±0.15	15.70±0.68
LN (n=5)	63.93±1.90	6.76±0.23	1.20±0.10	1.24±0.08	18.43±1.19

Table 5. 3 Chemical analysis of feed coals

Coal source	Concentration (Mean±SD)							
	Chlorine (g/kg)	**Bromine (mg/kg)**	**Mercury (µg/kg)**	**Arsenic (mg/kg)**	**Selenium (mg/kg)**	**Barium (g/kg)**	**Sodium (g/kg)**	**Calcium (g/kg)**
Plant 1 *(Bituminous; n= 15)*								
BC *(n=5)*	0.58±0.89	ND < 1.00	95.81±14.02	1.66±0.41	0.60±0.64	0.39±0.09	1.21±0.17	10.09±6.13
HV *(n=5)*	0.26±0.03	ND < 1.00	50.04±30.94	16.61±3.43	0.86±0.24	0.94±0.73	4.75±1.57	17.66±13.30
SU *(n=5)*	0.54±1.01	ND < 1.00	64.49±10.03	17.10±2.95	0.89±0.47	1.21±0.67	5.00±1.51	25.18±11.90
Plant 2 *(Lignite; n= 10)*								
CS1 *(n=5*)	0.09±0.02	ND < 1.00	198.78±25.43	411.63±47.43	0.76±0.28	0.10±0.03	12.49±0.48	93.36±16.28
CS2 *(n=5*)	0.15±0.03	ND < 1.00	132.31±36.33	290.12±46.05	1.29±0.20	0.26±0.04	9.21±0.30	116.44 ±12.12
Plant 3 *(Bituminous; n=15)*								

Table 5. 3 Chemical analysis of feed coals

Coal source	Concentration (Mean±SD)							
	Chlorine (g/kg)	**Bromine (mg/kg)**	**Mercury (µg/kg)**	**Arsenic (mg/kg)**	**Selenium (mg/kg)**	**Barium (g/kg)**	**Sodium (g/kg)**	**Calcium (g/kg)**
JM *(n=5)*	0.19±0.03	ND < 1.00	20.84±2.41	23.66±1.82	1.43±0.35	2.14±0.35	22.36±2.47	106.69±10.82
KP *(n=5)*	0.15±0.05	ND < 1.00	35.20±7.66	23.55±1.94	0.01±0.02	0.88±0.05	7.41±0.60	25.49±1.45
KM *(n=5)*	0.19±0.04	ND < 1.00	36.21±8.46	22.17±1.89	0.62±0.43	1.51±0.16	23.45±2.95	66.06±6.63
Plant 4 *(Bituminous; n=10)*								
BP *(n=5)*	0.20±0.03	ND < 1.00	49.09±9.82	38.87±4.53	0.02±0.02	0.52±0.05	15.89±1.54	37.32±4.75
LN (n=5)	0.29±0.10	ND < 1.00	65.74±14.82	43.71±0.60	0.00	1.87±0.22	1.20±0.13	56.43±6.36

5.2 Mercury concentration and speciation in samples from combustion process

As explained in section 4.4, the pulverized coal, combustion products and stack gas at the Plant 1 and 2 were collected and analyzed following the standard methods of the ASTM. It should be noted that the Plant 1 (one electricity generation unit) and Plant 2 (3 operation units) were selected as a representative of the power plants that use bituminous and lignite as fuel for generating electricity, respectively. In addition, at each power plant, five sampling cycles were repeatedly performed for five consecutive days. Results of mercury concentrations in solid/liquid samples and flue gas at each electricity generation unit are summarized in Table 5.4. Details of each sampling cycle are summarized in Annex-4.

Bituminous feed coal contains mercury content less than lignite around 50% (Table 5.4). Mercury content in fly ash was found to be higher than that in bottom ash, except for Plant 2/Unit 10. The oxidized mercury (Hg^{2+}) was most likely bound to gypsum slurry with concentration about 140.69 ± 8.79-168.92±38.92 µg/kg. However, it was found in SWFGD with very low concentration (0.09±0.02 µg/kg). Table 5.5 shows the results of mercury speciation and distribution at the downstream of the APCDs. In general, the total mercury concentration in the flue gas streams (i.e., Hg^0, Hg^{2+} and Hg_p) is correlated to the mercury content in the coal blends. The flue gases at stack of the Plant 1 contained all three forms with a similar portion about 32-36%, whereas in the Plant 2, the flue gases contained a significant

quantity of Hg^0, possessing 67-81% of the total mercury. It is to note that actually, approximate Hg speciation could be estimated from samples directly measured as three forms (Hg^0, Hg^{2+} and Hgp); however, in this study its speciation was assumed from the Hg behavior in flue gas at downstream of APCDs.

Table 5. 4 *Mercury concentrations in solid/liquid samples and flue gas at each sampling location*

Type of sample	Mercury concentrations as dry weight (Mean±SD)			
	Plant 1 (5 cycles)	Plant 2[a] (5 cycles)		
		Unit 6	Unit 10	Unit 13
Feed coal (µg/kg)	59.90±12.10	132.52±8.46	114.97 ± 14.28	124.43 ± 10.09
Sea water-In (µg/L)[b]	0.004±0.002			
Limestone (µg/kg)[c]		75.19±30.45	48.95 ± 8.40	54.65 ± 10.45
Bottom ash (µg/kg)	1.21±0.50	8.27±11.18	18.43 ± 23.62	7.50 ± 5.66
Fly ash (µg/kg)	47.59±17.22	22.37±3.60	18.39 ± 5.16	34.74 ± 12.00
Sea water-Out (µg/kg)[b]	0.09±0.02			
Gypsum (µg/kg)[c]		168.92±38.92	140.69 ± 8.79	165.98 ± 45.91
Stack gas (µg /m^3)	0.69±0.39	7.99±3.94	9.90 ± 1.98	5.22 ± 2.62
-particulate (µg /m^3)	0.07±0.14	0.01±0.01	0.03±0.05	0.02±0.02
-oxidized Hg (µg /m^3)	0.01±0.003	0.45±0.30	0.20±0.20	0.15±0.15
-Vapor Hg (µg /m^3)	0.61±0.34	7.52±3.88	9.67±2.04	5.04±2.54

Note: [a] denotes that in the plant 2, samples were collected from 3 electric generation unites, which were unit 6, 10 and 13.
[b] represents the power plant being installed with the sea water-FGD
[c] represents the power plant being installed with the wet-FGD

Table 5. 5 *Mercury speciation in flue gas at the down streams of APCDs*

Plant	Mercury species	Proportion (%)	
		Range	Mean±SD
Plant 1	Hg(p)	20-45	32±9
	Hg^{2+}	25-47	36±10
	Hg^0	21-53	33±12
Plant 2/Unit 6	Hg(p)	2-8	5±3
	Hg^{2+}	14-44	26±14
	Hg^0	47-84	70±16
Plant 2/Unit 10	Hg(p)	2-5	3±1
	Hg^{2+}	12-21	16±4
	Hg^0	76-83	81±3
Plant 2/Unit 13	Hg(p)	5-9	7±2
	Hg^{2+}	13-41	26±11
	Hg^0	49-82	67±12

5.3 Mercury mass balance in coal fired power plants

As explained in section 4.4, throughout the combustion process, mercury was emitted with three different forms. At the Plant 1 and 2, the mass balance of mercury was calculated from these following parameters, which are amount of feed coal, seawater (in), bottom ash, fly ash, seawater (out), and flue gas for Plant 1 and amount of feed coal, limestone, bottom ash, fly ash, gypsum, and flue gas for Plant 2 (Unit 6, 10 and 13). These data were obtained from the records of the Plant 1 and 2; and Hg concentrations from this study (Table 5.4). In order to establish the Hg mass flow rates entering and leaving plants, the quantities of coal combustion products as summarized in Annex-4 were multiplied by the mercury contents found in each combustion product and untreated flue gas.

Table 5.6 presents all the Hg mass flow rates entering and leaving the plants. From these data, the Hg mass balances across the entire process and across each of the air pollution control devices were calculated. The primary sources of Hg leaving the plant were the stack emissions. Some Hg also left the plant through the ESP fly ash. As would be expected, the very high temperatures in the boiler resulted in the Hg concentration in the bottom ash being low concentration. The overall Hg balance was around 38.6% for Plant 1, 82.2% for Plant 2/Unit 6, 109% for Plant 2/Unit 10 and about 64.8% for Plant 2/Unit 13. Only the result of the Plant 2 was within the acceptable error range of ±30 as proposed by Takahisa et al., 2000 and Yu et al., 2014.

Table 5. 6 Mercury mass flow rates of Plant 1 and 2

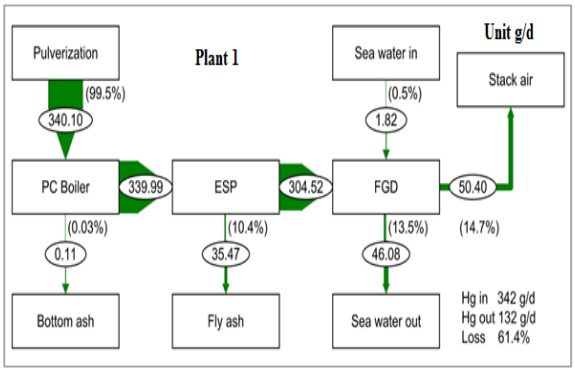
Mass flow	**Plant 1**	**Plant 2 (mean±SD)**		
	(*n*=5;mean±SD)	**Unit 6 (*n*=5)**	**Unit 10 *(n=5)***	**Unit 13 *(n=5)***
Hg in (g/d)				
Feed coal	340.00±68.00	735.00±44.00	543.50±71.46	595.00±49.00
Sea water (in)	1.82±1.20			
Limestone		44±18.00	22.85±3.87	19.00±4.00
Hg out (g/d)				
Bottom ash	0.11±0.00	5.00±6.00	8.51±10.17	3.00+2.00
Fly ash	35.00±13.00	19.00±3.00	11.44±3.01	22.00 ±8.00
Sea water (out)	46.08±12.15			
Gypsum		114.00±27.00	83.65±6.03	85.00±23.00
Stack gas	50.00±28.00	504.00±249.00	513.69±109.39	288.00±146.00
% Hg out/in				
Range	29.6-66.9	37.9-122.0	87.4-122.9	37.7-97.4
Mean	38.6	82.2	109.0	64.8

Table 5. 6 Mercury mass flow rates of Plant 1 and 2

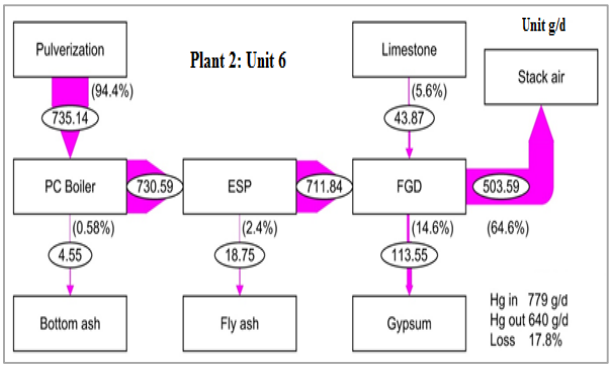
Mass flow	Plant 1 (*n=5*;mean±SD)	Plant 2 (mean±SD)		
		Unit 6 (*n=5*)	Unit 10 (*n=5*)	Unit 13 (*n=5*)
%Loss				
Range	33.1-70.4	(-) 22.0-62.1	(-) 22.9-12.6	2.6-62.3
Mean	61.4	17.8	(-) 9.0	35.2

Results of mercury mass flow rates obtained from this study (as shown in Table 5.6) were formed into the schematic flow diagram using the principle of mass balance to identify the potential sources of mercury accumulation in the system. Figure 5.1 illustrates Hg mass flow rates of Plant 1 and 2.

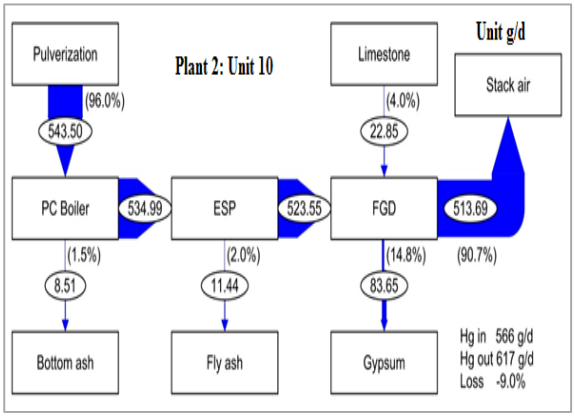
Figure 5. 1 *Hg mass flow rates of bituminous and lignite power plants (three units)*



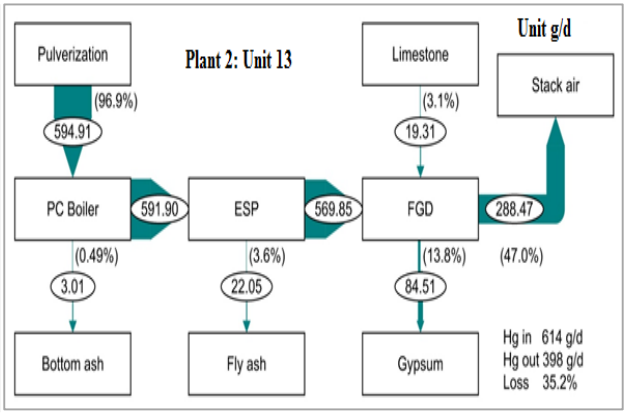
A: Plant 1 Bituminous



B: Plant 2 Lignite/Unit 6



C: Plant 2 Lignite/Unit 10



D: Plant 2 Lignite/Unit 13

5.4 Future mercury emission estimates from coal fired power plants in Thailand: Scenario of estimation for 2025

The future trend of an atmospheric mercury emission from 2017 to 2025 were estimated in associated with the projected coal consumption from Ministry of Energy (EPPO, 2015). The emission calculations were based on two approaches as follows:

5.4.1 Using the measured data from this study

Based on the actual data collected from this study, the calculations were performed following two scenarios. These are:

1) Assumingly, at the high combustion temperatures mercury contained in coal is practically entirely transferred to the gaseous state and, passed through the emission treatment systems, adhering to particle captured by the ESP, following by being soluble Hg^{2+} compounds in the wet or sea water flue gas desulfurization (WFGD/SWFGD) systems. Consequently, vapor-phase elemental mercury (Hg^0), and vapor-phase oxidized mercury are totally emitted to atmosphere. In addition, the mercury mass balance is assumed to be within the acceptable error range of ±30 as proposed by Takahisa et al., 2000 and Yu et al., 2014. Therefore, Hg emission factor can be estimated from the direct stack emission of mercury (actual concentrations);

2) Assumingly, during combustion, the mercury in the coal is transformed into particle-bound mercury (Hg_p), vapor-phase elemental mercury (Hg^0) and vapor-phase oxidized mercury (Hg^2). When passing through the ESP and WFGD/SWFGD, these Hg species are partially captured in bottom ash, fly ash, and sea water/gypsum, then the uncaptured fractions are thought to be the emission. Therefore, Hg emission factor can be estimated from the uncaptured emission.

Table 5.7 shows the emission factors of Plant 1, which uses bituminous as its fuel, and of Plant 2, which uses lignite as its fuel. The emission factor from the scenario 2 is higher than that from scenario 1. In addition, no matter what scenario applied, Plant 2 emitted higher mercury concentration than Plant 1. In associated with scenarios, the emission factor of Plant 1 are 8.59 ± 4.86 and 44.31 ± 11.40, respectively. Likewise, for the Plant 2, the emission factors are 69.67 ± 30.07 and 85.76 ± 9.91, respectively. Details of the results are presented in Annex-5

Table 5. 7 Emission factors based on two calculation approaches

Calculation scenarios	Mercury emission factor (mg/ton)	
	Range	**Mean±SD**
1. Using the direct stack measurement		
Plant 1	4.50-15.36	8.59±4.86
Plant 2	22.41-109.69	69.67±30.07
2. Using uncaptured Hg emission		
Plant 1	29.19-55.69	44.31±11.40
Plant 2	68.45-103.61	85.76±9.91

1) **Scenario 1:** Using emission factor derived from stack measurement to predict future mercury emission from coal-fired power plant

Atmospheric mercury emission factor (EF) used in this scenario was calculated from direct stack measurement (Table 5.7). Based on the EF and the predicted consumptions of coal and lignite from 2017 to 2025 (Table 5.8), the future trend of mercury emissions (between 2017 and 2025) from lignite fired power plant, existing bituminous fired power plant, and new bituminous fired power plant were then estimated by the equation (1).

$$ME = CC * EF_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where ME is Hg emission (kgHg/y); CC means coal consumption a year (Mton/y); EF_s is Hg emission factor estimated from stack measurement (mgHg/t)

As shown in Table 5.9, the atmospheric mercury emission from lignite power plant will gradually declines, whereas the emission from new bituminous power plants slightly increases from 2021 to 2025. The average atmospheric mercury emission from Thai coal-fired power plants is expected to be 555 kilograms by 2025, about 75.3% from lignite power plant, 10.8% from existing bituminous power plant and 13.9% from new bituminous power plant. Figure 5.2 shows the future trend of Hg emission from coal fired power plants in Thailand. In 2025, the

predicted Hg emission is expected to decrease about 52.8% compared with those in 2017. This is because lignite consumption is projected to decline by about 62.5%, even though bituminous consumption is expected to increase about 28.6% compared with bituminous consumed in 2017.

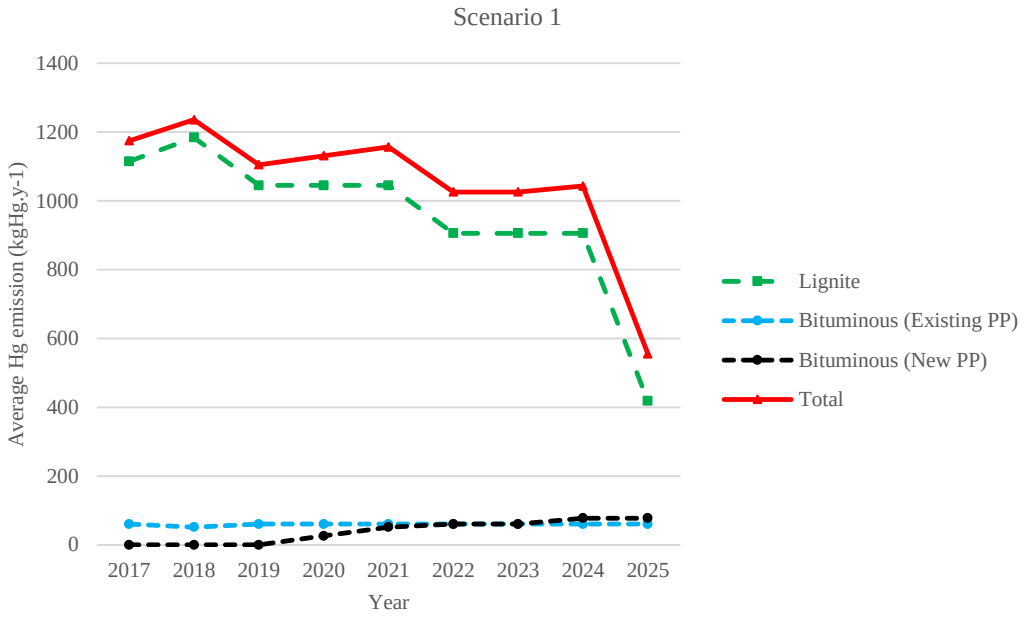
Table 5. 8 Coal and lignite consumption predicted for 2017-2025 (EPPO, 2015)

Type	**Consumption (Mton)**								
	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
Lignite	16	17	15	15	15	13	13	13	6
Bituminous	7	6	7	10	13	14	14	16	16
Total	**23**	**23**	**22**	**25**	**28**	**27**	**27**	**29**	**22**

***Table 5. 9** Mercury emission based on the emission factor estimated from mercury stack concentration*

Coal type	**Mercury emission**	**Unit**	**Year**								
			2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
Lignite	Minimum	kg/y	359	381	336	336	336	291	291	291	134
	Average	kg/y	1115	1184	1045	1045	1045	906	906	906	418
	Maximum	kg/y	1755	1865	1645	1645	1645	1426	1426	1426	658
Bituminous	Minimum	kg/y	32	27	32	32	32	32	32	32	32
(Existing	Average	kg/y	60	52	60	60	60	60	60	60	60
Plant)	Maximum	kg/y	108	92	108	108	108	108	108	108	108
Bituminous	Minimum	kg/y	0	0	0	14	27	32	32	41	41
(New Plant)	Average	kg/y	0	0	0	26	52	60	60	77	77
	Maximum	kg/y	0	0	0	46	92	108	108	138	138
Total	**Minimum**	**kg/y**	**390**	**408**	**368**	**381**	**395**	**354**	**354**	**363**	**206**
	Average	**kg/y**	**1175**	**1236**	**1105**	**1131**	**1157**	**1026**	**1026**	**1043**	**555**
	Maximum	**kg/y**	**1863**	**1957**	**1753**	**1799**	**1845**	**1641**	**1641**	**1672**	**904**

Figure 5. 2 *Future mercury emission estimated from stack measurement*



Scenario 2: Using uncaptured Hg emission factor to predict future mercury emission from coal-fired power plant

Based on the EF estimated from the uncaptured Hg emission, the future trend of mercury emissions (between 2017 and 2025) were then estimated by the equation (1). As expected for the future trend estimation, the atmospheric mercury emission from lignite power plant will be expected gradually declines, whereas the emission from bituminous power plants slightly increases from 2021 to 2025 (Table 5.10). The average atmospheric mercury emission from Thai coal-fired power plants is expected to be 1224 kilograms in 2025. Figure 5.3 shows the future trend of Hg emission from coal fired power plants in Thailand. In 2025, the Hg emission is expected to decrease about 27.2% compared with those in 2017. This findings were slightly different from those in scenario 1 as the EF in this scenario is higher than that in scenario 1. Mercury emission from bituminous power plant is also found to be higher than scenario 1, resulting in higher total Hg emission rate than the emission rate generated under scenario 1 assumption.

Table 5. 10 *Future mercury emission estimated from uncaptured mercury emission*

Coal type	Mercury emission	Unit	Year								
			2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
Lignite	Minimum	kg/y	2,054	1,985	1,917	1,574	1,574	1,437	1,437	1,437	890
	Average	kg/y	2,573	2,487	2,401	1,972	1,972	1,801	1,801	1,801	1,115
	Maximum	kg/y	3,108	3,005	2,901	2,383	2,383	2,176	2,176	2,176	1,347
Bituminous	Minimum	kg/y	204	175	204	292	379	409	409	467	467
	Average	kg/y	310	266	310	443	576	620	620	709	709
	Maximum	kg/y	390	334	390	557	724	780	780	891	891
Total	**Minimum**	**kg/y**	**2,258**	**2,160**	**2,121**	**1,866**	**1,954**	**1,846**	**1,846**	**1,904**	**1,357**
	Average	**kg/y**	**2,883**	**2,753**	**2,711**	**2,416**	**2,549**	**2,421**	**2,421**	**2,510**	**1,824**
	Maximum	**kg/y**	**3,498**	**3,339**	**3,291**	**2,940**	**3,107**	**2,955**	**2,955**	**3,067**	**2,238**

5.4.2 Using the existing Hg removal efficiency of relevant APCDs in literatures

In Thailand, 23 coal-fired power plants are equipped with various types of APCDs, then, removal efficiency of different installed APCD must be taken into account. Therefore, the mercury removal efficiencies given by literature were reviewed and selected in relevant to the APCDs installed in the coal-fired power plants in Thailand. The adopted Hg removal efficiencies are summarized in Table 5.11. However, it was not all types of APCD that were reported in the literature. For example, the removal efficiency of the power plant equipped with PC, CS-ESP, and SW-FGD has not been found, then the mercury removal efficiency for the PC, SCR, CS-ESP, and SW-FGD was assumingly used to estimate the mercury emission instead of the system composed of PC, CS-ESP, and SW-FGD. In addition, due to lack of information about the types of APCD that is installed in small coal fired power plants, we assumed that these plants operate without APCDs (as uncontrolled system). Thus, the removal efficiency of boiler from this study was used to estimate the emission for uncontrolled system (Table 5.12).

Table 5. 11 *Reviewed mercury removal efficiency of relevant air pollution control devices*

Coal Type	APCDs	Hg removal Efficiency (%)	Country	Reference
Bituminous	PC+CS-ESP	27	China	Wang et al., 2010
Bituminous	PC+CS-ESP+WFGD	21	China	Wang et al., 2010
Bituminous	PC+FF+WFGD	71	USA	ICR, 2010

Table 5. 11 *Reviewed mercury removal efficiency of relevant air pollution control devices*

Coal Type	APCDs	Hg removal Efficiency (%)	Country	Reference
Bituminous	PC+SCR+CS-ESP+WFGD	66	USA	Cheng et al., 2009
Bituminous	PC+SCR+CS-ESP+SW-FGD	29	China	Chen et al., 2008
Lignite	PC+SCR+CS-ESP+WFGD	39	China	Wang et al., 2010

PC: Pulverized boiler; CS-ESP: Cold side –Electro-static precipitation; WFGD: wet Flue gas desulfurization; FF: Filter fabric; SCR: selective catalytic reduction; SW-FGD: sea water flue gas desulfurization

Table 5. 12 *Removal efficiency of boiler*

Power plant	**Mercury removal efficiency (%)**	
	Range	**Mean±SD**
Plant 1	0.01-0.07	0.03±0.03
Plant 2	0.04-3.96	0.86±1.10

Using mercury removal efficiency described in Table 5.11 and 5.12, the future trend of mercury emission from 23 existing and new expected coal fired power plants in future were estimated from 2017-2025. Figure 5.3 shows that lignite plays the significant source of Hg emission. The current APCDs installed may not be able to efficiently control Hg emission from coal combustion (Table 5.13). By 2025, the total Hg emission is expected to decrease; and collectively, mercury emitted from a lignite power plant will be reduced around 66% comparing to the rate found in 2017 (Figure 5.4). It is expected that Hg emission from bituminous power plants may slightly increase after 2020. Apparently, the new bituminous power plants will be the significant source of increased mercury emission, whereas the emission from the existing bituminous power plants remain steadily (Figure 5.4). It is to note that the calculation for new power plants, which are not yet developed, was based on the worst-case assumption that these plants would be operated without APCDs. Details of results are shown in Annex-6.

Figure 5. 3 *Future Hg emission estimated using the adopted removal efficiency of different APCD systems, which was taken from literatures*

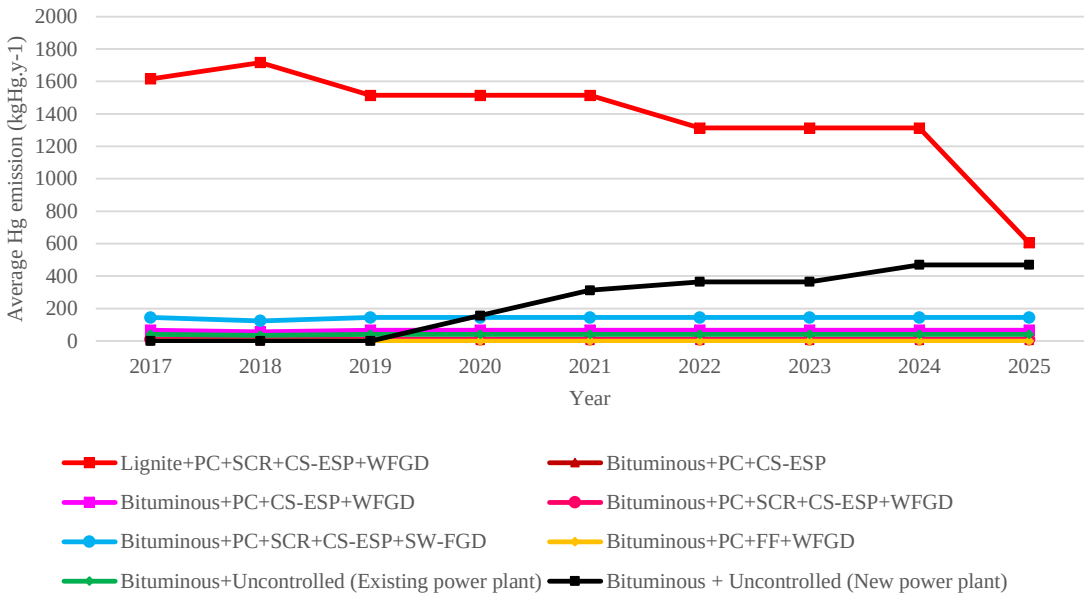


Figure 5. 4 *Future Hg emissions of 23 coal and lignite power plants and new power plants which were estimated by using the adopted Hg removal efficiency taken from literatures*

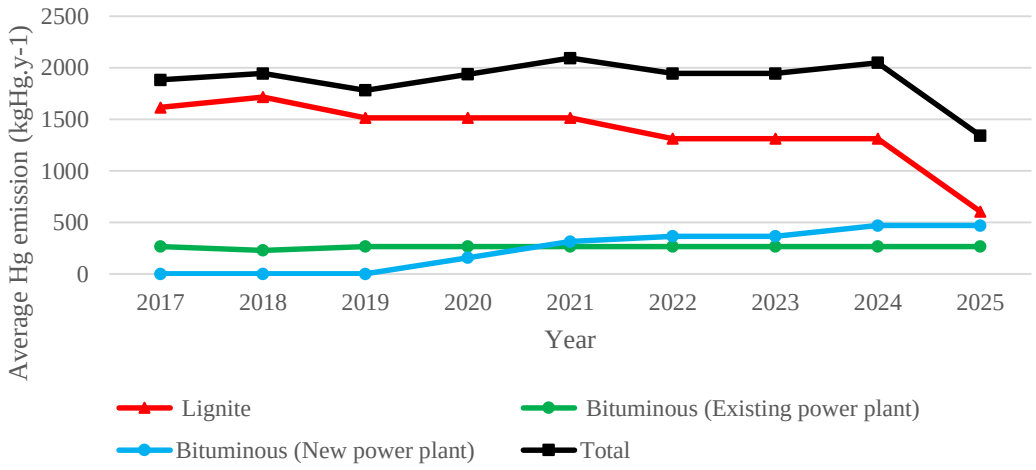


Table 5. 13 *Predicted Hg emissions from 23 existing coal fired power plants and new power plant equipped with different air pollution controlled devices*

APCD	Coal type	Average Hg emission (kg/y)								
		2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
PC+SCR+CS-ESP+WFGD	Lignite	1,616	1,717	1,515	1,515	1,515	1,313	1,313	1,313	606
PC+CS-ESP	Bituminous	3	3	3	3	3	3	3	3	3
PC+CS-ESP+WFGD	Bituminous	67	57	67	67	67	67	67	67	67
PC+SCR+CS-ESP+WFGD	Bituminous	11	9	11	11	11	11	11	11	11
PC+SCR+CS-ESP+SW-FGD	Bituminous	145	124	145	145	145	145	145	145	145
PC+FF+WFGD	Bituminous	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Uncontrolled (Existing plant)	Bituminous	41	35	41	41	41	41	41	41	41
Uncontrolled (New plant)	Bituminous	0	0	0	156	313	365	365	469	469

PC: Pulverized boiler; CS-ESP: Cold side –Electro-static precipitation; WFGD: wet Flue gas desulfurization; FF: Filter fabric; SCR: selective catalytic reduction; SW-FGD: sea water flue gas desulfurization; Uncontrolled: power plant that operates without APCD installation

5.5 Summary

The results of this study can be summarized as follows:

1) Bituminous had higher carbon and fixed carbon content, but lower content of sulfur, chlorine, mercury and arsenic than lignite. Both bituminous and lignite had very low concentration of bromine.

2) Mercury content in fly ash was found to be higher than that in bottom ash. The oxidized mercury form (Hg^{2+}) was most likely bound to gypsum slurry with concentration about 140.69 ± 8.79-168.92±38.92 µg/kg. However, it was found in SWFGD with very low concentration (0.09±0.02 µg/kg). The flue gases at stack of the Plant 1 contained all three forms with a similar portion about 32-36%, whereas in the Plant 2, the flue gases contained a significant quantity of Hg_0, possessing 67-81% of the total mercury. It is to note that in this study its speciation was assumed from the Hg behavior in flue gas at downstream of APCDs.

3) Overall Hg balance for each plant was around 38.6% for Plant 1 and for Plant 2 with the rate ranged from 64.8% to 109%. Only the result of the Plant 2 was within the acceptable error range of ±30.

4) To generate the most likely estimation of future trend of mercury emission, two approaches were applied, which were (1) using the measured data from this study and (2) using the existing Hg removal efficiency of relevant APCDs in literatures. For the approach 1, it was found that emission factors from the scenario 2 is higher than that from scenario 1. In addition, no matter what scenario applied, Plant 2 emitted higher mercury concentration than Plant 1.

When using the existing mercury removal efficiency of the co-benefit APCDs to predict the future trend of mercury emission from 23 existing and new expected power plants from 2017-2025, lignite power plant still plays the significant source of Hg emission. However, by 2025 the total Hg emission is expected to decrease and collectively the Hg emission from lignite combustion will be reduced around 66%. It is expected that Hg emission from bituminous power plants may slightly increase after 2020. Apparently, the new expected bituminous power plants will be the significant source of increasing mercury emission, whereas the emission from the existing bituminous power plants remain steadily. It is to note that the calculation for new power plants, which are not yet developed, was based on the worst-case assumption that these plants would be operated without APCDs. The most important factors affecting mercury

emissions are the mercury content of coal and the mercury removal efficiency of APCD (air pollutant control devices).

5.6 Quality assurance and quality control (QA/QC)

Quality assurance (QA) and quality control (QC) were planned and strictly followed to ensure quality of data gathered in this project as described in section 4. Results of QA/ QC are shown below.

5.6.1 QC in the field

Table 5.14 shows the results of blank testing. Each field blank was performed every 20 samples. The overall results indicated that there were no contamination during field sampling (Table 5.14). The trip blank was performed in every trip to the field. Results indicated that there were no contamination during transportation. In addition, at least one equipment blank was collected for every 20 samples per parameter group and per each matrix, results indicated that there were no contamination from sampling equipment.

Table 5. 14 Blanks for mercury samples

Parameter	DQI	Frequency	results
Field Blank	< detection limit	every 20 samples	< detection limit (0.020 µg/L)
Trip Blank	< detection limit	every trip to the field	< detection limit (0.020 µg/L)
Equipment Blank	< detection limit	every 20 samples per parameter group and per each matrix	< detection limit (0.020 µg/L)

Air sampling equipment for mercury in air emission were calibrated before sampling. The leak check, dry gas meter (Yc), % isokinetic and temperature control calibrating results indicated that equipment were well maintained. Equipment calibration results are shown in Table 5.15.

Table 5. 15 *Air sampling equipment calibration results*

Parameter DQI	Acceptance criteria	Frequency	Results
leak check	< 0.00057 m^3/min	Before and after every sampling	0.0000 m^3/min
dry gas meter (Yc)	0.97Y< Yc < 1.03Y	before every sampling	Y = 0.951
% isokinetic	90-110 %	before every sampling	98.05-105.16 %
temperature control	120 ±14 ºC (106-134 ºC)	before every sampling	118-119.42 ºC

5.6.2 QC in the laboratory

QC in the laboratory including QC in sampling receiving; QC for air sample analysis; coal, ash, gypsum and seawater analysis were done as previously described. QC results are shown in Table 5.16.

5.6.3 Instrument calibration

All instruments used in the analysis were calibrated with standard solution prior to analysis and maintained routinely. Analytical instrument used for sample analysis were calibrated by qualified personal, the certificate of calibrations were attached.

1) Quality assessment

All quality control results are in acceptance criteria as shown in the Tale 5.16.

2) Data Validation

In order to validate the results, test results were compared to data quality indicators (DQI) to ensure good quality of data. Results indicating that all test results were within the acceptance criteria. Data validation were shown in Table 5.16.

5.6.4 Inter-laboratory comparison

UAE (United Analyst and Engineering Consultant) is appointed to be the laboratory to measure all parameters in this study. According to UN environment, UAE has to conduct the inter-laboratory testing. Mann-Whitney U test was used to compare means. All parameter measurements were not significantly different, except for mercury measurement (Table 5.17 to Table 5.19). Details of the results are shown in Annex-1 and Annex-2 .

Table 5. 16 Quality Assurance/Quality Control results for mercury analysis

Parameter	DQI	Frequency of quality control	Acceptance criteria	Results
1. QC in Air Analysis				
Mercury Emission	Method Blank	Every 10% of all samples	< Detection Limit (< 0.001 mg/m^3)	All Sample < 0.001 mg/m^3
	Duplicate	Every 10% of all samples	RPD ≤ 10%	In Range 0 - 5.30 %
	Initial Calibration Verification (ICV)	Every 10% of all samples	Recovery 95-105%	Recovery = 99.2 - 103 %
	Second Source Calibration Verification standard (SSCV)	Every 10% of all samples	Recovery 90-110%	Recovery = 92.0 – 105 %
2. QC in Coal, Ash and Gypsum Analysis				
2.1 Proximate Analysis				
Moisture	Duplicate	All Samples	RPD ≤ 10%	In Range 0 - 6.55 %
Volatile Matter	Duplicate	All Samples	RPD ≤ 10%	In Range 0.01-5.87%
Fixed Carbon	Duplicate	All Samples	RPD ≤ 10%	In Range 0.02-7.67%
Ash	Duplicate	All Samples	RPD ≤ 10%	In Range 0 - 8.33%
2.2 Ultimate Analysis				
Carbon	Duplicate	Every 10% of all samples	RPD ≤ 10%	In Range 0.10-1.91%
	QC standard	Every 10% of all samples	As certificate of Analysis (40.86-41.32%)	41.023-41.080 %
Hydrogen	Duplicate	Every 10% of all samples	RPD ≤ 10%	In Range 0.17-1.51%
	QC standard	Every 10% of all samples	As certificate of analysis (5.46-5.56%)	5.499-5.520%
Nitrogen	Duplicate	Every 10% of all samples	RPD ≤ 10%	In Range 0.01-2.87%
	QC standard	Every 10% of all samples	As certificate of analysis (9.52-9.60%)	9.565-9.574%
Sulfur	Duplicate	All samples	RPD ≤ 10%	In Range 0.93-6.23%
	QC standard	Every 10% of all samples	As certificate of analysis (1.08-1.16%)	1.113-1.129 %
2.3 Chemical Composition				
Arsenic	Method Blank	Every 10% of all samples	< Detection Limit (<0.100 mg/L)	All Sample < 0.100 mg/kg (dry weight)
	Duplicate	Every 10% of all samples	RPD ≤ 10%	In Range 1.7 – 6.8 %
	Continuing Calibration Verification (CCV)	Every 10% of all samples	Recovery 90-110%	Recovery = 94.0 - 103 %

	Laboratory Fortified Blank (LFB)	Every 10% of all samples	Recovery 85-115%	Recovery = 93.6 - 104 %
	Second Source Calibration Verification (SSCV)	Every 10% of all samples	Recovery 90-110%	Recovery = 93.6 - 105 %
	Laboratory Fortified Matrix (LFM)	Every 10% of all samples	Recovery 80-120%	Recovery = 90.0 - 103 %
Selenium	Method Blank	Every 10% of all samples	< Detection Limit (<0.100 mg/kg)	All Sample < 0.100 mg/kg (dry weight)
	Duplicate	Every 10% of all samples	RPD ≤ 10%	In Range 3.9 – 9.6 %
	Continuing Calibration Verification(CCV)	Every 10% of all samples	Recovery 90-110%	Recovery = 95.0 - 106 %
	Laboratory Fortified Blank (LFB)	Every 10% of all samples	Recovery 85-115%	Recovery = 96.0 - 105 %
	Second Source Calibration Verification (SSCV)	Every 10% of all samples	Recovery 90-110%	Recovery = 95.4 - 102 %
	Laboratory Fortified Matrix (LFM)	Every 10% of all samples	Recovery 80-120%	Recovery = 95.1 - 110 %
Sodium	Method Blank	Every 10% of all samples	< Detection Limit (< 2.000 mg/kg)	All Sample < 2.000 mg/kg (dry weight)
	Duplicate	Every 10% of all samples	RPD ≤ 10%	In Range = 0.03 – 4.9 %
	Continuing Calibration Verification (CCV)	Every 10% of all samples	Recovery 90-110%	Recovery = 97.6 - 104 %
	Laboratory Fortified Blank (LFB)	Every 10% of all samples	Recovery 85-115%	Recovery = 98.7 - 104 %
	Second Source Calibration Verification (SSCV)	Every 10% of all samples	Recovery 90-110%	Recovery = 98.7 - 103 %
	Laboratory Fortified Matrix (LFM)	Every 10% of all samples	Recovery 80-120%	Recovery = 85.8 - 109 %
Calcium	Method Blank	Every 10% of all samples	< Detection Limit (< 2.000 mg/kg)	All Sample < 2.000 mg/kg (dry weight)
	Duplicate	Every 10% of all samples	RPD ≤ 10%	In Range = 0.12 – 1.9 %
	Continuing Calibration Verification (CCV)	Every 10% of all samples	Recovery 90-110%	Recovery = 98.2 - 101%
	Laboratory Fortified Blank (LFB)	Every 10% of all samples	Recovery 85-115%	Recovery = 95.6 - 105%
	Second Source Calibration Verification (SSCV)	Every 10% of all samples	Recovery 90-110%	Recovery = 95.3 - 101 %

	Laboratory Fortified Matrix (LFM)	Every 10% of all samples	Recovery 80-120%	Recovery = 93.0 – 107 %
Barium	Method Blank	Every 10% of all samples	< Detection Limit (< 1.000 mg/kg)	All Sample < 1.000 mg/kg (dry weight)
	Duplicate	Every 10% of all samples	RPD ≤ 10%	In Range= 0.10 – 6.9 %
	Continuing Calibration Verification(CCV)	Every 10% of all samples	Recovery 90-110%	Recovery = 100 - 104%
	Laboratory Fortified Blank (LFB)	Every 10% of all samples	Recovery 85-115%	Recovery = 100 - 108%
	Second Source Calibration Verification (SSCV)	Every 10% of all samples	Recovery 90-110%	Recovery = 97.8 - 105 %
	Laboratory Fortified Matrix (LFM)	Every 10% of all samples	Recovery 80-120%	Recovery = 95.7 – 110 %
Mercury	Method Blank	Every 10% of all samples	< Detection Limit (< 0.0100 mg/kg)	All Sample < 0.0100 mg/kg (dry weight)
	Duplicate	Every 10% of all samples	RPD ≤ 20%	In Range = 0.21 - 2.56 %
	QC Check Standard	Every 10% of all samples	Recovery 90-110%	Recovery = 94.1 - 105 %
Chlorine	Method Blank	Every 10% of all samples	< Detection Limit (< 2.0 mg/kg)	< 2.0 mg/kg
	Duplicate	Every 10% of all samples	RPD ≤10%	In Range = 0.54-2.46%
Bromine	Method Blank	Every 10% of all samples	< Detection Limit (< 1.0 mg/kg)	< 1.0 mg/kg
	Duplicate	Every 10% of all samples	RPD ≤ 10%	0%
	Continuing Calibration Verification (CCV)	Every 10% of all samples	Recovery 90-110%	Recovery 96.25-97.50%
3. QC in Seawater Analysis				
Mercury	Method Blank	Every 10% of all samples	< Detection Limit (< 0.020 µg/L)	All sample < 0.020 µg/L
	Duplicate	Every 10% of all samples	RPD ≤ 10%	0.25 %
	Initial Calibration Verification (ICV)	Every 10% of all samples	Recovery 95-105%	Recovery = 98.4 %
	Continuing Calibration Verification (CCV)	Every 10% of all samples	Recovery 90-110%	Recovery = 99.8 %
	Laboratory Fortified Blank (LFB)	Every 10% of all samples	Recovery 85-115%	Recovery = 107 %

Laboratory Fortified Matrix (LFM)	Every 5% of all samples	Recovery 85-115 %	Recovery = 105 %

Table 5. 17 *Inter-laboratory comparison: Proximate analysis*

Sample	Inherent Moisture (%)		Total Moisture (%)		Volatile Matter (% dry weight)		Ash (% dry weight)		Fixed Carbon (% dry weight)	
1	4.68	4.91	13.73	13.96	35.80	32.62	13.84	13.12	50.36	54.25
2	3.28	3.44	8.57	8.73	35.92	32.61	9.72	9.52	54.36	57.87
3	3.29	3.34	9.06	9.11	36.14	32.39	10.30	10.70	53.56	56.91
4	1.43	1.32	6.38	6.27	19.44	18.14	21.81	20.27	58.75	61.59
5	1.31	1.71	5.80	6.20	20.52	19.41	20.53	18.52	58.95	62.07
6	15.81	17.75	32.80	34.74	44.84	42.67	31.31	34.64	23.85	22.69
7	16.53	16.36	31.37	31.20	40.86	35.22	34.01	41.00	25.14	23.78
8	15.31	21.49	29.70	35.88	42.53	39.23	28.25	30.93	29.22	29.84
9	20.79	21.49	34.64	35.34	45.48	44.30	23.07	26.61	31.46	29.09
10	19.62	18.98	32.76	32.12	43.67	41.63	33.91	37.25	22.43	21.12
p-value*	0.571		0.623		0.241		0.791		0.910	

Note: ** tested by Mann-Whiteney U test*

Table 5. 18 *Inter-laboratory comparison: Ultimate analysis*

Sample	Carbon (% dry)		Hydrogen (% dry)		Nitrogen (% dry)		Sulfur (% dry)		Oxygen (% dry)	
1	59.73	69.32	5.08	5.36	1.08	1.72	0.42	0.82	19.86	9.64
2	61.81	74.12	5.29	5.47	1.58	1.72	0.54	0.91	21.06	8.26
3	71.23	73.29	5.31	5.40	1.36	1.67	0.49	0.96	11.30	7.99
4	54.69	69.30	4.13	4.26	0.71	1.30	0.34	0.60	18.31	4.28
5	60.34	69.02	4.21	4.40	0.83	1.30	0.35	0.60	13.74	6.17
6	48.52	46.60	5.71	6.30	1.69	1.51	3.06	4.16	9.71	6.80
7	44.50	42.66	5.71	6.05	1.76	1.54	5.51	4.33	8.50	4.42
8	50.62	48.25	5.75	7.46	1.89	1.68	5.34	4.19	8.15	7.49
9	54.30	51.46	6.89	7.46	1.91	1.68	4.00	4.23	9.83	8.56
10	47.47	43.94	6.29	6.86	1.68	1.44	6.80	4.79	3.84	5.71
p-value*	0.791		0.241		0.970		0.473		0.009	

Note: ** tested by Mann-Whiteney U test*

Table 5. ***19*** *Inter-laboratory comparison: Chemical analysis*

Sample	Mercury (Hg) (µg/kg)		Arsenic (As) (mg/kg)		Selenium (Se) (mg/kg)		Sodium (Na) (g/kg)		Calcium (Ca) (g/kg)		Barium (Ba) (mg/kg)		Chlorine (Cl) (mg/kg)		Bromine (Br) (mg/kg)	
1	64.89	21.03	16.7	16.8	0.9	<1	5.05	5.91	25.74	28.22	1716	1,358	104	261	ND < 1.00	< 10
2	38.53	10.36	17.0	16.6	0.6	<1	5.89	6.03	6.18	6.14	372	414	292	415	ND < 1.00	< 10
3	30.79	10.35	11.8	11.4	0.6	<1	4.72	3.55	5.35	6.20	313	337	233	339	ND < 1.00	< 10
4	119.61	50.67	1.4	< 1	NA	<1	1.18	0.74	6.41	8.00	363	350	185	413	ND < 1.00	< 10
5	90.27	40.70	1.8	< 1	0.8	<1	0.94	0.84	12.85	11.52	327	359	207	391	ND < 1.00	< 10
6	198.95	24.32	387	< 1	0.8	< 1	13.26	12.63	101.72	186.29	89	83	67.7	80	ND < 1.00	< 10
7	235.03	83.69	415	< 1	0.6	< 1	12.10	13.59	93.43	61.72	132	153	90	73	ND < 1.00	< 10
8	185.84	25.47	346	< 1	0.4	< 1	12.12	15.29	74.88	74.69	74	43	73	69	ND < 1.00	< 10
9	97.37	50.95	298	< 1	1.4	< 1	8.95	12.39	107.40	122.36	205	92	112	89	ND < 1.00	< 10
10	183.58	74.06	295	< 1	1.2	< 1	9.11	14.52	105.13	178.43	229	62	149	83	ND < 1.00	< 10
p- value*	0.000		0.002		NA		0.473		0.792		0.743		0.571		NA	
R-sq**	0.432															

Note: **tested by Mann–Whitney U test*
*** tested by Pearson correlation*

5.7 Uncertainty

Estimation of mercury emission in this study considered mainly from coal consumption which was taken from the Thailand energy projection plan. It is evidence that the actual energy consumption is lower than that the projection rate about 20% (IEA, 2016; EPPO, 2017). In addition, either emission factors or mercury removal efficiency, which were used for the calculation, was obtained from very small sample and few studies. As a result, emission factors or mercury removal efficiency are typically adopted from other studies with roughly similar conditions. The uncertainty components, which are found to contribute significantly during the subsequent calculation are described below:

5.7.1 Energy consumption and structure

As we calculated the Hg emission based on the projected coal consumption by EPPO, thus, the uncertainties from coal consumption prediction also relatively contribute to the estimation of Hg emission. Consumption projection for coal fired power plant involves many different sources of uncertainty. This includes uncertainties associated with model parameters, but also those related to model structure or disagreements between conceptual theories on a larger scale (Ruijvena, et, al., 2010).

5.7.2 Mercury content in coal

The mercury content of coal varies widely, introducing a high degree of uncertainty in estimating mercury emission from coal burning (UNEP, 2011). In particular, coal was sporadically sampled one time, but the result was used to calculate for the whole year of the operation.

5.7.3 Emission factor

The mercury mass balances during coal combustion in the Plant 1 and 2 (with 3 units) were 38.6% and 82.2% (Unit 6), 109% (Unit 10) and 64.8% (Unit 13), respectively. Only the result of the Plant 2 (lignite power plant) was within the acceptable error range of ±30 (Takahisa et al., 2000; Yu et al., 2014). As a result, the emission factor for bituminous may not be appropriate to use for estimating mercury emission. Consequently, it is necessary to adopt the mercury removal efficiency from other studies of China and USA. Because the processes and pollution control techniques used in Thailand may differ dramatically from those used in these countries, the adopted Hg emission factors could differ significantly from the actual field

conditions in this study. Thus, a large uncertainty could exist in the future estimation of mercury emission in this study.

5.8 Limitations

The limitations of this study are:

- Sample size is very small as well as all samples were collected sporadically. Thus, the results cannot be a meaningful representative for all coal fired power plants in Thailand;
- Approximate Hg mass balance could be calculated from a set of data in this study; however, a series of long-term and comprehensive study is required to evaluate the reliable Hg mass distribution and behavior in a coal-fired power plant. This study is one-year project, therefore, it has a limit tine to complete the project.
- Incomplete information about the existing coal fired power plants in Thailand.

6. Implications and policy recommendations

6.1 Mercury emission control options for coal fired power plant

According to the combustion processes, mercury bound to coal as a mineral associated with pyrite is transformed to be vapour elemental mercury (Hg^0), some of which is converted to gaseous oxidized mercury (Hg^{2+}) or particulate-bound mercury (Hg_p). This conversion also depends on coal properties (*e.g.*, mercury, chlorine, bromine, and ash content), combustion characteristics (*e.g.*, time/temperature profile), flue gas compositions, and fly ash characteristics (Wang et al., 2010). The efficiency of mercury capture of APCDs is strongly influenced by the mercury speciation profiles, which are plant-specific operations. It is found that Hg^{2+} and Hg_p are much easier to control than Hg^0; as well as; a high content of chlorine in the coal will enhance the oxidation of mercury (*i.e.*, its transformation from Hg^0 into Hg^{2+}). In contrast, high levels of sulfur in the coal will produce more SO_2 in the flue gas, which limits the ability of chlorine to oxidize the Hg^0.

As found in this study, lignite power plant emitted higher mercury than emission from bituminous power plants. In addition, combustion of bituminous generated Hg_p, Hg^{2+} and Hg^0 with similar proportions, whereas, for lignite combustion, most of the mercury form released is Hg^0. Regarding the APCDs installed in coal-fired power plants in Thailand, the combination of control devices is for controlling other air pollutants rather than mercury. Based on other studies from literature review, the efficiency of the existing APCDs to reduce mercury emission varies from 21-71% for bituminous power plants; and about 39% for lignite power plants (see Table 5.11).

Theoretically, the control measures available to reduce mercury emission from power plant include: (1) switching to a cleaner fuel containing less mercury; (2) installing effective control devices to reduce emission rate; (3) improving power generation efficiency to reduce emission rate; (4) considering alternative measures to lower mercury emission; and (5) increasing efficiency of electricity use in all sectors.

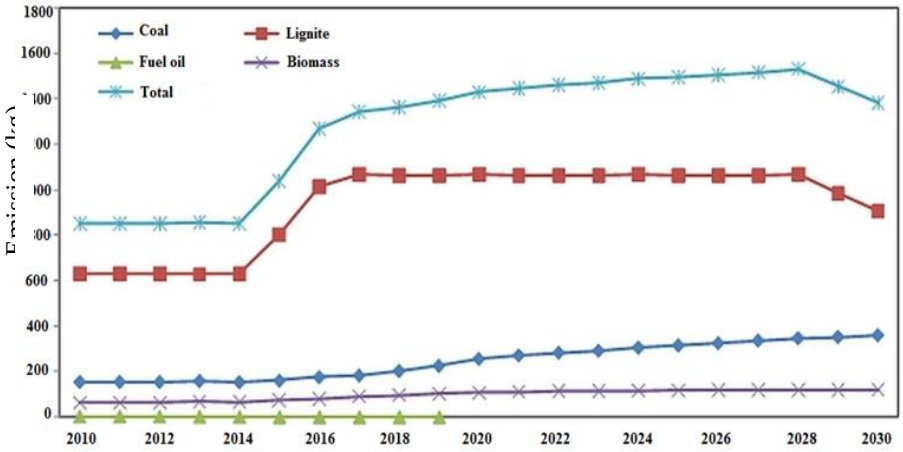
6.1.1 Switching to a cleaner fuel containing less mercury

The use of crop residues for energy production has been propagated as a substitute for fossil fuels including petroleum, coal, and natural gas. According to the environmental consequences, the alternative fuels in respect to less mercury content are thought to be necessary for reduction of mercury emission. At present, biomass is used for power generation. If sufficient biomass is available, bio-power and CHP (combined heat and power plants) are a clean and reliable power source suitable for base-load service (IEA, 2007).

- Biomass co-firing in modern, large scale coal power plants is efficient, cost-effective and requires moderate additional investment. In general, combustion efficiency of biomass can be 10 % lower than for coal at the same installation, but co-firing efficiency in large-scale coal plants (35%-45%) is higher than the efficiency of biomass-dedicated plants. Nevertheless, using low-cost local biomass, the incremental investment may have a short payback period, but low-quality biomass such as herbaceous crops and wet wood may produce tar and cause slagging and fouling that affects plant reliability and raises costs.
- Biomass can be burned to produce electricity and CHP via a steam turbine in dedicated power plants. The typical size of these plants is ten times smaller (from 1 to100 MW) than coal-fired plants because of the scarce availability of local feedstock and the high transportation cost. Typically, its electrical efficiency is lower than coal plants (30%-34% using dry biomass, and around 22% for municipal solid waste). In cogeneration mode the total efficiency may reach 85%-90%.
- Biogas can be used in combustion engines (10 kW to 10 MW) with efficiency of some 30%-35%; in gas turbines at higher efficiencies or in highly-efficient combined cycles. Biomass integrated gasification /gas turbines (BIG/GT) are not yet in commercial use, but their economics is expected to improve.

Based on the projection of Hg emissions in Thailand to 2030 by Thao, et al.(2015), Hg emission rate from biomass power plant is less than that from bituminous and lignite power plants (Figure 6.1).

Figure 6. 1 *Hg Emission Trends from Power Generation to National Grid during 2010–2030* (Thao, et al., 2015)



- Hydropower is the most efficient manner in converting energy with efficiency rates well above all other technologies. Because of its simplicity of using gravity to convert water mass to fall to a lower level and in between the two points using its potential energy converting to mechanical potential to electrical power.
- Solar thermal is the concentration of accumulated solar energy to a certain point where a boiler creates steam that will move a turbine shaft that in turn provides the rotational force that moves a generator. The thermal conversion of a solar thermal plant is about twelve percent.
- Photovoltaic is the process of converting solar light directly to electricity. Although breakthroughs for higher efficiencies are climbing this technology still ranks very low in converting sunlight directly to electricity. Although growing exponentially in market place, their overall market penetration and yearly efficiency of less than twenty percent limits their current use.
- Wind energy is the production of converting kinetic energy to electrical power. The use of the wind to produce electrical power has grown significantly all over the world. Wind energy just like solar thermal and photovoltaic is a market with limited penetration. The production of electricity from wind farms unlike thermal power plants depends on wind

distribution. This coupled with capacity factor limits their market efficiency to less than thirty percent.

- Geothermal power generation is the production of electricity using heat content under the surface of the Earth. As with other methods of converting heat from one source in order to generate mechanical energy in order to produce electrical power is commonly use in geological areas with thermal activities. The thermal efficiency is very low because the temperature of the heat source is very low compare to a steam boiler.

The Ministry of Energy has promoted the production of electricity from renewable energy since 1989 (EPPO, 2015). It encouraged the EGAT to purchase electricity from Co-generation power plant of small power producers (SPP) that used waste or residues in agricultural sector as feed stock to produce electricity and heat. Heat left over from the manufacturing process can be used to produce electricity for sale to a transmission line to promote generation efficiency and the public investment in the production and distribution of electricity. Later, the policy was expanded to purchase electricity from other renewable energy such as solar, hydropower, wind power, biogas, waste from very small power producers (VSPP: capacity no larger than 10 MW) to make more SPPs in remote areas to participate in the generation of electricity, reducing losses in the power system and to reduce the investment in large power plant to supply electricity. The proportion of electricity from renewable energy production from electricity generation system increased 9.87 % in 2014 (excluding large hydro).

With respect to commitment to develop a clean energy society and security of energy in Thailand, the government established the first 10-Year Alternative Energy Development Plan (AEDP) 2012-2021. By 2021, electricity will be generated by solar, wind, hydropower, waste-to-energy, biomass and biogases. The targets of AEDP 2012-2021 are summarized in Table 6.1. Biomass is expected to be the major energy for alternatively producing electricity by 2021 (Sutabutr, 2012).

Table 6. 1 Targets of alternative energy for electricity generation in Thailand under AEDP 2012-2021

Alternative energy	Unite	Targets by 2021
Solar	MW	2000
Wind	MW	1200
Small hydropower	MW	1608

Table 6. 1 Targets of alternative energy for electricity generation in Thailand under AEDP 2012-2021

Alternative energy	Unite	Targets by 2021
Biomass	MW	3630
Biogas	MW	600
Municipal solid waste	MW	160

Since then, this plan has been implemented and revised in 2015. Now, the revised ADEP has been planned from 2015-2030. Under the ADEP 2015, the target of electricity from all renewable energy is 20 % of the net electrical energy demand, which complies with the fuel diversification ratio in the power development plan 2015 - 2036 (EPPO, 2015). Table 6.2 shows the status and target of electricity generation by 2036. Biomass and solar are expected to be the large proportion for electricity generation (EPPO, 2015). In addition, Thai government has established three key strategies to continuously promote the development of renewable energy from 2015 – 2036, which are preparation of raw materials and renewable energy technologies; increasing renewable energy production, utilization and market potential; and motivating public awareness and knowledge on renewable energy.

Table 6. 2 *Status and targets of electricity generation by renewable energy under ADEP 2015*

Alternative energy	**Status in 2014 (MW)**	**Target by 2036 (MW)**
MSW	65.72	500.00
Industrial Waste	-	50.00
Biomass	2,451.82	5,570.00
Biogas (WW/SW)	311.50	600.00
Small Hydro	142.01	376.00
Biogas (Energy Crop)	-	680.00
Wind	224.47	3,002.00
Solar	1,298.51	6,000.00
Large Hydro	-	2,906.40*
Total install capacity (MW)	**4,494.03**	**19,684.40**
Electrical Energy (Million Units)	17,217	65,588.07
Total Electrical Energy Demand (Million Units)	174,467	326,119.00

Table 6. 2 Status and targets of electricity generation by renewable energy under ADEP 2015

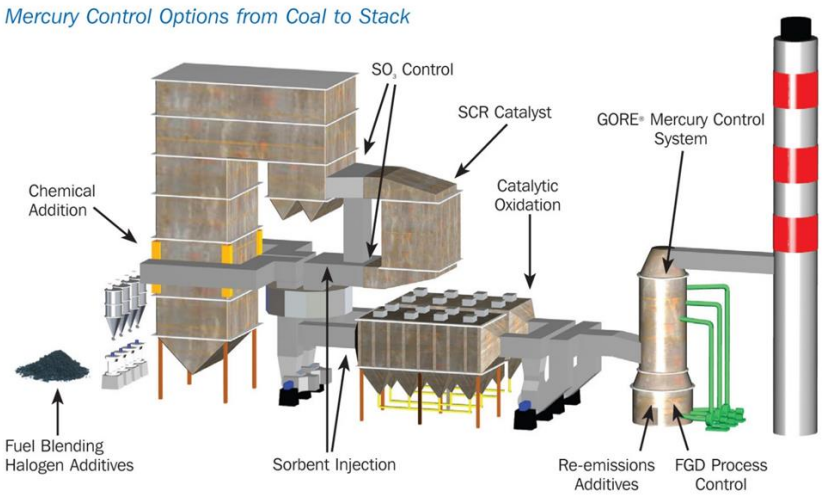
Alternative energy	Status in 2014 (MW)	Target by 2036 (MW)
Share of RE in Electricity Generation (%)	9.87	20.11

* It has been included as renewable energy for electricity since 2015.

6.1.2 Installing effective control devices to reduce emission rate

Controls designed to remove other pollutants can remove a substantial amount of mercury under certain conditions. APCDs designed to control other pollutants can also provide co-benefit mercury removal. Figure 6.2 illustrates the mercury control point of a power plant.

***Figure 6. 2** Example of mercury control options from coal to stack*



Source: http://readingrat.net/oil-fired-power-plant-overview-diagram/oil-fired-power-plant-overview-diagram-the-wiring-diagram/

In downstream particulate matter control devices, Gaseous mercury can be adsorbed onto bottom ash, fly ash and collected by the electrostatic precipitator (ESP) and fabric filter (FF). Both devices effectively capture Hg_p in flue gas (Lie, et. al., 2010; Zhang, et. al., 2012). The intimate contact between the gas and collected particles on the filter cake of FF significantly enhances the gas-phase mercury collection efficiency relative to what is possible with an ESP (for both bituminous and sub-bituminous coals).

The oxidized mercury can be absorbed in the aqueous slurry of a WFGD system. The dissolved species react with dissolved sulfides from the flue gas, such as H_2S, to form mercuric sulfide (HgS), which precipitates from the liquid solution as sludge. The capture of mercury in power plants equipped with WFGD is dependent on the relative amount of Hg^{2+} in the inlet flue gas and, on the PM control technology used. A selective catalytic reduction (SCR) can promote the oxidization of a significant portion of Hg_0, enhancing subsequent capture in WFGD.

Activated carbon injection (ACI) and halogen injection (HI) are the most commercially mature mercury-specific control technologies (Ancora, et.al., 2015). ACI technology has been proved that it can remove mercury in the flue gas through injection of activated carbon. Activated carbon is the most common sorbent due to its high degree of micro-porosity, which increases the surface area available for adsorption or chemical reactions. Mercury and other pollutants are adsorbed onto the surface of the activated carbon and subsequently removed by PM control technologies. Table 6.3 shows that the mercury removal efficiencies achieved by APCD combinations reflect their effectiveness in mercury control.

Table 6. 3 Reviewed mercury removal efficiency of relevant air pollution control devices

Coal Type	APCDs	Hg removal Efficiency (%)	Country	Reference
Bituminous	PC+CS-ESP	27	China	Wang et al., 2010
	PC+CS-ESP+WFGD	21	China	Wang et al., 2010
	PC+FF+WFGD	71	USA	ICR, 2010
	PC+SCR+CS-ESP+WFGD	66	USA	Cheng et al., 2009
	PC+SCR+CS-ESP+SW-FGD	29	China	Chen et al., 2008
	SCR + ACI + FF + WFGD	97	China	Ancora et al., 2015
	SCR + ESP + ACI-FF + WFGD	99	China	Ancora et al., 2015
	HI + SCR + ESP + WFGD	95	China	Ancora et al., 2015
Lignite	PC+SCR+CS-ESP+WFGD	39	China	Wang et al., 2010

ACI: activated carbon injection; HI: halogen injection; FF: fabric filter; SCR: selective catalytic reduction; WFGD: wet flue gas desulfurization; SW-FGD: sea water flue gas desulfurization; ESP: Electrostatic precipitator. PC: Pulverized coal-fired boiler; CS-ESP: Cold side-electro-static precipitation

Economic feasibility of implementation must be taken into consideration. Ancora, et al. (2015) proposed costs of co-benefit mercury control technologies based on data of coal-fired power

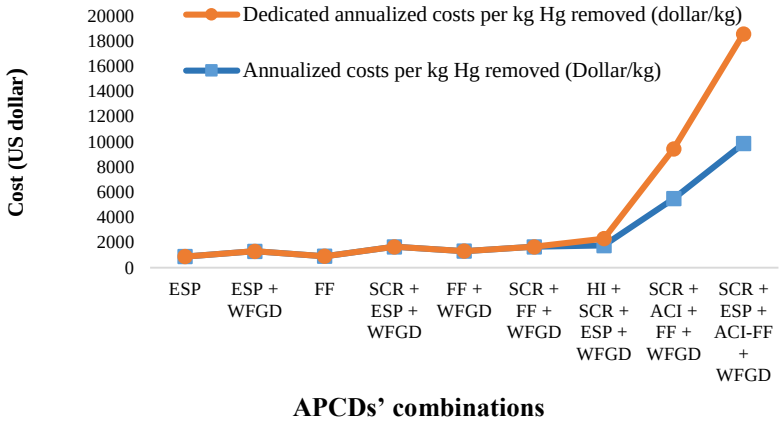
plants in China. Costs for conventional APCDs and dedicated mercury control technologies are summarized in Table 6.4. The WFGD is not dedicated to mercury emission control (about 21% removal), however, it took highest capital cost. It was assumed that mercury would be controlled not with specific standards or technologies but with a variety of actions including mandatory installations of high-efficiency APCDs. The cost estimates for mercury removal efficiency of air pollution control devices' combinations are shown in Figure 6.3. Compared with the mercury-apportioned costs of co-benefit APCDs, dedicated technologies with higher mercury removal efficiencies have higher costs.

Table 6. 4 Costs of air pollution control devices in power plants

APCD	capacity (MW)	Capital cost (US$ /kW)	O&M cost (US$/kW/year)
ESP	<100	16.32±1.21	1.06±0.30
ESP	<300	15.11±1.06	0.91±0.30
ESP	>300	14.20±1.06	0.76±0.30
FF	<100	13.75±1.21	1.51±0.60
FF	<300	12.09±1.06	1.36±0.45
FF	>300	10.73±0.91	1.36±0.45
WFGD	<100	111.21±26.90	11.18±4.38
WFGD	<300	61.95±14.96	8.46±3.32
WFGD	>300	22.82±5.59	5.44±2.12
SCR	<100	18.59±4.38	6.50±2.72
SCR	<300	14.96±3.48	4.68±1.96
SCR	>300	11.33±2.72	3.02±1.21
ACI (for SCR + FF + WFGD)		1.51±1.06	1.66±0.91
ACI-FF (for SCR + ESP + WFGD)		12.24±4.38	3.02±0.60
HI (for SCR + ESP + WFGD)		-	0.26±0.08

ACI: activated carbon injection; HI: halogen injection; FF: fabric filter; SCR: selective catalytic reduction; WFGD: wet flue gas desulfurization; ESP: electrostatic precipitator; O&M: operation and maintenance.

Figure 6. 3 *Annualized costs apportioned to mercury removal by different technologies for a 600 MW power plant in China (Ancora, et al., 2015)*



6.1.3 Improving power generation efficiency to reduce emission rate

At present, producing electricity at the most economic price while also meeting the environmental standards applicable to the size and location of the power plant is the ultimate goal. In most countries, pulverized coal boilers have been built to match steam turbines, which currently have outputs between 50 MW and 1300 MW although most new capacity has output rated at 600 MW or larger to take advantage of economies of scale. This entails a trade-off between the capital and operating costs involved, the risk element in the decision and the amount of additional energy converted. When considering measures to improve energy efficiency, a new coal power plant must be designed technically as well as an existing plant needs to be upgrading and retrofitting.

At the design stage, there is a reasonable level of flexibility, with the following options all offering possibilities to raise efficiency. A conventional plant typically operates at temperatures up to 540°C and has a thermal efficiency of between 30% and 39%, depending on the unit size, coal quality and local conditions. To achieve higher efficiencies, new higher temperature alloys are being developed. The aim is to achieve steam temperatures of 700°C or higher, which would result in net thermal efficiencies approaching 50% or higher. In a higher efficiency plant, the coal consumption for a given electricity output is lower, while it also has a smaller footprint with respect to the central components, the size of coal handling facilities and its emissions

control systems (Schwämmle, et. al., 2014). In addition, other conditions involve inclusion of a second reheat stage on the steam turbine, decreasing the condenser pressure, reducing the excess air ratio and reducing the stack gas exit temperature.

Power plants are typically designed for a lifetime of between 25 and 35 years. It is not normally economic to retire plants prematurely. The potential to improve existing units through upgrade and retrofit normally requires an exhaustive examination of the major functions, the combustion process, the steam cycle and major balance of plant equipment.

6.1.4 Considering alternative measures to lower mercury emission

There are many ways to reduce mercury emissions from coal across the entire combustion process, from start to finish, including pre-treating coal, improving process efficiency, and using post-combustion technologies.

Before coal is burned, several actions can reduce mercury emissions. Coal switching and coal blending can allow mercury emissions to be captured more easily. This is a low-tech, potentially low-cost form of mercury reduction. Coal can also be pre-treated through a variety of processes, including washing, beneficiation, and the application of additives. Depending on the type of cleaning and variety of coal, washing alone can remove about 10-80% of the mercury content in coal before combustion takes place.

Operations and maintenance can be improved so that the emissions intensity of coal-related pollutants can be lower. Various O&M measures are effective options. Typically, these approaches target improved combustion efficiency, improved flue-gas ventilation, and reduced leakage and fouling.

6.1.5 Increasing efficiency of electricity use in all sectors

The previous studies stated that aggregate energy demand is closely correlated with the population and wealth of human societies, but there is considerable variation from one country to another (Sorrell, 2015). The rate of growth of global primary energy consumption has been remarkably stable since 1850 (2.4%/year $\pm$ 0.08%) and shows no sign of slowing down. Hence, if energy demand reduction is to be measured as a departure from this 150-year trend, there appears to be little sign of it yet at the global level.

Improving energy efficiency and reducing energy demand are widely considered as the most promising, fastest, cheapest and safest means to reduce energy consumption. An effective policy approach for reducing energy demand can therefore draw upon all these perspectives, combining energy policy with sociotechnical systems (Sorrell, 2015).

In Thailand, the average demand for electricity increased by 3.6% per year during 2005–2016. Total electricity consumption in 2016 was 182,846 gigawatt-hours (GWh), a 4.6% increase from the 2015 level of 174,834 GWh. Peak demand reached a record 29,619 MW in 2016, an 8.3% increase from 27,346 MW in 2015. The overall growth in electricity consumption resulted from the economic recovery (mainly increased manufacturing activities due to the government stimulus program), while the rise in peak demand was largely caused by hot summer weather. The Ministry of Energy expects electricity demand in 2017 to exceed the 2016 total by 2.9%. Electricity demand in Thailand has fairly predictable seasonal and daily cycles. Annual peak demand is generally from March to May, during periods of high temperature. The lowest loads are generally during the coolest months, in December and January.

According to Thailand's Power Development Plan (PDP), 2015–2036, EGAT is projecting average annual growth of 2.68% in net electricity demand and 2.67% in peak demand during 2015–2036. EGAT forecasts 326,119 GWh in consumption by 2036, and peak generation of 49,655 MW. The PDP projects 6% lower energy demand and 5% lower peak demand than the previous plan. This is based on the expectation that the government's PDP will succeed in improving energy efficiency in the country. The PDP assumes total installed capacity will be 70,335 MW by 2036, including 57,459 MW of added capacity (more than double the 24,736 MW of capacity that is expected to be retired).

The PDP also incorporates two energy policy frameworks: (i) the Energy Efficiency Development Plan, 2015–2036, which aims for a 30% reduction in energy intensity by 2036, and would lower the country's long-term power demand needs; and (ii) the Alternative Energy Development Plan, 2015–2036, which seeks to increase the share of renewable energy and alternative energy used for power generation to 30% by 2036.

6.2 Recommendations on control policies and emission standards

In this study, mercury emissions were predicted. Although the total Hg emission rate will be expected to decrease, Hg emitted to atmosphere is still public concerns. The UNEP Global Mercury Partnership provides a guidance on Best Available Techniques (BATs) and Best Environmental Practices (BEPs) for controlling and, where feasible, reducing mercury emissions from coal-fired power plants and coal-fired industrial boilers. We consider to select the control measures with respect to the Guidance in relation to mercury emissions (article 8) referred to in paragraphs 8 (a) and 8 (b) (UNEP, 2017). The guidance stats that parties may adopt different measures in respect of different source categories.

6.2.1 Addressing information gaps

Important information gaps related to actual emissions, coal characteristics and available control technology became the major obstacles in developing a standard limit for the sector. As the regulation of mercury emission from power plant is not clearly established. The PDP and AEDP have been announced; however, the implementation is still less efficient.

6.2.2 Technology gap

Co-benefit control measures are considered as the appropriate approaches. However, the suitability and cost for each plant have been not yet assessed totally. Currently, Thailand power plants install only conventional APCDs. The dedicated technologies may not be adopted as the cost is too high to additionally installed, especially for a small power plant. Thailand has not developed the mercury control-testing program in order to test and identify the most effective technologies for controlling mercury emissions from coal-fired power plants.

6.2.3 Recommendation

The design and implementation of mercury control policies and emission standards involve a great deal of work with stakeholder engagement from industries, non-government groups, experts in the field, and the general public. We propose that all coal-fired power plants in Thailand shall implement actions to reduce mercury emissions. The recommendations are proposed as follows:

1) Mercury emission inventory must be applied in both the existing and new expected power plants; and must be regularly performed and reviewed. It is therefore the emission factors appropriated for Thailand will be established;
2) promoting technology capacity building and research on the efficiency of power plants and APCDs relevant to the system in Thailand;
3) applying Best Available Technique/Best Environmental Practices for all industries using coal and lignite as fuels. The implementation should consider these conditions as follows:
    - The actions include full range of options presented in section 6.2, where feasible and applicable, to control emission;
    - The performance and effectiveness of selective control technique options are taken into account in order to ensure the high level of protection of human health and the environment as a whole;
    - Furthermore, cost and benefits of each control technique option need to be assessed. The need should also be taken into account for sound maintenance and operational control of the techniques, so as to maintain the achieved performance over time.
4) establishing the emission standard imposed limits on the concentration of mercury emitted from coal-fired power plant;
5) supporting a capacity building program for researchers, technicians and national coordinators of the mercury monitoring.

Recognizing the need to allow both the existing and expected new coal-fired power plants sufficient time to test, plan, and implement actions, including technology optimization as well as the control policies, the action plan is necessary and should be implemented in phases. Proposed action plan for reducing mercury emission from coal-fired power plant is presented in Table 6.5.

Table 6. 5 *Action plan for reducing mercury emission from coal-fired power plants*

Task	Action	Time-frame	Responsible/Involvement*
1	Capacity building programs of mercury emission inventory	1 years	PCD
2	Mercury emission inventory	2-3 years	PCD, EPPO,DIW, ERC and power plants
3	Capacity building programs of mercury monitoring	5 years	PCD,EPPO,DIW,ERC and power plants
4	Review of law and regulation at national and international levels	1 year	PCD, DIW,ERC
5	Establishment of Hg emission standard applied for power plants in Thailand	5 years	PCD,EPPO,DIW,ERC and power plants
6	Implementation of BAT/BEP, which are appropriated for power plants in Thailand	5 years	PCD,EPPO,DIW,ERC and power plants

PCD: Pollution Control Department; EPPO: Energy Policy and Planning Office, Ministry of Energy; DIW: Department of Industrial Works, Ministry of Industry; ERC: Energy Regulatory Commission; BAT/BEP: Best available techniques /Best environmental practices.

*These organizations/departments are expected to be a focal point or to involve with each action plan. However, in future, they can be changed to appropriate situation.

6.3 Capacity building

As part of the objectives of this study, the capacity building was conducted in two activities. These were: (1) visiting three coal power plants and (2) organizing the workshop on developing a national overview of mercury emission from coal fired power plant for national action plan.

6.3.1 Visiting coal fired power plant

We went to visit three relevant coal-fired power plants from May to June 2017. In the meeting with those, we shared and discussed mainly on how to minimize mercury emission to environment as well as invited them to join the workshop.

6.3.2 Workshop on developing a national overview of mercury emission from coal fired power plant for national action plan

The workshop was to deliver the key concept of the Process Optimization Guidance for Reducing Mercury Emissions from Coal Combustion in Power Plants (POG); and the INC guidance on Best Available Techniques and Best Environmental Practices (BAT/BEP); and to

disseminate information to relevant stakeholders (policymakers, administrative staff in the power plant sector).

The expected result of the workshop was to encourage the best practices for operating a coal fired power plant; and to gather the opinions of stakeholders. As a result, the national plan on reducing mercury emission from a coal-fired power plant would be developed.

1) Participant

The workshop was well attended. There were 105 participants in the workshop. The participants were government institutions; Universities; EPPO: Energy Policy and Planning Office, Ministry of Energy, Thailand; EGAT; Electricity Generating Authority of Thailand; IPPs: Independent Power Producers; Environmental consulting firms and industrial sectors, who are involved coal use as the fuel. The leader for the workshop was Assistant professor Pensri Watchalayann, PhD. (Thammasat University, Thailand) and the UNEP representatives were Dr. Wojciech Jozewicz and Dr. Lesley Sloss. Ms. Teeraporn Wiriwutikorn, Chief of Hazardous Waste Division, Pollution Control Department, Ministry of Natural Resources and Environment, Thailand, was responsible for the local organization.

2) Workshop programme

The workshop was formally inaugurated by Ms. Teeraporn Wiriwutikorn. The information about the goals, intended outcome and results of the study in the context of developing options to reduce mercury emissions and releases from coal-fired power plants in Thailand was presented by Assistant professor Pensri Watchalayann, Followed by the keynote speakers, the two sessions including Process optimization guidance (POG) and BAT/BEP were shared by Dr. Wojciech Jozewicz and Dr. Lesley Sloss, respectively. Finally, the stakeholder argument on the project and how to reduce mercury emission from coal combustion was deliberately explored and discussed. Following the discussion, the workshop was closed for the day. The agenda of the workshop displays in Annex A-7.

3) Outcome of the workshop

The participants agreed and proposed suggestions and recommendations as follows:

3.1) participants made some questions or concerns related to the methodology and results of this project. The key issues can be summarized as follows:

- Information from this project is little comparing to the whole situation of mercury emission of coal-fired power plants in Thailand due to uncertainties and limitations (see section 5.6 and 5.7). It is necessary to be careful about what may be disseminated to public.
- Development of mercury emission factor which was based on the mass balance and limitation
- Uncertainty of scenarios for estimating mercury emission, which involved projected coal consumption, emission factor and removal efficiency of co-benefit APCDs.
- Impact of this project on the decision-making about the mercury emission standard in Thailand

3.2) participants proposed their opinions and recommendations related to reduction of mercury emission and establishment of mercury emission standard as follows:

- Government should organize the roadmap for reducing mercury emission from a coal fired power plant in Thailand;
- Cost benefit analysis should be taken into consideration for selecting the dedicated APCDs for removing mercury;
- It is necessary to expand the study for more coal fired power plants. Further study for other types of power plants that also contribute mercury emitted to environment is needed;
- Mercury emission factor should be set specific to situation in Thailand rather than that uses in other countries;
- If the mass balance method would be recommended for establishing emission factor, sample size and collection period should cover the full range of processes in order to ensure the result with statistical significance;
- The PCD (Pollution Control Department) should be the focal point for conducting the meeting to inform stakeholders about the policy, procedure and clear direction of how to follow the national plan.
- Other suggestions include:
    - controlling mercury import;
    - totally assessing all sources of mercury emission

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Annex- 1 Proximate and ultimate analysis data: Inter-lab comparison

Coal Source	Proximate Analysis									
	Inherent Moisture		Total Moisture		Volatile Matter		Ash		Fixed Carbon	
	As-Received (%)				As-Dry (%)					
	UAE	InterLab	UAE	InterLab	UAE	InterLab	UAE	InterLab	UAE	InterLab
Plant 1-1 (SU)	4.68	4.91	13.73	13.96	35.80	32.62	13.84	13.12	50.36	54.25
Plant 1-2 (HV)	3.28	3.44	8.57	8.73	35.92	32.61	9.72	9.52	54.36	57.87
Plant 1-3 (HV)	3.29	3.34	9.06	9.11	36.14	32.39	10.30	10.70	53.56	56.91
Plant 1-4 (BC)	1.43	1.32	6.38	6.27	19.44	18.14	21.81	20.27	58.75	61.59
Plant 1-5 (BC)	1.31	1.71	5.80	6.20	20.52	19.41	20.53	18.52	58.95	62.07
Plant 2-1 (CS1)	15.81	17.75	32.80	34.74	44.84	42.67	31.31	34.64	23.85	22.69
Plant 2-2 (CS1)	16.53	16.36	31.37	31.20	40.86	35.22	34.01	41.00	25.14	23.78
Plant 2-3 (CS1)	15.31	21.49	29.70	35.88	42.53	39.23	28.25	30.93	29.22	29.84
Plant 2-4 (CS2)	20.79	21.49	34.64	35.34	45.48	44.30	23.07	26.61	31.46	29.09
Plant 2-5 (CS2)	19.62	18.98	32.76	32.12	43.67	41.63	33.91	37.25	22.43	21.12

Coal Source	Ultimate Analysis									
	Carbon (C)		Hydrogen (H)		Nitrogen (N)		Sulfur (S)		Oxygen (O)	
	As-Dry (%)									
	UAE	InterLab	UAE	InterLab	UAE	InterLab	UAE	InterLab	UAE	InterLab
Plant 1-1 (SU)	59.73	69.32	5.08	5.36	1.08	1.72	0.42	0.82	19.86	9.64
Plant 1-2 (HV)	61.81	74.12	5.29	5.47	1.58	1.72	0.54	0.91	21.06	8.26
Plant 1-3 (HV)	71.23	73.29	5.31	5.40	1.36	1.67	0.49	0.96	11.30	7.99
Plant 1-4 (BC)	54.69	69.30	4.13	4.26	0.71	1.30	0.34	0.60	18.31	4.28
Plant 1-5 (BC)	60.34	69.02	4.21	4.40	0.83	1.30	0.35	0.60	13.74	6.17
Plant 2-1 (CS1)	48.52	46.60	5.71	6.30	1.69	1.51	3.06	4.16	9.71	6.80
Plant 2-2 (CS1)	44.50	42.66	5.71	6.05	1.76	1.54	5.51	4.33	8.50	4.42
Plant 2-3 (CS1)	50.62	48.25	5.75	7.46	1.89	1.68	5.34	4.19	8.15	7.49
Plant 2-4 (CS2)	54.30	51.46	6.89	7.46	1.91	1.68	4.00	4.23	9.83	8.56
Plant 2-5 (CS2)	47.47	43.94	6.29	6.86	1.68	1.44	6.80	4.79	3.84	5.71

Annex-2 Chemical composition: Inter-lab comparison

Coal Source	Chemical Composition															
	Chlorine (Cl)		Bromine (Br)		Mercury (Hg)		Arsenic (As)		Selenium (Se)		Barium (Ba)		Sodium (Na)		Calcium (Ca)	
	(g/kg)		(mg/kg)		(µg/kg)		(mg/kg)		(mg/kg)		(g/kg)		(g/kg)		(g/kg)	
	UAE	InterLab	UAE	InterLab	UAE	InterLab	UAE	InterLab	UAE	InterLab	UAE	InterLab	UAE	InterLab	UAE	InterLab
Plant 1-1 (SU)	0.10	0.26	ND < 1.00	< 10	64.89	21.03	16.7	16.8	0.9	<1	1.72	1.36	5.05	5.91	25.74	28.22
Plant 1-2 (HV)	0.29	0.42	ND < 1.00	< 10	38.53	10.36	17.0	16.6	0.6	<1	0.37	0.41	5.89	6.03	6.18	6.14
Plant 1-3 (HV)	0.23	0.34	ND < 1.00	< 10	30.79	10.35	11.8	11.4	0.6	<1	0.31	0.34	4.72	3.55	5.35	6.20
Plant 1-4 (BC)	0.18	0.41	ND < 1.00	< 10	119.61	50.67	1.4	< 1	NA	<1	0.36	0.35	1.18	0.74	6.41	8.00
Plant 1-5 (BC)	0.21	0.39	ND < 1.00	< 10	90.27	40.70	1.8	< 1	0.8	<1	0.33	0.36	0.94	0.84	12.85	11.52
Plant 2-1 (CS1)	0.07	0.08	ND < 1.00	< 10	198.95	24.32	387	< 1	0.8	< 1	0.09	0.08	13.26	12.63	101.72	186.29
Plant 2-2 (CS1)	0.09	0.07	ND < 1.00	< 10	235.03	83.69	415	< 1	0.6	< 1	0.13	0.15	12.10	13.59	93.43	61.72
Plant 2-3 (CS1)	0.07	0.07	ND < 1.00	< 10	185.84	25.47	346	< 1	0.4	< 1	0.07	0.04	12.12	15.29	74.88	74.69
Plant 2-4 (CS2)	0.11	0.09	ND < 1.00	< 10	97.37	50.95	298	< 1	1.4	< 1	0.21	0.09	8.95	12.39	107.40	122.36
Plant 2-5 (CS2)	0.15	0.08	ND < 1.00	< 10	183.58	74.06	295	< 1	1.2	< 1	0.23	0.06	9.11	14.52	105.13	178.43

Annex-3 Proximate and ultimate analysis and chemical composition of coal: Plant1 to Plant 4

Table A3-1 Proximate analysis of feed coal

Coal Source	% Content				
	Inherent Moisture	**Total Moisture**	**Volatile Matter**	**Ash**	**Fixed Carbon**
Plant 1*(Bituminous coal; n= 15)*					
BC 1	1.27	7.59	19.73	20.32	59.95
BC 2	1.43	6.38	19.44	21.81	58.75
BC 3	1.44	6.38	21.40	20.69	57.91
BC 4	1.31	5.80	20.52	20.53	58.95
BC 5	1.38	6.83	20.40	21.58	58.02
Mean±SD	*1.37±0.07*	*6.60±0.67*	*20.30±0.76*	*20.99±0.67*	*58.72±0.82*
HV 1	3.28	8.57	35.92	9.72	54.36
HV 2	3.21	7.01	35.87	10.53	53.60
HV 3	3.21	6.37	35.77	11.18	53.05
HV 4	2.75	7.69	31.50	14.64	53.86
HV 5	3.29	9.06	36.14	10.30	53.56
Mean±SD	*3.15±0.23*	*7.74±1.10*	*35.04±1.98*	*11.27±1.95*	*53.69±0.48*
SU 1	5.56	15.06	36.83	15.29	47.88
SU 2	4.96	10.72	36.82	14.28	48.90
SU 3	5.52	14.08	38.96	13.78	47.26
SU 4	4.68	13.73	35.80	13.84	50.36
SU 5	5.33	12.75	38.08	13.34	48.58
Mean±SD	*5.21±0.38*	*13.27±1.65*	*37.30±1.23*	*14.11±0.74*	*48.60±1.17*
Plant 2*(Lignite; n=10)*					
CS 1	15.81	32.80	44.84	31.31	23.85
CS 1	15.76	28.96	42.60	32.54	24.87
CS 1	16.53	31.37	40.86	34.01	25.14

Table A3-1 Proximate analysis of feed coal

Coal Source	% Content				
	Inherent Moisture	**Total Moisture**	**Volatile Matter**	**Ash**	**Fixed Carbon**
CS 1	15.31	29.70	42.53	28.25	29.22
CS 1	15.77	30.02	42.08	34.80	23.13
Mean±SD	*15.83±0.44*	*30.57±1.52*	*42.58±1.44*	*32.18±2.57*	*25.24±2.37*
CS 2	16.90	30.53	43.61	31.82	24.58
CS 2	20.79	34.64	45.48	23.07	31.46
CS 2	18.77	32.42	42.70	32.39	24.92
CS 2	19.62	32.76	43.67	33.91	22.43
CS 2	19.24	32.10	39.84	36.08	24.09
Mean±SD	*19.06±1.42*	*32.49±1.47*	*43.06±2.06*	*31.45±4.97*	*25.49±3.47*
Plant 3*(Bituminous coal; n=15)*					
JM 1	12.41	18.64	45.86	5.23	48.92
JM 2	12.04	19.06	46.61	4.76	48.64
JM 3	12.64	20.92	46.11	4.23	49.67
JM 4	11.92	20.51	45.85	5.96	48.19
JM 5	11.51	17.10	45.98	5.83	48.20
Mean±SD	*12.10±0.44*	*19.25±1.53*	*46.08±0.31*	*5.20±0.73*	*48.72±0.61*
KP 1	10.38	20.18	44.14	7.72	48.14
KP 2	10.67	16.90	44.23	8.58	47.20
KP 3	11.69	19.74	44.40	7.59	48.02
KP 4	12.21	20.23	44.93	7.53	47.55
KP 5	11.65	18.65	44.45	6.67	48.88

Table A3-1 Proximate analysis of feed coal

Coal Source	% Content				
	Inherent Moisture	**Total Moisture**	**Volatile Matter**	**Ash**	**Fixed Carbon**
Mean±SD	*11.32±0.77*	*19.14±1.40*	*44.43±0.31*	*7.62±0.68*	*47.96±0.64*
KM 1	13.13	23.58	46.15	4.00	49.86
KM 2	12.46	22.79	45.95	7.54	46.51
KM 3	12.39	24.54	45.84	6.25	47.92
KM 4	11.42	17.82	45.58	7.71	46.72
KM 5	12.52	22.38	46.17	6.51	47.32
Mean±SD	*12.38±0.62*	*22.22±2.60*	*45.94±0.24*	*6.40±1.49*	*47.67±1.35*
Plant 4*(Bituminous coal; n=10)*					
BP 1	11.13	20.98	44.38	6.88	48.75
BP 2	11.20	21.77	44.22	8.49	47.30
BP 3	11.33	20.84	44.24	7.48	48.29
BP 4	11.63	19.89	43.95	7.76	48.29
BP 5	13.65	24.65	44.90	5.22	49.89
Mean±SD	*11.78±1.06*	*21.62±1.82*	*44.34±0.35*	*7.16±1.23*	*48.50±0.94*
LN 1	14.90	33.92	47.13	6.49	46.39
LN 2	16.33	35.64	47.79	10.82	41.40
LN 3	15.11	35.74	46.79	9.81	43.41
LN 4	16.20	34.79	47.53	6.97	45.51
LN 5	14.18	37.17	47.56	8.13	44.32
Mean±SD	*15.34±0.91*	*35.45±1.21*	*47.36±0.40*	*8.44±1.84*	*44.20±1.94*

Table A3-1 Proximate analysis of feed coal

Coal Source	% Content				
	Inherent Moisture	**Total Moisture**	**Volatile Matter**	**Ash**	**Fixed Carbon**

Table A3-2 Ultimate analysis of feed coal

Coal Source	% Content				
	Carbon (C)	**Hydrogen (H)**	**Nitrogen (N)**	**Sulfur (S)**	**Oxygen (O)**
Plant 1*(Bituminous coal; n= 15)*					
BC 1	55.01	4.12	0.76	0.33	19.46
BC 2	54.69	4.13	0.71	0.34	18.31
BC 3	56.72	4.21	0.80	0.33	17.25
BC 4	60.34	4.21	0.83	0.35	13.74
BC 5	56.84	4.04	0.71	0.32	16.51
Mean±SD	*56.72±2.25*	*4.14±0.07*	*0.76±0.05*	*0.34±0.01*	*17.05±2.16*
HV 1	61.81	5.29	1.58	0.54	21.06
HV 2	68.87	5.31	1.67	0.53	13.09
HV 3	64.14	5.23	1.25	0.51	17.70
HV 4	58.54	4.82	1.11	0.48	20.40
HV 5	71.23	5.31	1.36	0.49	11.30
Mean±SD	*64.92±5.16*	*5.19±0.21*	*1.40±0.23*	*0.51±0.02*	*16.71±4.36*
SU 1	63.39	5.06	1.43	0.38	14.44
SU 2	63.45	5.12	1.25	0.43	15.47
SU 3	66.11	5.44	1.35	0.40	12.91

Table A3-1 Proximate analysis of feed coal

Coal Source	% Content				
	Inherent Moisture	**Total Moisture**	**Volatile Matter**	**Ash**	**Fixed Carbon**
SU 4	59.73	5.08	1.08	0.42	19.86
SU 5	66.10	5.50	1.50	0.42	13.13
Mean±SD	*63.76±2.62*	*5.24±0.21*	*1.32±0.16*	*0.41±0.02*	*15.16±2.82*
Plant 2*(Lignite; n=10)*					
CS 1	48.52	5.71	1.69	3.06	9.71
CS 1	47.84	5.65	1.80	4.27	7.90
CS 1	44.50	5.71	1.76	5.51	8.50
CS 1	50.62	5.75	1.89	5.34	8.15
CS 1	46.26	5.54	1.75	5.29	6.36
Mean±SD	*47.55±2.31*	*5.67±0.08*	*1.78±0.08*	*4.70±1.03*	*8.12±1.21*
CS 2	47.67	5.75	1.79	4.46	8.51
CS 2	54.30	6.89	1.91	4.00	9.83
CS 2	49.13	6.33	1.81	2.61	7.74
CS 2	47.47	6.29	1.68	6.80	3.84
CS 2	45.75	6.15	1.68	4.41	5.92
Mean±SD	*48.86±3.27*	*6.28±0.41*	*1.77±0.10*	*4.46±1.51*	*7.17±2.34*
Plant 3*(Bituminous coal; n=15)*					
JM 1	67.97	6.51	1.40	0.15	18.74
JM 2	69.08	6.88	1.50	0.11	17.68

Table A3-1 Proximate analysis of feed coal

Coal Source	% Content				
	Inherent Moisture	**Total Moisture**	**Volatile Matter**	**Ash**	**Fixed Carbon**
JM 3	68.67	6.62	1.40	0.13	18.97
JM 4	67.30	6.46	1.36	0.12	18.79
JM 5	67.16	6.40	1.36	0.17	19.09
Mean±SD	*68.04±0.84*	*6.57±0.19*	*1.40±0.06*	*0.14±0.02*	*18.65±0.56*
KP 1	65.89	6.09	1.35	0.69	18.26
KP 2	65.95	6.07	1.38	0.73	17.31
KP 3	67.86	6.41	1.37	0.78	16.00
KP 4	67.90	6.48	1.39	0.64	16.06
KP 5	67.48	6.33	1.36	0.85	17.32
Mean±SD	*67.01±1.02*	*6.28±0.19*	*1.37±0.02*	*0.74±0.08*	*16.99±0.96*
KM 1	67.65	6.56	1.36	0.59	19.85
KM 2	67.63	6.61	1.36	0.73	16.12
KM 3	67.24	6.54	1.37	0.51	18.09
KM 4	65.21	6.29	1.32	0.70	18.77
KM 5	67.00	6.49	1.36	0.64	18.00
Mean±SD	*66.95±1.01*	*6.50±0.13*	*1.35±0.02*	*0.63±0.09*	*18.17±1.36*
Plant 4*(Bituminous coal; n=10)*					
BP 1	66.52	6.30	1.37	2.13	16.80
BP 2	67.07	6.13	1.37	2.00	14.94

Table A3-1 Proximate analysis of feed coal

Coal Source	% Content				
	Inherent Moisture	**Total Moisture**	**Volatile Matter**	**Ash**	**Fixed Carbon**
BP 3	67.07	6.29	1.41	2.18	15.58
BP 4	67.18	6.33	1.39	1.81	15.53
BP 5	68.81	6.74	1.41	2.17	15.65
Mean±SD	*67.33±0.87*	*6.36±0.23*	*1.39±0.02*	*2.06±0.15*	*15.70±0.68*
LN 1	67.00	6.97	1.37	1.21	16.96
LN 2	62.69	6.90	1.12	1.15	17.33
LN 3	62.19	6.49	1.15	1.37	18.99
LN 4	64.39	6.91	1.19	1.23	19.31
LN 5	63.39	6.53	1.18	1.24	19.54
Mean±SD	*63.93±1.90*	*6.76±0.23*	*1.20±0.10*	*1.24±0.08*	*18.43±1.19*

Table A3-3 Chemical analysis of feed coals

Coal Source	Concentration							
	Chlorine (g/kg)	**Bromine** (mg/kg)	**Mercury** (µg/kg)	**Arsenic** (mg/kg)	**Selenium** (mg/kg)	**Barium** (g/kg)	**Sodium** (g/kg)	**Calcium** (g/kg)
Plant 1*(Bituminous coal; n= 15)*								
BC 1	2.17	ND < 1.00	86.45	1.24	0.01	0.38	1.38	6.18
BC 2	0.18	ND < 1.00	119.61	1.39	0.00	0.36	1.18	6.41
BC 3	0.20	ND < 1.00	85.78	1.59	1.54	0.54	1.22	19.65
BC 4	0.21	ND < 1.00	90.27	1.81	0.83	0.33	0.94	12.85
BC 5	0.15	ND < 1.00	96.95	2.28	0.61	0.33	1.34	5.37
Mean±SD	*0.58±0.89*	*ND < 1.00*	*95.81±14.02*	*1.66±0.41*	*0.60±0.64*	*0.39±0.09*	*1.21±0.17*	*10.09±6.13*

Table A3-3 Chemical analysis of feed coals

Coal Source	Concentration							
	Chlorine (g/kg)	**Bromine** (mg/kg)	**Mercury** (µg/kg)	**Arsenic** (mg/kg)	**Selenium** (mg/kg)	**Barium** (g/kg)	**Sodium** (g/kg)	**Calcium** (g/kg)
HV 1	0.29	ND < 1.00	38.53	17.03	0.62	0.37	5.89	6.18
HV 2	0.22	ND < 1.00	38.54	15.03	1.20	0.53	2.05	16.77
HV 3	0.28	ND < 1.00	37.25	18.37	0.91	1.74	5.36	37.69
HV 4	0.27	ND < 1.00	105.08	20.83	0.94	1.73	5.72	22.32
HV 5	0.23	ND < 1.00	30.79	11.77	0.64	0.31	4.72	5.35
Mean±SD	*0.26±0.03*	*ND < 1.00*	*50.04±30.94*	*16.61±3.43*	*0.86±0.24*	*0.94±0.73*	*4.75±1.57*	*17.66±13.30*
SU 1	0.09	ND < 1.00	80.82	20.65	0.53	1.65	6.33	35.83
SU 2	0.03	ND < 1.00	59.51	16.68	1.68	0.52	2.80	15.41
SU 3	2.35	ND < 1.00	63.18	18.74	0.63	1.72	6.43	37.81
SU 4	0.10	ND < 1.00	64.89	16.68	0.93	1.72	5.05	25.74
SU 5	0.12	ND < 1.00	54.04	12.74	0.66	0.42	4.39	11.13
Mean±SD	*0.54±1.01*	*ND < 1.00*	*64.49±10.03*	*17.10±2.95*	*0.89±0.47*	*1.21±0.67*	*5.00±1.51*	*25.18±11.90*
Plant 2*(Lignite; n=10)*								
CS 1	0.07	ND < 1.00	198.95	386.66	0.78	0.09	13.26	101.72
CS 1	0.09	ND < 1.00	207.39	444.57	0.82	0.10	12.34	81.08
CS 1	0.09	ND < 1.00	235.03	415.03	0.62	0.13	12.10	93.43
CS 1	0.07	ND < 1.00	185.84	345.89	0.41	0.07	12.12	74.88
CS 1	0.12	ND < 1.00	166.68	466.00	1.16	0.13	12.62	115.67
Mean±SD	*0.09±0.02*	*ND < 1.00*	*198.78±25.43*	*411.63±47.43*	*0.76±0.28*	*0.10±0.03*	*12.49±0.48*	*93.36±16.28*
CS 2	0.12	ND < 1.00	119.06	336.68	1.31	0.29	9.72	122.83
CS 2	0.11	ND < 1.00	97.37	297.90	1.45	0.21	8.95	107.40
CS 2	0.15	ND < 1.00	105.78	308.23	1.48	0.31	9.04	134.36
CS 2	0.15	ND < 1.00	183.58	294.52	1.20	0.23	9.11	105.13
CS 2	0.20	ND < 1.00	155.78	213.27	1.00	0.27	9.26	112.46
Mean±SD	*0.15±0.03*	*ND < 1.00*	*132.31±36.33*	*290.12±46.05*	*1.29±0.20*	*0.26±0.04*	*9.21±0.30*	*116.44±12.12*

Table A3-3 Chemical analysis of feed coals

Coal Source	Concentration							
	Chlorine (g/kg)	**Bromine** (mg/kg)	**Mercury** (µg/kg)	**Arsenic** (mg/kg)	**Selenium** (mg/kg)	**Barium** (g/kg)	**Sodium** (g/kg)	**Calcium** (g/kg)
Plant 3*(Bituminous coal; n=15)*								
JM 1	0.13	ND < 1.00	24.10	25.46	1.11	1.91	21.21	101.02
JM 2	0.19	ND < 1.00	21.05	23.09	1.52	2.47	22.96	113.05
JM 3	0.22	ND < 1.00	17.85	23.53	1.90	2.47	25.28	119.62
JM 4	0.20	ND < 1.00	21.92	20.97	1.06	1.66	18.79	91.64
JM 5	0.20	ND < 1.00	19.27	25.23	1.57	2.19	23.58	108.10
Mean±SD	*0.19±0.03*	*ND < 1.00*	*20.84±2.41*	*23.66±1.82*	*1.43±0.35*	*2.14±0.35*	*22.36±2.47*	*106.69±10.82*
KP 1	0.12	ND < 1.00	38.84	24.63	0.03	0.83	6.71	24.52
KP 2	0.14	ND < 1.00	45.99	24.00	0.00	0.81	8.35	24.19
KP 3	0.11	ND < 1.00	34.99	25.39	0.00	0.90	7.25	27.59
KP 4	0.16	ND < 1.00	26.67	20.34	0.00	0.90	7.50	26.39
KP 5	0.23	ND < 1.00	29.52	23.40	0.03	0.94	7.26	24.74
Mean±SD	*0.15±0.05*	*ND < 1.00*	*35.20±7.66*	*23.55±1.94*	*0.01±0.02*	*0.88±0.05*	*7.41±0.60*	*25.49±1.45*
KM 1	0.19	ND < 1.00	44.03	22.62	1.18	1.58	26.37	77.30
KM 2	0.16	ND < 1.00	41.92	22.38	0.74	1.29	21.97	61.70
KM 3	0.14	ND < 1.00	23.28	23.00	0.79	1.67	21.04	66.13
KM 4	0.22	ND < 1.00	39.45	23.91	0.15	1.42	20.96	64.31
KM 5	0.23	ND < 1.00	32.37	18.95	0.24	1.60	26.93	60.85
Mean±SD	*0.19±0.04*	*ND < 1.00*	*36.21±8.46*	*22.17±1.89*	*0.62±0.43*	*1.51±0.16*	*23.45±2.95*	*66.06±6.63*
Plant 4*(Bituminous coal; n=10)*								
BP 1	0.21	ND < 1.00	62.15	37.26	0.02	0.60	16.78	37.14
BP 2	0.26	ND < 1.00	40.60	34.37	0.00	0.52	13.64	37.50
BP 3	0.18	ND < 1.00	56.71	35.55	0.01	0.46	15.81	31.55
BP 4	0.19	ND < 1.00	45.37	42.18	0.00	0.52	15.42	44.69
BP 5	0.19	ND < 1.00	40.64	44.98	0.05	0.52	17.73	35.74

Table A3-3 Chemical analysis of feed coals

Coal Source	Concentration							
	Chlorine (g/kg)	**Bromine** (mg/kg)	**Mercury** (µg/kg)	**Arsenic** (mg/kg)	**Selenium** (mg/kg)	**Barium** (g/kg)	**Sodium** (g/kg)	**Calcium** (g/kg)
Mean±SD	*0.20±0.03*	*ND < 1.00*	*49.09±9.82*	*38.87±4.53*	*0.02±0.02*	*0.52±0.05*	*15.88±1.54*	*37.32±4.75*
LN 1	0.19	ND < 1.00	70.59	43.79	0.00	2.19	1.43	63.58
LN 2	0.25	ND < 1.00	64.91	43.42	0.00	1.92	1.13	55.90
LN 3	0.22	ND < 1.00	58.60	43.47	0.00	1.61	1.16	46.29
LN 4	0.44	ND < 1.00	47.31	43.16	0.00	1.77	1.12	58.93
LN 5	0.33	ND < 1.00	87.28	44.71	0.00	1.85	1.13	57.47
Mean±SD	*0.29±0.10*	*ND < 1.00*	*65.74±14.82*	*43.71±0.60*	*0.00*	*1.87±0.22*	*1.20±0.13*	*56.43±6.36*

Annex-4 Mercury mass balance

Table A4-1 Mercury concentrations in solid/liquid samples and flue gas at each sampling location

Type of sample (unit of conc.)	Concentration at each sampling cycle						
	1	**2**	**3**	**4**	**5**	**Mean**	**SD**
Plant 1							
Coal (µg/kg)	69.04	55.83	43.51	74.31	56.81	59.90	12.10
Bottom ash (µg/kg)	1.04	1.21	0.57	1.31	1.94	1.21	0.50
Fly ash (µg/kg)	25.87	50.64	36.92	71.20	53.34	47.59	17.21
Sea water in (µg/m^3)	2.89	4.29	2.18	1.34	7.44	3.63	2.39
Sea water out (µg/m^3)	109.30	84.07	86.32	58.71	121.00	91.88	24.21
Stack emission (µg/m^3)_ Actual O_2	0.97	0.36	1.24	0.50	0.39	0.69	0.39
Plant 2 (unit 6)							
Coal (µg/kg)	125.57	124.67	135.02	145.53	131.80	132.52	8.46
Bottom ash (µg/kg)	27.99	0.47	3.70	3.53	5.66	8.27	11.18
Fly ash (µg/kg)	22.02	22.54	27.48	22.51	17.30	22.37	3.60
Limestone (µg/kg)	51.47	48.82	79.12	124.45	72.09	75.19	30.45
Gypsum (µg/kg)	214.12	139.77	181.52	190.63	118.57	168.92	38.92
Stack emission (µg/m^3)_ Actual O_2	6.00	12.25	2.51	11.13	8.05	7.99	3.94
Plant 2 (unit10)							
Coal (µg/kg)	101.37	99.47	116.72	126.01	131.28	114.97	14.28
Bottom ash (µg/kg)	0.62	3.00	7.153	57.40	23.96	18.43	23.62
Fly ash (µg/kg)	15.01	11.04	22.26	20.67	22.94	18.38	5.16
Limestone (µg/kg)	39.08	50.27	42.96	51.65	60.78	48.94	8.40
Gypsum (µg/kg)	140.82	127.75	150.91	146.07	137.88	140.69	8.79
Stack emission (µg/m^3)_ Actual O_2	6.73	9.92	10.34	12.18	10.33	9.90	1.98
Plant 2 (unit13)							
Coal (µg/kg)	130.45	136.59	121.67	109.76	123.68	124.43	10.09

Table A4-1 Mercury concentrations in solid/liquid samples and flue gas at each sampling location

Type of sample (unit of conc.)	Concentration at each sampling cycle						
	1	**2**	**3**	**4**	**5**	**Mean**	**SD**
Bottom ash (µg/kg)	16.59	4.60	6.21	8.49	1.61	7.50	5.66
Fly ash (µg/kg)	49.69	44.91	30.12	21.51	27.49	34.74	12.00
Limestone (µg/kg)	44.02	47.77	65.12	66.60	49.72	54.65	10.45
Gypsum (µg/kg)	178.82	221.20	183.19	97.99	148.69	165.98	45.91
Stack emission (µg/m^3)_ Actual O_2	5.92	8.92	2.46	5.86	2.92	5.22	2.62

Table A4-2 Quantification of mercury mass flows throughout the coal-fired power plant: Plant 1

Flow (Unit of Hg conc.)	Quantity	Moisture	Quantity	Concentration	Hg mass flows	
	t/d (as wet weight)	%	t/d (as dry weight)	(as dry weight)	(µg/d)	(g/d)
Sampling cycle 1						
Feed coal (µg/kg)	5871.36	0.96%	5814.994944	69.044	401490510.9	401.4905109
Seawater-In (µg/L)	502560000		502560000	0.0028925	1453654.8	1.4536548
Bottom Ash (µg/kg)	72	23.59%	55.0152	1.0446	57468.87792	0.057468878
Fly Ash (µg/kg)	811.2	0.11%	810.30768	25.869	20961849.37	20.96184937
Seawater-Out (µg/L)	502560000		502560000	0.1093	54929808	54.929808
Stack gas (mg/m3)	72921810.12		72921810.12	0.000971589		70.84999867
Sampling cycle 2						
Feed coal (µg/kg)	5879.76	1.08%	5816.258592	55.831	324727533.4	324.73
Seawater-In (µg/L)	501000000		501000000	0.0042885	2148538.5	2.1485
Bottom Ash (µg/kg)	72	36.31%	45.8568	1.2115	55555.5132	0.056
Fly Ash (µg/kg)	816	24.14%	619.0176	50.635	31343956.18	31.34
Seawater-Out (µg/L)	501000000		501000000	0.084065	42116565	42.117
Stack gas (mg/m3)	73015943.28		73015943.28	0.000362347		26.46

Table A4-2 Quantification of mercury mass flows throughout the coal-fired power plant: Plant 1

Flow (Unit of Hg conc.)	Quantity	Moisture	Quantity	Concentration	Hg mass flows	
	t/d (as wet weight)	%	t/d (as dry weight)	(as dry weight)	(µg/d)	(g/d)
Sampling cycle 3						
Feed coal (µg/kg)	5847.6	4.48%	5585.62752	43.509	243025067.8	243.03
Seawater-In (µg/L)	501432000		501432000	0.002181	1093623.192	1.0936
Bottom Ash (µg/kg)	72	20.51%	57.2328	0.56648	32421.23654	0.032
Fly Ash (µg/kg)	816	0.06%	815.5104	36.919	30107828.46	30.11
Seawater-Out (µg/L)	501432000		501432000	0.08632	43283610.24	43.284
Stack gas (mg/m3)	72702166.13		72702166.13	0.001235142		89.80
Sampling cycle 4						
Feed coal (µg/kg)	5876.64	6.36%	5502.885696	74.306	408897424.5	408.90
Seawater-In (µg/L)	501360000		501360000	0.001337	670318.32	0.6703
Bottom Ash (µg/kg)	189.84	23.08%	146.024928	1.3074	190912.9909	0.191
Fly Ash (µg/kg)	769.92	0.68%	764.684544	71.199	54444774.85	54.44
Seawater-Out (µg/L)	501360000		501360000	0.05871	29434845.6	29.435
Stack gas (mg/m3)	74239674.17		74239674.17	0.000498174		36.98
Sampling cycle 5						
Feed coal (µg/kg)	5883.36	3.54%	5675.089056	56.805	322373433.8	322.37
Seawater-In (µg/L)	501024000		501024000	0.0074395	3727368.048	3.7274
Bottom Ash (µg/kg)	189.84	36.82%	119.940912	1.942	232925.2511	0.233
Fly Ash (µg/kg)	769.92	1.37%	759.372096	53.342	40506426.34	40.51
Seawater-Out (µg/L)	501024000		501024000	0.121	60623904	60.624
Stack gas (mg/m3)	72419766.67		72419766.67	0.000385404		27.91

Table A4-3 Quantification of mercury mass flows throughout the coal-fired power plant: Plant 2/Unit 6

Flow (Unit of Hg conc.)	Quantity	Moisture	Quantity	Concentration	Hg mass flows	
	t/d (as wet weight)	%	t/d (as dry weight)	(as dry weight)	(µg/d)	(g/d)
Sampling cycle 1						
Feed coal (µg/kg)	6977.9	19.20%	5638.1432	125.57	707981641.6	707.9816416
Seawater-In (µg/L)	591.7	0.20%	590.5166	51.472	30395070.44	30.39507044
Bottom Ash (µg/kg)	746.37	27.48%	541.2675	27.999	15154949.4	15.1549494
Fly Ash (µg/kg)	839.68	0.26%	837.4968	22.017	18439167.75	18.43916775
Seawater-Out (µg/L)	781.47	14.22%	670.3450	214.12	143534264.1	143.5342641
Stack gas (mg/m3)	61841089.1		61841089.1040	0.006002493		371.2006859
Sampling cycle 2						
Feed coal (µg/kg)	6977.9	20.47%	5549.52387	124.67	691859140.9	691.86
Seawater-In (µg/L)	591.7	1.98%	579.98434	48.817	28313095.53	28.3131
Bottom Ash (µg/kg)	746.37	19.15%	603.440145	0.46514	280684.149	0.281
Fly Ash (µg/kg)	839.68	0.20%	838.00064	22.541	18889372.43	18.89
Seawater-Out (µg/L)	781.47	14.02%	671.907906	139.77	93912568.02	93.913
Stack gas (mg/m3)	62502491.11		62502491.11	0.012245685		765.39
Sampling cycle 3						
Feed coal (µg/kg)	6977.9	19.46%	5620.00066	135.02	758812489.1	758.81
Seawater-In (µg/L)	591.7	2.77%	575.30991	79.121	45519095.39	45.5191
Bottom Ash (µg/kg)	746.37	23.08%	574.107804	3.6969	2122419.141	2.122
Fly Ash (µg/kg)	839.68	0.11%	838.756352	27.478	23047347.04	23.05
Seawater-Out (µg/L)	781.47	13.29%	677.612637	181.52	123000245.9	123.000
Stack gas (mg/m3)	62408005.1		62408005.1	0.002505375		156.36
Sampling cycle 4						
Feed coal (µg/kg)	6977.9	21.15%	5502.07415	145.53	800716851	800.72
Seawater-In (µg/L)	591.7	1.42%	583.29786	124.45	72591418.68	72.5914
Bottom Ash (µg/kg)	746.37	31.61%	510.442443	3.5324	1803086.886	1.803

Table A4-3 Quantification of mercury mass flows throughout the coal-fired power plant: Plant 2/Unit 6

Flow (Unit of Hg conc.)	Quantity	Moisture	Quantity	Concentration	Hg mass flows	
	t/d (as wet weight)	%	t/d (as dry weight)	(as dry weight)	(µg/d)	(g/d)
Fly Ash (µg/kg)	839.68	0.09%	838.924288	22.51	18884185.72	18.88
Seawater-Out (µg/L)	781.47	12.96%	680.191488	190.63	129664903.4	129.665
Stack gas (mg/m3)	63707187.65		63707187.65	0.011127908		708.93
Sampling cycle 5						
Feed coal (µg/kg)	6977.9	22.11%	5435.08631	131.8	716344375.7	716.34
Seawater-In (µg/L)	591.7	0.34%	589.68822	72.092	42511803.16	42.5118
Bottom Ash (µg/kg)	746.37	19.92%	597.693096	5.6617	3383959.002	3.384
Fly Ash (µg/kg)	839.68	0.10%	838.84032	17.301	14512776.38	14.51
Seawater-Out (µg/L)	781.47	16.23%	654.637419	118.57	77620358.77	77.620
Stack gas (mg/m3)	64132374.67		64132374.67	0.008047195		516.09

Table A4-4 Quantification of mercury mass flows throughout the coal-fired power plant: Plant 2/Unit 10

Flow (Unit of Hg conc.)	Quantity	Moisture	Quantity	Concentration	Hg mass flows	
	t/d (as wet weight)	%	t/d (as dry weight)	(as dry weight)	(µg/d)	(g/d)
Sampling cycle 1						
Feed coal (µg/kg)	5879.24	20.04%	4701.040304	101.37	476544455.6	476.54
Seawater-In (µg/L)	473	1.65%	465.1955	39.076	18177979.36	18.1780
Bottom Ash (µg/kg)	595.74	28.57%	425.537082	0.61834	263126.5993	0.263
Fly Ash (µg/kg)	670.21	0.23%	668.668517	15.012	10038051.78	10.04
Seawater-Out (µg/L)	720.33	19.16%	582.314772	140.82	82001566.19	82.002
Stack gas (mg/m3)	50532197.06		50532197.06	0.006734038		340.29
Sampling cycle 2						
Feed coal (µg/kg)	5879.24	20.18%	4692.809368	99.47	466793747.8	466.79
Seawater-In (µg/L)	473	0.96%	468.4592	50.268	23548507.07	23.5485
Bottom Ash (µg/kg)	595.74	28.16%	427.979616	3.0011	1284409.626	1.284

Table A4-4 Quantification of mercury mass flows throughout the coal-fired power plant: Plant 2/Unit 10

Flow (Unit of Hg conc.)	Quantity	Moisture	Quantity	Concentration	Hg mass flows	
	t/d (as wet weight)	%	t/d (as dry weight)	(as dry weight)	(µg/d)	(g/d)
Fly Ash (µg/kg)	670.21	0.21%	668.802559	11.035	7380236.239	7.38
Seawater-Out (µg/L)	720.33	17.73%	592.615491	127.75	75706628.98	75.707
Stack gas (mg/m3)	50951094	[redacted]	50951094	0.009924025	[redacted]	505.64
Samplingr cycle 3						
Feed coal (µg/kg)	5879.24	20.10%	4697.51276	116.72	548293689.3	548.29
Seawater-In (µg/L)	473	0.87%	468.8849	42.956	20141419.76	20.1414
Bottom Ash (µg/kg)	595.74	28.11%	428.277486	7.1527	3063340.374	3.063
Fly Ash (µg/kg)	670.21	0.23%	668.668517	22.262	14885898.53	14.89
Seawater-Out (µg/L)	720.33	15.76%	606.805992	150.91	91573092.25	91.573
Stack gas (mg/m3)	52075501.51	[redacted]	52075501.51	0.010338874	[redacted]	538.40
Sampling cycle 4						
Feed coal (µg/kg)	5879.24	19.16%	4752.777616	126.01	598897507.4	598.90
Seawater-In (µg/L)	473	0.94%	468.5538	51.647	24199398.11	24.1994
Bottom Ash (µg/kg)	595.74	30.64%	413.205264	57.397	23716742.54	23.717
Fly Ash (µg/kg)	670.21	0.16%	669.137664	20.673	13833082.93	13.83
Seawater-Out (µg/L)	720.33	17.07%	597.369669	146.07	87257787.55	87.258
Stack gas (mg/m3)	52626681.67	[redacted]	52626681.67	0.012184155	[redacted]	641.21
Sampling cycle 5						
Feed coal (µg/kg)	5879.24	18.77%	4775.706652	131.28	626954769.3	626.95
Seawater-In (µg/L)	473	1.94%	463.8238	60.776	28189355.27	28.1894
Bottom Ash (µg/kg)	595.74	0.42%	593.237892	23.964	14216352.84	14.216
Fly Ash (µg/kg)	670.21	27.89%	483.288431	22.942	11087603.18	11.09
Seawater-Out (µg/L)	720.33	17.73%	592.615491	137.88	81709823.9	81.710
Stack gas (mg/m3)	52582587.26	[redacted]	52582587.26	0.010325355	[redacted]	542.93

Table A4-5 Quantification of mercury mass flows throughout the coal-fired power plant: Plant 2/Unit 13

Flow (Unit of Hg conc.)	Quantity	Moisture	Quantity	Concentration	Hg mass flows	
	t/d (as wet weight)	%	t/d (as dry weight)	(as dry weight)	(µg/d)	(g/d)
Sampling cycle 1						
Feed coal (µg/kg)	5830.73	20.81%	4617.355087	130.45	602333971.1	602.33
Seawater-In (µg/L)	357.6	1.18%	353.38032	44.018	15555094.93	15.5551
Bottom Ash (µg/kg)	573.59	31.37%	393.654817	16.586	6529158.795	6.529
Fly Ash (µg/kg)	645.29	0.30%	643.35413	49.688	31966980.01	31.97
Seawater-Out (µg/L)	628.73	15.57%	530.836739	178.82	94924225.67	94.924
Stack gas (mg/m3)	55628634.38		55628634.38	0.005920497		329.35
Sampling cycle 2						
Feed coal (µg/kg)	5830.73	20.10%	4658.75327	136.59	636339109.1	636.34
Seawater-In (µg/L)	357.6	1.29%	352.98696	47.774	16863599.03	16.8636
Bottom Ash (µg/kg)	573.59	33.50%	381.43735	4.6015	1755183.966	1.755
Fly Ash (µg/kg)	645.29	0.33%	643.160543	44.914	28886912.63	28.89
Seawater-Out (µg/L)	628.73	20.44%	500.217588	221.2	110648130.5	110.648
Stack gas (mg/m3)	55510526.88		55510526.88	0.008918468		495.07
Sampling cycle 3						
Feed coal (µg/kg)	5830.73	19.23%	4709.480621	121.67	573002507.2	573.00
Seawater-In (µg/L)	357.6	1.17%	353.41608	65.116	23013041.47	23.0130
Bottom Ash (µg/kg)	573.59	28.01%	412.927441	6.2124	2565270.434	2.565
Fly Ash (µg/kg)	645.29	0.30%	643.35413	30.12	19377826.4	19.38
Seawater-Out (µg/L)	628.73	19.55%	505.813285	183.19	92659935.68	92.660
Stack gas (mg/m3)	55132582.87		55132582.87	0.002464425		135.87
Sampling cycle 4						
Feed coal (µg/kg)	5830.73	18.44%	4755.543388	109.76	521968442.3	521.97
Seawater-In (µg/L)	357.6	1.35%	352.7724	66.596	23493230.75	23.4932
Bottom Ash (µg/kg)	573.59	27.61%	415.221801	8.4918	3525980.49	3.526

Table A4-5 Quantification of mercury mass flows throughout the coal-fired power plant: Plant 2/Unit 13

Flow (Unit of Hg conc.)	Quantity	Moisture	Quantity	Concentration	Hg mass flows	
	t/d (as wet weight)	%	t/d (as dry weight)	(as dry weight)	(µg/d)	(g/d)
Fly Ash (µg/kg)	645.29	0.28%	643.483188	21.507	13839392.92	13.84
Seawater-Out (µg/L)	628.73	16.48%	525.115296	97.987	51454472.51	51.454
Stack gas (mg/m3)	55227068.88		55227068.88	0.005857679		323.50
Sampling cycle 5						
Feed coal (µg/kg)	5830.73	11.13%	5181.769751	123.68	640881282.8	640.88
Seawater-In (µg/L)	357.6	0.99%	354.05976	49.721	17604205.33	17.6042
Bottom Ash (µg/kg)	573.59	25.51%	427.267191	1.6113	688455.6249	0.688
Fly Ash (µg/kg)	645.29	8.82%	588.375422	27.491	16175028.73	16.18
Seawater-Out (µg/L)	628.73	22.06%	490.032162	148.69	72862882.17	72.863
Stack gas (mg/m3)	54353073.34		54353073.34	0.002917232		158.56

Table A4-6 Mercury mass balances throughout the coal-fired power plant

Flow		Sampling cycle						
		1	2	3	4	5	Ave	SD
Plant 1								
Hg in (g/d)		**403**	**327**	**244**	**410**	**326**	**342**	**68**
	Feed coal	401	324.728	243	409	322	340	68
	Sea water	1.4537	2.1485	1.0936	0.6703	3.7274	1.8187	1.1968
	Limestone	0	0	0	0	0	0	0
Hg out (g/d)		**147**	**100**	**163**	**121**	**129**	**132**	**24**
	Bottom ash	0.06	0.06	0.03	0.19	0.23	0.11	0
	Fly ash	21	31	30	54	41	35	13
	Sea water	54.930	42.117	43.284	29.435	60.624	46.078	12.149
	Gypsum	0	0	0	0	0	0	0
	Stack gas	71	26	90	37	28	50	28

Table A4-6 Mercury mass balances throughout the coal-fired power plant

Flow		Sampling cycle						
		1	**2**	**3**	**4**	**5**	**Ave**	**SD**
Hg out/in (%)		**36.4**	**30.6**	**66.9**	**29.6**	**39.6**	**38.6**	**15**
Plant 2 (Unit 6)								
Hg in (g/d)		**738**	**720**	**804**	**873**	**759**	**779**	**61**
	Feed coal	708	692	759	801	716	735	44
	Sea water	0	0	0	0	0	0	0
	Limestone	30	28	46	73	43	44	18
Hg out (g/d)		**548**	**878**	**305**	**859**	**612**	**640**	**238**
	Bottom ash	15	0.28	2.12	2	3	5	6
	Fly ash	18	19	23	19	15	19	3
	Sea water	0	0	0	0	0	0	0
	Gypsum	144	94	123	130	78	114	27
	Stack gas	371	765	156	709	516	504	249
Hg out/in (%)		**74.3**	**122.0**	**37.9**	**98.4**	**80.6**	**82.2**	**31.1**
Plant 2 (Unit 10)								
Hg in (g/d)		**495**	**490**	**568**	**623**	**655**	**566**	**74**
	Feed coal	476.54	466.79	548.29	598.90	626.95	543.50	71.46
	Sea water	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Limestone	18.18	23.55	20.14	24.20	28.19	22.85	3.87
Hg out (g/d)		**432.59**	**590.01**	**647.92**	**766.02**	**649.95**	**617.30**	**121.43**
	Bottom ash	0.26	1.28	3.06	23.72	14.22	8.51	10.17
	Fly ash	10.04	7.38	14.89	13.83	11.09	11.44	3.01
	Sea water	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Gypsum	82.00	75.71	91.57	87.26	81.71	83.65	6.03
	Stack gas	340.29	505.64	538.40	641.21	542.93	513.69	109.39
Hg out/in (%)		**87.44**	**120.33**	**113.98**	**122.94**	**99.21**	**109.00**	**15.07**

Table A4-6 Mercury mass balances throughout the coal-fired power plant

Flow		Sampling cycle						
		1	**2**	**3**	**4**	**5**	**Ave**	**SD**
Plant 2 (Unit 13)								
Hg in (g/d)		**618**	**653**	**596**	**545**	**658**	**614**	**46**
	Feed coal	602	636	573	522	641	595	49
	Sea water	0	0	0	0	0	0	0
	Limestone	16	17	23	23.5	18	19	4
Hg out (g/d)		**463**	**636**	**250**	**392**	**248**	**398**	**162**
	Bottom ash	7	2	3	4	1	3	2
	Fly ash	32	29	19	14	16	22	8
	Sea water	0	0	0	0	0	0	0
	Gypsum	95	111	93	51	73	85	23
	Stack gas	329	495	136	324	159	288	146
Hg out/in (%)		**74.9**	**97.4**	**42.0**	**71.9**	**37.7**	**64.8**	**24.8**

Table A4-7 Mercury mass fractions throughout the coal-fired power plant

Flow		Sampling cycle					
		1	**2**	**3**	**4**	**5**	**Ave**
Plant 1							
Hg in (%)							
	Feed coal	99.6	99.3	99.6	99.8	98.9	99.5
	Sea water	0.36076	0.65729	0.44799	0.16366	1.14301	0.53191
	Limestone	0.0	0.0	0.0	0.0	0.0	0.0
Hg out (%)							
	Bottom ash	0.014	0.017	0.013	0.047	0.071	0.033

Table A4-7 Mercury mass fractions throughout the coal-fired power plant

Flow		Sampling cycle					
		1	**2**	**3**	**4**	**5**	**Ave**
	Fly ash	5.2	9.6	12.3	13.3	12.4	10.4
	Sea water	13.632	12.885	17.731	7.187	18.591	13.476
	Gypsum	0.0	0.0	0.0	0.0	0.0	0.0
	Stack gas	17.6	8.1	36.8	9.0	8.6	14.7
Hg out/in (%)		36.4	30.6	66.9	29.6	39.6	38.6
Loss (%)		63.6	69.4	33.1	70.4	60.4	61.4
Plant 2 (Unit 6)							
Hg in (%)							
	Feed coal	95.9	96.1	94.3	91.7	94.4	94.4
	Sea water	0.0	0.0	0.0	0.0	0.0	0.0
	Limestone	4.1	3.9	5.7	8.3	5.6	5.6
Hg out (%)							
	Bottom ash	2.1	0.0	0.3	0.2	0.4	0.6
	Fly ash	2.5	2.6	2.9	2.2	1.9	2.4
	Sea water	0.0	0.0	0.0	0.0	0.0	0.0
	Gypsum	19.4	13.0	15.3	14.8	10.2	14.6
	Stack gas	50.3	106.3	19.4	81.2	68.0	64.6
Hg out/in (%)		74.3	122.0	37.9	98.4	80.6	82.2
Loss (%)		25.7	-22.0	62.1	1.6	19.4	17.8
Plant 2 (Unit 10)							
Hg in (%)							
	Feed coal	96.3	95.2	96.5	96.1	95.7	96.0
	Sea water	0.0	0.0	0.0	0.0	0.0	0.0
	Limestone	3.7	4.8	3.5	3.9	4.3	4.0
Hg out (%)							

Table A4-7 Mercury mass fractions throughout the coal-fired power plant

Flow		Sampling cycle					
		1	**2**	**3**	**4**	**5**	**Ave**
	Bottom ash	0.1	0.3	0.5	3.8	2.2	1.5
	Fly ash	2.0	1.5	2.6	2.2	1.7	2.0
	Sea water	0.0	0.0	0.0	0.0	0.0	0.0
	Gypsum	16.6	15.4	16.1	14.0	12.5	14.8
	Stack gas	68.8	103.1	94.7	102.9	82.9	90.7
Hg out/in (%)		87.4	120.3	114.0	122.9	99.2	109.0
Loss (%)		12.6	-20.3	-14.0	-22.9	0.8	-9.0
Plant 2 (Unit 13)							
Hg in (%)							
	Feed coal	97.5	97.4	96.1	95.7	97.3	96.9
	Sea water	0.0	0.0	0.0	0.0	0.0	0.0
	Limestone	2.5	2.6	3.9	4.3	2.7	3.1
Hg out (%)							
	Bottom ash	1.1	0.3	0.4	0.6	0.1	0.5
	Fly ash	5.2	4.4	3.3	2.5	2.5	3.6
	Sea water	0.0	0.0	0.0	0.0	0.0	0.0
	Gypsum	15.4	16.9	15.5	9.4	11.1	13.8
	Stack gas	53.3	75.8	22.8	59.3	24.1	47.0
Hg out/in (%)		74.9	97.4	42.0	71.9	37.7	64.8
Loss (%)		25.1	2.6	58.0	28.1	62.3	35.2

Annex-5 Calculation of mercury emission factor

Table A5-1 Raw data and calculation of atmospheric mercury emission of Plant 1

Parameters	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 4**	**Cycle 5**
Average coal consumption rate (ton/hr)[a]	244.64	244.99	243.65	244.86	245.14
Flow rate at actual condition (m^3/hr)	3038408.76	3042330.97	3029256.92	3093319.76	3017490.28
Percent oxygen (%)	4.7	4.9	4.9	4.8	4.8
Flow rate at 7% oxygen condition (m^3/hr)	2401348.2	2432580.04	2384275.97	2441922.9	2367642.6
Atmospheric mercury concentration (mg/m^3) at actual	0.000972	0.000362	0.001235	0.000498	0.000385
Atmospheric mercury concentration (mg/m^3) at 7% oxygen	0.000833	0.000315	0.001074	0.000431	0.000333
Atmospheric mercury emission factor (mg/ton)[b] at actual	12.07	4.50	15.36	6.29	4.74

Remarks: [a] Wet weight basis (as received),
[b] milligram per ton coal (as received)

Table A5-2 Raw data and calculation of atmospheric mercury emission of Plant 2/Unit 6

Parameters	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 4**	**Cycle 5**
Average coal consumption rate (ton/hr)[a]	290.75	290.75	290.75	290.75	290.75
Flow rate at actual condition (m^3/hr)	2576712.05	2604270.46	2600333.55	2654466.15	2672182.28
Percent oxygen (%)	6.1	6.5	6.3	6.5	6.6
Flow rate at 7% oxygen condition (m^3/hr)	1513809.43	1515181.09	1505031.21	1561227.57	1565162.39
Atmospheric mercury concentration (mg/m^3) at actual	0.006002	0.012246	0.002505	0.011128	0.008047
Atmospheric mercury concentration (mg/m^3) at 7% oxygen	0.005637	0.011822	0.002385	0.010742	0.007822
Atmospheric mercury emission factor (mg/ton)[b] at actual	53.20	109.69	22.41	101.60	73.96

Remarks: [a] Wet weight basis (as received),
[b] milligram per ton coal (as received)

Table A5-3 Raw data and calculation of atmospheric mercury emission of Pant2/Unit 10

Parameters	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 4**	**Cycle 5**
Average coal consumption rate (ton/hr)[a]	244.97	244.97	244.97	244.97	244.97
Flow rate at actual condition (m^3/hr)	2105508.21	2122962.25	2169812.56	2192778.40	2190941.14
Percent oxygen (%)	6.3	6.3	6.0	6.1	6.0
Flow rate at 7% oxygen condition (m^3/hr)	1304392.75	1330354.41	1333634.17	1338712.23	1331922.28
Atmospheric mercury concentration (mg/m^3) at actual	0.006734	0.009924	0.010339	0.012184	0.010325
Atmospheric mercury concentration (mg/m^3) at 7% oxygen	0.006411	0.009448	0.009645	0.0114431	0.009633
Atmospheric mercury emission factor (mg/ton)[b] at actual	57.88	86.00	91.58	109.06	92.35

Remarks: [a] Wet weight basis (as received),
[b] milligram per ton coal (as received)

Table A5-4 Raw data and calculation of atmospheric mercury emission of Plant 2/Unit 13

Parameters	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 4**	**Cycle 5**
Average coal consumption rate (ton/hr)[a]	242.95	242.95	242.95	242.95	242.95
Flow rate at actual condition (m^3/hr)	2317859.77	2312938.62	2297190.95	2301127.87	2264711.39
Percent oxygen (%)	5.0	5.1	5.1	5.0	5.3
Flow rate at 7% oxygen condition (m^3/hr)	1459566.91	1448662.85	1457657.97	1454545.48	1423048.19
Atmospheric mercury concentration (mg/m^3) at actual	0.005920	0.008918	0.002464	0.005858	0.002917
Atmospheric mercury concentration (mg/m^3) at 7% oxygen	0.005175	0.007846	0.002168	0.005122	0.002600
Atmospheric mercury emission factor (mg/ton)[b] at actual	56.48	84.91	23.30	55.48	27.19

Remarks: [a] Wet weight basis (as received),
[b] milligram per ton coal (as received)

Table A5-5 Concentration of mercury speciation from down-stream of flue gas (at stack sampling) at actual condition

Sites	Mercury species	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Min	Average	Max	SD
Plant 1	$Hg_{(p)}$ (µg/m^3)	0.311	0.000	0.044	0.000	0.000	0.000	0.071	0.311	0.135
	Hg^{2+} (µg/m^3)	0.002	0.009	0.005	0.010	0.004	0.002	0.006	0.010	0.003
	Hg^0 (µg/m^3)	0.658	0.353	1.186	0.488	0.381	0.353	0.613	1.186	0.342
	Total (µg/m^3)	0.972	0.362	1.235	0.498	0.385	**0.362**	**0.691**	**1.235**	**0.392**
Plant 2/ Unit 6	$Hg_{(p)}$ (µg/m^3)	0.008	0.026	0.011	0.005	0.021	0.005	0.014	0.026	0.009
	Hg^{2+} (µg/m^3)	0.882	0.453	0.179	0.589	0.149	0.149	0.450	0.882	0.304
	Hg^0 (µg/m^3)	5.112	11.766	2.316	10.534	7.878	2.316	7.521	11.766	3.877
	Total (µg/m^3)	6.002	12.246	2.505	11.128	8.047	**2.505**	**7.986**	**12.246**	**3.937**
Plant 2/ Unit 10	$Hg_{(p)}$ (µg/m^3)	0.008	0.119	0.010	0.016	0.003	0.003	0.031	0.119	0.049
	Hg^{2+} (µg/m^3)	0.190	0.522	0.238	0.034	0.037	0.034	0.204	0.522	0.200
	Hg^0 (µg/m^3)	6.536	9.284	10.090	12.134	10.286	6.536	9.666	12.134	2.037
	Total (µg/m^3)	6.734	9.924	10.339	12.184	10.325	**6.734**	**9.901**	**12.184**	**1.976**
Plant 2/ Unit 13	$Hg_{(p)}$ (µg/m^3)	0.001	0.044	0.024	0.041	0.002	0.001	0.022	0.044	0.021
	Hg^{2+} (µg/m^3)	0.080	0.395	0.203	0.010	0.073	0.010	0.152	0.395	0.153
	Hg^0 (µg/m^3)	5.840	8.479	2.237	5.807	2.842	2.237	5.041	8.479	2.537
	Total (µg/m^3)	5.920	8.918	2.464	5.858	2.917	**2.464**	**5.216**	**8.918**	**2.621**

Table A5-6 Concentration of mercury speciation from down-stream of flue gas (at stack sampling) at actual condition

Sites	Mercury species	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Min	Average	Max	SD
Plant 1	$Hg_{(p)}$ (%)	32.00	0.00	3.56	0.00	0.00	0.00	7.11	32.00	14.00
	Hg^{2+} (%)	0.25	2.51	0.42	2.03	1.13	0.25	1.27	2.51	0.99
	Hg^{0} (%)	67.75	97.49	96.02	97.97	98.87	67.75	91.62	98.87	13.38
	Total (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00
Plant 2/ Unit 6	$Hg_{(p)}$ (%)	0.14	0.21	0.43	0.04	0.26	0.04	0.22	0.43	0.14
	Hg^{2+} (%)	14.69	3.70	7.13	5.30	1.85	1.85	6.53	14.69	4.96
	Hg^{0} (%)	85.17	96.08	92.44	94.66	97.89	85.17	93.25	97.89	4.94
	Total (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00
Plant 2/ Unit 10	$Hg_{(p)}$ (%)	0.12	1.20	0.10	0.13	0.03	0.03	0.32	1.20	0.49
	Hg^{2+} (%)	2.82	5.26	2.30	0.28	0.35	0.28	2.20	5.26	2.05
	Hg^{0} (%)	97.06	93.55	97.59	99.59	99.62	93.55	97.48	99.62	2.49
	Total (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00
Plant 2/ Unit 13	$Hg_{(p)}$ (%)	0.01	0.49	0.98	0.70	0.06	0.01	0.45	0.98	0.41
	Hg^{2+} (%)	1.34	4.43	8.24	0.17	2.52	0.17	3.34	8.24	3.16
	Hg^{0} (%)	98.64	95.08	90.78	99.13	97.42	90.78	96.21	99.13	3.42
	Total (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00

Table A5-7 Amount of mercury speciation from mercury outputs at actual condition

Site	Speciation	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Min	Average	Max	SD
Plant 1	$Hg_{(p)}$ (g/d)	43.7	31.4	33.3	54.6	40.7	31.4	40.8	54.6	9.3
	Hg^{2+} (g/d)	55.1	42.8	43.7	30.2	60.9	30.2	46.5	60.9	11.9
	Hg^{0} (g/d)	48.0	25.8	86.2	36.2	27.6	25.8	44.8	86.2	24.8
	Total (g/d)	146.8	100.0	163.2	121.1	129.3	100.0	132.1	163.2	24.2
Plant 2/ Unit 6	$Hg_{(p)}$ (g/d)	34.1	20.8	25.8	21.0	19.2	19.2	24.2	34.1	6.1
	Hg^{2+} (g/d)	198.1	122.3	134.2	167.2	87.2	87.2	141.8	198.1	42.5
	Hg^{0} (g/d)	316.1	735.4	144.5	671.1	505.2	144.5	474.5	735.4	245.8
	Total (g/d)	548.3	878.5	304.5	859.3	611.6	304.5	640.4	878.5	238.1
Plant 2/ Unit 10	$Hg_{(p)}$ (g/d)	10.7	14.7	18.5	38.4	25.4	10.7	21.6	38.4	10.9
	Hg^{2+} (g/d)	91.6	102.3	104.0	89.0	83.6	83.6	94.1	104.0	8.7
	Hg^{0} (g/d)	330.3	473.0	525.5	638.6	540.9	330.3	501.6	638.6	113.0
	Total (g/d)	432.6	590.0	647.9	766.0	649.9	432.6	617.3	766.0	121.4
Plant 2/ Unit 13	$Hg_{(p)}$ (g/d)	38.5	33.1	23.3	19.6	17.0	17.0	26.3	38.5	9.2
	Hg^{2+} (g/d)	99.3	132.6	103.8	52.0	76.9	52.0	92.9	132.6	30.3
	Hg^{0} (g/d)	324.9	470.7	123.3	320.7	154.5	123.3	278.8	470.7	141.7
	Total (g/d)	462.8	636.4	250.5	392.3	248.3	248.3	398.0	636.4	162.2

Table A5-8 Percentage of mercury speciation from mercury outputs at actual condition

Sites	Mercury species	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Min	Average	Max	SD
Plant 1	$Hg_{(p)}$ (%)	29.76	31.41	20.42	45.13	31.51	20.42	31.65	45.13	8.82
	Hg^{2+} (%)	37.54	42.79	26.75	24.93	47.14	24.93	35.83	47.14	9.75
	Hg^{0} (%)	32.70	25.80	52.83	29.93	21.35	21.35	32.52	52.83	12.14

Table A5-8 Percentage of mercury speciation from mercury outputs at actual condition

Sites	Mercury species	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Min	Average	Max	SD
	Total (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00
Plant 2/ Unit 6	$Hg_{(p)}$ (%)	6.22	2.37	8.48	2.44	3.15	2.37	4.53	8.48	2.71
	Hg^{2+} (%)	36.12	13.92	44.05	19.46	14.25	13.92	25.56	44.05	13.73
	Hg^{0} (%)	57.66	83.71	47.46	78.10	82.60	47.46	69.91	83.71	16.38
	Total (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00
Plant 2/ Unit 10	$Hg_{(p)}$ (%)	2.48	2.49	2.85	5.01	3.92	2.48	3.35	5.01	1.10
	Hg^{2+} (%)	21.17	17.34	16.05	11.62	12.87	11.62	15.81	21.17	3.79
	Hg^{0} (%)	76.35	80.17	81.10	83.36	83.22	76.35	80.84	83.36	2.86
	Total (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00
Plant 2/ Unit 13	$Hg_{(p)}$ (%)	8.33	5.20	9.29	5.00	6.83	5.00	6.93	9.29	1.89
	Hg^{2+} (%)	21.47	20.83	41.46	13.25	30.95	13.25	25.59	41.46	10.87
	Hg^{0} (%)	70.20	73.97	49.24	81.74	62.21	49.24	67.47	81.74	12.38
	Total (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00

Table A5-9 Emission factors for atmospheric mercury emission (mg/ton) for Scenario 1 (at actual condition)

Sites	Atmospheric mercury emission (mg/ton)					Min	Average	Max	SD
	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5				
Plant 1	12.07	4.50	15.36	6.29	4.74	4.50	8.59	15.36	4.86
Plant 2/Unit 6	53.20	109.69	22.41	101.60	73.96	22.41	72.17	109.69	35.75
Plant 2/Unit 10	57.88	86.00	91.58	109.06	92.35	57.88	87.37	109.06	18.61
Plant 2/Unit 13	56.49	84.91	23.30	55.48	27.19	23.30	49.47	84.91	25.11

Table A5-10 Emission factors for atmospheric mercury emission (mg/ton) for Scenario 2 (at actual condition)

Sites	Atmospheric mercury emission (mg/ton)					Min	Average	Max	SD
	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5				
Plant 1	55.69	43.09	29.19	55.39	38.20	29.19	44.31	55.69	11.40
Plant 2/Unit 6	80.43	87.00	94.03	103.61	95.06	80.43	92.03	103.61	8.76
Plant 2/Unit 10	68.45	69.05	78.06	84.75	93.23	68.45	78.71	93.23	10.56
Plant 2/Unit 13	83.09	87.80	82.56	81.75	97.55	81.75	86.55	97.55	6.58

Table A5-11 Percent efficiency (%) of mercury removal in Scenario 3 (at actual condition)

Sites	Percent efficiency (%)					Min	Average	Max	SD
	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5				
Plant 1	18.85	22.49	30.08	20.53	31.08	18.85	24.61	31.08	5.62
Plant 2/Unit 6	23.99	15.70	18.42	17.22	12.59	12.59	17.58	23.99	4.19
Plant 2/Unit10	18.66	17.21	19.27	20.03	16.33	16.33	18.30	20.03	1.51
Plant 2/Unit 13	21.59	21.63	19.23	12.62	13.63	12.62	17.74	21.63	4.34

Table A5-12 Percent efficiency (%) of mercury removal for uncontrolled emission in Scenario 3 (at actual condition)

Sites	Percent efficiency (%)					Min	Average	Max	SD
	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5				
Plant 1	0.01	0.02	0.01	0.05	0.07	0.01	0.03	0.07	0.03
Plant 2/Unit 6	2.14	0.04	0.28	0.23	0.47	0.04	0.63	2.14	0.86
Plant 2/Unit 10	0.06	0.28	0.56	3.96	2.27	0.06	1.42	3.96	1.66
Plant 2/Unit 13	1.08	0.28	0.45	0.68	0.11	0.11	0.52	1.08	0.38

Annex-6 Future mercury emission estimates from coal fired power plants in Thailand:

Scenario of estimation for 2025

Table A6-1 Predicted Hg emissions from existing and new coal and lignite power plants in Thailand from 2017 to 2025: using the selected Hg removal efficiency taken from literatures

Power plant	Hg emission (kg/y)								
	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
Minimum Hg emission									
Existing Bituminous plant	91	78	91	91	91	91	91	91	91
New Bituminous plant	0	0	0	54	107	125	125	161	161
Coal power plant	950	1010	891	891	891	772	772	772	356
Total	1041	1088	982	1036	1089	988	988	1024	608
Average Hg emission									
Existing Bituminous plant	266	228	266	266	266	266	266	266	266
New Bituminous plant	0	0	0	156	313	365	365	469	469
Coal power plant	1616	1717	1515	1515	1515	1313	1313	1313	606
Total	1882	1945	1781	1938	2094	1944	1944	2049	1342
Maximum Hg emission									
Existing Bituminous plant	610	523	610	610	610	610	610	610	610
New Bituminous plant	0	0	0	359	717	837	837	1076	1076
Coal power plant	2294	2437	2151	2151	2151	1864	1864	1864	860
Total	2904	2961	2761	3120	3478	3311	3311	3550	2547

Table A6-2 Predicted Hg emissions from existing and new coal and lignite power plants in Thailand from 2017 to 2025: using the selected Hg removal efficiency taken from literatures (Minimum Hg emission): Note: B: Bituminous; L: Lignite

Power plant	Coal type	Minimum Hg emission (kg/y)								
		2017	2018	2019	2020	2021	2022	2023	2024	2025
Nanyang Energy	B	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
EkaratPattana	B	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
TPI Polene	B	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ajinomoto (Thailand)	B	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Inter Pacific Paper	B	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
United Paper	B	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Elite-Kraft Paper	B	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Thai Cane Paper PLC	B	0.9	0.7	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Thai Acrylic Fibre	B	0.7	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Environment pulp and paper	B	1.1	0.9	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Panjapol Pulp Industry	B	1.3	1.1	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Siam Kraft Industry	B	1.8	1.5	1.8	1.8	1.8	1.8	1.8	1.8	1.8
TPT Petrochemicals	B	1.8	1.6	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Siam Kraft Industry	B	2.8	2.4	2.8	2.8	2.8	2.8	2.8	2.8	2.8
IRPC public company limited	B	3.6	3.1	3.6	3.6	3.6	3.6	3.6	3.6	3.6
Glow SPP 3(Project 1)	B	1.8	1.5	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Glow SPP 3 (Project 2)	B	1.8	1.5	1.8	1.8	1.8	1.8	1.8	1.8	1.8
National Power Supply (P1)	B	4.3	3.7	4.3	4.3	4.3	4.3	4.3	4.3	4.3
National Power Supply (P2)	B	4.3	3.7	4.3	4.3	4.3	4.3	4.3	4.3	4.3
National Power Supply	B	14.2	12.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2
GHECO-One	B	15.6	13.3	15.6	15.6	15.6	15.6	15.6	15.6	15.6
BLCP Power	B	33.9	29.0	33.9	33.9	33.9	33.9	33.9	33.9	33.9
Mae Moh	L	950.3	1009.7	890.9	890.9	890.9	772.1	772.1	772.1	356.4
New Plant	B	0.0	0.0	0.0	53.5	107.0	124.9	124.9	160.6	160.6

Table A6-3 Predicted Hg emissions from existing and new coal and lignite power plants in Thailand from 2017 to 2025: using the selected Hg removal efficiency taken from literatures (Average Hg emission): Note: B: Bituminous; L: Lignite

Power plant	Coal type	Average Hg emission (kg/y)								
		2017	2018	2019	2020	2021	2022	2023	2024	2025
Nanyang Energy	B	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
EkaratPattana	B	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
TPI Polene	B	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Ajinomoto (Thailand)	B	0.8	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Inter Pacific Paper	B	0.7	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7
United Paper	B	0.7	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Elite-Kraft Paper	B	1.0	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Thai Cane Paper PLC	B	2.5	2.2	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Thai Acrylic Fibre	B	1.9	1.7	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Environment pulp and paper	B	3.1	2.7	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Panjapol Pulp Industry	B	3.9	3.3	3.9	3.9	3.9	3.9	3.9	3.9	3.9
Siam Kraft Industry	B	5.2	4.4	5.2	5.2	5.2	5.2	5.2	5.2	5.2
TPT Petrochemicals	B	5.3	4.6	5.3	5.3	5.3	5.3	5.3	5.3	5.3
Siam Kraft Industry	B	8.3	7.1	8.3	8.3	8.3	8.3	8.3	8.3	8.3
IRPC public company limited	B	10.5	9.0	10.5	10.5	10.5	10.5	10.5	10.5	10.5
Glow SPP 3(Project 1)	B	5.3	4.5	5.3	5.3	5.3	5.3	5.3	5.3	5.3
Glow SPP 3 (Project 2)	B	5.3	4.5	5.3	5.3	5.3	5.3	5.3	5.3	5.3
National Power Supply (P1)	B	12.6	10.8	12.6	12.6	12.6	12.6	12.6	12.6	12.6
National Power Supply (P2)	B	12.6	10.8	12.6	12.6	12.6	12.6	12.6	12.6	12.6
National Power Supply	B	41.5	35.5	41.5	41.5	41.5	41.5	41.5	41.5	41.5
GHECO-One	B	45.5	39.0	45.5	45.5	45.5	45.5	45.5	45.5	45.5
BLCP Power	B	99.1	84.9	99.1	99.1	99.1	99.1	99.1	99.1	99.1
Mae Moh	L	1615.8	1716.8	1514.8	1514.8	1514.8	1312.8	1312.8	1312.8	605.9
New Plant	B	0.0	0.0	0.0	156.5	313.0	365.1	365.1	469.4	469.4

Table A6-4 Predicted Hg emissions from existing and new coal and lignite power plants in Thailand from 2017 to 2025: using the selected Hg removal efficiency taken from literatures (Maximum Hg emission): Note: B: Bituminous; L: Lignite

Power plant	Coal type	Maximum Hg emission (kg/y)								
		2017	2018	2019	2020	2021	2022	2023	2024	2025
Nanyang Energy	B	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
EkaratPattana	B	0.7	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7
TPI Polene	B	0.4	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Ajinomoto (Thailand)	B	1.9	1.6	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Inter Pacific Paper	B	1.5	1.3	1.5	1.5	1.5	1.5	1.5	1.5	1.5
United Paper	B	1.5	1.3	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Elite-Kraft Paper	B	2.2	1.9	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Thai Cane Paper PLC	B	5.8	5.0	5.8	5.8	5.8	5.8	5.8	5.8	5.8
Thai Acrylic Fibre	B	4.4	3.8	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Environment pulp and paper	B	7.1	6.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
Panjapol Pulp Industry	B	8.9	7.6	8.9	8.9	8.9	8.9	8.9	8.9	8.9
Siam Kraft Industry	B	11.9	10.2	11.9	11.9	11.9	11.9	11.9	11.9	11.9
TPT Petrochemicals	B	12.2	10.5	12.2	12.2	12.2	12.2	12.2	12.2	12.2
Siam Kraft Industry	B	18.9	16.2	18.9	18.9	18.9	18.9	18.9	18.9	18.9
IRPC public company limited	B	24.0	20.6	24.0	24.0	24.0	24.0	24.0	24.0	24.0
Glow SPP 3(Project 1)	B	12.1	10.4	12.1	12.1	12.1	12.1	12.1	12.1	12.1
Glow SPP 3 (Project 2)	B	12.1	10.4	12.1	12.1	12.1	12.1	12.1	12.1	12.1
National Power Supply (P1)	B	28.9	24.7	28.9	28.9	28.9	28.9	28.9	28.9	28.9
National Power Supply (P2)	B	28.9	24.7	28.9	28.9	28.9	28.9	28.9	28.9	28.9
National Power Supply	B	95.0	81.4	95.0	95.0	95.0	95.0	95.0	95.0	95.0
GHECO-One	B	104.4	89.5	104.4	104.4	104.4	104.4	104.4	104.4	104.4
BLCP Power	B	227.1	194.6	227.1	227.1	227.1	227.1	227.1	227.1	227.1
Mae Moh	L	2293.9	2437.3	2150.5	2150.5	2150.5	1863.8	1863.8	1863.8	860.2
New Plant	B	0.0	0.0	0.0	358.7	717.4	837.0	837.0	1076.2	1076.2

Annex-7 Workshop agenda

Workshop on Dissemination of Results of the Project entitled

"Reducing Mercury Emission from Coal Combustion in the Energy Sector in Thailand"

Tuesday 7th November 2017: 08:30 am – 4:30 pm

Thammasat Conference Center, Pathumthani, Thailand

Time	Topic	Speaker
08:30 - 09:00	Registration	
09:00 - 09:15	Opening remarks	Dr. Chaiyuth Chavalitnitikul Dean of Faculty of Public Health Ms. Teeraporn Wiriwutikorn Chief of Hazardous Waste Division
9:15 - 09:30	Introduction to the workshop, objectives and participants	Ms. Teeraporn Wiriwutikorn Chief of Hazardous Waste Division
09:30 - 10:30	Reducing Mercury Emission from Coal Combustion in the Energy Sector in Thailand • Objectives • Methodology • Results and discussion	Dr. Pensri Watchalayann
10:45 - 12:00	Process optimization guidance (POG)	Dr. Wojciech Jozewicz, UN Environment
12:00 – 1.00 pm	Lunch	
1.00-1.30 pm	BAT/BEP	Dr. Lesley Sloss, UN Environment
1.50- 3.15 pm	Linking alternative options for reducing mercury emission from a coal fired power plant in Thailand: Dialogue and Discussion	Ms. Teeraporn Wiriwutikorn Dr. Pensri Watchalayann Dr. Nantika Soonthornchaikul
3:15 - 3:30 pm	Summary	Ms. Teeraporn Wiriwutikorn Dr. Pensri Watchalayann
3:30 pm	Closing remarks	Dr. Sheila Logan UN Environment

Note: Coffee break at 10:30 - 10:45 am. and 2:30 - 2.45 pm.