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Social Benefit of Clean Coal Technology

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Foreword

Coal power generation is a realistic way for many developing countries to ensure stable, affordable electricity supply. However, its heavy environment load such as air pollution sometimes raises serious health concerns, giving rise to protests against coal power generation. Although tighter regulation is needed to avoid the environmental side effects of coal power generation, considerations such as increasing power generation cost and subsequent rising electricity tariff make a political decision difficult. This study quantifies the health benefits of tighter regulation – air emission standards, to be precise – in monetary terms. The recognition that that the health benefit of tighter air emission standards exceeds the cost of investment in an air quality control system to comply with them may weaken resistance to tighter regulation, thereby lowering the environmental footprint of coal power generation.

I hope this study will serve as a good reference for policymakers in the region.

Ichiro Kutani
Leader, Working Group
June 2019

Acknowledgements

The analysis was undertaken by the Economic Research Institute for ASEAN and East Asia (ERIA) and the Institute of Energy Economics, Japan (IEEJ), with valuable inputs from workshop participants. I would like to express my gratitude to the participants, ERIA, and study members from the IEEJ.

Ichiro Kutani
Leader, Working Group
June 2019

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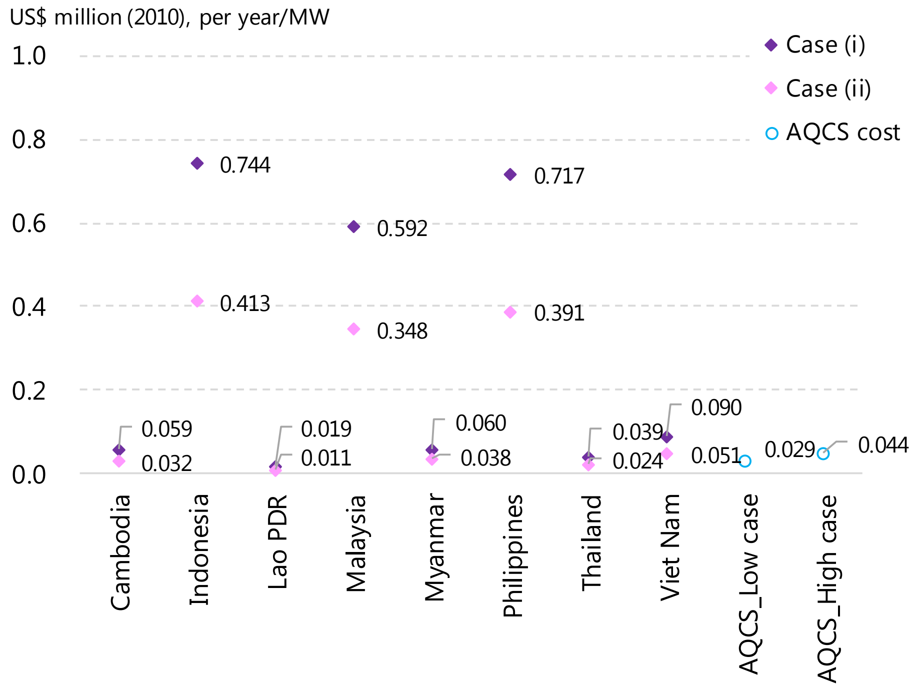
Abbreviations and Acronyms

AF	attributable fraction
AQCS	air quality control system
ASEAN	Association of Southeast Asian Nations
BC	black carbon
CAPEX	capital expenditure
CO_2	carbon dioxide
CONCAWE	Conservation of Clean Air and Water in Western Europe
CPI	consumer price index
CRF	concentration response function
DALY	disability adjusted life year
EPA	Environmental Protection Agency (United States)
ERIA	Economic Research Institute for ASEAN and East Asia
HIA	health impact assessment
IEA	International Energy Agency
IEEJ	The Institute of Energy Economics, Japan
LIME	Life-cycle Impact Assessment Method Based on Endpoint
MHPS	Mitsubishi Hitachi Power Systems
NOx	nitrogen oxides
OC	organic carbon
OECD	Organisation for Economic Co-operation and Development
O&M	operation and maintenance
PM	particulate matter
PPP	purchasing power parity
SOx	sulphur oxides
VSL	value of statistical life
WTP	willingness-to-pay

Executive Summary

This study analyses the cost and benefit of more-stringent air emission standards for coal-fired power plants. The cost is assumed to be the investment amount needed for a typical air quality control system (AQCS) to comply with strengthened air emission standards. The benefit is the reduced health impact in monetary terms thanks to better air quality. In the countries surveyed for this study, the potential benefit gained by tightening air pollutant emission standards often exceeds the cost required to install AQCS. In many Association of Southeast Asian Nations (ASEAN) members, tightening emission standards for coal-fired power plants and installing AQCS to conform to such standards may be considered economically rational.

Figure: Results of Cost-and-Benefit Analysis



AQCS = air quality control system, Lao PDR = Lao People's Democratic Republic.
Note: Case (i) = most strengthened emission standard. Case (ii) = half of existing emission standard.
Source: Author.

Coal-fired power generation is forecast to increase in ASEAN countries until 2040. They should install AQCS in coal-fired power plants that started operating in or after 1990. Because financing from overseas financial institutions for coal-fired power generation–related technology is often no longer feasible, financing should be procured locally. The government should declare its support for coal-fired power generation and AQCS to encourage local financial institutions to fund new coal-fired power plants and related technology such as AQCS. To enhance the investment capacity of local electric power companies, government must withdraw energy subsidies to encourage sound management. Investment decisions for large-scale infrastructure and facilities, including AQCS, will become more difficult for electric power companies if they are placed in a competitive market where future profitability is uncertain.

Investment in coal-fired power generation–related technology is complicated where multiple political issues exist simultaneously. However, for ASEAN countries, where energy demand continues to increase along with economic growth, coal-fired power generation will continue to be an important power source because local resources can be utilised or fuel costs are low. ASEAN policymakers will be required to tighten air emission standards for coal-fired power generation at the right time and on the right scale, and to make coal use sustainable.

Chapter 1

Background

The number of coal-fired power plants is expected to increase in Association of Southeast Asian Nations (ASEAN) members because the energy is produced from abundant, relatively cheap resources and offers security and economic benefit. Coal-fired power generation provides stable and affordable electricity supply but also emits carbon dioxide (CO_2) and pollutes the air. Air pollution caused by sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM) is a policy priority in many ASEAN countries and one of the biggest reasons for the strong opposition against coal-fired power plants. Applying clean coal technology to reduce coal-fired power's environmental load is indispensable to make coal use sustainable. Although an air quality control system (AQCS) is commercially available, not all power plants in ASEAN countries use it. Reducing air pollution from coal-fired power plants would help the public understand how important an AQCS is and improve the investment environment for it. AQCS requires additional investment but the benefits are numerous, including good air quality and continuous development of a low-cost power generation fleet.

This study is structured based on two studies. The FY 2016 study (ERIA, 2017) summarised existing air pollutant emission standards and their implementation mechanism in ASEAN countries. The FY 2017 study (ERIA, 2018) reviewed commercially available clean coal technologies and whether they were installed or not, and estimated the cost of AQCS installation and its impact on electricity prices. This study quantifies the cost and benefit of more-stringent air emission standards. To be precise, it will estimate the social (health) benefit of good air quality and compare it with the typical cost of investing in AQCS. The analysis shows the rewards of additional investment in AQCS.

Chapter 2

Coal Power Plants in ASEAN

1. Coal Use in the Power Sector

1.1. Power Generation Output

According to *Energy Outlook and Energy Saving Potential in East Asia 2019* (ERIA, 2019), electricity generated in ASEAN countries[1] will continue to increase until 2040 under the business as usual (BAU) scenario and advanced policy scenario (APS). Coal-fired power generation is forecast to increase under both scenarios.

In the BAU scenario, electric energy generated in ASEAN will increase from 829.76 TWh in 2015 to 2,565.96 TWh in 2040 (Figure 2.1), of which coal-fired power generation increases from 318.97 TWh in 2015 to 1,465.13 TWh in 2040, or from 38.4% of all electricity generated in 2015 to 57.1% in 2040.

In the APS, which assumes stronger political measures for energy saving, power generation will increase from 829.76 TWh in 2015 to 2,128.95 TWh in 2040 (Figure 2.2), of which coal-fired power generation increases from 318.97 TWh in 2015 to 900.91 TWh in 2040, or from 38.4% of all electricity generated in 2015 to 42.3% in 2040.

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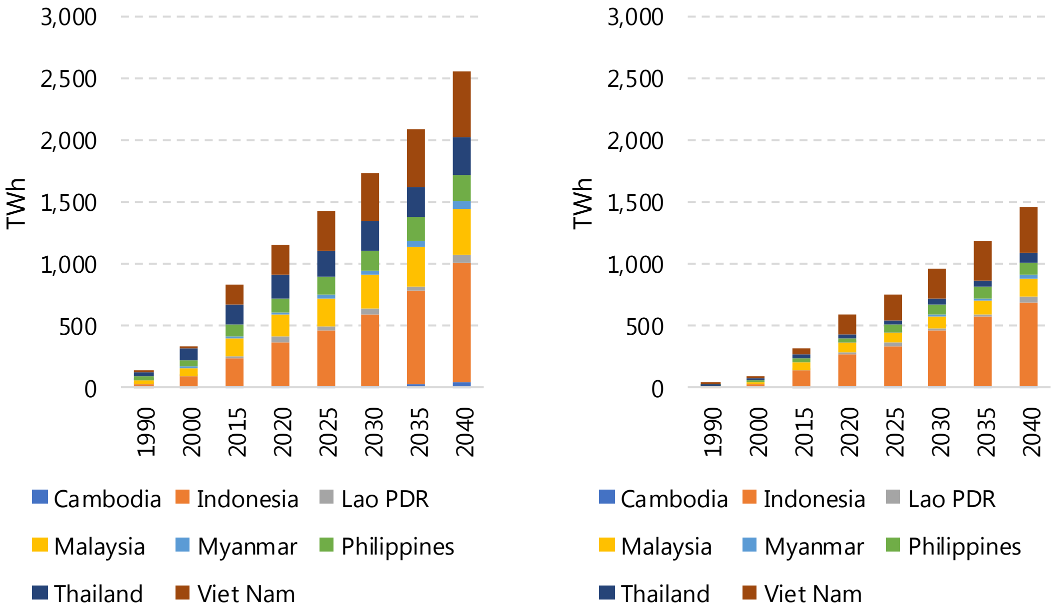
[1] Excluding Brunei Darussalam and Singapore, which do not generate coal-fired power.

Figure 2.1: Power Generation Output in ASEAN, Business as Usual

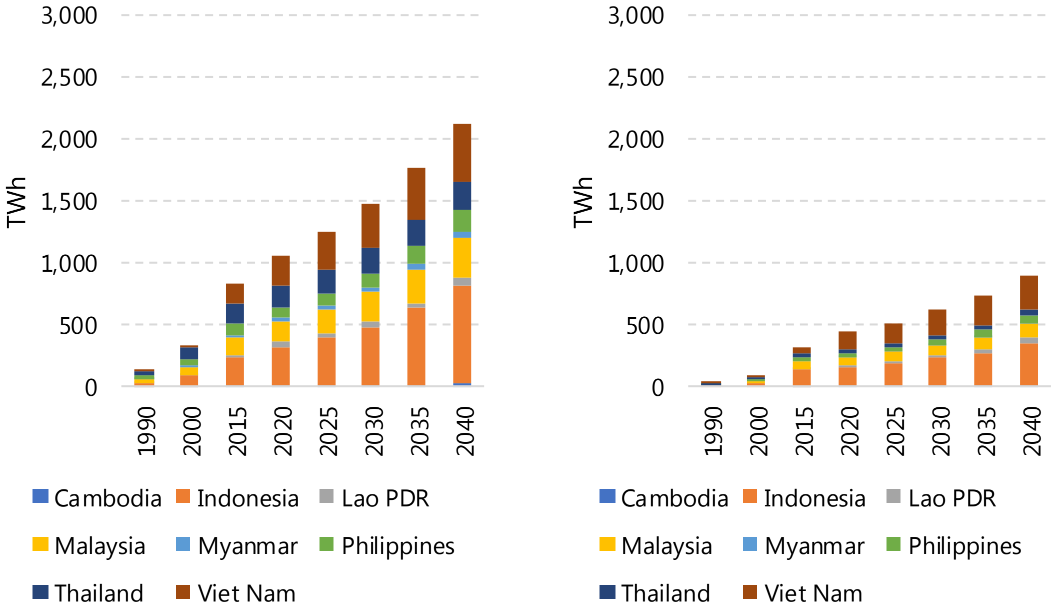
Left: Total generation. Right: Coal generation



Lao PDR = Lao People's Democratic Republic.
Source: ERIA (2019).

Figure 2.2: Coal-fired Power Generation Output, ASEAN, Advanced Policy Scenario

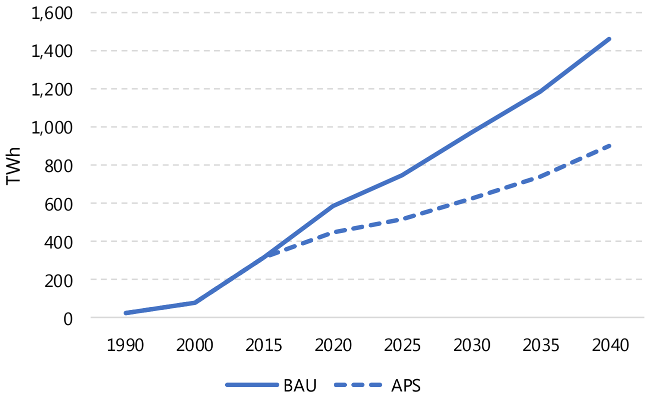
Left: Total generation. Right: Coal generation



Lao PDR = Lao People's Democratic Republic.
Source: ERIA (2019).

In ASEAN countries where power demand increases significantly and affordability of electricity is important, utilisation of coal-fired power generation is expected to continue under both scenarios (Figure 2.3).

Figure 2.3: Coal-fired Power Generation Output, ASEAN, Business as Usual and Advanced Policy Scenario

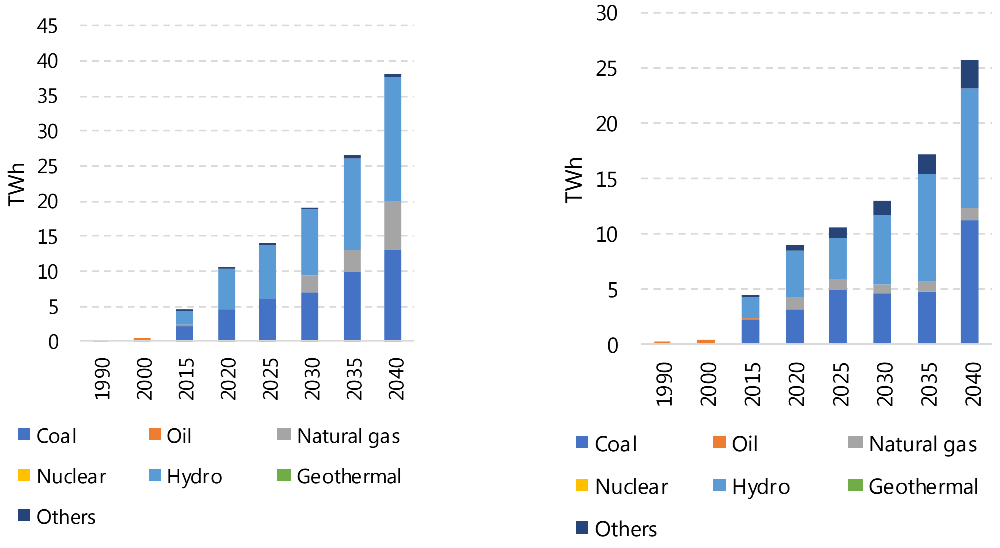


APS = advanced policy scenario, BAU = business as usual.
Source: ERIA (2019).

(a) Cambodia

In BAU, power generation will increase from 4.40 TWh in 2015 to 38.20 TWh in 2040, and in APS, from 4.40 TWh to 25.73 TWh (Figure 2.4).

Figure 2.4: Power Generation Output by Fuel, Cambodia

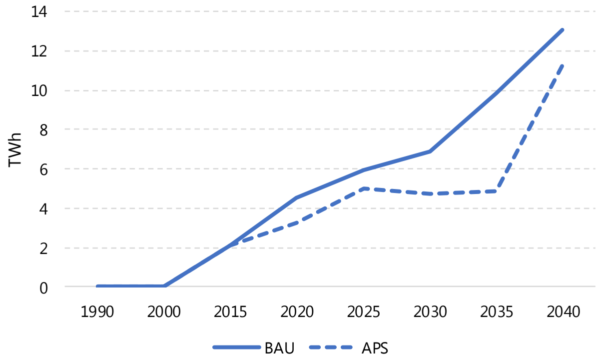


Business as Usual **Advanced Policy Scenario**

Source: ERIA (2019).

Coal-fired power generation will grow under BAU and APS (Figure 2.5). In BAU, coal-fired power generation will increase from 2.13 TWh in 2015 to 13.04 TWh in 2040. In APS, coal-fired power generation will decrease from 2025 through 2030, but then increase to 11.29 TWh in 2040 in both BAU and APS.

Figure 2.5: Coal-fired Power Generation Output, Cambodia, Business as Usual and Advanced Policy Scenario

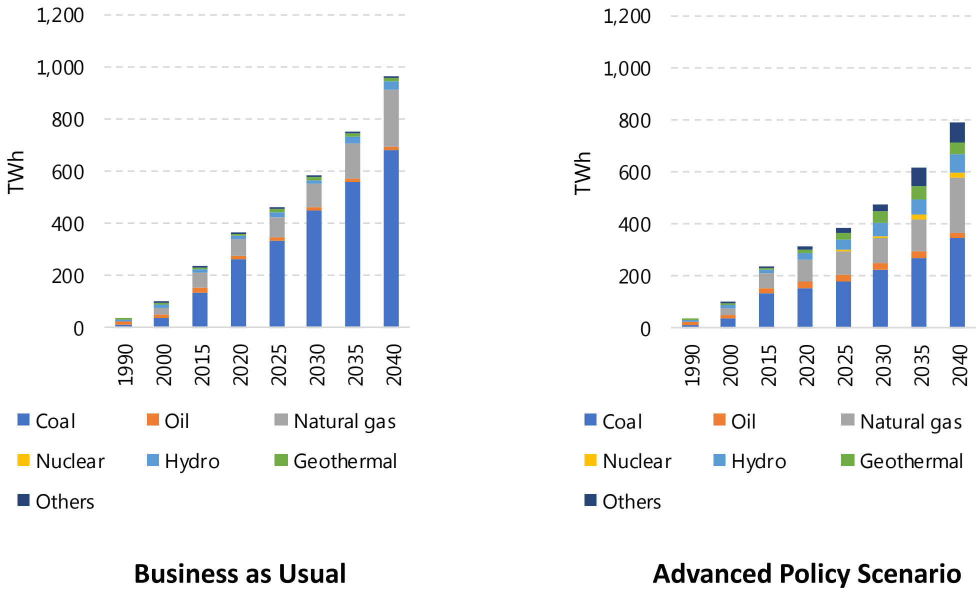


APS = advanced policy scenario, BAU = business as usual.
Source: ERIA (2019).

(b) Indonesia

In BAU, power generation will increase from 233.33 TWh in 2015 to 968.73 TWh in 2040, and in the APS, from 233.33 TWh to 792.47 TWh (Figure 2.6).

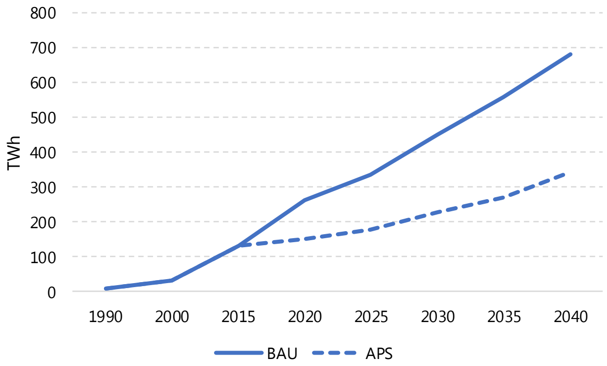
Figure 2.6: Power Generation Output, by Fuel, Indonesia



Source: ERIA (2019).

Coal-fired power output is forecast to grow in BAU from 130.51 TWh in 2015 to 681.30 TWh in 2040, and in the APS from 130.51 TWh to 344.12 TWh (Figure 2.). Output is expected to continue growing under both scenarios.

Figure 2.7: Coal-fired Power Generation Output, Indonesia, Business as Usual and Advanced Policy Scenario

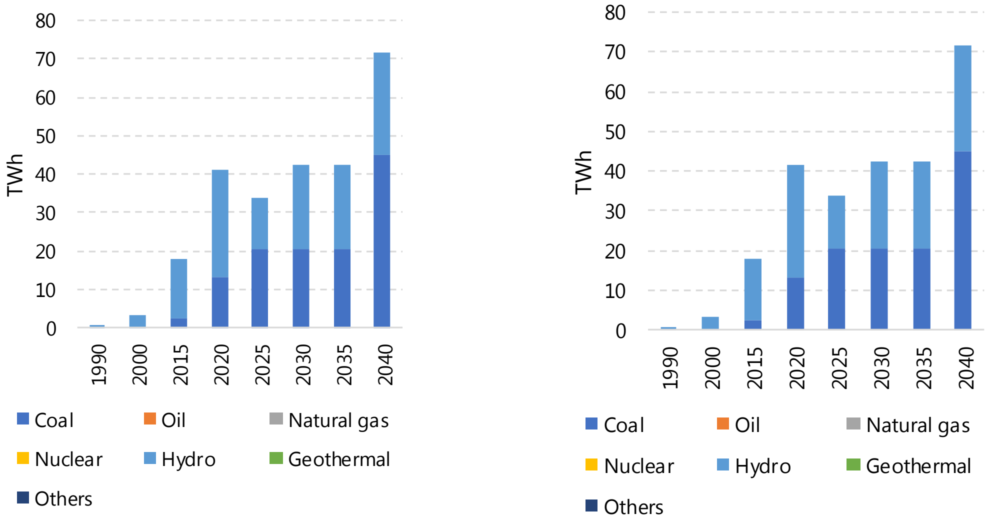


APS = advanced policy scenario, BAU = business as usual.
Source: ERIA (2019).

(c) Lao People's Democratic Republic

In BAU and the APS, power generation will increase from 2.26 TWh in 2015 to 45.17 TWh in 2040 (Figure 2.8).

Figure 2.8: Power Generation Output, by Fuel, Lao People's Democratic Republic

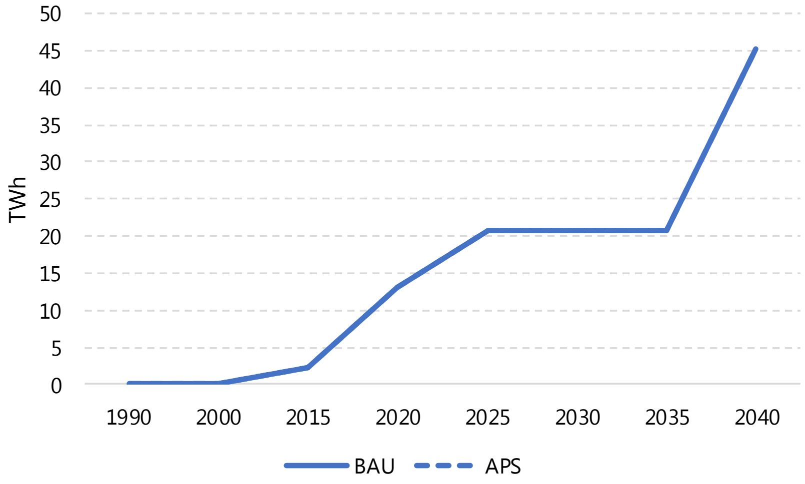


Business as Usual **Advanced Policy Scenario**

Source: ERIA (2019).

Coal-fired power output will increase from 2.26 TWh in 2015 to 45.17 TWh in 2040 in BAU and the APS (Figure 2.9)

Figure 2.9: Coal-fired Power Generation Output, Lao People's Democratic Republic, Business as Usual and Advanced Policy Scenario

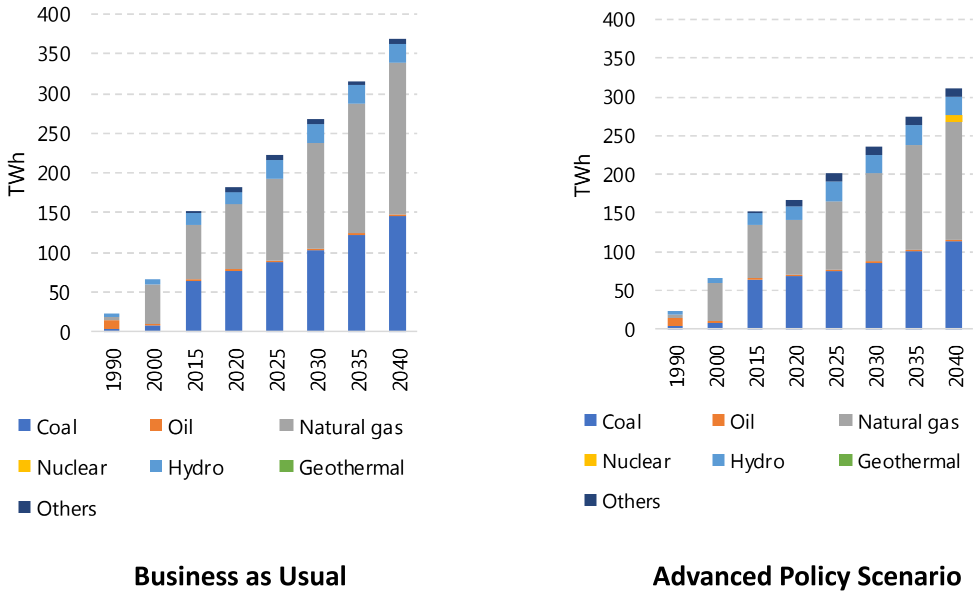


APS = advanced policy scenario, BAU = business as usual.
Source: ERIA (2019).

(d) Malaysia

In BAU, power generation will increase from 150.37 TWh in 2015 to 368.13 TWh in 2040, and in the APS, from 150.37 TWh to 312.18 TWh (Figure 2.10).

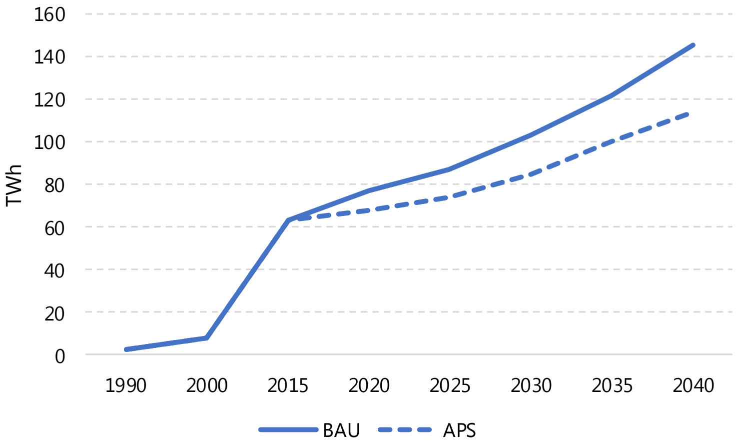
Figure 2.10: Power Generation Output, by Fuel, Malaysia



Source: ERIA (2019).

Coal-fired power output will increase in BAU from 63.47 TWh in 2015 to 145.83 TWh in 2040, and in the APS, from 63.47 TWh to 113.92 TWh (Figure 2.11). Starting in 2040, output is expected to increase in BAU and the APS.

Figure 2.11: Coal-fired Power Generation Output, Malaysia, Business as Usual and Advanced Policy Scenario

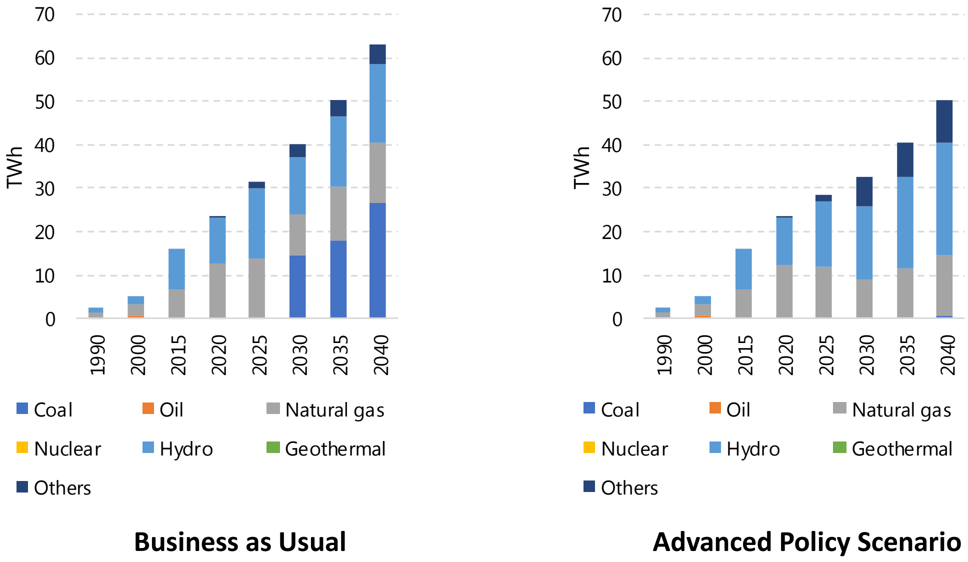


BAU = business as usual, APS = advanced policy scenario.
Source: ERIA (2019).

(e) Myanmar

In BAU, power generation will increase from 15.97 TWh in 2015 to 63.00 TWh in 2040, and in the APS, from 15.97 TWh to 50.40 TWh (Figure 2.12)

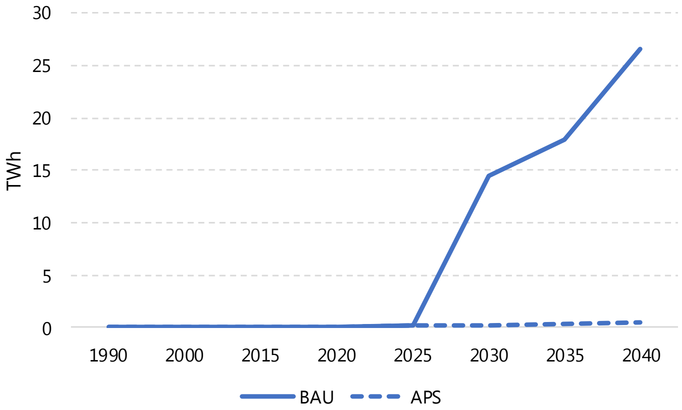
Figure 2.12: Power Generation Output, by Fuel, Myanmar



Source: ERIA (2019).

Coal-fired power output in BAU is forecast to increase from 0.00 TWh in 2015 to 26.61 TWh in 2040, and in the APS, from 0.00 TWh to 0.52 TWh (Figure 2.13). Starting in 2040, output is expected to increase in BAU and the APS.

Figure 2.13: Coal-fired Power Generation Output, Myanmar, Business as Usual and Advanced Policy Scenario

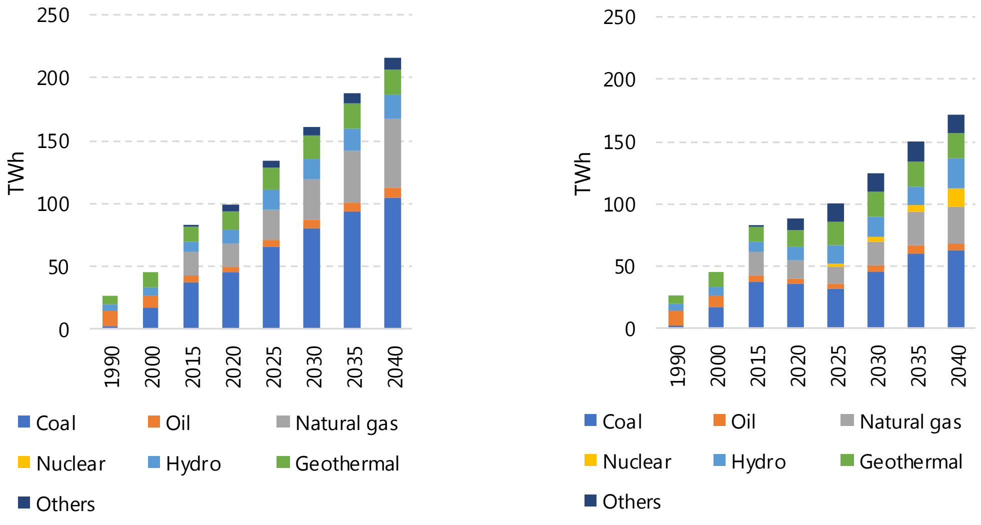


APS = advanced policy scenario, BAU = business as usual.
Source: ERIA (2019).

(f) Philippines

In BAU, power generation will increase from 82.41 TWh in 2015 to 215.33 TWh in 2040, and in the APS, from 82.41 TWh to 172.26 TWh (Figure 2.14).

Figure 2.14: Power Generation Output, by Fuel, Philippines

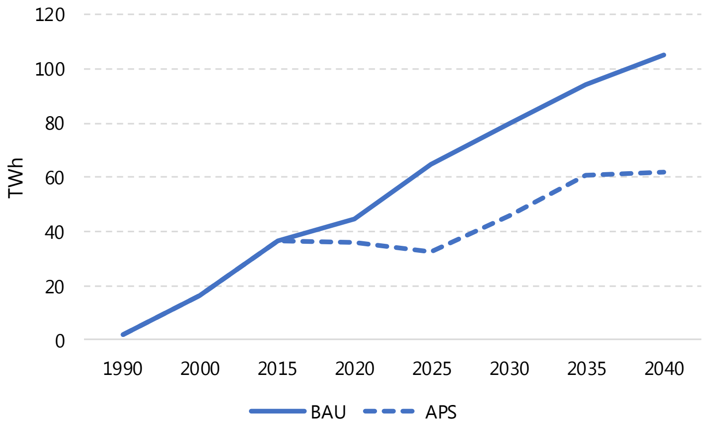


Business as Usual **Advanced Policy Scenario**

Source: ERIA (2019).

Coal-fired power output in BAU will increase from 36.69 TWh in 2015 to 104.96 TWh in 2040, and in the APS, decrease from 2020 through 2025 but increase to 62.16 TWh in 2040 (Figure 2.15). Starting in 2040, output is expected to increase in BAU and the APS.

Figure 2.15: Coal-fired Power Generation Output, Philippines, Business as Usual and Advanced Policy Scenario

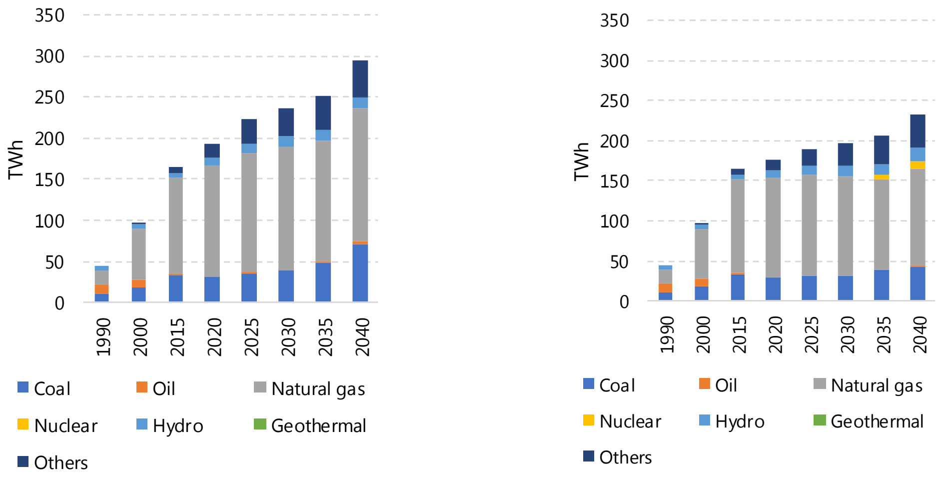


APS = advanced policy scenario, BAU = business as usual.
Source: ERIA (2019).

(g) Thailand

In BAU, power generation will increase from 165.71 TWh in 2015 to 294.57 TWh in 2040, and in the APS, from 165.71 TWh to 233.22 TWh (Figure 2.16).

Figure 2.16: Power Generation Output, by Fuel, Thailand

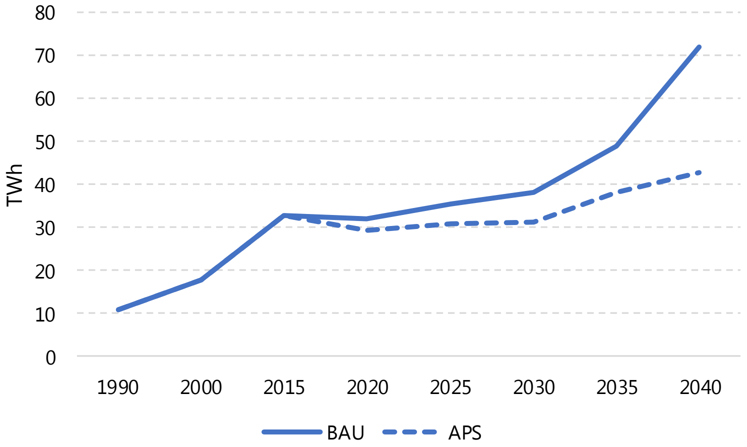


Business as Usual **Advanced Policy Scenario**

Source: ERIA (2019).

Coal-fired power output will grow in BAU from 32.92 TWh in 2015 to 71.82 TWh in 2040, and in the APS, decrease from 2015 through 2020 but increase to 42.96 TWh in 2040 (Figure 2.17). Starting in 2040, output is expected to increase in BAU and the APS.

Figure 2.17: Coal-fired Power Generation Output, Thailand, Business as Usual and Advanced Policy Scenario

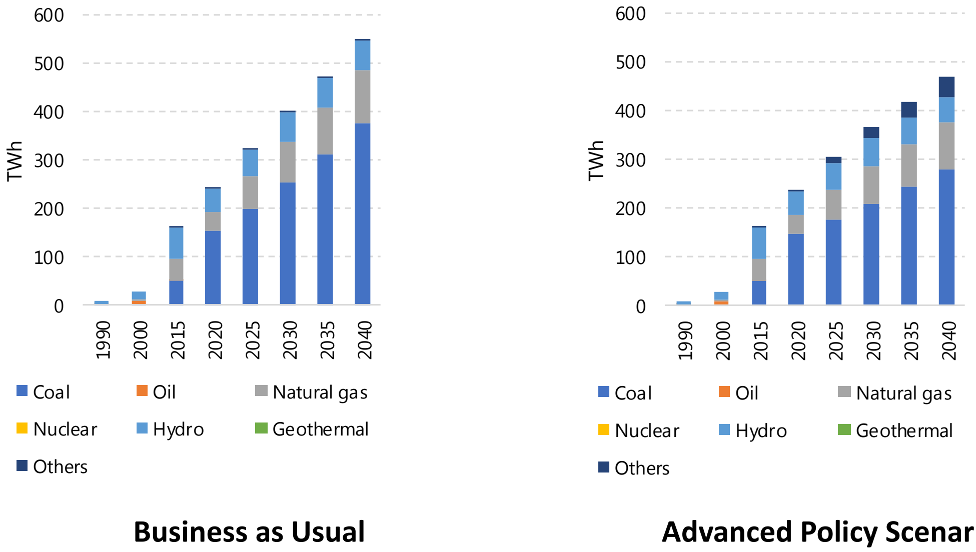


APS = advanced policy scenario, BAU = business as usual.
Source: ERIA (2019).

(h) Viet Nam

Power generation will increase in BAU from 159.81 TWh in 2015 to 546.15 TWh in 2040, and in the APS, from 159.81 TWh to 470.84 TWh (Figure 2.18).

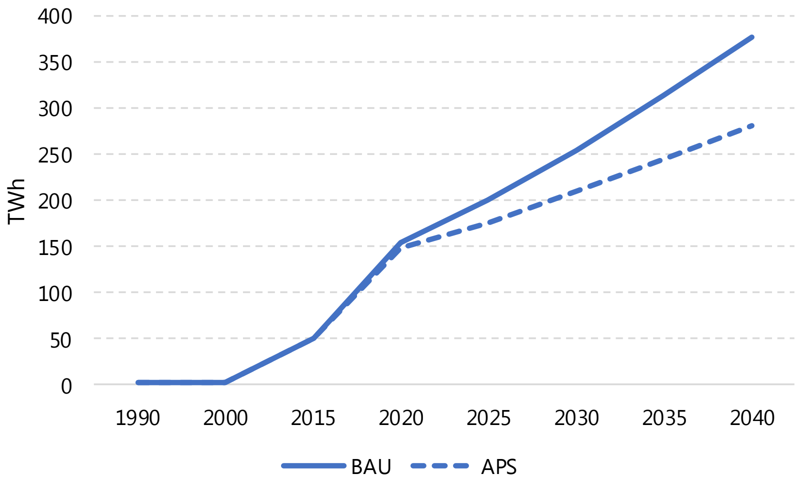
Figure 2.18: Power Generation Output, by Fuel, Viet Nam



Source: ERIA (2019).

Coal-fired power output will grow in BAU from 51.00 TWh in 2015 to 376.39 TWh in 2040, and in the APS, from 51.00 TWh to 280.77 TWh (Figure 2.19). Starting in 2040, output is expected to increase in BAU and the APS.

Figure 2.19. Coal-fired Power Generation Output, Viet Nam, Business as Usual and Advanced Policy Scenario



APS = advanced policy scenario, BAU = business as usual.
Source: ERIA (2019).

1.2. AQCS Installation Status at Coal-fired Power Plants

AQCS installation status is summarised in Table 2.1 (ERIA, 2018):

- A power plant that has been operating for 30 years or longer is classified as ageing. Power plants are sorted into two groups: those that started in or before 1989 and those in or after 1990.
- Whether AQCS is installed (with) or not installed (without) is indicated for each power plant by figures representing the aggregated processing capacity of three reduction system types: PM, SO_2, and NOx.

The capacity of coal-fired power plants (MW) in ASEAN countries that started operation in or before 1989 is 4,198 MW, and in or after 1990, 59,616 MW.

Amongst coal-fired power plants that started operation in or before 1989, the capacity of those that have AQCS is 3,743 MW (89.2%) for PM, 3,633 MW (86.5%) for SO_2, and 600 MW (14.3%) for NOx. Amongst those that started operation in or after 1990, the capacity of those that have AQCS is 49,062 MW (82.2%) for PM, 53,832 MW (90.2%) for SO_2, and 23,122 MW (38.8%) for

NOx. The level of countermeasures against NOx has been improved but is still lower than for PM and SO_2.

Amongst coal-fired power plants that started operation in or after 1990, the capacity of those that do not have AQCS is 10,555 MW for PM, 5,785 MW for SO_2, and 36,495 MW for NOx. It is safe to say that the potential for improvement is substantial (Figure 2.20).

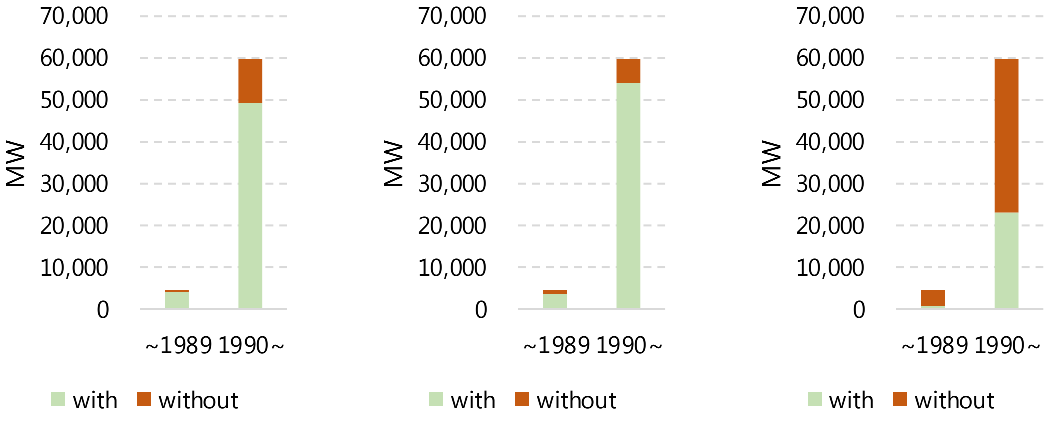
Table 2.1: Air Quality Control System Installation Status at Coal-fired Power Plants in ASEAN Countries

Country	**AQCS Installation Status**	**Coal-fired Power Plant (MW)**					
		~1989			**1990~**		
		PM	**SO_2**	**NOx**	**PM**	**SO_2**	**NOx**
Cambodia	with	0	0	0	390	390	0
	without	0	0	0	10	10	400
Indonesia	with	1,600	1,600	0	16,092	18,206	7,260
	without	130	130	1,730	7,251	5,137	16,083
Lao PDR	with	0	0	0	1,878	1,878	0
	without	0	0	0	0	0	1,878
Malaysia	with	600	600	0	9,489	9,489	6,504
	without	0	0	600	0	0	2,985
Myanmar	with	0	0	0	0	0	0
	without	0	0	0	8	8	8
Philippines	with	393	393	0	6,121	6,897	2,037
	without	105	105	498	776	0	4,860
Thailand	with	600	600	600	4,238	4,693	4,238
	without	0	0	0	455	0	455
Viet Nam	with	550	440	0	10,854	12,279	3,083
	without	220	330	770	2,055	630	9,826
ASEAN	with	3,743	3,633	600	49,062	53,832	23,122
	without	455	565	3,598	10,555	5,785	36,495

AQCS = air quality control system, Lao PDR = Lao People's Democratic Republic.

Source: ERIA (2018).

Figure 2.20: Air Quality Control System Installation Status at Coal-fired Power Plants in ASEAN



PM Reduction System **SO_2 Reduction System** **NOx Reduction System**

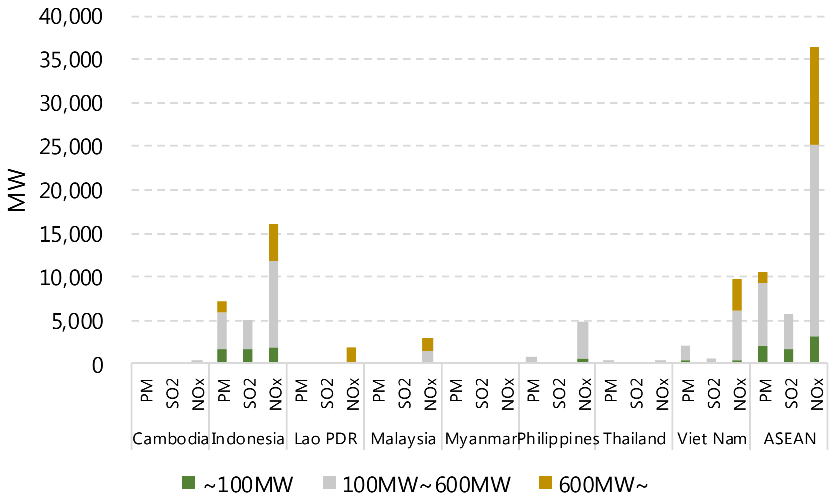
NOx = nitrogen oxides, PM = particulate matter, SO_2 = sulphur dioxide.

Source: ERIA (2018).

Some coal-fired power plants without AQCS that started operation in or after 1990 are not equipped with PM or NOx control, whilst all coal-fired power plants with a capacity of over 600 MW have SOx control (Figure 2.21). The potential for improvement is substantial in coal-fired power plants over 600 MW. Total capacity of 17 coal-fired power plants over 600 MW without NOx control is 11,269 MW.

AQCS installation status varies country to country. In Indonesia, Lao PDR, Malaysia, and Viet Nam, AQSC is not installed even in some large (over 600 MW) coal-fired power plants, while AQSC is installed in all large coal-fired power plants in the Philippines and Thailand.

Figure 2.21: Capacity of Coal-fired Power Plants Without AQCS In and After 1990



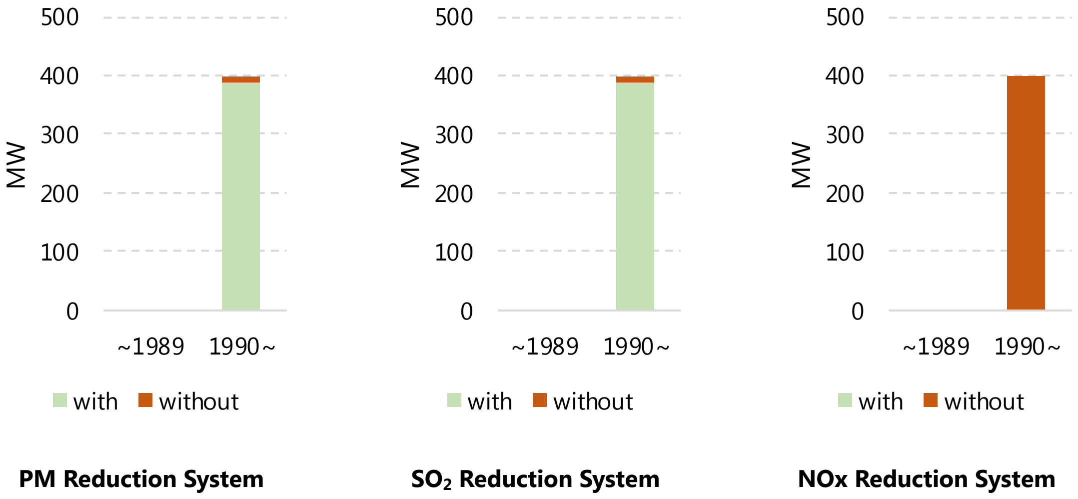
NOx = nitrogen oxides, PM = particulate matter, SO_2 = sulphur dioxide.

Source: ERIA (2018).

(a) Cambodia

Whilst no operating coal-fired power plant started operation in or before 1989, installed capacity of operating coal-fired power plants that started operation in or after 1990 is 400 MW. Amongst them, the capacity of those that do not have AQCS is 10 MW for PM, 10 MW for SO_2, and 400 MW for NOx.

Figure 2.22: Air Quality Control System Installation Status at Coal-fired Power Plants, Cambodia



NOx = nitrogen oxides, PM = particulate matter, SO_2 = sulphur dioxide.

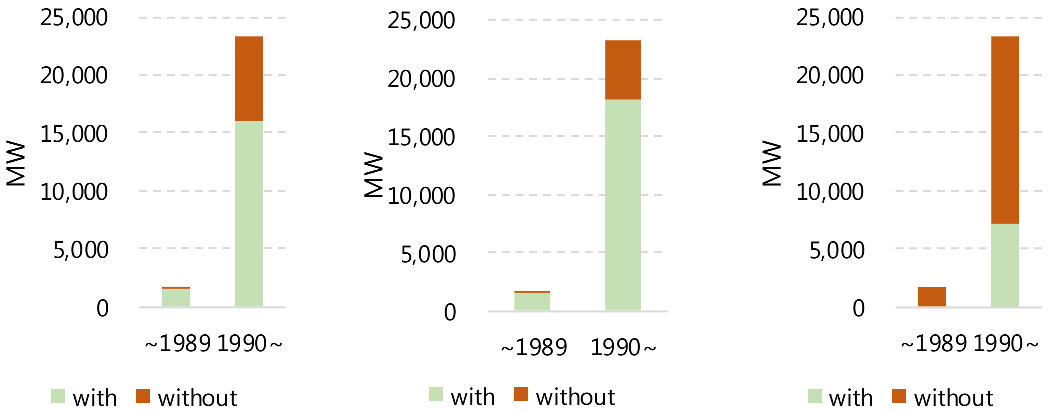
Source: ERIA (2018).

(b) Indonesia

Installed capacity of operating coal-fired power plants that started operation in or before 1989 is 1,730 MW. Amongst them, the capacity of those that do not have AQCS is 130 MW for PM, 130 MW for SO_2, and 1,730 MW for NOx.

Installed capacity of operating coal-fired power plants that started operation in or after 1990 is 23,343 MW. Amongst them, the capacity of those that do not have AQCS is 7,251 MW for PM, 5,137 MW for SO_2, and 16,083 MW for NOx.

Figure 2.23: Air Quality Control System Installation Status at Coal-fired Power Plants, Indonesia



PM Reduction System **SO_2 Reduction System** **NOx Reduction System**

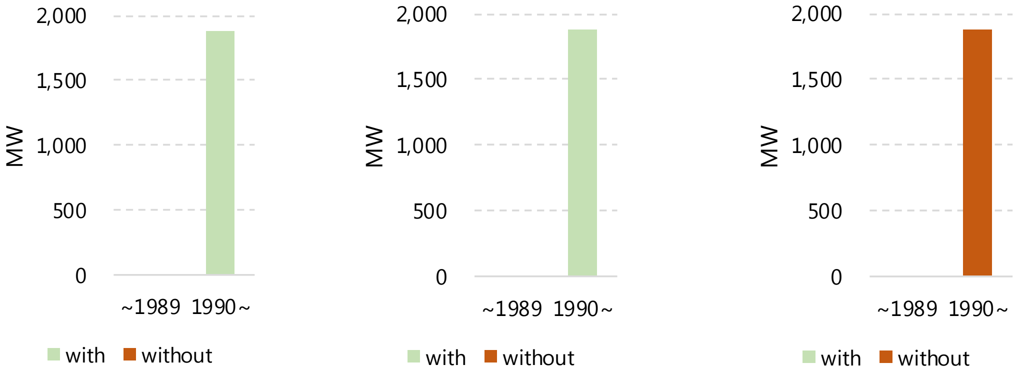
NOx = nitrogen oxides, PM = particulate matter, SO_2 = sulphur dioxide.

Source: ERIA (2018).

(c) Lao People’s Democratic Republic

Whilst no operating coal-fired power plant started operation in or before 1989, the installed capacity of operating coal-fired power plants that started operation in or after 1990 is 1,878 MW. Amongst them, the capacity of those that do not have AQCS for NOx is 1,878 MW, whilst all coal-fired power plants have AQCS for PM and SO_2.

Figure 2.24: Air Quality Control System Installation Status at Coal-fired Power Plants, Lao People’s Democratic Republic



PM Reduction System **SO_2 Reduction System** **NOx Reduction System**

NOx = nitrogen oxides, PM = particulate matter, SO_2 = sulphur dioxide.

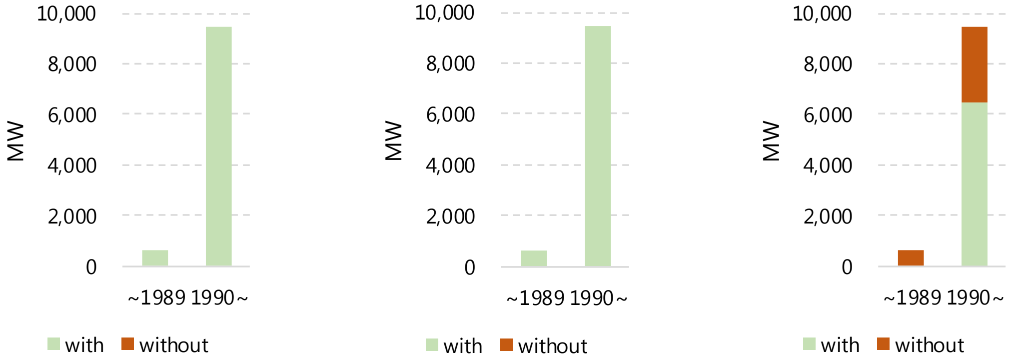
Source: ERIA (2018).

(d) Malaysia

Installed capacity of operating coal-fired power plants that started operation in or before 1989 is 600 MW. Amongst them, the capacity of those that do not have AQCS for NOx is 600 MW. All such coal-fired power plants have AQCS for PM and SO_2.

Installed capacity of operating coal-fired power plants that started operation in or after 1990 is 9,489 MW. Amongst them, the capacity of those that do not have AQCS for NOx is 2,985 MW, whilst all such coal-fired power plants have AQCSs for PM and SO_2.

Figure 2.25: Air Quality Control System Installation Status at Coal-fired Power Plants, Malaysia



PM Reduction System **SO_2 Reduction System** **NOx Reduction System**

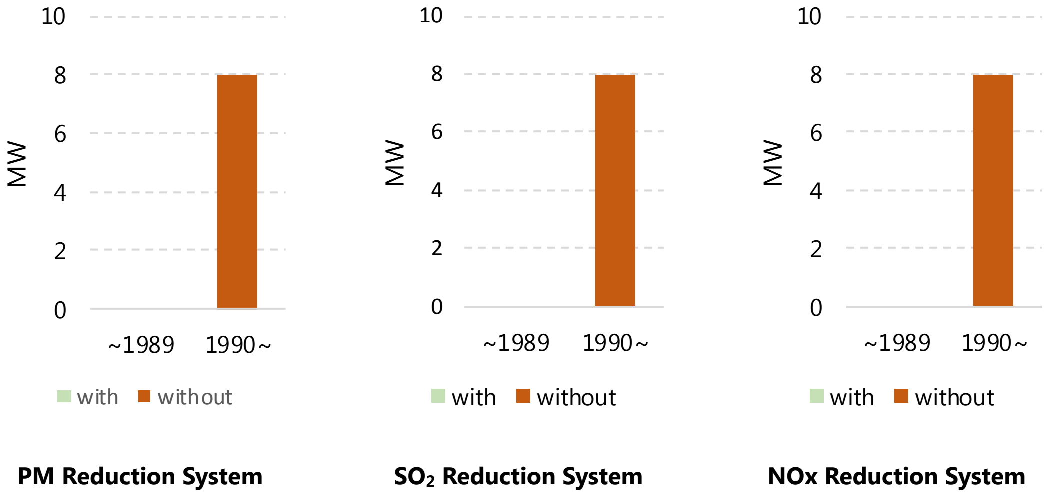
NOx = nitrogen oxides, PM = particulate matter, SO_2 = sulphur dioxide.

Source: ERIA (2018).

(e) Myanmar

Whilst no operating coal-fired power plant started operation in or before 1989, the installed capacity of the operating coal-fired power plant that started operation in or after 1990 is 8 MW. It has no AQCS installed.

Figure 2.26: Air Quality Control System Installation Status at the Coal-fired Power Plant, Myanmar



NOx = nitrogen oxides, PM = particulate matter, SO_2 = sulphur dioxide.

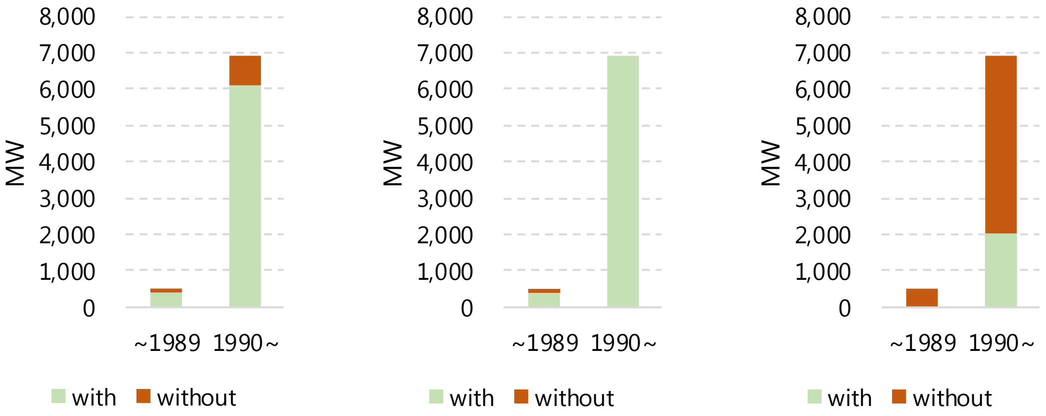
Source: ERIA (2018).

(f) Philippines

Installed capacity of operating coal-fired power plants that started operation in or before 1989 is 498 MW. Amongst them, the capacity of those that do not have AQCS is 105 MW for PM, 105 MW for SO_2, and 498 MW for NOx.

Installed capacity of operating coal-fired power plants that started operation in or after 1990 is 6,897 MW. Amongst them, the capacity of those that do not have AQCS is 776 MW for PM and 4,860 MW for NOx. All coal-fired power plants have AQCS for SO_2.

Figure 2.27: Air Quality Control System Installation Status at Coal-fired Power Plants, Philippines



PM Reduction System **SO_2 Reduction System** **NOx Reduction System**

NOx = nitrogen oxides, PM = particulate matter, SO_2 = sulphur dioxide.

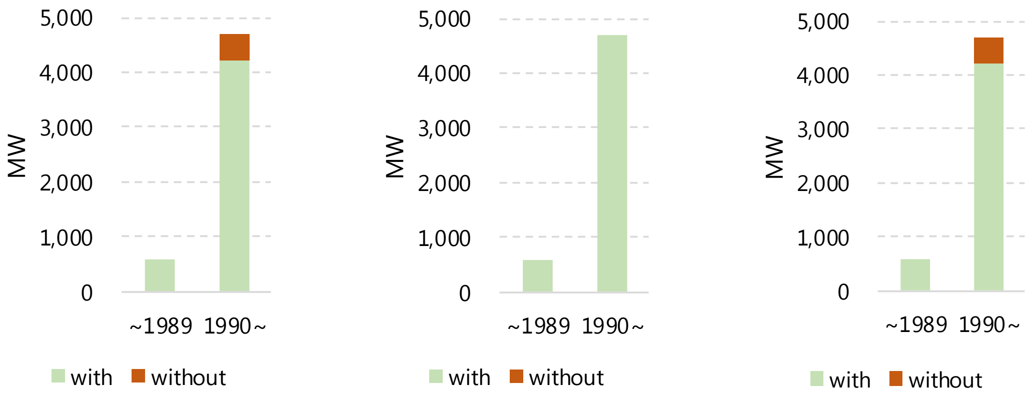
Source: ERIA (2018).

(g) Thailand

Installed capacity of operating coal-fired power plants that started operation in or before 1989 is 600 MW. All have AQCS.

Installed capacity of operating coal-fired power plants that started operation in or after 1990 is 4,693 MW. Amongst them, the capacity of those that do not have AQCS is 455 MW for PM and 455 MW for NOx. All coal-fired power plants have AQCS for SO_2.

Figure 2.28: Air Quality Control System Installation Status at Coal-fired Power Plants, Thailand



PM Reduction System **SO_2 Reduction System** **NOx Reduction System**

NOx = nitrogen oxides, PM = particulate matter, SO_2 = sulphur dioxide.

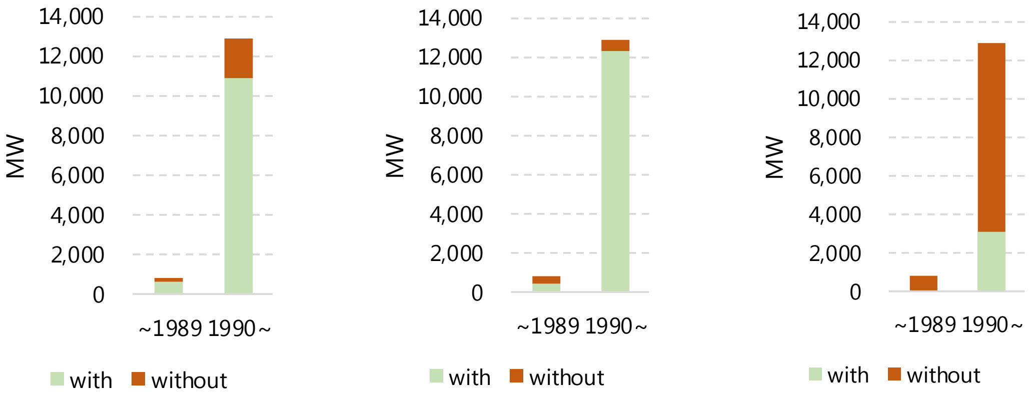
Source: ERIA (2018).

(h) Viet Nam

Installed capacity of operating coal-fired power plants that started operation in or before 1989 is 770 MW. Amongst them, the capacity of those that do not have AQCS is 220 MW for PM, 330 MW for SO_2, and 770 MW for NOx.

Installed capacity of operating coal-fired power plants that started operation in or after 1990 is 12,909 MW. Amongst them, the capacity of those that do not have AQCS is 2,055 MW for PM, 630 MW for SO_2, and 9,826 MW for NOx.

Figure 2.29: Air Quality Control System Installation Status at Coal-fired Power Plants, Viet Nam



PM Reduction System **SO_2 Reduction System** **NOx Reduction System**

NOx = nitrogen oxides, PM = particulate matter, SO_2 = sulphur dioxide.

Source: ERIA (2018).

2. Air Quality Control System of Coal-fired Power Plants

2.1. Air Emission Standards for Coal-fired Power Plants

Table 2.2 shows the emission standards of SOx, NOx, and PM for new coal-fired power plants in selected ASEAN countries, with some Organisation for Economic Co-operation and Development (OECD) countries as a reference. In case they differed depending on plant scale, the large-scale case was adopted. In case they differed depending on the period, the daily basis (24 hours) was adopted. SOx and NOx have different units from one country to another. In the countries where parts per million (ppm) is used, SOx and NOx are converted into mg/m^3 or SO_2 and NO_2.

Table 2.2: Emission Standards for Coal-fired Power Plants

Country	SOx	NOx	PM
Germany	SOx: 150 mg/m^3	NOx: 150 mg/m^3	10 mg/m^3
Japan	SOx: 50 ppm [*1] (SO_2: 133 mg/m^3)	NOx: 200 ppm (NO_2: 383 mg/m^3)	100 mg/m^3
Republic of Korea	SOx: 50 ppm (SO_2: 133 mg/m^3)	NOx: 50 ppm (NO_2: 96 mg/m^3)	10 mg/m^3
Cambodia	SO_2: 500 mg/m^3	NO_2: 1,000 mg/m^3	400 mg/m^3
Indonesia	SO_2: 750 mg/m^3	NO_2: 750 mg/m^3	100 mg/m^3
Lao PDR	SO_2: 320 ppm (SO_2: 853 mg/m^3)	NOx: 350 ppm (NO_2: 670 mg/m^3)	120 mg/m^3
Malaysia	SOx: 500 mg/m^3	NOx: 500 mg/m^3	50 mg/m^3
Myanmar	SOx: 200 mg/m^3	NOx: 400 mg/m^3	50 mg/m^3
Philippines	SO_2: 700 mg/m^3	NO_2: 1000 mg/m^3	150 mg/m^3
Singapore	SO_2: 500 mg/m^3	NO_2: 700 mg/m^3	100 mg/m^3
Thailand	SO_2: 180 ppm (SO_2: 480 mg/m^3)	NOx: 200 ppm (NO_2: 383 mg/m^3)	80 mg/m^3
Viet Nam	SO_2: 500 mg/m^3	NO_2: 650 mg/m^3 [*2]	200 mg/m^3

Lao PDR = Lao People's Democratic Republic. NOx = nitrogen oxides, NO_2 = nitrogen dioxide, PM = particulate matter, ppm = parts per million, SOx = sulphur oxides, SO_2 = sulphur dioxide.

Notes:

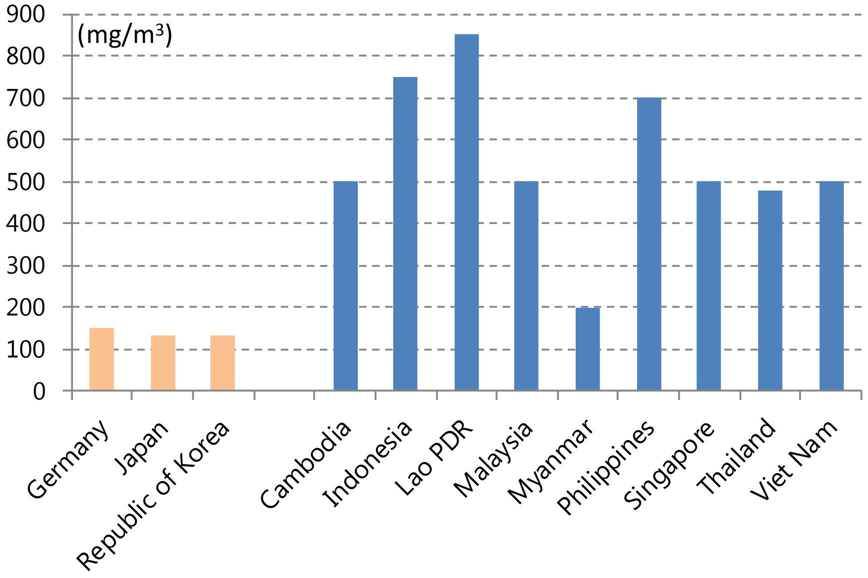
*1. Based on a coal-fired power plant's location, sulphur content of fuel, stack height, etc., the emission standard varies plant by plant. The value is an example of a specific coal-fired power plant based on agreement between the plant and the local government.

*2. Coal volatile content >10%.

Source: ERIA (2017).

The following figures compare national emission standards based on SOx, NOx, and PM. The SOx emission limit is higher (looser) in the selected ASEAN countries than in the selected OECD countries. NOx is lower in the selected OECD countries. For PM, the regulation values in the selected ASEAN countries, except Cambodia, are approximately the same as those in Japan.

Figure 2.30: Comparison of Emission Standards in Selected Countries (SOx)

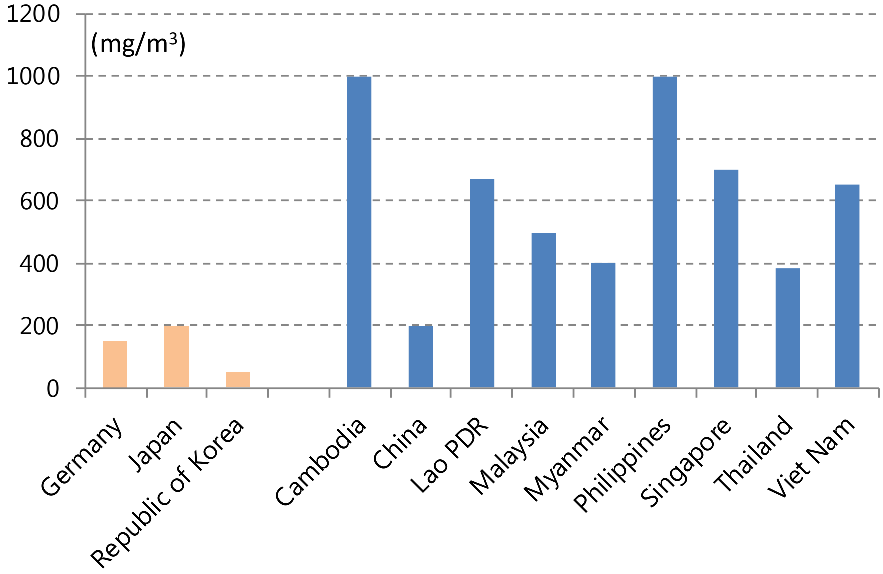


Lao PDR = Lao People’s Democratic Republic, SOx = sulphur oxides.

Note: The emission standard of coal-fired power plant for SOx in Japan varies from power plant to power plant based on location, sulphur content of fuel, stack height etc. The data here is an example of a specific coal-fired power plant in Japan.

Source: ERIA (2017).

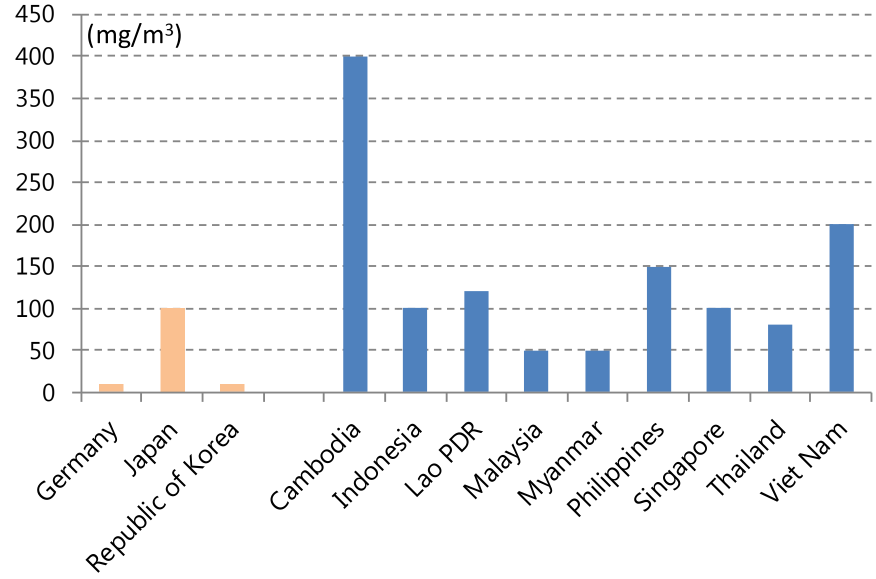
Figure 2.31: Comparison of Emission Standards in Selected Countries (NOx)



Lao PDR = Lao People’s Democratic Republic, NOx = nitrogen oxides.

Source: ERIA (2017).

Figure 2.32: Comparison of Emission Standards in Selected Countries (PM)



Lao PDR = Lao People’s Democratic Republic, PM = particulate matter.

Source: ERIA (2017).

2.2. Management System of Air Quality

Without an effective air quality management system, no country can achieve good air quality. We surveyed the air quality management systems of coal-fired power plants in selected ASEAN countries as well as some OECD countries as a reference. We divided management systems into the following elements:

(a) General

- Existence of legislation (national or local)
- Authority to suspend operation
- Relation to local community

(b) Management process

- Monitoring of emission by operator and/or authority
- Data archive requirement
- Reporting to authority
- Inspection by authority
- Public announcements
- Penalty, fine

The following are the survey results:

2.2.1.1. General

At the central government level, environment-related laws have been enacted, regulated air pollutants identified, and emission standards stipulated. Cambodia, Indonesia, and Thailand are known to authorise local governments to enact emission standards. Like Japan, Cambodia set emission standards voluntarily with coal-fired power plant operators.

Authority to suspend operation varies as follows:

- ➢ Central government: Malaysia, Myanmar, Thailand
- ➢ Central and local governments: Indonesia, Lao PDR
- ➢ Local government: Cambodia (based on agreement with coal-fired power plants)

Periodic meetings with the community after starting to operate a coal-fired power plant:

- ➢ Lao PDR: Dependent on an agreement with the coal-fired power plant

- Thailand: Implemented every 3 months
- Other countries: Not obligated

Management process
Local governments implement regular monitoring in Cambodia, Lao PDR, and Myanmar. They started operating coal-fired power plants only after the 2000s. Thailand is the only country where the requirement to archive measured data is not enacted by law.

Reports should be submitted as follows:

- Central government: Cambodia, Malaysia, Myanmar, Thailand
- Central and local governments: Indonesia, Lao PDR
- Local government: None

Inspection agencies vary as follows:

- Central government: Cambodia, Malaysia, Myanmar, Thailand
- Central and local governments: Indonesia, Lao PDR
- Local government: None

Public announcement varies from one country to another:

- Cambodia: Central government publishes it through public screen monitors.
- Indonesia: Central government is developing an online system.
- Lao PDR: Local government publishes the status.
- Malaysia: Central government uses its website.
- Myanmar: Coal-fired power plant publishes the status through an LED screen in front of the plant.
- Thailand: Coal-fired power plant operator issues an annual report.

Every country has implemented a system but, compared with OECD countries, there is room for improvement in two fields:

(1) Reporting frequency (Table 2.)

Coal-fired power plants in Cambodia, Lao PDR, Malaysia, and OECD countries automatically send data to the authorities, whilst plants in some ASEAN countries send data in any period enacted by law.

(2) Public announcements (Table 2.)

The public can see the measured data on a website in Malaysia and in OECD countries. Indonesia is developing an online reporting system. The public cannot, however, access real-time data in some ASEAN countries.

The following tables compare monitoring in ASEAN and selected OECD countries.

Table 2.3: Monitoring

Cambodia	Prefecture governors continuously monitor the status of air pollution.
Indonesia	Irregular monitoring by local government.
Lao PDR	Provincial authorities continuously monitor the status of air pollution. Local governments have observing stations.
Malaysia	Department of Environment monitors the status of air pollution.
Myanmar	The Ministry of Electricity and Energy, state and regional governments continuously monitor the status of air pollution. The owner or occupiers of any business have the duty to monitor environmental pollution.
Thailand	Coal-fired power plants submit environmental impact assessments to the Ministry of Environment, Ministry of Natural Resources, and Ministry of Energy. Report: Coal-fired power plant → central government → local government. Local government has the power to check emission data but rarely does so.
Australia	Areas with populations greater than 25,000 are required to install monitoring stations. E.g. in New South Wales, the Office of Environment and Heritage operates the air quality monitoring network. Data from the network is presented online every hour as the air quality index, stored in a searchable database.
Germany	Monitoring networks are operated by (1) the German Federal Environment

	Agency, which measures stations far from cities; and (2) state networks that monitor air quality in populated areas. The data from the two monitoring networks provide the foundation of the country's air quality.
Japan	Prefecture governors continuously monitor the status of air pollution. Local governments have observing stations.
United States	E.g. PM: Operator of a facility installs, calibrates, maintains, and operates opacity monitoring systems, and records the output of the system for measuring the opacity of emissions discharged into the atmosphere.

Table 2.4: Reporting to Authority

Cambodia	The power plant operator submits data on air pollution emissions to the government every month, although coal-fired power plants automatically send data through to a telemeter. The Ministry of Environment conducts an integrated survey of quantity of air pollution emission every 3 years. Archive requirement: All coal-fired power plant operators should store important emission data permanently every 6 months.
Indonesia	Government regulation 21, year 2012, article 9. The power plant is obliged to do the following: a. Report every 3 months to the regent or mayor, with a copy to the governor and environment minister, the results of emission monitoring and measurement of power plants equipped with continuous emission monitoring systems. b. Report every 6 months to the regent or mayor, with a copy to the governor and environment minister, the results of emission monitoring and measurement of power plants that manually measure emissions. c. Report to the regent or mayor, with a copy to the governor and environment minister, annual total emissions (tons/year) emitted for NOx, SOx, and CO_2. Archive requirement: Most coal-fired power plant owners keep important data permanently.
Lao PDR	The Ministry of Natural Resource and Environment (MoNRE) or provincial authorities (environmental management units) jointly with coal-fired power

	plant operators report the status of air pollutant emissions. MoNRE conducts integrated surveys of the quantity of air pollutant emissions every 6 months. As agreed between the coal-fired power plant operator and local government, the operator submits a report to the local government every month, although the plant automatically and continuously sends data through a telemeter. Archive requirement: The data should be kept for 3 years.
Malaysia	Continuous emission monitoring systems Archive requirement. The Environmental Quality (Clean Air) Regulations 2014 require that records be kept for at least 3 years.
Myanmar	The project proponent submits monitoring reports to the Ministry of Electricity and Energy not less frequently than every 6 months, as scheduled in the environmental management plan, or periodically as prescribed by the ministry. The Ministry of Electricity and Energy requires operators to report the status of air pollutant emissions. Archive requirement: Coal-fired power plant operator keeps important data permanently as paper and electronic files.
Thailand	The operator must submit data twice a year. Archive requirement: None
Australia	E.g. New South Wales law does not require licensees to report emission data to Environment Protection Authority periodically. Instead, licensees must publish pollution monitoring data. Archive requirement: Unknown
Germany	The operator supplies monitoring results to the authority regularly and at least annually. Archive requirement: Publications are lodged in the archives of the German Patents Office for safe custody and reference.
Japan	Governors may require operators to report the status of air pollutant emissions. As agreed, operators submit reports to local government every month, although coal-fired power plants automatically and continuously send data through a telemeter. Archive requirement: The data should be kept for 3 years. Generally, most operators keep important data permanently.

United States	Performance test data from continuous monitors must be reported to the administrator. The owner or operator of the facility submits a signed statement. Archive requirement: It is subject to '40 CFR §60.52Da Record-keeping requirements'.

Table 2.5: Inspection

Cambodia	The Ministry of Environment or other government agency should inspect each coal-fired power plant through the telemeter. Independent inspector: The Air Pollution Control Act requires operators to have a special environmental technician to control plant emissions.
Indonesia	Law 32, year 2009, article 72. The Ministry of Environment or the governor, regent, or mayor is obliged to conduct supervision, and may conduct on-site inspection. Law 30, year 2009, article 46. The Ministry of Energy and Mineral Resources or regional government, with authority to guide and supervise the electricity supply business' compliance with environmental protection laws, may conduct on-site inspections.
Lao PDR	The environmental management unit conducts official inspections jointly with provincial authorities. Independent inspector: Based on concession agreement for coal-fired power plant.
Malaysia	Department of Environment is in charge of inspection. Independent inspector: Not required by law.
Myanmar	A screening team, organised by the Ministry of Electricity and Energy, frequently inspects coal-fired power plants. An inspection team is organised by ministries and other organizations. Independent inspector: Not required by law.
Thailand	The Department of Estate, Ministry of Industry inspects every industrial plant. In the case of large coal-fired power plants, site visits are not be carried out. In case of a severe accident, the Ministry of Environment inspects the plant. Local government has the power to inspect plants but there has been no precedent for this. Independent inspector: Not required by law.

Australia	E.g. New South Wales: Protection of the Environment Operations Act 1997 The operator must notify the government of pollution incidents. Audits may be required as a condition of license if the Environment Protection Authority reasonably suspects wrongdoing. Independent inspector: Not required by law.
Germany	The law requires environmental inspections to be done at least every 1–3 years. Each inspection plan includes a general assessment of significant environmental issues. Independent inspector: Not required by law.
Japan	Governors may conduct official inspections. On-site inspection by the Ministry of Economy, Trade and Industry: Irregular, every 5 or 6 years. On-site inspection by a local government: Depends on the agreement between the coal-fired power plant operator and local government; generally once a year, typically during Environment Month. Independent inspector: Not required by law.
United States	Environmental Protection Agency (EPA) policy. Incentives for self-policing (discovery, disclosure, correction, and prevention) On-site visit by EPA, civil investigations, record reviews, information requests. Independent inspector: Not required by law.

Table 2.6: Public Announcement

Cambodia	The Ministry of Environment or other government agency collects environment data from various facilities and displays the status of air pollution on public screen monitors.
Indonesia	The Ministry of Environment and Forests is developing a public online reporting system. The Directorate General of Electricity is developing information systems to monitor power plant emissions through a pilot project at Cirebon 1 x 660 MW.
Lao PDR	Provincial authorities and environmental management unit make public the status of air pollution within prefectures.
Malaysia	Announcements are published through the official portal of the Department of Environment and through newspapers. The Air Pollutant Index is regularly updated.

Myanmar	Coal-fired power plants display the status of air pollution on LED screens in front of the plants. (For example, Tigyit Coal-fired Thermal Power Plant.)
Thailand	Information is distributed through operators' annual reports. Local governments do not publish emission data.
Australia	E.g. New South Wales: - The law requires licensees to publish pollution monitoring data instead of reporting. - Failure to publish monitoring data and publication of false or misleading data are penalised. - A summary of monitoring data must be posted on a website monthly, or less than monthly when necessary.
Germany	All data on air quality are published on the Internet shortly after they are gathered, providing information on current pollution level. The EU Pollutant Release and the Transfer Register (E-PRTR) provides to the public environmental information and includes data on emissions as reported by Member State.
Japan	Local governments collect environmental data from various facilities and publish the status of air pollution on a screen monitor in their city hall. Everyone can see the situation any time. Local governments publish environmental reports periodically.
United States	Anyone can access air monitoring results from https://www.epa.gov/outdoor-air-quality-data

Table 2.7: Penalties

Cambodia	Violation of the air pollution control act is penalised with a fine, cancellation of the license, and shutdown of the coal-fired power plant. Compensation for damage and losses: Strict liability
Indonesia	Penalties under Law No. 32, year 2009: - Administrative sanction - Fine and imprisonment Anyone who violates the emissions quality standards is imprisoned for 3 years and fined a maximum of IDR3 billion (approximately US$210,000). A violation is deemed a criminal offence if the offender does not comply with administrative sanctions or commits the offence more than once. Compensation for damage and losses: Strict liability

	Law 32, year 2009, article 54. Anyone who pollutes and damages the environment must take steps towards environmental recovery.
Lao PDR	Based on a concession agreement. Compensation for damage and losses: Strict liability
Malaysia	Any person who contravenes or fails to comply with any provision of Environmental Quality (Clean Air) Regulations 2014 will be fined not more than MYR100,000 (approximately US$24,000) or imprisoned for not more than 2 years or both. Compensation for damage and losses: Environmental Quality Act 1974, section 46E. Compels 'the person so convicted to pay the other person the costs and expenses incurred or compensation for loss or damage to the property and any other costs, in the amount as the court considers fit'.
Myanmar	Penalties. US$2,500 to US$10,000 or equivalent in kyat Specific administrative punishment by the Ministry of Electricity and Energy: - Issue enforcement notice - Suspension of approval of environmental management plan (EMP), EMP-construction phase (EMP-CP), or EMP-operational phase (EMP-OP) in whole or in part - Revocation of approval of EMP, EMP-CP, or EMP-OP in whole or in part Compensation for damage and losses: Failure to take reasonable steps to prevent an imminent threat of damage to the environment, society, human health, livelihoods, or property, where applicable, based on the EMP, EMP-CP, or EMP-OP.
Thailand	Industry Act. The Ministry of Industry can impose fines of up to THB200,000 (approximately US$6,000). Compensation for damage and losses: The central government requires the coal-fired power plant to pay compensation but there has been no precedent for this. (It is difficult to determine who is responsible for air pollution and to evaluate damage and losses.) Operators pay damages and losses voluntarily, i.e. hospital expenses, medical examinations, etc.
Australia	E.g. New South Wales Environmental offences and penalties Compensation for damage and losses: Strict liability
Germany	Severe cases of noncompliance can result in criminal liability. Criminal

	sanctions include imprisonment and fines of up to EUR50,000. Compensation for damage and losses: Strict liability
Japan	Punishment for violating the Air Pollution Control Act includes disclosure of the offending operator's name, imprisonment, and a fine. Compensation for damage and losses: Strict liability
United States	If a civil defendant is found liable or agrees to settle: monetary penalty, injunctive relief, additional actions to improve the environment If a criminal defendant is convicted or pleads guilty: monetary fine, restitution, incarceration Compensation for damage and losses: Strict liability

3. Cost of Air Quality Control System and Implications for Electricity Prices

3.1. Cost of Air Quality Control System

An FY 2017 survey (ERIA, 2018) covered the cost of AQCS and its implications for electricity prices in ASEAN countries. Some respondents thought that raising government emission standards could induce private generation companies to install an AQCS if it added only 10%–20% to the price of electricity. Respondents noted that governments are extremely cautious when it comes to increasing electricity prices caused by installing AQCS.

Table 2.8 indicates the AQCS capital expenditure (CAPEX) range surveyed by Mitsubishi Hitachi Power Systems (MHPS). AQCS equipment is high quality, high performance, and highly efficient, and fulfils the loan criteria of the World Bank.

Table 2.8: Surveyed Air Quality Control System Cost (CAPEX) (US$/kW)

	PM	PM	SOx	NOx
	Fabric Filters	ESP	FGD System	SCR System
Low case	35	20	80	50
High case	45	60	100	70

ESP = electrostatic precipitator, FGD = flue-gas desulfurization scrubber, NOx = nitrogen oxides, PM = particulate matter, SCR = selective catalytic reduction, SOx = sulphur oxides.

Source: MHPS (2018).

Table 2.9: World Bank Emission Standards (mg/Nm^3) (Reference)

Air pollutant	SO_2	NOx	PM
Emission standard	200	200	30

NOx = nitrogen oxides, PM = particulate matter, SO_2 = sulphur dioxide.

Source: MHPS (2018).

3.2. Impact on Electricity Prices

This section estimates the impact of AQCS installation on electricity prices in ASEAN countries per scenario and AQCS cost range. The coal-fired power plants within scope and the state of existing AQCS installation are detailed separately. The CAPEX depreciation equivalent cost, estimated loan interest cost, and estimated operation and maintenance cost (O&M) were used to calculate the cost of AQCS installation. The impact is divided into the first 10 years and the subsequent 10 years. The cost assumptions are detailed below:

Depreciation equivalent	10 years straight-line, 100% depreciation rate
Loan interest	Currency: US$ Repayment term: 10 years Rate: OECD’s commercial interest reference rates[2]
O&M	15% of CAPEX (per year)
Calculation of impact	AQCS installation cost per kWh/electricity price

The impact on electricity prices in ASEAN countries is analysed based on the MHPS’s AQCS cost (CAPEX) survey. Cost figures also take finance cost and O&M cost into account. Two scenarios (Table 2.10) were developed to analyse the impact AQCS installation would have on electricity prices.

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[2] This study used 3.64%, the average rate from 15 January to 14 June 2018.

Table 2.10: Impact of Air Quality Control System Installation on Electricity Prices: Two Scenarios

Scenario 1
- Installation in plants where AQCSs are not installed.

Scenario 2
- More-stringent emission standards will be introduced.
- Existing AQCSs cannot comply with more-stringent emission standards.
- High-quality, high-performance, and highly efficient AQCSs will be installed in all power plants.

AQCS = air quality control system.

Source: Author.

Table 2.11 shows the impact of AQCS installation cost on electricity prices in seven ASEAN countries, as found in this study. Whilst Lao PDR reaches a maximum of 28%, many cases show less than 10% impact.

The impact of AQCS installation cost on electricity prices may not, therefore, be significant. Raising electricity prices, however, is a politically difficult and sensitive issue and should be implemented carefully.

Table 2.11: Impact on Electricity Prices

Country	Scenario	AQCS cost range	First 10 years				Subsequent 10 years			
			Res.	Com.	Ind.	Total	Res.	Com.	Ind.	Total
Cambodia	Scenario 1	Low case	0.5%	0.5%		-	0.3%	0.3%		-
		High case	0.6%	0.7%		-	0.4%	0.4%		-
	Scenario 2	Low case	1.3%	1.4%		-	0.7%	0.8%		-
		High case	2.0%	2.1%		-	1.1%	1.2%		-
Indonesia	Scenario 1	Low case	-	-	-	-	-	-	-	-
		High case	-	-	-	-	-	-	-	-
	Scenario 2	Low case	7.6%	5.3%	6.1%	6.5%	4.3%	3.0%	3.5%	3.7%
		High case	11.6%	8.2%	9.3%	10.0%	6.6%	4.6%	5.3%	5.7%
Lao PDR	Scenario 1	Low case	-	-	-	-	-	-	-	-
		High case	-	-	-	-	-	-	-	-
	Scenario 2	Low case	-	-	-	18.2%	-	-	-	10.3%
		High case	-	-	-	27.9%	-	-	-	15.8%
Malaysia	Scenario 1	Low case	0.5%	0.4%	0.5%	0.4%	0.3%	0.2%	0.3%	0.3%
		High case	0.7%	0.5%	0.7%	0.6%	0.4%	0.3%	0.4%	0.4%
	Scenario 2	Low case	4.9%	3.5%	4.4%	4.1%	2.8%	2.0%	2.5%	2.3%
		High case	7.5%	5.3%	6.7%	6.3%	4.3%	3.0%	3.8%	3.6%
Philippines	Scenario 1	Low case	0.5%	0.6%	0.8%	0.6%	0.3%	0.3%	0.4%	0.3%
		High case	0.8%	0.9%	1.2%	0.9%	0.4%	0.5%	0.7%	0.5%
	Scenario 2	Low case	1.8%	2.2%	2.8%	2.2%	1.0%	1.2%	1.6%	1.2%
		High case	2.8%	3.3%	4.3%	3.4%	1.6%	1.9%	2.4%	1.9%
Thailand	Scenario 1	Low case	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		High case	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	0.1%	0.0%
	Scenario 2	Low case	1.1%	1.0%	1.2%	1.1%	0.6%	0.6%	0.7%	0.6%
		High case	1.6%	1.6%	1.8%	1.7%	0.9%	0.9%	1.0%	1.0%
Viet Nam	Scenario 1	Low case	1.1%	1.1%	1.8%	1.4%	0.6%	0.6%	1.0%	0.8%
		High case	1.6%	1.6%	2.7%	2.1%	0.9%	0.9%	1.6%	1.2%
	Scenario 2	Low case	3.4%	3.4%	5.8%	4.4%	1.9%	1.9%	3.3%	2.5%
		High case	5.2%	5.2%	8.8%	6.7%	3.0%	3.0%	5.0%	3.8%

AQCS = air quality control system, Com. = commercial, Ind. = industry, Res. = residential.

Source: ERIA (2018).

a) Cambodia

(1) CAPEX

Table 2.12 shows the AQCS installation CAPEX per scenario and AQCS cost range. In scenario 1, the low case was US$$21.0 million and the high case US$29.6 million. In scenario 2, the low case was US$60.0 million and the high case US$92.0 million.

Table 2.12: Capital Expenditure of Air Quality Control System Installation, Cambodia

Scenario	Capacity (MW)			CAPEX (US$ million)							
				Low case				High case			
	PM	SOx	NOx	PM (ESP)	SOx	NOx	**Total**	PM (ESP)	SOx	NOx	**Total**
(US$/kW)				(20)	(80)	(50)		(60)	(100)	(70)	
Scenario 1	10	10	400	0.2	0.8	20.0	**21.0**	0.6	1.0	28.0	**29.6**
Scenario 2	400	400	400	8.0	32.0	20.0	**60.0**	24.0	40.0	28.0	**92.0**

CAPEX = capital expenditure, ESP = electrostatic precipitator, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxides.

Source: ERIA (2018). Autoproducers are excluded.

(2) AQCS installation cost

Table 2.13 shows AQCS installation cost per scenario and AQCS cost range. In the first 10 years, cost reached a maximum of US$24.3 million per year, and in the subsequent 10 years US$13.8 million.

Table 2.13: Air Quality Control System Installation Cost, Cambodia

Scenario	AQCS cost range	CAPEX	AQCS installation cost (US$ million)							
			First 10 years (per year)				Subsequent 10 years (per year)			
			Depreciation equivalent	Loan interest	O&M	**Total**	Depreciation equivalent	Loan interest	O&M	**Total**
Scenario 1	Low case	21.0	2.1	0.3	3.2	**5.6**			3.2	**3.2**
	High case	29.6	3.0	0.4	4.4	**7.8**			4.4	**4.4**
Scenario 2	Low case	60.0	6.0	0.9	9.0	**15.9**			9.0	**9.0**
	High case	92.0	9.2	1.3	13.8	**24.3**			13.8	**13.8**

AQCS = air quality control system, CAPEX = capital expenditure, O&M = operation and maintenance.

Source: ERIA (2018).

(3) AQCS installation cost per kWh

Table 2.14 shows the AQCS installation cost divided by the annual electricity sales volume.

Table 2.14: Air Quality Control System Installation Cost per kWh, Cambodia

Scenario	CAPEX	Electricity sales (2017) (GWh)	First 10 years (per year) Installation Cost (US$ million)	First 10 years (per year) Cost per kWh (US cent/kWh)	Subsequent 10 years (per year) Installation Cost (US$ million)	Subsequent 10 years (per year) Cost per kWh (US cent/kWh)
		(a)	(b)	(c)=(b)/(a)	(d)	(e)=(d)/(a)
Scenario 1	Low case	6,782	5.6	**0.082**	3.2	**0.046**
	High case		7.8	**0.115**	4.4	**0.066**
Scenario 2	Low case		15.9	**0.234**	9.0	**0.133**
	High case		24.3	**0.359**	13.8	**0.204**

CAPEX = capital expenditure.

Source: ERIA (2018).

(4) Impact on electricity prices

Table 2.15 shows the impact AQCS installation cost has on electricity price per scenario and AQCS cost range. The AQCS installation cost has a maximum impact of 2.1% on electricity prices in the first 10 years, and 1.2% in the subsequent 10 years.

Table 2.15: Impact of Air Quality Control System Installation on Electricity Price, Cambodia

		First 10 years (per year) Residential	First 10 years (per year) Industrial Commercial	Subsequent 10 years (per year) Residential	Subsequent 10 years (per year) Industrial Commercial
Electricity price (2017)	KHR/kWh	720			
	US cent/kWh	17.8	16.7	<--	<--
Impact					
Scenario 1	Low case	0.5%	0.5%	0.3%	0.3%
	High case	0.6%	0.7%	0.4%	0.4%
Scenario 2	Low case	1.3%	1.4%	0.7%	0.8%
	High case	2.0%	2.1%	1.1%	1.2%

Note: Price: Electricity supplied by Electricite Du Cambodge in Phnom Penh and Takhmao.

US$1 = KHR4,051 (2017)

Source: ERIA (2018).

b) Indonesia

(1) CAPEX

Table 2.16 shows AQCS installation CAPEX per scenario and AQCS cost range. In scenario 1, the cost was 0. In scenario 2, the low case was US$3,892.7 million and the high case US$5,968.7 million.

Table 2.16: Capital Expenditure of Air Quality Control System Installation, Indonesia

Scenario	Capacity (MW)			CAPEX (US$ million)							
				Low case				High case			
	PM	SOx	NOx	PM (ESP)	SOx	NOx	**Total**	PM (ESP)	SOx	NOx	**Total**
(US$/kW)				(20)	(80)	(50)		(60)	(100)	(70)	
Scenario 1	0	0	0	0.0	0.0	0.0	**0.0**	0.0	0.0	0.0	**0.0**
Scenario 2	25,951	25,951	25,951	519.0	2,076.1	1,297.6	**3,892.7**	1,557.1	2,595.1	1,816.6	**5,968.7**

CAPEX = capital expenditure, ESP = electrostatic precipitator, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxides.

Source: ERIA (2018).

(2) AQCS installation cost

Table 2.17 shows AQCS installation cost per scenario and AQCS cost range. In the first 10 years, cost reached a maximum of US$1,578.3 million per year, and in the subsequent 10 years US$895.3 million.

Table 2.17: Air Quality Control System Installation Cost, Indonesia

Scenario	AQCS cost range	CAPEX	AQCS installation cost (US$ million)							
			First 10 years (per year)				Subsequent 10 years (per year)			
			Depreciation equivalent	Loan interest	O&M	**Total**	Depreciation equivalent	Loan interest	O&M	**Total**
Scenario 1	Low case	0.0	0.0	0.0	0.0	**0.0**			0.0	**0.0**
	High case	0.0	0.0	0.0	0.0	**0.0**			0.0	**0.0**
Scenario 2	Low case	3,892.7	389.3	56.1	583.9	**1,029.3**			583.9	**583.9**
	High case	5,968.7	596.9	86.1	895.3	**1,578.3**			895.3	**895.3**

AQCS = air quality control system, CAPEX = capital expenditure, O&M = operation and maintenance.

Source: ERIA (2018).

(3) AQCS installation cost per kWh

Table 2.18 shows the AQCS installation cost divided by the annual electricity sales volume.

Table 2.18: Air Quality Control System Installation Cost per kWh, Indonesia

Scenario	CAPEX	Electricity sales (2016) (GWh)	First 10 years (per year)		Subsequent 10 years (per year)	
			Installation Cost (US$ million)	Cost per kWh (US cent/kWh)	Installation Cost (US$ million)	Cost per kWh (US cent/kWh)
		(a)	(b)	(c)=(b)/(a)	(d)	(e)=(d)/(a)
Scenario 2	Low case	216,013	1,029.3	**0.476**	583.9	**0.270**
	High case		1,578.3	**0.731**	895.3	**0.414**

CAPEX = capital expenditure.

Source: ERIA (2018).

(4) Impact on electricity prices

Table 2.19 shows the impact the AQCS installation cost has on electricity prices per scenario and AQCS cost range. The AQCS installation cost has a maximum impact of 11.6% on electricity prices in the first 10 years, and 6.6% in the subsequent 10 years.

Table 2.19: Impact on Electricity Prices, Indonesia

		First 10 years (per year)				Subsequent 10 years (per year)			
		Res.	Com.	Ind.	Total	Res.	Com.	Ind.	Total
Electricity price (2016)	US cent/ kWh	6.28	8.94	7.83	7.33	<--	<--	<--	<--
Impact									
Scenario 2	Low case	7.6%	5.3%	6.1%	6.5%	4.3%	3.0%	3.5%	3.7%
	High case	11.6%	8.2%	9.3%	10.0%	6.6%	4.6%	5.3%	5.7%

Com. = commercial, Ind. = industry, Res. = residential.

Source: ERIA (2018).

c) Lao PDR

(1) CAPEX

Table 2.20 shows AQCS installation CAPEX per scenario and AQCS cost range. In scenario 1, the cost was 0. In scenario 2, the low case was US$281.7 million and the high case US$431.9 million.

Table 2.20: Capital Expenditure of Air Quality Control System Installation, Lao People's Democratic Republic

Scenario	Capacity (MW)			CAPEX (US$ million)							
				Low case				High case			
	PM	SOx	NOx	PM (ESP)	SOx	NOx	**Total**	PM (ESP)	SOx	NOx	**Total**
(US$/kW)				(20)	(80)	(50)		(60)	(100)	(70)	
Scenario 1	0	0	0	0.0	0.0	0.0	**0.0**	0.0	0.0	0.0	**0.0**
Scenario 2	1,878	1,878	1,878	37.6	150.2	93.9	**281.7**	112.7	187.8	131.5	**431.9**

CAPEX = capital expenditure, ESP = electrostatic precipitator, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxides.

Source: ERIA (2018). Autoproducers are excluded.

(2) AQCS installation cost

Table 2.21 shows Lao PDR's AQCS installation cost per scenario and AQCS cost range. In the first 10 years, cost reached a maximum of US$114.2 million per year, and in the subsequent 10 years US$64.8 million per year.

Table 2.21: Air Quality Control System Installation Cost, Lao People's Democratic Republic

Scenario	AQCS cost range	CAPEX	AQCS installation cost (US$ million)							
			First 10 years (per year)				Subsequent 10 years (per year)			
			Depreciation equivalent	Loan interest	O&M	**Total**	Depreciation equivalent	Loan interest	O&M	**Total**
Scenario 1	Low case	0.0	0.0	0.0	0.0	**0.0**			0.0	**0.0**
	High case	0.0	0.0	0.0	0.0	**0.0**			0.0	**0.0**
Scenario 2	Low case	281.7	28.2	4.1	42.3	**74.5**			42.3	**42.3**
	High case	431.9	43.2	6.2	64.8	**114.2**			64.8	**64.8**

AQCS = air quality control system, CAPEX = capital expenditure, O&M = operation and maintenance.

Source: ERIA (2018).

(3) AQCS installation cost per kWh

Table 2.22 shows the AQCS installation cost divided by the annual electricity sales volume. Because electricity sales are low relative to AQCS installation cost, the cost per kWh is higher than in other countries.

Table 2.22: Air Quality Control System Installation Cost per kWh, Lao People's Democratic Republic

Scenario	CAPEX	Electricity sales (2016) (GWh)	First 10 years (per year)		Subsequent 10 years (per year)	
			Installation Cost (US$ million)	Cost per kWh (US cent/kWh)	Installation Cost (US$ million)	Cost per kWh (US cent/kWh)
		(a)	(b)	(c)=(b)/(a)	(d)	(e)=(d)/(a)
Scenario 1	Low case	4,660	0.0	**0.000**	0.0	**0.000**
	High case		0.0	**0.000**	0.0	**0.000**
Scenario 2	Low case		74.5	**1.598**	42.3	**0.907**
	High case		114.2	**2.451**	64.8	**1.390**

CAPEX = capital expenditure.

Source: ERIA (2018).

(4) Impact on electricity prices

Table 2.23 shows the impact of AQCS installation cost on Lao PDR's electricity price per scenario and AQCS cost range. The AQCS installation cost has a maximum impact of 27.9% on electricity prices in the first 10 years, and 15.8% in the subsequent 10 years. The impact in Lao PDR is much higher than in other countries because of Lao PDR's low average electricity prices, together with its high AQCS installation cost and low volume of electricity sales. Lao PDR has one coal-fired power plant in operation – Hongsa – and all the electricity it generates is exported. Some think it is not reasonable for Lao PDR to assume the AQCS installation cost at Hongsa. Lao PDR, however, plans to build new coal-fired power plants to supply electricity domestically. The figures here estimate the future impact of AQCS installation on electricity prices.

Table 2.23: Impact on Electricity Prices, Lao People's Democratic Republic

		First 10 years (per year)	Subsequent 10 years (per year)
		Total	Total
Electricity price	LAK/kWh		
(2016)	US cent/ kWh	8.8	<--
Impact			
Scenario 2	Low case	18.2%	10.3%
	High case	27.9%	15.8%

Source: ERIA (2018).

d) Malaysia

(1) CAPEX

Table 2.24 shows AQCS installation CAPEX per scenario and AQCS cost range. In scenario 1, the cost in the low case was US$174.0 million and in the high case US$243.6 million. In scenario 2, the low case was US$1,603.5 million and the high case US$2,458.7 million.

Table 2.24: Capital Expenditure of Air Quality Control System Installation, Malaysia

Scenario	Capacity (MW)			CAPEX (US$ million)							
				Low case				High case			
(US$/kW)	PM	SOx	NOx	PM (ESP) (20)	SOx (80)	NOx (50)	**Total**	PM (ESP) (60)	SOx (100)	NOx (70)	**Total**
Scenario 1	0	0	3,480	0.0	0.0	174.0	**174.0**	0.0	0.0	243.6	**243.6**
Scenario 2	10,690	10,690	10,690	213.8	855.2	534.5	**1,603.5**	641.4	1,069.0	748.3	**2,458.7**

CAPEX = capital expenditure, ESP = electrostatic precipitator, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxides.

Source: ERIA (2018). Autoproducers are excluded.

(2) AQCS installation cost

Table 2.25 shows the AQCS installation cost per scenario and AQCS cost range. In the first 10 years, cost reached a maximum of US$650.1 million per year and in the subsequent 10 years US$368.8 million.

Table 2.25: Air Quality Control System Installation Cost, Malaysia

Scenario	AQCS cost range	CAPEX	AQCS installation cost (US$ million)							
			First 10 years (per year)				Subsequent 10 years (per year)			
			Depreciation equivalent	Loan interest	O&M	**Total**	Depreciation equivalent	Loan interest	O&M	**Total**
Scenario 1	Low case	174.0	17.4	2.5	26.1	**46.0**			26.1	**26.1**
	High case	243.6	24.4	3.5	36.5	**64.4**			36.5	**36.5**
Scenario 2	Low case	1,603.5	160.4	23.1	240.5	**424.0**			240.5	**240.5**
	High case	2,458.7	245.9	35.5	368.8	**650.1**			368.8	**368.8**

AQCS = air quality control system, CAPEX = capital expenditure, O&M = operation and maintenance.

Source: ERIA (2018).

(3) AQCS installation cost per kWh

Table 2.26 shows the AQCS installation cost divided by the annual electricity sales volume.

Table 2.26: Air Quality Control System Installation Cost per kWh, Malaysia

Scenario	CAPEX	Electricity sales (2016) (GWh)	First 10 years (per year)		Subsequent 10 years (per year)	
			Installation Cost (US$ million)	Cost per kWh (US cent/kWh)	Installation Cost (US$ million)	Cost per kWh (US cent/kWh)
		(a)	(b)	(c)=(b)/(a)	(d)	(e)=(d)/(a)
Scenario 1	Low case	108,169	46.0	**0.043**	26.1	**0.024**
	High case		64.4	**0.060**	36.5	**0.034**
Scenario 2	Low case		424.0	**0.392**	240.5	**0.222**
	High case		650.1	**0.601**	368.8	**0.341**

CAPEX = capital expenditure.

Source: ERIA (2018).

(4) Impact on electricity prices

Table 2.27 shows the impact of AQCS installation cost as on electricity price per scenario and AQCS cost range. The AQCS installation cost has a maximum impact of 7.5% on electricity prices in the first 10 years, and 4.3% in the subsequent 10 years.

Table 2.27: Impact of Air Quality Control System Installation on Electricity Prices, Malaysia

		First 10 years (per year)				Subsequent 10 years (per year)			
		Res.	Com.	Ind.	Total	Res.	Com.	Ind.	Total
Electricity price (2016)	US cent/ kWh	8.01	11.28	8.96	9.58	<--	<--	<--	<--
Impact									
Scenario 1	Low case	0.5%	0.4%	0.5%	0.4%	0.3%	0.2%	0.3%	0.3%
	High case	0.7%	0.5%	0.7%	0.6%	0.4%	0.3%	0.4%	0.4%
Scenario 2	Low case	4.9%	3.5%	4.4%	4.1%	2.8%	2.0%	2.5%	2.3%
	High case	7.5%	5.3%	6.7%	6.3%	4.3%	3.0%	3.8%	3.6%

Com. = commercial, Ind. = industry, Res. = residential.

Source: ERIA (2018).

e) Philippines

(1) CAPEX

Table 2.28 shows AQCS installation CAPEX per scenario and AQCS cost range. In scenario 1, the cost of the low case was US$311.6 million and the high case US$470.3 million. In scenario 2, the low case was US$1,117.6 million and the high case US$ 1,713.7 million.

Table 2.28: Capital Expenditure of Air Quality Control System Installation, Philippines

Scenario	Capacity (MW)			CAPEX (US$ million)							
				Low case				High case			
	PM	SOx	NOx	PM (ESP)	SOx	NOx	**Total**	PM (ESP)	SOx	NOx	**Total**
(US$/kW)				(20)	(80)	(50)		(60)	(100)	(70)	
Scenario 1	1,150	224	5,414	23.0	17.9	270.7	**311.6**	69.0	22.4	379.0	**470.3**
Scenario 2	7,451	7,451	7,451	149.0	596.1	372.5	**1,117.6**	447.0	745.1	521.5	**1,713.7**

CAPEX = capital expenditure, ESP = electrostatic precipitator, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxides.

Source: ERIA (2018). Autoproducers are excluded.

(2) AQCS installation cost

Table 2.29 shows AQCS installation cost per scenario and AQCS cost range. In the first 10 years, cost reached a maximum of US$453.1 million per year, and in the subsequent 10 years US$257.0 million.

Table 2.29: Air Quality Control System Installation Cost, Philippines

Scenario	AQCS cost range	CAPEX	AQCS installation cost (US$ million)							
			First 10 years (per year)				Subsequent 10 years (per year)			
			Depreciation equivalent	Loan interest	O&M	Total	Depreciation equivalent	Loan interest	O&M	Total
Scenario 1	Low case	311.6	31.2	4.5	46.7	82.4			46.7	46.7
	High case	470.3	47.0	6.8	70.5	124.4			70.5	70.5
Scenario 2	Low case	1,117.6	111.8	16.1	167.6	295.5			167.6	167.6
	High case	1,713.7	171.4	24.7	257.0	453.1			257.0	257.0

AQCS = air quality control system, CAPEX = capital expenditure, O&M = operation and maintenance.

Source: ERIA (2018)

(3) AQCS installation cost per kWh

Table 2.30 shows the AQCS installation cost divided by the annual electricity sales volume.

Table 2.30: Air Quality Control System Installation Cost per kWh, Philippines

Scenario	CAPEX	Electricity sales (2016) (GWh)	First 10 years (per year)		Subsequent 10 years (per year)	
			Installation Cost (US$ million)	Cost per kWh (US cent/kWh)	Installation Cost (US$ million)	Cost per kWh (US cent/kWh)
		(a)	(b)	(c)=(b)/(a)	(d)	(e)=(d)/(a)
Scenario 1	Low case	90,798	82.4	0.091	46.7	0.051
	High case		124.4	0.137	70.5	0.078
Scenario 2	Low case		295.5	0.325	167.6	0.185
	High case		453.1	0.499	257.0	0.283

CAPEX = capital expenditure.

Source: ERIA (2018).

(4) Impact on electricity prices

Table 2.31 shows the impact of AQCS installation cost on the electricity price per scenario and AQCS cost range. The AQCS installation cost has a maximum impact of 4.3% on electricity prices in the first 10 years, and 2.4% in the subsequent 10 years.

Table 2.31: Impact on Electricity Prices, Philippines

		First 10 years (per year)				Subsequent 10 years (per year)			
		Res.	Com.	Ind.	Total	Res.	Com.	Ind.	Total
Electricity price (2016)	US cent/ kWh	17.80	14.98	11.68	14.88	<--	<--	<--	<--
Impact									
Scenario 1	Low case	0.5%	0.6%	0.8%	0.6%	0.3%	0.3%	0.4%	0.3%
	High case	0.8%	0.9%	1.2%	0.9%	0.4%	0.5%	0.7%	0.5%
Scenario 2	Low case	1.8%	2.2%	2.8%	2.2%	1.0%	1.2%	1.6%	1.2%
	High case	2.8%	3.3%	4.3%	3.4%	1.6%	1.9%	2.4%	1.9%

Com. = commercial, Ind. = industry, Res. = residential.

Source: ERIA (2018).

f) Thailand

(1) CAPEX

Table 2.32 shows AQCS installation CAPEX per scenario and AQCS cost range. In scenario 1, the low case was US$311.6 million and the high case US$470.3 million. In scenario 2, the low case was US$1,117.6 million and the high case US$1,713.7 million.

Table 2.32: Capital Expenditure of Air Quality Control System Installation, Thailand

Scenario	Capacity (MW)			CAPEX (US$ million)							
				Low case				High case			
(US$/kW)	PM	SOx	NOx	PM (ESP) (20)	SOx (80)	NOx (50)	**Total**	PM (ESP) (60)	SOx (100)	NOx (70)	**Total**
Scenario 1	455	0	455	9.1	0.0	22.8	**31.9**	27.3	0.0	31.9	**59.2**
Scenario 2	5,293	5,293	5,293	105.9	423.4	264.7	**794.0**	317.6	529.3	370.5	**1,217.4**

CAPEX = capital expenditure, ESP = electrostatic precipitator, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxides.

Source: ERIA (2018). Autoproducers are excluded.

(2) AQCS installation cost

Table 2.33 shows AQCS installation cost per scenario and AQCS cost range. In the first 10 years, cost reached a maximum of US$321.9 million per year, and in the subsequent 10 years US$182.6 million.

Table 2.33: Air Quality Control System Installation Cost, Thailand

Scenario	AQCS cost range	CAPEX	AQCS installation cost (US$ million)							
			First 10 years (per year)				Subsequent 10 years (per year)			
			Depreciation equivalent	Loan interest	O&M	**Total**	Depreciation equivalent	Loan interest	O&M	**Total**
Scenario 1	Low case	31.9	3.2	0.5	4.8	**8.4**			4.8	**4.8**
	High case	59.2	5.9	0.9	8.9	**15.6**			8.9	**8.9**
Scenario 2	Low case	794.0	79.4	11.4	119.1	**209.9**			119.1	**119.1**
	High case	1,217.4	121.7	17.6	182.6	**321.9**			182.6	**182.6**

AQCS = air quality control system, CAPEX = capital expenditure, O&M = operation and maintenance.

Source: ERIA (2018).

(3) AQCS installation cost per kWh

Table 2.34 shows the AQCS installation cost divided by the annual electricity sales volume.

Table 2.34: Air Quality Control System Installation Cost per kWh, Thailand

Scenario	CAPEX	Electricity sales (2016) (GWh)	First 10 years (per year)		Subsequent 10 years (per year)	
			Installation Cost (US$ million)	Cost per kWh (US cent/kWh)	Installation Cost (US$ million)	Cost per kWh (US cent/kWh)
		(a)	(b)	(c)=(b)/(a)	(d)	(e)=(d)/(a)
Scenario 1	Low case	182,620	8.4	**0.005**	4.8	**0.003**
	High case		15.6	**0.009**	8.9	**0.005**
Scenario 2	Low case		209.9	**0.115**	119.1	**0.065**
	High case		321.9	**0.176**	182.6	**0.100**

CAPEX = capital expenditure.

Source: ERIA (2018).

(4) Impact on electricity prices

Table 2.35 shows the impact of AQCS installation cost on electricity price per scenario and AQCS cost range. AQCS installation cost has a maximum impact of 1.8% on electricity prices in the first 10 years, and 1.0% in the subsequent 10 years.

Table 2.35: Impact on Electricity Prices, Thailand

		First 10 years (per year)				Subsequent 10 years (per year)			
		Res.	Com.	Ind.	Total	Res.	Com.	Ind.	Total
Electricity price (2016)	US cent/ kWh	10.9	11.3	9.5	10.3	<--	<--	<--	<--
Impact									
Scenario 1	Low case	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	High case	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	0.1%	0.0%
Scenario 2	Low case	1.1%	1.0%	1.2%	1.1%	0.6%	0.6%	0.7%	0.6%
	High case	1.6%	1.6%	1.8%	1.7%	0.9%	0.9%	1.0%	1.0%

Com. = commercial, Ind. = industry, Res. = residential.

Source: ERIA (2018).

g) Viet Nam

(1) CAPEX

Table 2.36 shows AQCS installation CAPEX per scenario and AQCS cost range. In scenario 1, the low case was US$652.1 million and the high case US$974.2 million. In scenario 2, the low case was US$2,051.8 million and the high case US$3,146.1 million.

Table 2.36: Capital Expenditure of Air Quality Control System Installation, Viet Nam

Scenario	Capacity (MW)			CAPEX (US$ million)							
				Low case				High case			
(US$/kW)	PM	SOx	NOx	PM (ESP) (20)	SOx (80)	NOx (50)	**Total**	PM (ESP) (60)	SOx (100)	NOx (70)	**Total**
Scenario 1	2,275	960	10,596	45.5	76.8	529.8	**652.1**	136.5	96.0	741.7	**974.2**
Scenario 2	13,679	13,679	13,679	273.6	1,094.3	683.9	**2,051.8**	820.7	1,367.9	957.5	**3,146.1**

CAPEX = capital expenditure, ESP = electrostatic precipitator, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxides.

Source: ERIA (2018). Autoproducers are excluded.

(2) AQCS installation cost

Table 2.37 shows AQCS installation cost per scenario and AQCS cost range. In the first 10 years, the maximum was US$831.9 million per year, and in the subsequent 10 years, US$471.9 million.

Table 2.37: Air Quality Control System Installation Cost, Viet Nam

Scenario	AQCS cost range	CAPEX	AQCS installation cost (US$ million)							
			First 10 years (per year)				Subsequent 10 years (per year)			
			Depreciation equivalent	Loan interest	O&M	Total	Depreciation equivalent	Loan interest	O&M	Total
Scenario 1	Low case	652.1	65.2	9.4	97.8	**172.4**			97.8	**97.8**
	High case	974.2	97.4	14.0	146.1	**257.6**			146.1	**146.1**
Scenario 2	Low case	2,051.8	205.2	29.6	307.8	**542.5**			307.8	**307.8**
	High case	3,146.1	314.6	45.4	471.9	**831.9**			471.9	**471.9**

AQCS = air quality control system, CAPEX = capital expenditure, O&M = operation and maintenance.

Source: ERIA (2018).

(3) AQCS installation cost per kWh

Table 2.38 shows AQCS installation cost divided by annual electricity sales volume.

Table 2.38: Air Quality Control System Installation Cost per kWh, Viet Nam

Scenario	CAPEX	Electricity sales (2016) (GWh)	First 10 years (per year)		Subsequent 10 years (per year)	
			Installation Cost (US$ million)	Cost per kWh (US cent/kWh)	Installation Cost (US$ million)	Cost per kWh (US cent/kWh)
		(a)	(b)	(c)=(b)/(a)	(d)	(e)=(d)/(a)
Scenario 1	Low case	142,800	172.4	**0.121**	97.8	**0.068**
	High case		257.6	**0.180**	146.1	**0.102**
Scenario 2	Low case		542.5	**0.380**	307.8	**0.216**
	High case		831.9	**0.583**	471.9	**0.330**

CAPEX = capital expenditure.

Source: ERIA (2018).

(4) Impact on electricity prices

Table 2.39 shows the impact of AQCS installation cost on electricity price per scenario and AQCS cost range. AQCS installation cost has a maximum impact of 8.8% on electricity prices in the first 10 years, and 5.0% in the subsequent 10 years.

Table 2.39: Impact of Air Quality Control System Installation Cost on Electricity Prices, Viet Nam

		First 10 years (per year)				Subsequent 10 years (per year)			
		Res.	Com.	Ind.	Total	Res.	Com.	Ind.	Total
Electricity price (2016)	US cent/ kWh	11.2	11.1	6.6	8.7	<--	<--	<--	<--
Impact									
Scenario 1	Low case	1.1%	1.1%	1.8%	1.4%	0.6%	0.6%	1.0%	0.8%
	High case	1.6%	1.6%	2.7%	2.1%	0.9%	0.9%	1.6%	1.2%
Scenario 2	Low case	3.4%	3.4%	5.8%	4.4%	1.9%	1.9%	3.3%	2.5%
	High case	5.2%	5.2%	8.8%	6.7%	3.0%	3.0%	5.0%	3.8%

Com. = commercial, Ind. = industry, Res. = residential.

Source: ERIA (2018).

Chapter 3

Social and Health Benefits of Good Air Quality

1. Methodology

1.1. Overview

This study analyses the costs and benefits of strengthened (more-stringent) air emission standards for coal-fired power plants. Since air emission standards in ASEAN countries are laxer than those in OECD countries, the FY 2016 study (ERIA, 2017) pointed out the significance of tightening standards for air pollutants from coal-fired power plants in ASEAN to a level equivalent to those in OECD. The FY 2017 study (ERIA, 2018) calculated the typical cost of an AQCS that conforms to air emission standards as stringent as OECD countries'. This study analyses a cost–benefit comparison for tightening air emission standards by quantifying the monetary value of social benefits therefrom, of which a concrete example is mitigation of damage to the health of people living around a coal-fired power plant.

Cost is assumed as the investment amount (US$) a typical AQCS needs to comply with strengthened air emission standards. To determine benefit, we calculate the reduced health impact in monetary terms thanks to better air quality. We estimate residents' willingness-to-pay (WTP)[3] to avoid mortality and morbidity risk. For example, if a health-related benefit (WTP) from reduced air pollution is larger than the cost required for the improvement (i.e. investment amount of AQCS), tightening air emission standards and investing in AQCS can be considered economically rational.

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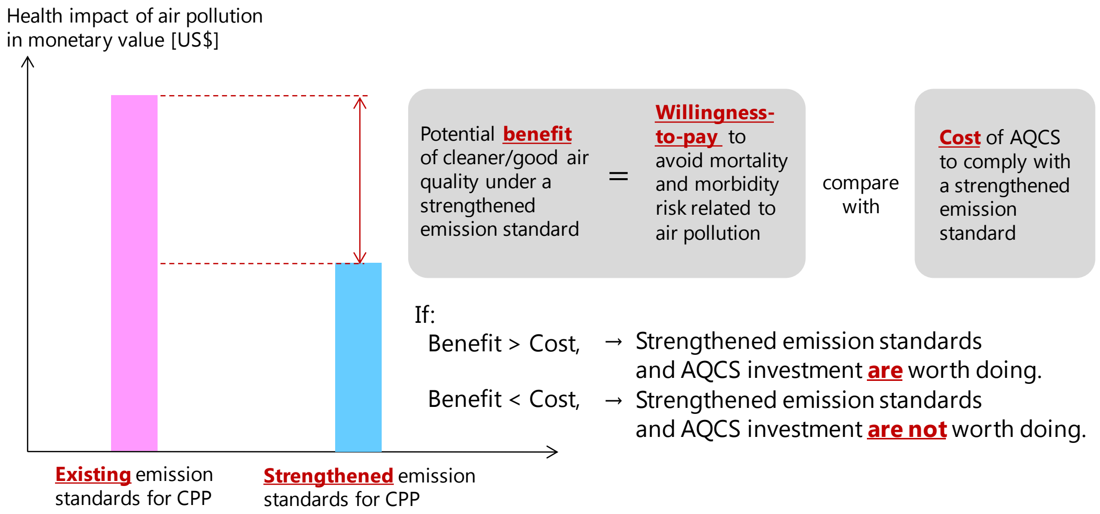
[3] Conversion of damage quantity received by residents into economic index in terms of WTP.

Figure 3.1: Cost and Benefit Analysis in This Study



AQCS = air quality control system, CPP = coal-fired power plant.

Source: Author.

To convert the health impact of air pollution caused by coal-fired power plants into a monetary value, calculations follow these steps:

1. Identify the emission source of air pollutants and the technology and fuel used.
2. Calculate the spatial distribution of pollutants (concentration of pollutants) from the point source of pollution.
3. Estimate the health impact on residents caused by changes (increases) in the atmospheric concentration of pollutants.
4. Convert the health impact into monetary value by using mortality- and morbidity-related reference values and calculation formulas.

Calculation methods and major assumptions used in this study are as follows and equation details are described in section 1.2:

Table 3.1: Calculation Methods and Major Assumptions

1. Identification of emission source of air pollutants, etc.	• Applicable to coal-fired power plants (based on assumptions of supercritical pressure, electric output of 631 MW, and exhaust gas amount of 2,550,000 Nm^3/h) • Sites are chosen from existing coal-fired power plants in eight ASEAN countries (one power plant in each country [Table 3.2]). • Targeted air pollutants are SOx (SO_2), NOx (NO_2), and PM (PM2.5/PM10). Neither changes in the state of pollutant due to chemical reaction nor secondary particulates are considered. • Emission amount of air pollutants is calculated based on reference values for emission amounts of air pollutants in the surveyed country and in developed countries. (Actual values recorded at each power plant are not used). • The following are examined: (i) A case where the most-stringent air emission standards amongst developed countries' are adopted for SOx, NOx, and PM (ii) A case where half the existing standard values of air pollutant emission standards in the surveyed country are adopted Calculate the potential benefit of cleaner/good air quality, i.e. willingness-to-pay to avoid mortality and morbidity risk related to coal-fired power plants, by using the difference between values for each case above (i)/(ii) and the existing reference values for emission amounts of air pollutants in the surveyed country.
2. Calculation of spatial distribution of air pollutants	• Use an estimation method (Conservation of Clean Air and Water in Western Europe [CONCAWE]-plume Method) referred to in 'Guidebook for power plant–related environmental

	impact assessment' (in Japanese) by the Ministry of Economy, Trade and Industry (2019) ● The area to be surveyed is within a 20 km radius from the power plant stack.
3. Estimation of health impact on residents	● Calculate the number of cases of premature mortality caused by exposure to air pollutants (a) by using the equation presented in World Health Organization (2004) (Table 3.16 and Table 3.17 of this study).
4. Conversion of health impact into monetary value	● Calculate reference values (b), which are the basis for conversion into monetary value, for each country to be surveyed by using an equation presented by OECD (2017). Value of statistical life, which is a concept based on willingness-to-pay, is used to calculate (b) (Figure 3.12 of this study). Health impact in the surveyed country is converted into a monetary value by multiplying (a) by (b).

Source: Author.

This study covers Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Philippines, Thailand, and Viet Nam, and excludes Brunei Darussalam and Singapore, neither of which has coal-fired power plants.

Most of the coal-fired power plants in ASEAN countries use subcritical pressure technology. Future power plants are expected to use supercritical or ultra-supercritical pressure technology. We assumed a power plant using supercritical pressure technology (with electric output of 631 MW and exhaust gas of 2,550,000 Nm^3/h) as the basis for estimations. The said electricity output is an average output of supercritical pressure power plants operating in Japan as of January 2019.

Power plants selected as point sources of air pollutants are listed below. We selected one power plant from each country to calculate diffusive concentration of air pollutants within a 20 km radius therefrom. A power plant with the largest total electricity output in each country was chosen as a point source of air pollutants.

Table 3.2: Point Sources of Air Pollution (coal-fired power plants)

Country	Power Plant	Output (MWe)	Start of Operation (year)
Cambodia	Sihanoukville Stung Hav	60*2	2014
Indonesia	Suralaya	400*4 600*3	1984/1985/1988/1989 1996/1997*2
Lao PDR	Hongsa	626*3	2015*2/2016
Malaysia	Tanjung Bin	748*3 1000*1	2006/2007*2 2016
Myanmar	Kyaukphyu Power	660*2	-
Philippines	Calaca Semirara	300*2	1984
Thailand	Mae Moh	75*3 150*4 300*6	1978*2/1981 1984*2/1985*2 1990*2/1991*2/1995*2
Viet Nam	Vinh Tan-2	622*2	2014*2

Lao PDR = Lao People's Democratic Republic.

Source: Author.

The results of ERIA (2017) are adopted as air pollutant emission standards for coal-fired power plants in the surveyed countries (Table 2.).

The results of ERIA (2018) are adopted as the installation cost of AQCS. Yearly average costs are calculated based on total investment cost per MW, assuming the operating life of AQCS to be 20 years.

Table 3.3: Cost of Air Quality Control System Installation for Seven ASEAN Countries

	Yearly Average Installation Cost per MW, 2010 (US$)
Low case	0.02860
High case	0.04385

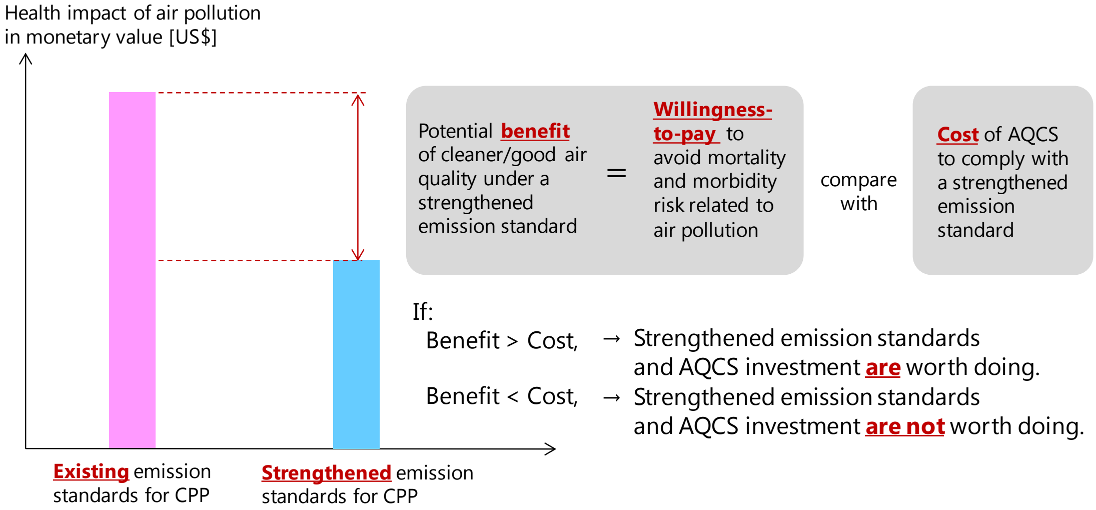
Note: We calculate the average installation cost of an air quality control system based on Table 2. and the calculation formula used in the FY 2017 study (ERIA,2018). Source: Author.

2. World Health Organization Method and Results

2.1. Standard Data to be Referenced

Two cases each are examined for SOx, NOx, and PM: (i) where the most stringent reference value amongst air pollutants emission standards is adopted, and (ii) where half of the reference value of existing air pollutant emission standards in the surveyed country is adopted.

Figure 3.2: Cost and Benefit Analysis in This Study



AQCS = air quality control system, CPP = coal-fired power plant.
Source: Author.

The cost–benefit analysis for tightening air emission standards is conducted by comparing monetary value converted from health impacts on residents, which are avoidable when air emission standards are strengthened (tightened) to a certain level, and installation costs of air pollutant-removal equipment. The cases where air emission standards are tightened to a certain level correspond to cases (i) and (ii). We assumed that an amount of air pollutants equivalent to that specified in standards is emitted and examined the health impact on residents under such conditions. As detailed in section 3.2.4, the health impact converted into monetary value is based on WTP. Therefore, 'potential benefit/social benefit of good air quality' can also be expressed as 'WTP to avoid mortality and morbidity risk related to coal-fired power plants'.

Table 3.4: Most Strengthened Emission Standard for Case (i)

	SOx (mg/m^3)	NOx (mg/m^3)	PM (mg/m^3)
Most strengthened standard	133	50	10

NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide.
Note: Air pollutant standards come from developed countries. SOx: Japan; NOx: Republic of Korea; PM: Germany.
Source: Author.

Table 3.5: Half of Existing Emission Standard for Case (ii)

	SOx (mg/m^3)	NOx (mg/m^3)	PM (mg/m^3)
Cambodia	250	500	200
Indonesia	375	375	50
Lao PDR	426.5	335	60
Malaysia	250	250	25
Myanmar	100	200	25
Philippines	350	500	75
Thailand	240	191.5	40
Viet Nam	250	325	100

NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide.

Source: Author.

The health impact that is avoidable when the air emission standard is tightened to a certain level can be calculated from the difference between an existing air emission standard value and the standard values in cases (i) and (ii). In case (i), the difference between the value of an existing air pollutant emission standard and the value of the most stringent air pollutant emission standard for SOx, NOx, and PM amongst developed countries is used for the calculation, and in case (ii), the difference between the value of an existing air pollutant emission standard and half of the value of air pollutant emission standard of the surveyed country. In this way, whenever the health impact is converted into a monetary value, the same equations and factors, except standard values, can be used equally for calculations for case (i), case (ii), or the existing air emission standard. The difference between such standard values is incorporated into the equation for the air pollutant diffusion forecast as emission rate of air pollutant (section 3.2.2). The difference will be 'Q_p' in equation (5). In the said equation, the emission rate of air pollutants is indicated in µg/Nm^3/h per MW to make the comparison with the installation cost of AQCS (indicated as a yearly average cost/ MW) easier. The differences in the standard values used in case (i) and case (ii) (emission rate of air pollutants) are shown below:

Table 3.6: Emission Rate of Air Pollutants for Case (i)

Country	SOx (µg/Nm^3/h/MW)	NOx (µg/Nm^3/h/MW)	PM (µg/Nm^3/h/MW)
Cambodia	582	1,506	618
Indonesia	978	1,109	143
Lao PDR	1,141	983	174
Malaysia	582	713	63
Myanmar	106	555	63
Philippines	899	1,506	222
Thailand	550	528	111
Viet Nam	582	951	301

NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide.

Source: Author.

Table 3.7: Emission Rate of Air Pollutants for Case (ii)

Country	SOx (µg/Nm^3/h/MW)	NOx (µg/Nm^3/h/MW)	PM (µg/Nm^3/h/MW)
Cambodia	396	792	317
Indonesia	594	594	79
Lao PDR	676	531	95
Malaysia	396	396	40
Myanmar	158	317	40
Philippines	555	792	119
Thailand	380	304	63
Viet Nam	396	515	158

NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide.

Source: Author.

If the conditions conform to equation (1) below, the residents in the surveyed ASEAN countries may be considered to be willing to pay the installation costs of AQCS to avoid a health impact caused by coal-fired power plant–derived air pollution.

$$WTP_{ES} - WTP_{SS} > C_{AQCS} \tag{1}$$

Where,

WTP_{ES}: WTP to avoid mortality and morbidity risk related to coal-fired power generation with existing emission standards (US$)

WTP_{SS}: WTP to avoid mortality and morbidity risk related to coal-fired power generation with strengthened emission standards (US$)

$WTP_{ES} - WTP_{SS}$: Potential benefit of cleaner/good air quality with strengthened emission standards for coal-fired power plants: i.e. WTP to avoid mortality and morbidity risk related to coal-fired power plants (US$)

C_{AQCS}: AQCS installation cost in each ASEAN country (US$)

2.2. Calculation of Spatial Distribution of Air Pollutants

(a) Diffusion forecast of air pollutants

METI (2019) cites a forecast method described in Environmental Research and Control Center (2000) as a referential method relating to thermal power plants and nuclear power plants. For exhaust gases generated by operation of power generation facilities, except nuclear power plants, the referential method is used to calculate concentration changes and diffusion conditions of air quality.

Because a yearly average of ground-level pollutant concentration is sought in the course of the forecast, the survey area is, in principle, set within a 20 km radius from a power plant, because such an area includes a location where the ground-level pollutant concentration becomes relatively high.

In consideration of the assessment’s validity and the forecast’s accuracy, it would be appropriate to focus mainly on the forecast of the yearly average value that has a longer time scale. The yearly average value is forecast as follows:

- Calculation method. The diffusion forecast of exhaust gas from a thermal power plant is made by calculating values that are simulated based on diffusion from an effective height of a stack in consideration of ascension of smoke. The effective height of the stack is obtained by adding the actual stack height to the ascension height of smoke, which is obtained by a calculation formula for smoke ascension height.
- Conditions of forecast. The conditions of the smoke source required for diffusion forecast, such as the exhaust gas amount and emission amount of air pollutants, are calculated from a model that is simulated based on a yearly utilisation ratio and daily load patterns of the smoke source to be surveyed.

In the case of large-scale high smoke sources such as power plants, meteorological conditions that affect the exhaust gas diffusion are often different from those at ground level because of the high effective height of the stack. Therefore, the diffusion field in the upper layer is set by considering various meteorological observations, amongst others. To estimate wind velocity in the upper layer, based on the result of ground-based meteorological observation, the power law of vertical wind velocity distribution is used. The power law to indicate vertical wind velocity distribution is defined below:

$$V_z = V_r \left(\frac{Z}{Z_r}\right)^{1/n} \tag{2}$$

Where,

V_z: Wind velocity in upper layer (m/s)

V_r: Wind velocity at reference height (m/s)

Z: Height of upper layer (m)

Z_r: Reference height (m)

The National Astronomical Observatory of Japan (2008) shows the relationships between the situations of ground surface and ‘n’:

Table 3.8: Relationship Between the Situations of Ground Surface and n

Situations of Ground Surface	n
Plain field, grassland	7
Forest, urban area without high-rise building, residential area	4
Suburb of a large city and its circumference, urban area	3
Central zone of a large city and its vicinity	2

Source: National Astronomical Observatory of Japan (2008).

Wind force scales are in accordance with the Beaufort wind force scale, which has been adopted by the World Meteorological Organization as a standard expression method of wind force. The wind force scale at ground level is commonly between 1 and 4 (wind velocity from 0.3 to 7.9 m/s). If the wind velocity at ground level is assumed to be 8 m/s, the velocity at the top of a stack 200 m high will be 12.3–35.8 m/s, depending on ground surface conditions. A coal-fired power plant is rarely located in a central zone of a large city. If such a circumstance is excluded from the above range of wind velocity, the wind velocity at the top of a stack 200 m high will be 12.3–21.7 m/s depending on ground surface conditions.

Table 3.9: Beaufort Wind Scale

Wind Scale	Corresponding Wind Velocity (m/s)
0	0.0 or more, less than 0.3
1	0.3 or more, less than 1.6
2	1.6 or more, less than 3.4
3	3.4 or more, less than 5.5
4	5.5 or more, less than 8.0
5	8.0 or more, less than 10.8
6	10.8 or more, less than 13.9
7	13.9 or more, less than 17.2
8	17.2 or more, less than 20.8
9	20.8 or more, less than 24.5
10	24.5 or more, less than 28.5
11	28.5 or more, less than 32.7
12	32.7 or more

Source: Japan Meteorological Agency (2018).

The stack height of a power plant is 100–200 m and wind conditions at such a height are rarely calm. If calculated based on power law and the values of Table 3.9, the wind velocity at a height of 200 m from the ground will be 0.6–1.8 m/s, depending on ground surface conditions, even if wind conditions 10 m from the ground are calm (wind velocity of up to 0.4 m/s). This study, therefore, examines conditions with a certain level of wind.

Peculiar meteorological conditions (formation of inversion layer, occurrence of downwash, and occurrence of fumigation due to development of inner boundary layer) are not considered because they are infrequent. The effective stack height and concentration are calculated using the method below in accordance with the Environmental Research and Control Center (2000).

(b) Calculation of effective stack height

Stacks discharge exhaust gas, which is generally generated by combustion. Therefore, when exhaust gas is discharged from a stack, it has an inertia effect caused by discharging speed and a buoyance effect caused by the heat quantity of the exhaust gas. Due to such effects, exhaust gas continues to ascend after it is discharged from a stack, whilst it wafts in the wind and gradually mixes with surrounding air. Interfusion of air lowers the power to ascend and the exhaust gas reaches its ultimate height. The height of exhaust gas ascension after it is discharged from the stack is expressed by ΔH, the actual height of the stack by H_o, and the height of the emission source (effective stack height, H_e) by the equation below:

$$H_e = H_o + \Delta H \tag{3}$$

As for exhaust gas discharged from the stack, buoyance force is a dominant factor to determine the effective stack height. (The dominant factor that determines ΔH is buoyance force and is referred to as ‘buoyant plume’.) The Conservation of Clean Air and Water in Western Europe (CONCAWE) formula (METI, 2019) is adopted for conditions with a certain level of wind. The equation was developed by a research group of a Western European petroleum-related company using a regressive approach from many actual measurement values. Amongst various estimation formulae, only the CONCAWE formula has been verified through domestic and overseas research studies as coinciding with the actual state of smoke.

$$\Delta H = 0.175 * Q_H^{1/2} * u^{-3/4} \tag{4}$$

Where,

ΔH: Ascending height of exhaust gas (m)

Q_H: Discharged heat quantity (cal/s)

u: Wind velocity at the top of stack (m/s)

and

$$Q_H = \rho C_p Q \Delta T \tag{5}$$

Where,

ρ: Density of exhaust gas at 0°C ($1.293*10^3$ g/m^3)

C_p: Specific heat under constant pressure (0.24 cal/K/g)

Q: Exhaust gas amount per unit time (Nm^3/s)

ΔT: Temperature difference (T_G-15°C) between exhaust gas temperature (T_G) and ambient temperature

The effective stack height was calculated using the CONCAWE formula, assuming an exhaust gas amount from a coal-fired power plant of 2,550,000 Nm^3/h and an actual stack height of 200 m.

(c) Calculation of concentration

Due to the same reasons as above, calculations are made only for conditions with wind. Exhaust gas from a stack of a power plant is smoke from a point source. Therefore, it is appropriate to use a normal distribution-type plume formula as a diffusion formula to be used for diffusion simulation and to use Pasquill-Gifford stability as a diffusion parameter. A plume formula suits conditions with a wind velocity of 0.5 m/s or more. The equation for diffusion at a certain point (horizontal distance 'R' and height 'z') is shown below. Assuming the concentration to be constant within one single wind direction, a plume that is irrelevant to the horizontal diffusion parameter is defined by the following equation:

$$\mathrm{C(R,z)} = \sqrt{\frac{1}{2\pi}} * \frac{Q_p}{\frac{\pi}{8}R\sigma_z u} * \left[exp\left\{-\frac{(z-H_e)^2}{2{\sigma_z}^2}\right\} + exp\left\{-\frac{(z+H_e)^2}{2{\sigma_z}^2}\right\}\right] \tag{6}$$

Where,

R: Horizontal distance between point source of smoke and calculated point (m)

z: z-coordinate of calculated point (m) (Origin of coordinate is set at a point on the ground surface just below the smoke source, x-axis is set in a downwind direction, y-axis is set horizontally in a direction orthogonal to x-axis, and y-axis is set in a height direction.)

σ_z: Diffusion parameter representing spread of smoke in z-axis direction

Q_p: Strength of point source of smoke (Nm^3/s)

u: Wind velocity (m/s)

H_e: Effective stack height (m)

As a diffusion parameter to be used in combination with the plume formula, the Pasquill-Gifford chart is popular. It creates diffusion parameter 'σ_z' ('σ_y' is also a diffusion parameter but is not used in this study) as a function of the downwind distance 'x' for each of the Pasquill-Gifford stability classes A through G. The approximation formula of the Pasquill-Gifford chart is mentioned below:

$$\sigma_z(x) = \gamma_z * x^{\alpha z} \tag{7}$$

Table 3.10: Pasquill-Gifford Stability Classes

Atmospheric Stability	α_z	γ_z	Downwind Distance x(m)
A	1.122	0.0800	0–300
	1.514	0.00855	300–500
	2.109	0.000212	500–
B	0.964	0.1272	0–500
	1.094	0.0570	500–
C	0.918	0.1068	0–
D	0.826	0.1046	0–1,000
	0.632	0.4000	1,000–10,000
	0.555	0.811	10,000–

E	0.788	0.0928	0–1,000
	0.565	0.433	1,000–10,000
	0.415	1.732	10,000–
F	0.784	0.0621	0–1,000
	0.526	0.370	1,000–10,000
	0.323	2.41	10,000–
G	0.794	0.0373	0–1,000
	0.637	0.1105	1,000–2,000
	0.431	0.529	2,000–10,000
	0.222	3.62	10,000–

Source: Environmental Research and Control Center (2000).

As for atmospheric stability, stability class D is most common in Japan. Because of the larger amount of insolation in Southeast Asia, class C, which is less stable by one level than that of Japan, is adopted in this study as a yearly average value.

R from 100 m to 20,000 m is calculated by using the normal distribution-type plume formula, and the average concentration of SOx, NOx, and PM is calculated for zones with a horizontal distance of 1,500–20,000 m from the point source of smoke. To simplify the calculation, the concentration of air pollutants in the area within a 20 km radius from a power plant is assumed to be equal to the said average concentration. As detailed in section 3.2.3, the number of cases of premature mortality is calculated for each air pollutant by using such an average concentration for each air pollutant. Diffusive concentrations (average values) in the surveyed countries are as follows:

Table 3.11: Average Concentration of Air Pollutants for Case (i)

Country	Average Concentration (mg/m^3)		
	SOx	NOx	PM
Cambodia	9.873E-06	2.556E-05	1.049E-05
Indonesia	1.660E-05	1.883E-05	2.421E-06
Lao PDR	1.937E-05	1.668E-05	2.959E-06
Malaysia	9.873E-06	1.211E-05	1.076E-06
Myanmar	1.802E-06	9.415E-06	1.076E-06
Philippines	1.525E-05	2.556E-05	3.766E-06
Thailand	9.335E-06	8.958E-06	1.883E-06
Viet Nam	9.873E-06	1.614E-05	5.111E-06

NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide.

Source: Author.

Table 3.12: Average Concentration of Air Pollutants for Case (ii)

Country	Average Concentration (mg/m^3)		
	SOx	NOx	PM
Cambodia	6.725E-06	1.345E-05	5.380E-06
Indonesia	1.009E-05	1.009E-05	1.345E-06
Lao PDR	1.147E-05	9.012E-06	1.614E-06
Malaysia	6.725E-06	6.725E-06	6.725E-07
Myanmar	2.690E-06	5.380E-06	6.725E-07
Philippines	9.415E-06	1.345E-05	2.018E-06
Thailand	6.456E-06	5.151E-06	1.076E-06
Viet Nam	6.725E-06	8.743E-06	2.690E-06

NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide.

Source: Author.

2.3. Calculation of Number of Cases of Premature Mortality

This study refers to equations provided by the World Health Organization (WHO) (2004) to calculate the number of cases of premature mortality from all causes from exposure to air pollutants. The WHO has coordinated the preparation of practical guidance to estimate disease burden at national or local levels for selected environmental and occupational risk factors. The guidance is compiled in the *Environmental burden of disease series* and contains the scientific basis for the estimates, as well as a step-by-step approach and a numerical example to assist scientists in estimating the size of an environmental health problem in a selected area (WHO, 2019). WHO (2004) is part of the series and provides the method of the quantitative assessment of the health impact of outdoor air pollution, using PM10 or PM2.5 measurements, for a given city or region.[4]

This study estimates the effects of all-cause mortality associated with short-term exposure for the full population based on equations in WHO (2004). According to the WHO (2004: 9), 'It is important to note that estimation of the effects of short-term exposure would, to a certain extent, double-count those cases estimated to result from long-term exposure, and the burden specifically estimated for children under age 5'. Therefore, this study only focuses on short-term exposure to air pollutants to avoid double-count and simplify our estimation.

To quantify the effect of all-cause mortality associated with short-term exposure for the full population, the relative risk (RR)[5] can be specified as follows:

$$RR = exp[\beta(X - X_o)] \tag{8}$$

Where,

β: Concentration–response functions from the epidemiological literature that relates ambient concentrations of air pollutants to selected health effects

X: Current pollutant concentration (µg/m^3)

X_o: Target or threshold concentration of pollutants (µg/m^3)

The results of $X - X_o$ are in Table 3.11 and Table 3.12.

'β' refers to values from the Health Effects Institute (HEI) (2010). HEI (2010) enumerates and classifies more than 400 studies identified through a 2007 literature survey. A systematic and

---

[4] The evidence in WHO (2004) is being revised.

[5] A measure of the risk of a certain event happening in one group compared with the risk of the same event happening in another group (National Cancer Institute, 2019).

quantitative assessment of 82 time-series studies estimates the effect of short-term exposure to air pollution on daily mortality and hospital admissions for cardiovascular and respiratory disease. ADB (2014) reviews the summary estimates presented in HEI (2010) and examines whether they can be applied with reasonable reliability to Asian countries. ADB (2014) concludes that they are confident that HEI's estimates are the best available estimates to date in the literature on Asia and that the combined analysis from the 82 studies is applicable to Asian countries.

Table 3.13: Concentration–Response Functions

Pollutant	Outcome	Percent Change (95% CI), Fixed Effect, per 10μg/m^3
SO_2	Mortality, all causes, all ages	0.35
NO_2	Mortality, all causes, all ages	0.83
PM10	Mortality, all causes, all ages	0.14

NO_2 = nitrogen dioxides, PM = particulate matter, SO_2 = sulphur dioxide.

Source: HEI (2010).

Once the relative risks have all been determined, the attributable fractions (AFs) of health effects from air pollution for the exposed population can be calculated by

$$\mathrm{AF} = \frac{RR - 1}{RR} \tag{9}$$

To calculate the expected number of mortality cases due to air pollution (E), the AF is applied to the total number of deaths:

$$E = AF \times B \times P \tag{10}$$

Where,

E: Expected number of deaths due to outdoor air pollution

B: Population incidence of the given health effect (i.e. deaths per 1,000 people)

P: Relevant exposed population for the health effect

The WHO (2004) states that the AF is based on relative risks derived from epidemiological studies and from the change in PM being evaluated, B is obtained or approximated from available health statistics, and P from census or other data for the area under study. Table 3.14 shows the values of B for eight countries, and Table 3.15 the values of P.

Table 3.14: Crude Death Rate in Eight ASEAN Countries

Country	Deaths/1,000 population, 2017 est.
Cambodia	7.5
Indonesia	6.5
Lao PDR	7.4
Malaysia	5.1
Myanmar	8.19
Philippines	6.1
Thailand	8
Viet Nam	5.9

Lao PDR = Lao People's Democratic Republic.

Source: Central Intelligence Agency (2019).

Table 3.15: Population Within a 20 km Radius of Specific Coal-fired Power Plants

Country	Population	Census Data (as of)
Cambodia	109,724	3 March 2008
Indonesia	558,901	1 May 2015
Lao PDR	28,048	1 March 2015
Malaysia	478,187	6 July 2010
Myanmar	165,352	29 March 2014
Philippines	808,301	1 August 2015
Thailand	38,464	1 September 2010
Viet Nam	140,708	3 March 2008

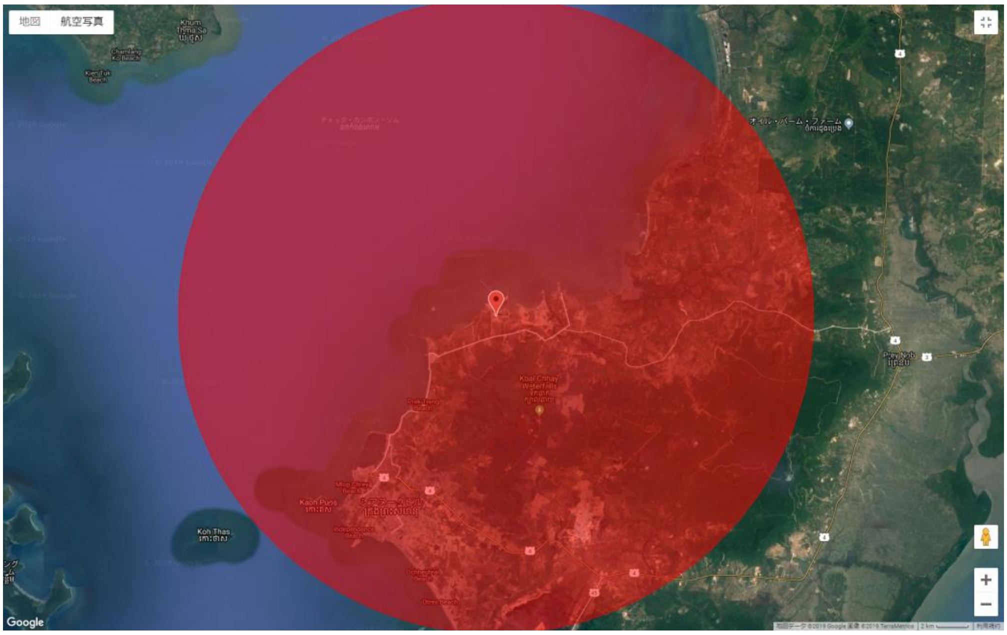
Lao PDR = Lao People's Democratic Republic.

Source: City Population, Asia (2019).

Areas within a 20 km radius from specific coal-fired power plants (Table 3.2) are shown in Figure 3.3 through Figure 3.10 for each power plant. This study does not consider absorption of air pollutants by seawater and cross-border transfer of air pollutants by atmospheric circulation.

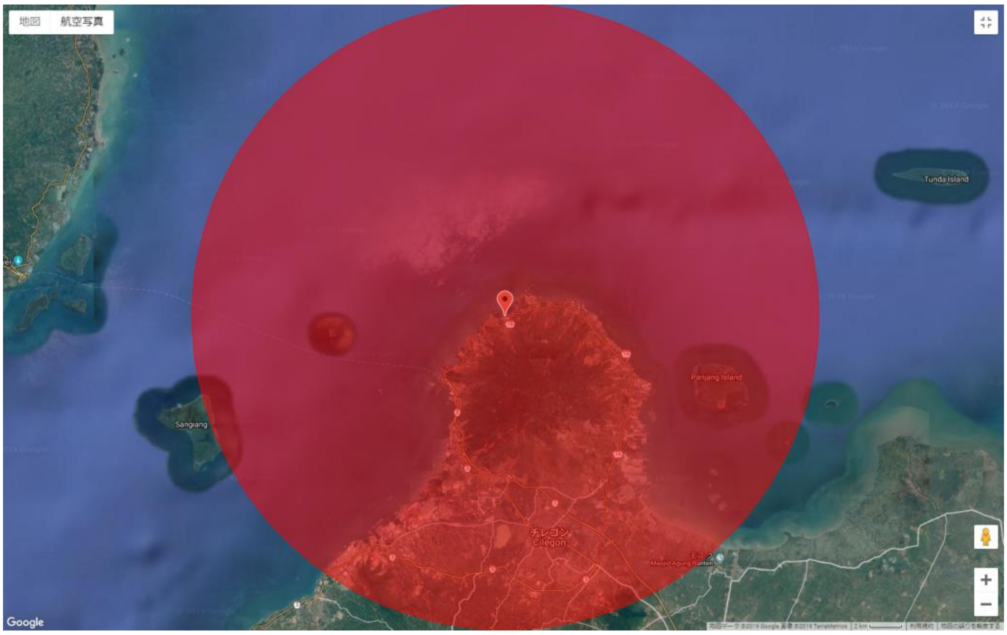
This study assumes that those who suffer health impacts are limited only to residents of the surveyed country, even if such a zone of a 20 km radius may expand to a part of another surveyed country's territory (e.g. Malaysia).

Figure 3.3: Point Source of Air Pollutants, Cambodia



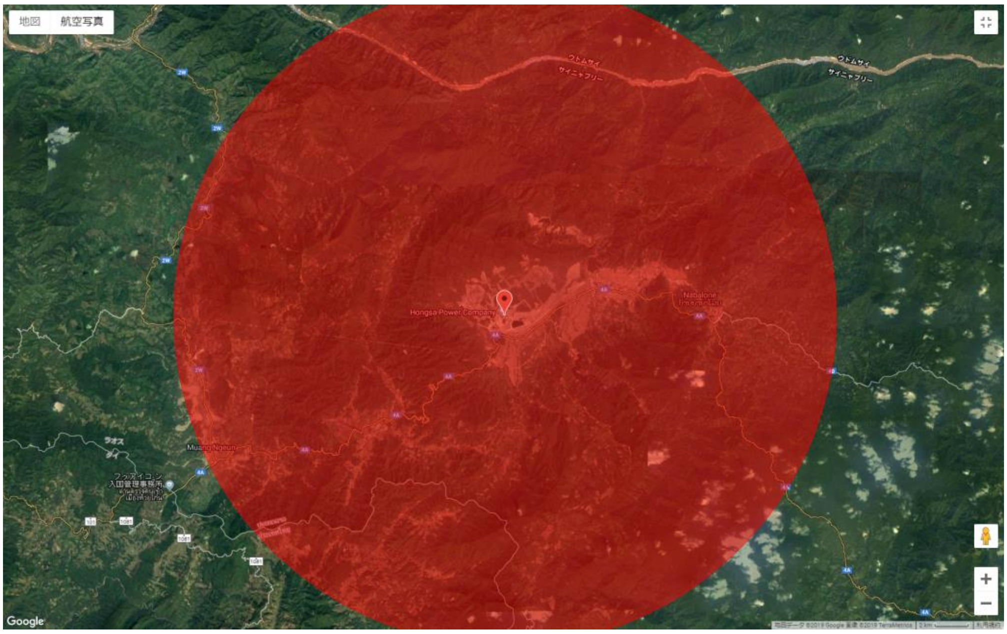
Source: Google Maps.

Figure 3.4: Point Source of Air Pollutants, Indonesia



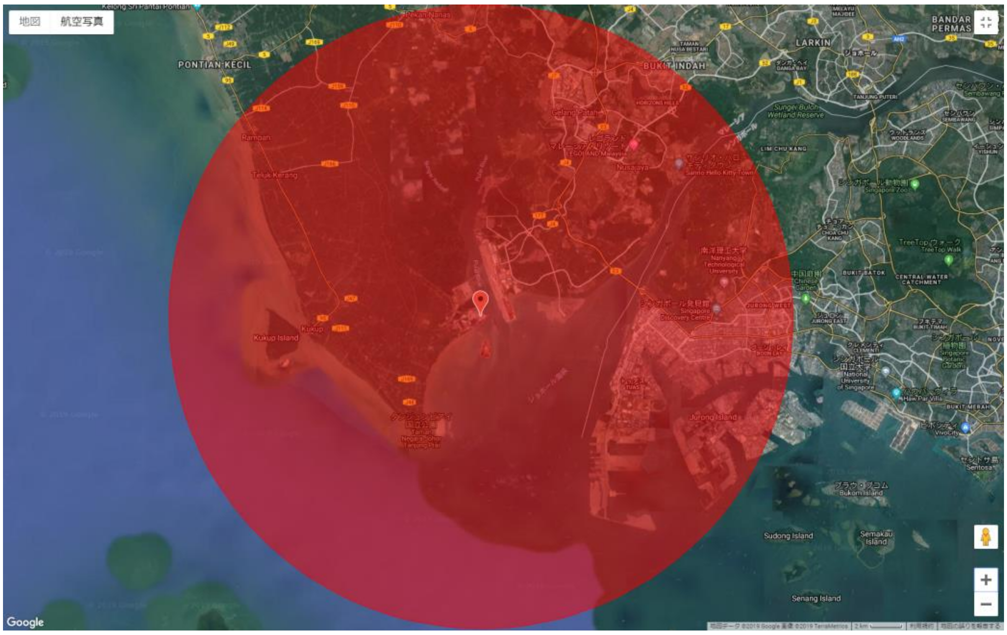
Source: Google Maps.

Figure 3.5: Point Source of Air Pollutants, Lao People's Democratic Republic



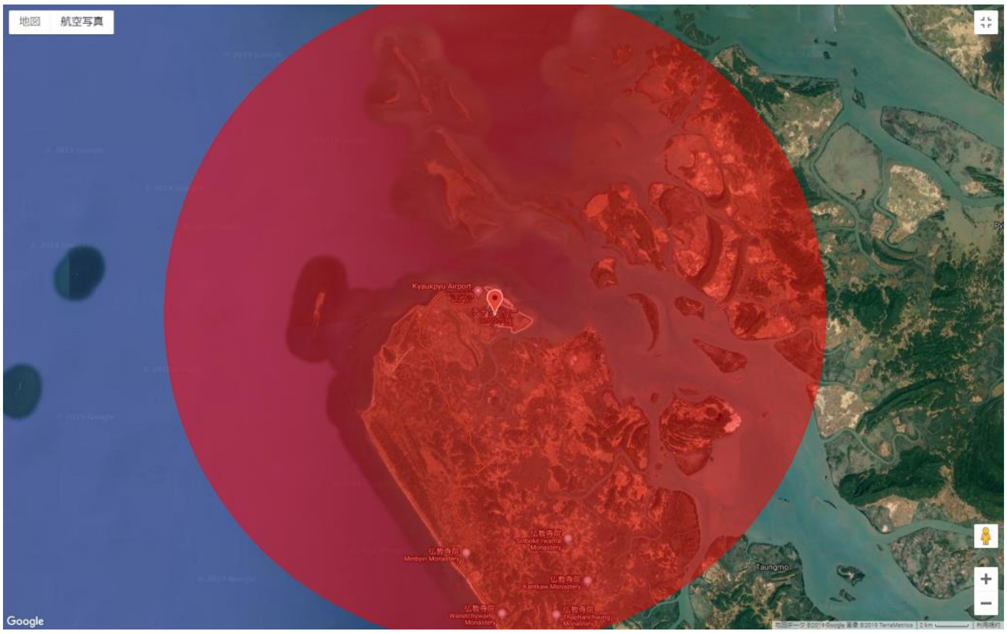
Source: Google Maps.

Figure 3.6: Point Source of Air Pollutants, Malaysia



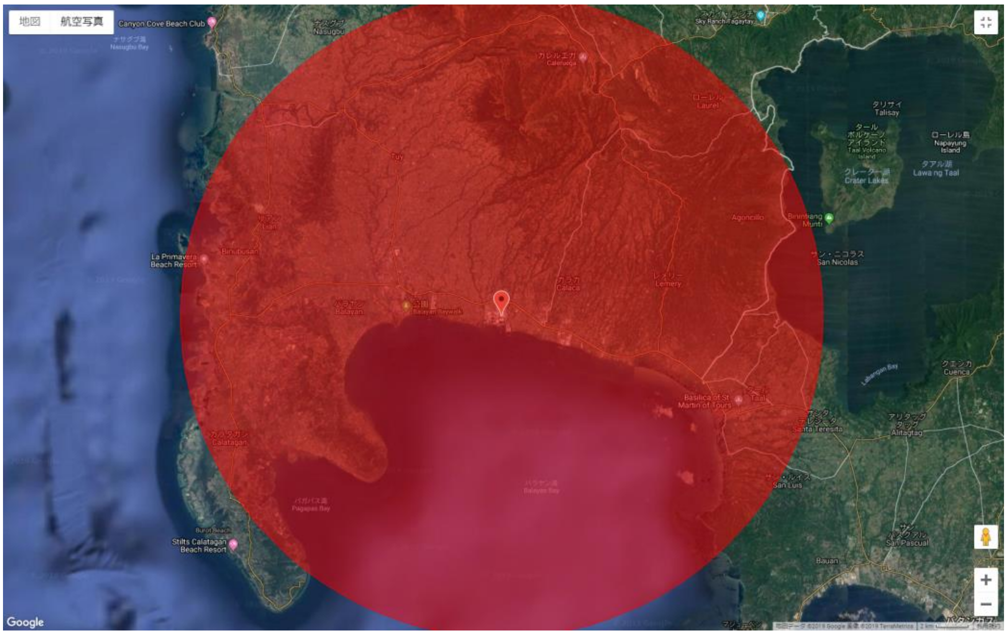
Source: Google Maps.

Figure 3.7: Point Source of Air Pollutants, Myanmar



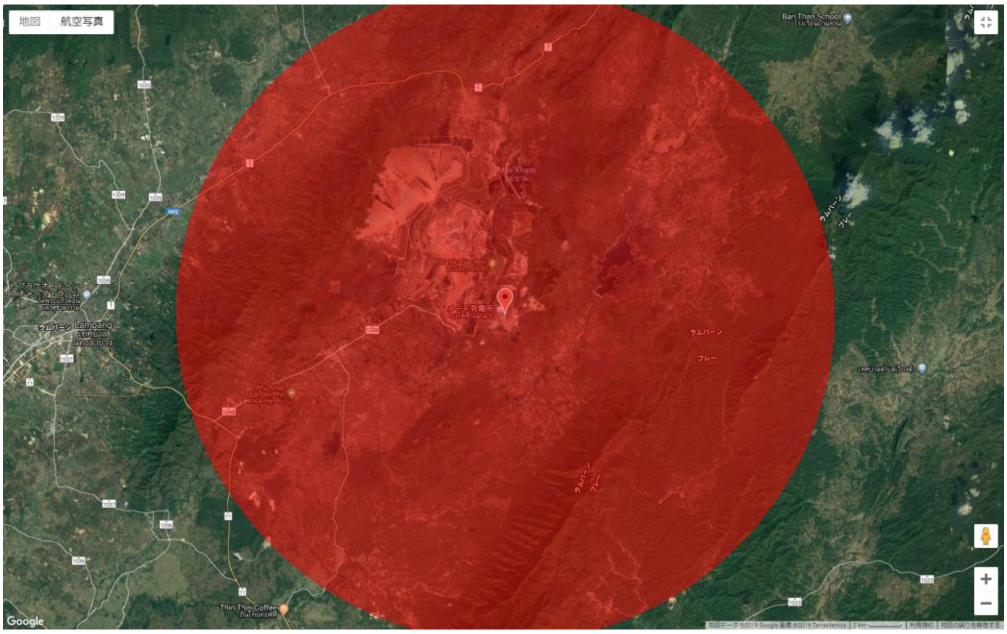
Source: Google Maps.

Figure 3.8: Point Source of Air Pollutants, Philippines



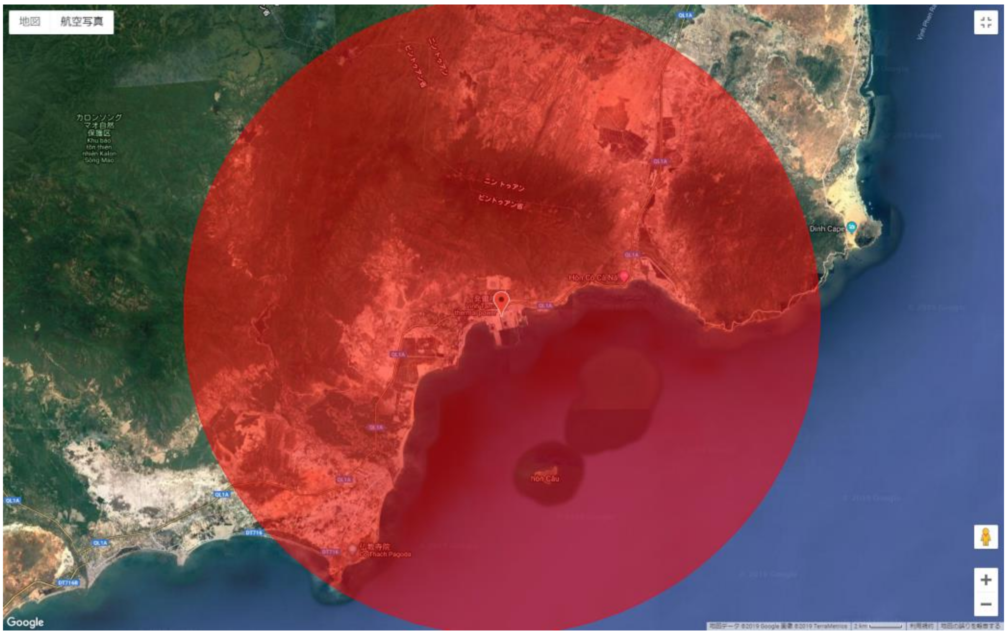
Source: Google Map

Figure 3.9: Point Source of Air Pollutants, Thailand



Source: Google Maps.

Figure 3.10: Point Source of Air Pollutants, Viet Nam



Source: Google Maps.

To calculate the number of yearly premature mortalities using equation (10), the load factor of coal-fired power plants is set at 70%. The yearly numbers of cases of premature mortalities in the surveyed countries for each type of air pollutant are shown in Table 3.16. By multiplying the values in Table 3.16 and Table 3.17 by the estimated value of statistical life (VSL) (section 3.2.4), we can obtain the cost of mortality or morbidity due to air pollution caused by coal-fired power generation, i.e. WTP to avoid mortality and morbidity risk related to coal-fired power plants.

Table 3.16: Expected Number of Deaths Due to Outdoor Air Pollution, Case (i)

Country	Cases of Mortality		
	SO_2	NO_2	PM10
Cambodia	0.01744	0.10704	0.00741
Indonesia	0.12941	0.34817	0.00755
Lao PDR	0.00863	0.01762	0.00053
Malaysia	0.05167	0.15025	0.00225
Myanmar	0.00524	0.06489	0.00125
Philippines	0.16141	0.64131	0.01594
Thailand	0.00616	0.01403	0.00050
Viet Nam	0.01759	0.06820	0.00364

NO_2 = nitrogen dioxides, PM = particulate matter, SO_2 = sulphur dioxide.

Source: Author.

Table 3.17: Expected Number of Deaths Due to Outdoor Air Pollution, Case (ii)

Country	Cases of Mortality		
	SO_2	NO_2	PM10
Cambodia	0.01188	0.05633	0.00380
Indonesia	0.07865	0.18652	0.00419
Lao PDR	0.00511	0.00952	0.00029
Malaysia	0.03520	0.08347	0.00141
Myanmar	0.00782	0.03708	0.00078
Philippines	0.09963	0.33753	0.00854
Thailand	0.00426	0.00807	0.00028
Viet Nam	0.01198	0.03694	0.00192

NO_2 = nitrogen dioxides, PM = particulate matter, SO_2 = sulphur dioxide.

Source: Author.

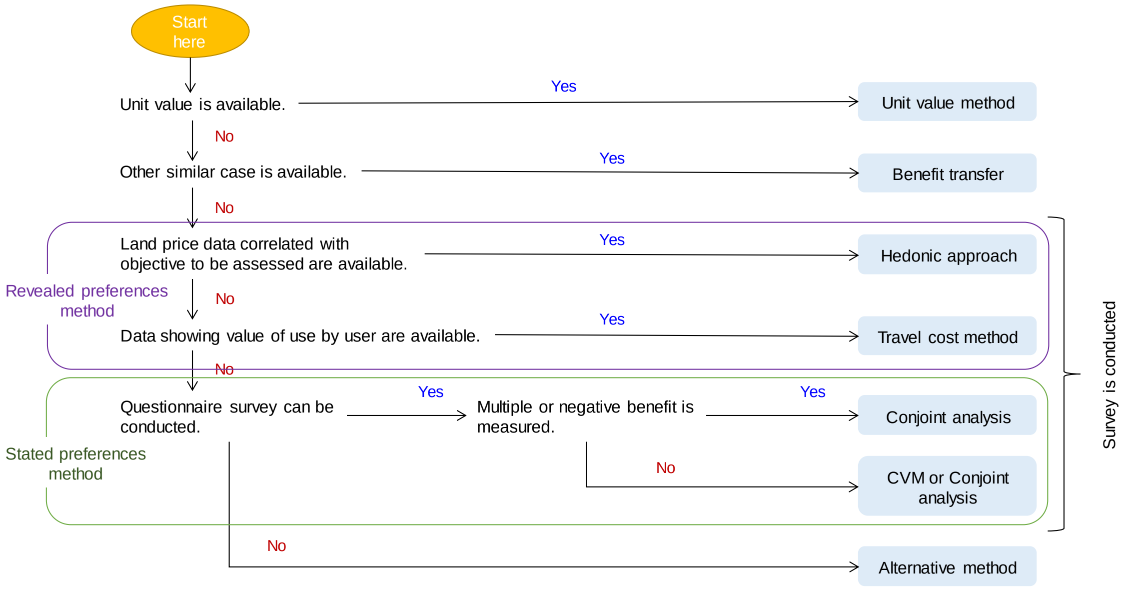
2.4. Cost of Mortality and Morbidity

Environmental economics analyses environmental issues and assesses the impact of environmental disruption from an economics point of view, i.e. it prices the environment that is not traded in the market. Multiple methods have been developed to assess the environment's monetary value. The following listed external economic evaluation methods have different features. When conducting an economic evaluation, it is necessary to comprehensively consider types of available data, characteristics of items to be evaluated, costs required for the survey, and so on (Ministry of Land, Infrastructure, Transport and Tourism, 2004).

WTP is the core of the method to evaluate the environmental benefits and costs in monetary terms. WTP means the upper limit of an amount of money that a person is willing to pay to avoid certain damage (Itsubo and Inaba, 2018), or an amount of money that a person is willing to pay to perform a certain business (in the case where things may get worse if such a business is not performed) (Ministry of Land, Infrastructure, Transport and Tourism, 2004).

To understand WTP with regard to the value that is not traded through monetary transactions (i.e. for the purpose of this study, the value of the environment), researchers commonly interview people influenced by the environment either adversely or positively, through a questionnaire survey, amongst other methods. However, no questionnaire survey or the like has ever been conducted in the countries surveyed in this study, and we do not have the human resources, funding, and time to undertake such a survey. Therefore, we calculate WTP in the surveyed countries using benefit transfer – 'a method to apply a basic original unit taken from other cases of economic assessment to a business to be evaluated' (Ministry of Land, Infrastructure, Transport and Tourism, 2004: 12). This method allows the conduct of a simplified economic assessment but is difficult to apply if conditions are not approximate between cases.

Figure 3.11: An Example of Setting Flow of Evaluation Methods



CVM = contingent valuation method.

Source: Ministry of Land, Infrastructure, Transport and Tourism (2004).

Economic evaluations of air pollution in ASEAN countries include Thanh and Lefevre (2000) and Quah and Boon (2003), which used the benefit transfer method:

> Benefit transfer suggests the possibility that some results of valuation study in other countries can be adopted for the valuation in country under consideration, given proper adjustments. In practice, almost all health impacts valuation studies inherently bear an element of benefit transfer. This is because contingent valuation studies to determine WTP values and epidemiological studies to obtain E–R functions are usually carried out separately, with different population groups, but their results are used jointly in health impact valuation studies (i.e. transfer of value of WTP from one population group to another). This element of transfer can easily be accepted when the population sample of the contingent valuation study and that of the epidemiological study are considered to be close to identical (e.g. within one country). Problems arise when the population at risk and the sample population for whom WTP is known do not have similar characteristics and their preferences are not identical. This is the case when transferring values of WTP between two different countries, such

> as the United States and Thailand. However, various approximations can be made for such a transfer (Thanh and Lefevre, 2000: 146–7).
>
> The Benefit Transfer Approach (BTA) involves the use of the estimates of environmental loss of a project to estimate the economic value of environmental impact of a similar project on the assumption that the latter project will have similar impact (Pearce, Whittington, Georgiou & James, 1994) … Similarly, for the transfer of unit economic values of the mortality and morbidity, it is also assumed that the stated preferences of people in the developed countries are similar to that of the people in Singapore. The assumption is not really farfetched since Singapore is now recognized by the World Bank and IMF as more or less a developed country… On the other hand, transfer of values may also neglect factors that would cause people to value health differently. For example, the concept of what constitutes full health may vary with culture, not only with income. In general, there are numerous environmental factors specific to location and culture; and these factors limit the reliability of the BTA in assessing environmental problems. In spite of these limitations, the cost advantages, in terms of time and resources, of benefits transfer will continue to encourage its use (Quah and Boon, 2003: 79).

Because this study examines environmental impacts that appear in the form of air pollution caused by coal-fired power generation, WTP can be interpreted as an amount of money that people are willing to pay to avoid mortality and morbidity risks posed by air pollution derived from coal-fired power generation. The value obtained by dividing the amount of WTP by mortality (or morbidity) is VSL. The value of mortality (or morbidity) is small. After the 1980s in Western countries, mainly the United States and the United Kingdom, a method using VSL has become mainstream for cost–benefit analysis to determine the pros and cons of political measures.

VSL can be defined as follows:

$$VSL = \frac{WTP_{\Delta R}}{\Delta R} \tag{11}$$

Where,

VSL: Value of statistical life

$WTP_{\Delta R}$: WTP for reduced amount of risk (ΔR)

ΔR: Reduced amount of risk

The purpose of VSL is not to calculate the price of human life; it is an expedient method based on WTP to reduce mortality or morbidity and estimate the benefit gained from saving one person. VSL varies depending on organisations that make such calculations. In this study, we use the base VSL calculated by the OECD and obtain the VSLs of the surveyed countries through benefit transfer calculated by using the OECD equation.

OECD (2017) cites the following survey results of OECD (2012) as VSL that serves as a reference value:

> The survey finds an average WTP of US$30 for a reduction in the annual risk of dying from air pollution from 3 in 100 000 to 2 in 100 000. This means that each individual is willing to pay US$30 to have this 1 in 100 000 reduction in risk. In this example, for every 100 000 people, one death would be prevented with this risk reduction. Summing the individual WTP values of US$30 over 100 000 people gives the VSL value – US$3 million in this case. It is important to emphasise that the VSL is not the value of an identified person's life, but rather an aggregation of individual values for small changes in risk of death (OECD, 2012; 2017: 15).

OECD (2012) shows the multiyear research effort, including its meta-analysis of VSLs starting with 1,095 values from 92 published studies. In units of 2005 US dollars, the recommended range for OECD countries is US$$_{2015}$1.5 million–US$4.5 million, the recommended base value in 2005 is US$$_{2005}$3 million. Using this base value, it is possible to calculate country-specific VSL values for countries within and outside the OECD and for years beyond 2005 (OECD, 2017).

The result for any given country, C, for any given year, here 2013, is thus as follows:

$$\begin{aligned} VSL\ C_{2013} &= VSL\ OECD_{2005} \times (Y\ C_{2005}/Y\ OECD_{2005})^{\beta} \\ &\quad \times (1 + \%\Delta P + \%\Delta Y)^{\beta} \end{aligned} \tag{12}$$

Where,

$VSL\ OECD$: OECD's base value for the OECD group of countries as a whole, US$3 million (2005 US$)

$Y\ C$: Gross domestic product (GDP) per capita at the purchasing power parity (PPP)

$Y\ OECD$: The average GDP per capita of OECD countries at PPP

β: Income elasticity of VSL. It measures the percentage increase in VSL for a percentage increase in income.

$\%\Delta P$: The percentage increase in consumer price from 2005 to 2013 This is measured by the consumer price index (CPI).

$\%\Delta Y$: The percentage change in real GDP per capita growth from 2005 to 2013. This is derived from real GDP per capita annual growth.

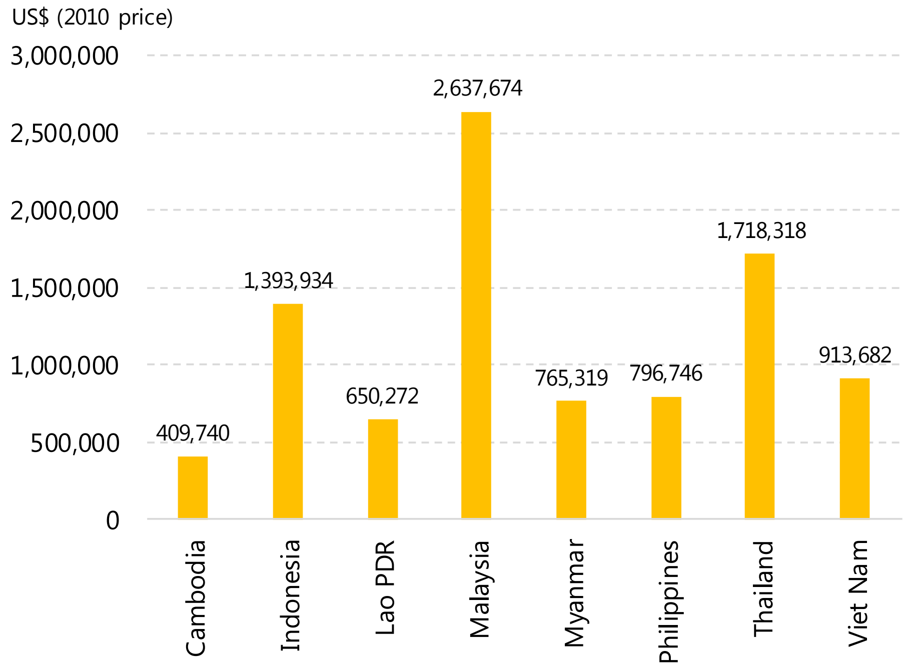
OECD (2017) refers to the use of 1 as an income elasticity of non-OECD countries. Therefore, in this study, 1 is assigned to β of equation (12). OECD (2017: 17) states:

> [T]he assumption of an income-elasticity with a value of < 1 means this: as incomes rise, the willingness-to-pay for a marginal reduction in the risk of death from a given risk also rises but not quite in proportion to the rise in incomes. And this assumption is empirically well grounded in the case of the advanced economies – as is the estimate of 0.8. Here, a step-change in life circumstances away from deep poverty alters the 'willingness-to-pay' more sharply than does a gradual but modest rise in incomes in the already high-income countries. There is therefore a case for adopting the more common assumption in the development literature of an income elasticity of 1 for the non-OECD countries under study.

Estimated values of the eight ASEAN countries were calculated based on equation (12). Data for GDP per capita at PPP, CPI, and GDP per capita growth are based on *World Development*

Indicators (World Bank, 2019). VSLs of ASEAN countries are estimated using equation (12), based on the VSL of the OECD standard ($3 million as of 2005).[6] Corrections of prices are made using the GDP deflators of IEEJ (2019). Estimated VSLs of the surveyed countries in this study are as follows:

Figure 3.12: Estimated Values of Statistical Life of Eight ASEAN Countries



Lao PDR = Lao People's Democratic Republic.

Source: Author.

The cost of mortality due to coal-fired power generation–derived air pollution in each country can be obtained by multiplying the estimated VSL of the country, which is obtained through equation (12), by the calculated number of mortal cases (Table 3.18, Table 3.19). Examinations are made for (i) a case where the most stringent standard amongst the emission standards of developed countries for air pollutants is adopted for SOx, NOx, and PM; and (ii) a case where half the values of the existing air emission standard of the surveyed country for air pollutants are adopted. The costs of mortality are as follows:

---

[6] There are variations in VSLs. For example, the US Environmental Protection Agency recommends that the central estimate of US$7.4 million (in 2006) be used in all benefits analyses that seek to quantify mortality risk reduction benefits regardless of age, income, or other population characteristics of the affected population until revised guidance becomes available (US EPA, 2019). The estimated VSL in Japanese researches (Matsuoka et al., 2002) shows $3.14 million~US$4.32 million (2002) as the estimated VSL for mortality risk due to air pollution, and used the contingent valuation method (Chen, Ohno, Morisugi, and Sao, 2010).

Table 3.18: Costs of Mortality for Eight ASEAN Countries

Country	Case (i), US$ (2010)	Case (ii), US$ (2010)
Cambodia	54,038	29,507
Indonesia	676,236	375,478
Lao PDR	17,410	9,701
Malaysia	538,558	316,736
Myanmar	54,631	34,962
Philippines	652,262	355,113
Thailand	35,554	21,678
Viet Nam	81,710	46,451

Lao PDR = Lao People's Democratic Republic.

Source: Author.

The cost of morbidity is then examined. A standard and commonly agreed method by which to measure the cost of morbidity is not yet available. Therefore, in this study, we set the cost of morbidity at 10% of the cost of mortality, obtained by multiplying the estimated VSL of the surveyed country by the number of mortal cases based on the conclusion of OECD (2015: viii): 'Recent practice and available evidence provide a rationale for using an additional 10% of the overall cost of mortality as a best estimate for the additional cost of morbidity'. The costs of morbidity of the surveyed countries are as follows:

Table 3.19: Costs of Morbidity for Eight ASEAN Countries

Country	Case (i), US$ (2010)	Case (ii), US$ (2010)
Cambodia	5,404	2,951
Indonesia	67,624	37,548
Lao PDR	1,741	970
Malaysia	53,856	31,674
Myanmar	5,463	3,496
Philippines	65,226	35,511
Thailand	3,555	2,168
Viet Nam	8,171	4,645

Lao PDR = Lao People's Democratic Republic.

Source: Author.

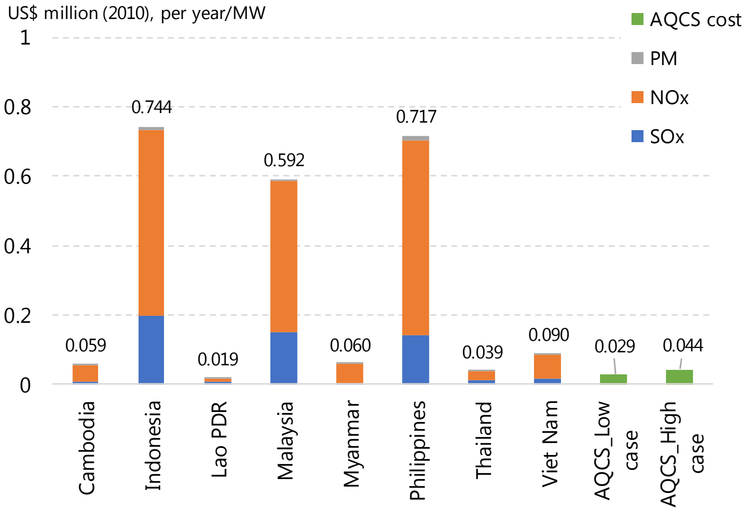
OECD (2016), a report about the cost of morbidity (and not adopted in this study), recommends a common core set of pollutant–health (morbidity) combinations to be applied in China and India, but highlights the difficulties of doing so. The following are five pollutant–health pairs for consideration in the report (OECD, 2016: 39–40):

- Respiratory hospital admissions and cardiovascular hospital admissions in relation to PM and to ozone. Whilst strongly based on evidence, experience from HIAs [health impact assessments] in Europe and the US is that these, when quantified and monetised, make little difference to the bottom line of aggregated monetised benefits.
- Restricted activity days and associated work-loss days in relation to PM and/or ozone. These are widely used in HIAs internationally and, when applied, suggest a noticeable effect on aggregate monetised benefits – small relative to mortality but one of the higher morbidity effects. However, they rest on a narrow evidence base – a series of studies in California in the 1980s. The health outcomes are strongly socio-culturally determined and there may be difficulty in obtaining credible background rates. These various difficulties point to major uncertainties about transferability.
- Chronic bronchitis in adults in relation to PM only. This has been a long-standing pollutant–health combination quantified in HIAs in the US, Europe, and elsewhere. There are studies, in the US and Europe, from which concentration–response functions can be derived and, when applied to HIAs, give monetised results, which typically are amongst the most influential of morbidity impacts. In Europe and the US, however, a recent expert review has questioned the overall evidence base relating air pollution to prevalence and incidence of chronic bronchitis in adults, concluding that the case for causality is not as strongly established as had previously been thought. Consequently, in Europe this pathway is not included amongst those that can be quantified with greater confidence, and it is not part of the primary analysis in the most recent regulatory impact assessments of the US EPA.
- Acute bronchitis in children 6–12 or 6–18 years old, defined as 'bronchitis in the past 12 months' (Hoek et al., 2012), is based on responses to symptoms questionnaires.
- Acute lower respiratory illnesses in children aged <5 years relate to children only, and may be expected not to have a major influence on final monetised results, compared with the monetised impacts on mortality.

2.5. Results

Based on all assumptions and calculations, we compared the health benefit in monetary terms thanks to less air pollution caused by coal-fired power generation under strengthened air emission standards and the cost of AQCS installation. The results follow.

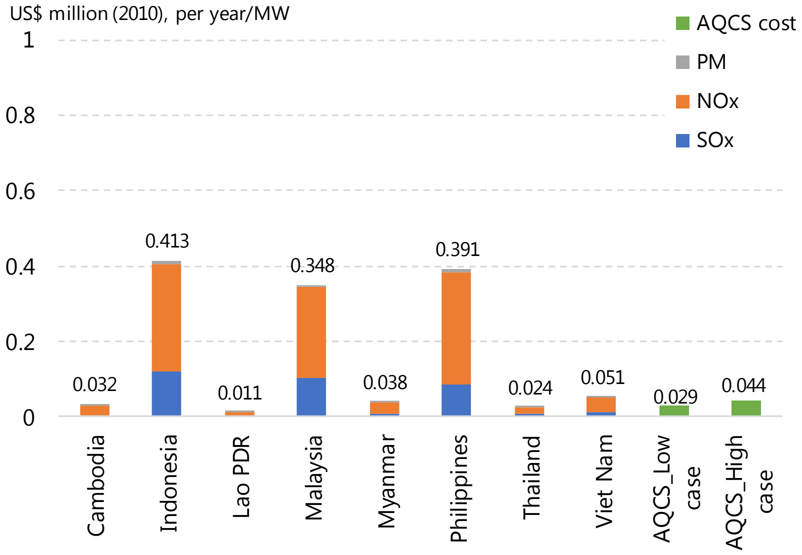
Figure 3.13: Results for Case (i)



AQCS = air quality control system, Lao PDR = Lao People's Democratic Republic, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxides.

Source: Author.

Figure 3.14: Results for Case (ii)



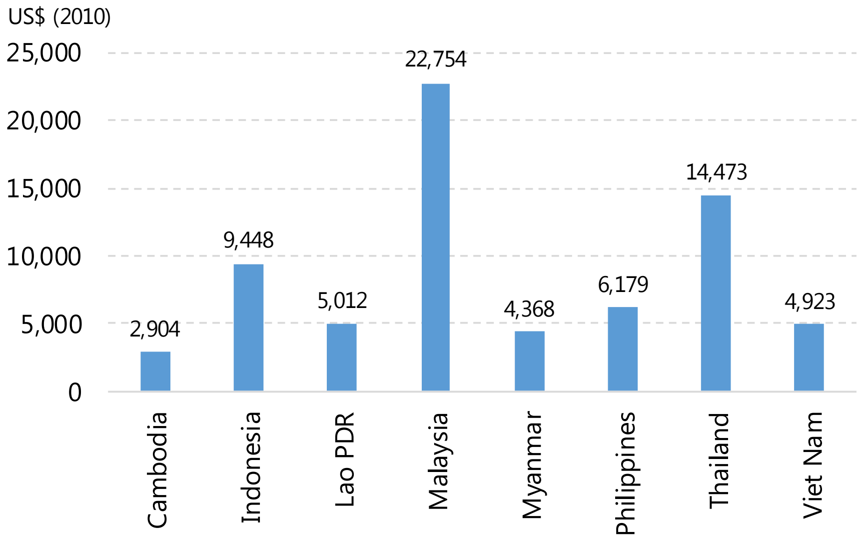
AQCS = air quality control system, Lao PDR = Lao People's Democratic Republic, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxides.

Source: Author.

Amongst the reference values of emission standards for air pollutants in ASEAN, those for NOx are set at a notably easier level than those in developed countries (Table 2.). This fact explains the reason for a significant difference in the level of health impacts between NOx and SOx/PM, and this study's results confirm it. Lax standards for NOx result in inadequate installation of denitrification facilities in the surveyed countries (Table 2.1).

The following two points can be considered as reasons for the substantial difference in the health benefits amongst countries. First, as indicated in equation (12), the estimated VSL of each country is calculated based on GDP per capita at PPP and real GDP per capita growth. However, the surveyed countries have substantial differences in GDP per capita (Figure 3.14), which have a substantial impact on the calculated values of health benefits. To obtain the expected number of deaths due to outdoor air pollution (Table 3.16 and Table 3.17), we use the population in the zone covered by the red circle (Figure 3.3 through Figure 3.10). The figures show that conditions in locations of the modelled power plants are different amongst countries: they are deep in the mountains or relatively close to a populated area. As a result, differences are created in the population amongst the 20 km radius zones, and such differences affect the calculation results of the expected number of deaths, i.e. the health benefit.

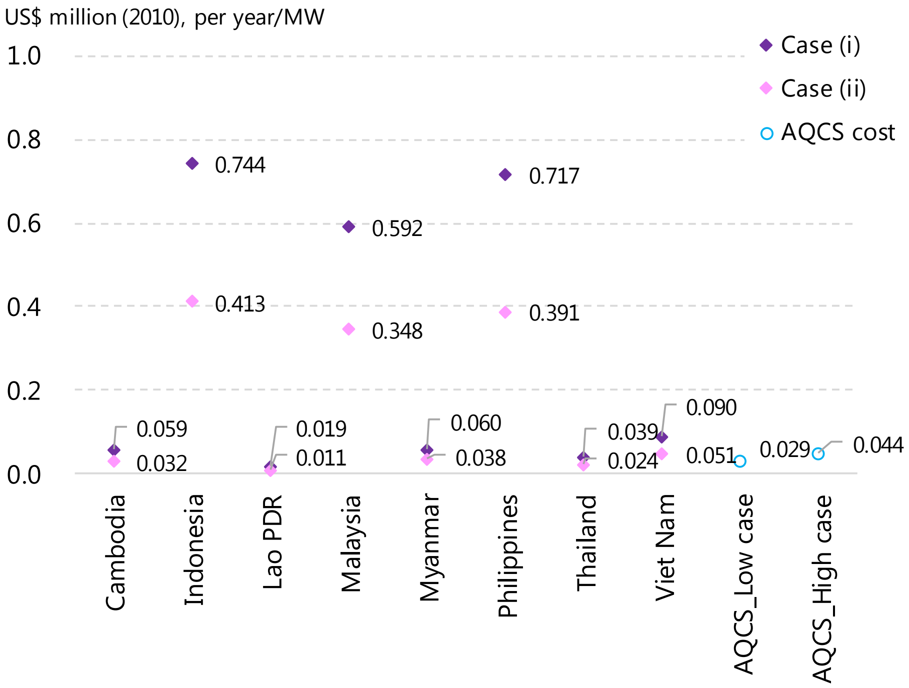
Figure 3.15: GDP per Capita for Eight ASEAN Countries in 2013



Lao PDR = Lao People's Democratic Republic.

Source: World Bank (2019).

Figure 3.16: Results for Cases (i) and (ii)



AQCS = air quality control system, Lao PDR = Lao People's Democratic Republic.

Source: Author.

The calculation results of case (i) and case (ii) can be summarised as follows:

Case (i)

- In the surveyed countries, except Lao PDR and Thailand, the benefit from tightening air pollutant emission standards exceeds the cost thereof. In Thailand, the benefit and the cost are at almost equivalent levels, whilst the cost exceeds the benefit only in the high case of AQCS installation cost.
- The FY 2017 study (ERIA, 2018) shows that the impact of the installation cost of AQCS on electricity prices is less than 10% in Cambodia, Indonesia, Malaysia, Philippines, Thailand, and Viet Nam. In the six countries, except Thailand, the benefit from strengthening emission standards exceeds the cost thereof. It is safe to say that tightening regulations is adequately beneficial.

Case (ii)

- The benefit from tightening air pollutant emission standards exceeds the cost thereof in Indonesia, Malaysia, the Philippines, and Viet Nam. The reference values in case (ii) are substantially laxer than those in case (i) (Table 3.4 and Table 3.5). If reducing air pollutant emissions by strengthening standards is limited to the level of case (ii), the benefit is small. However, it is still adequately beneficial to tighten emission standards in Indonesia, Malaysia, the Philippines, and Viet Nam.

- In Cambodia, Lao PDR, Myanmar, and Thailand, the benefit either exceeds or falls below the cost, depending on AQCS installation cost: it is not worth investing in AQCS installation if standards are lax. If AQCS is installed, emission standards should be tightened to a level equivalent to regulatory standards of developed countries. Many ASEAN economies are expected to continue growing. Therefore, even in Cambodia and Lao PDR, where the cost exceeds the benefit in case (ii), the benefit may increase with future economic growth. The installation cost of AQCS may be sufficiently paid off by its health benefit.

3. Life-cycle Impact Assessment Method Based on Endpoint (LIME) 3: Method and Result

3.1. Overview of the Method

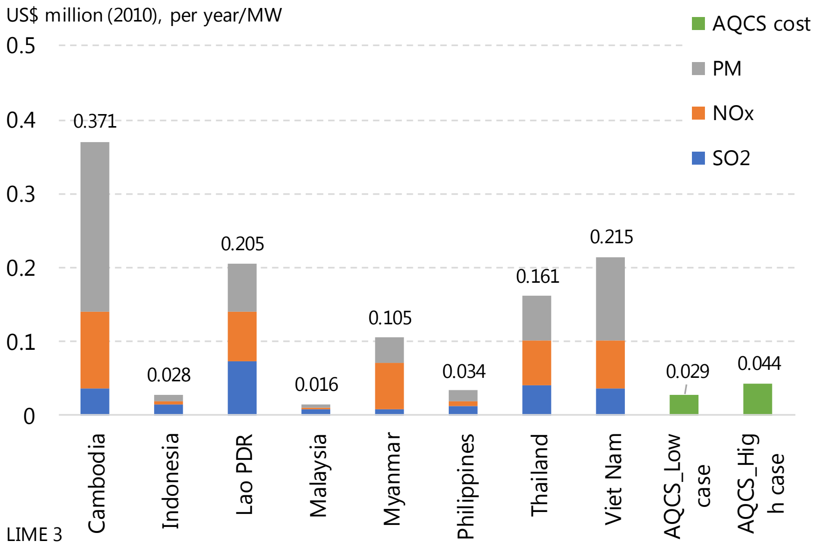
LIME 3 is the latest method modelling for a global scale, developed by Japanese experts and published in September 2018. LIME is a type of life-cycle impact assessment and complies with ISO14044 (2006). It has been used for environmental evaluation of companies' products or the companies themselves, environmental performance, and cost–benefit analysis, amongst others. LIME 1 and LIME 2 reflected domestic environmental conditions and ideas in Japan. LIME 3 provides damage factors and weighting factors in 193 countries for 11 global environmental issues in four areas of protection (human health, social assets, biodiversity, primary production). Damage factors are used to calculate damage in each area of protection. Fate analysis, impact analysis, and damage analysis were conducted before calculation of damage factors in LIME 3. Weighting factors are used to calculate economic value and are based on a conjoint analysis to give a weighting between the four areas of protection. A conjoint analysis is suitable for measuring the value of each of the multiple attributes of the environment and is based on a questionnaire administered in all G20 countries.

Whilst the WHO methodology is suitable for estimating the level of local health impact due to air pollution, the calculation using LIME 3 provides the health impact of avoiding air pollution at the world level or the macroscopic impact. To supplement the calculation using the WHO method, we show the results of the LIME 3 method (Appendix 1).

3.2. Results

The results of the calculation using LIME 3 are in Figure 3.17.

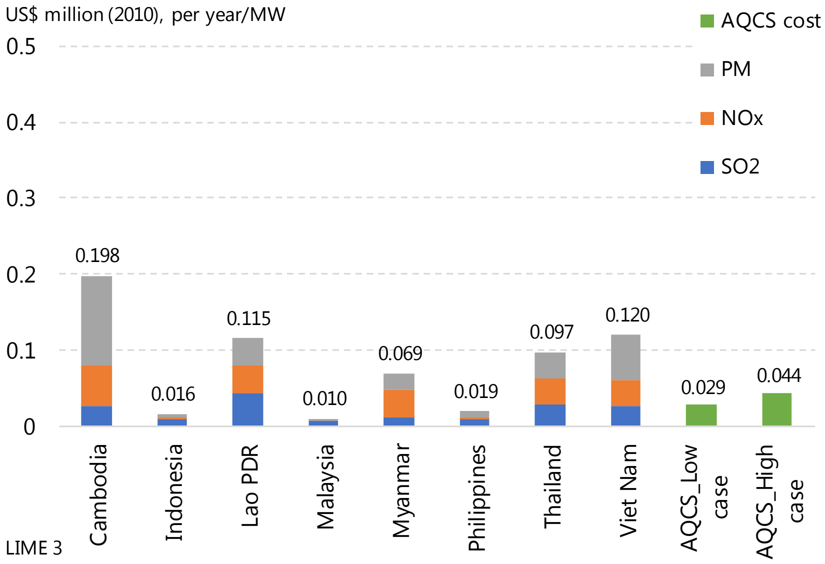
Figure 3.17: Results of LIME 3 for Case (i)



AQCS = air quality control system, Lao PDR = Lao People's Democratic Republic, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxides.

Note: Case (i) = most strengthened emission standard. Case (ii) = half of existing emission standard. Source: Author.

Figure 3.18: Results of LIME 3 for Case (ii)



AQCS = air quality control system, Lao PDR = Lao People's Democratic Republic, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxides.

Note: Case (i) = most strengthened emission standard. Case (ii) = half of existing emission standard.

Source: Author.

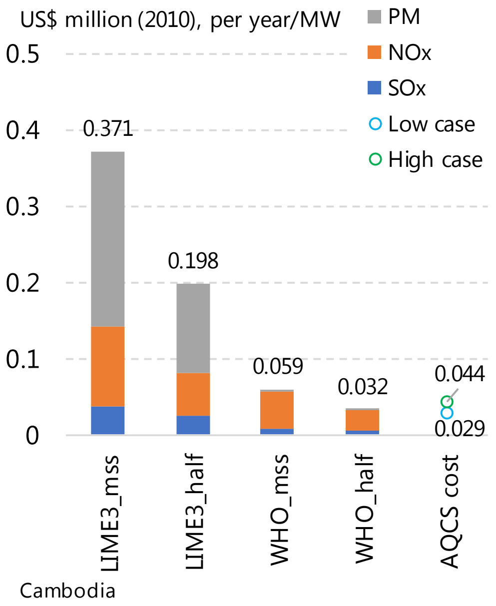
Although it varies depending on AQCS installation cost, the benefit from tightening emission standards may sometimes fall below the cost thereof in Indonesia, Malaysia, and the Philippines, which all have damage factors that are smaller than those of the other countries. The reason is that cross-border transfer and absorption into seawater of air pollutants are considered, because the concentration forecast of air pollutants is calculated in LIME 3 by using a model that can simulate the atmospheric chemistry process and aerosol process in the troposphere and stratosphere. The damage factor, therefore, is smaller in countries with many islands. Thus, the calculation result is smaller.

Whilst Cambodia, Lao PDR, Myanmar, Thailand, and Viet Nam have different levels of air pollutant emissions, strengthening emission standards has an adequate benefit in case (i) and case (ii).

4. Results of Methodologies

Results based on the WHO and LIME 3 methodologies are shown by country in the following figures. Estimation results vary substantially depending on the methodologies used, and are obtained based on various assumptions. Estimation results also vary depending on changes in the calculation method for a concentration forecast of air pollutants adopted as an assumption, factors or coefficients for conversion of health impact into monetary units, and reference VSLs, amongst others.

Figure 3.19: Results for Cambodia

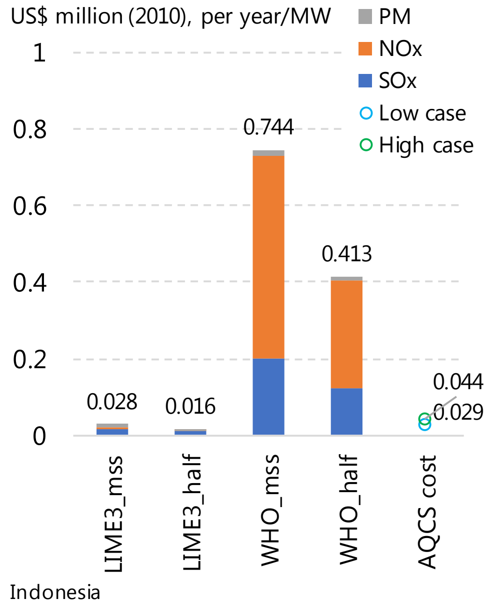


(US$ million, 2010)	SOx	NOx	PM
LIME 3_most strengthen standard	0.03724	0.10346	0.23008
LIME 3_half of ext. standard	0.02537	0.05445	0.11799
WHO_most strengthen standard	0.00786	0.04824	0.00334
WHO_half of ext. standard	0.00535	0.02539	0.00171
AQCS installation cost	0.02860	～	0.04385

AQCS = air quality control system, LIME = Life-cycle Impact Assessment Method Based on Endpoint, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide, WHO = World Health Organization.

Source: Author.

Figure 3.20: Results for Indonesia

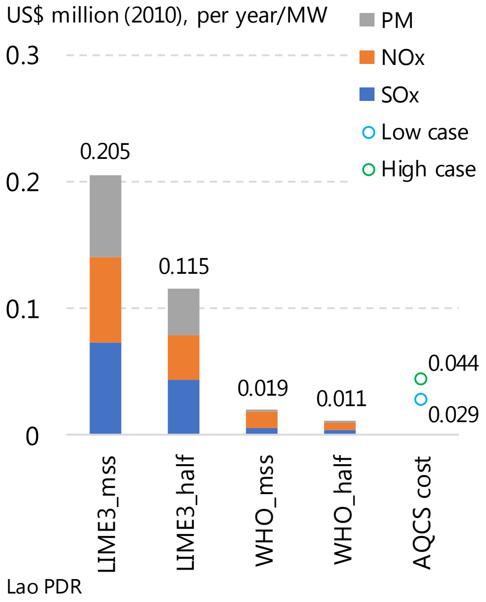


(US$ million, 2010)	SOx	NOx	PM
LIME 3_most strengthen standard	0.01475	0.00469	0.00874
LIME 3_half of ext. standard	0.00897	0.00251	0.00486
WHO_most strengthen standard	0.19843	0.53386	0.01158
WHO_half of ext. standard	0.12060	0.28599	0.00643
AQCS installation cost	0.02860	～	0.04385

AQCS = air quality control system, LIME = Life-cycle Impact Assessment Method Based on Endpoint, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide, WHO = World Health Organization.

Source: Author.

Figure 3.21: Results for Lao People’s Democratic Republic

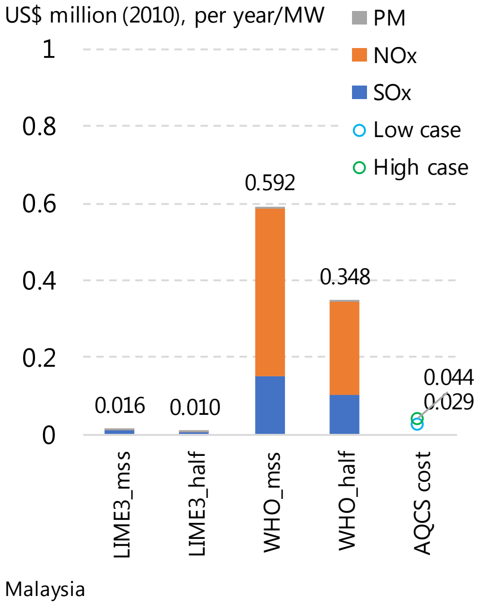


(US$ million, 2010)	SOx	NOx	PM
LIME 3_most strengthen standard	0.07307	0.06752	0.06489
LIME 3_half of ext. standard	0.04328	0.03648	0.03540
WHO_most strengthen standard	0.00617	0.01260	0.00038
WHO_half of ext. standard	0.00366	0.00681	0.00021
AQCS installation cost	0.02860	～	0.04385

AQCS = air quality control system, LIME = Life-cycle Impact Assessment Method Based on Endpoint, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide, WHO = World Health Organization.

Source: Author.

Figure 3.22: Results for Malaysia

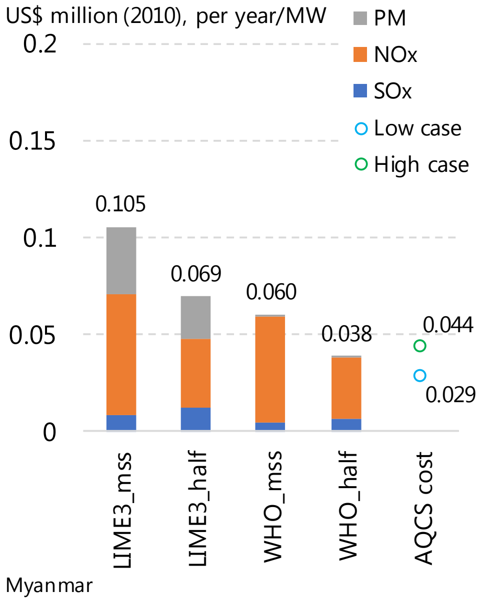


(US$ million, 2010)	SOx	NOx	PM
LIME 3_most strengthen standard	0.00878	0.00301	0.00389
LIME 3_half of ext. standard	0.00598	0.00167	0.00243
WHO_most strengthen standard	0.14993	0.43595	0.00654
WHO_half of ext. standard	0.10213	0.24219	0.00409
AQCS installation cost	0.02860	～	0.04385

AQCS = air quality control system, LIME = Life-cycle Impact Assessment Method Based on Endpoint, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide, WHO = World Health Organization.

Source: Author.

Figure 3.23: Results for Myanmar

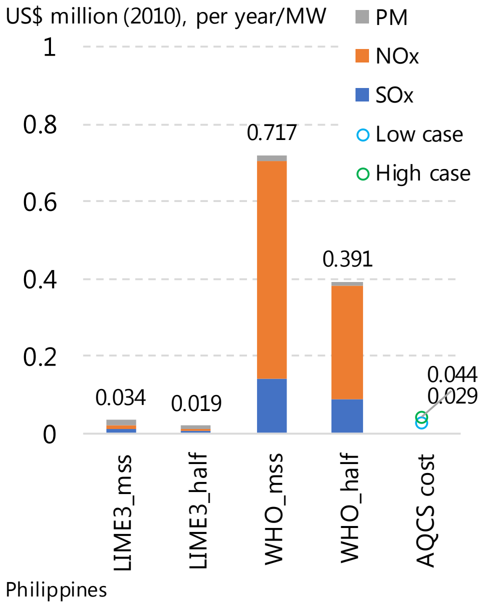


(US$ million, 2010)	SOx	NOx	PM
LIME 3_most strengthen standard	0.00803	0.06307	0.03412
LIME 3_half of ext. standard	0.01199	0.03604	0.02133
WHO_most strengthen standard	0.00441	0.05463	0.00105
WHO_half of ext. standard	0.00658	0.03122	0.00066
AQCS installation cost	0.02860	～	0.04385

AQCS = air quality control system, LIME = Life-cycle Impact Assessment Method Based on Endpoint, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide, WHO = World Health Organization.

Source: Author.

Figure 3.24: Results for the Philippines

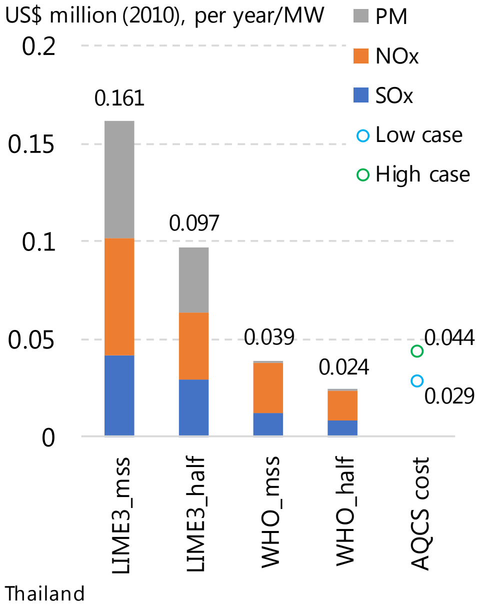


(US$ million, 2010)	SOx	NOx	PM
LIME 3_most strengthen standard	0.01356	0.00636	0.01360
LIME 3_half of ext. standard	0.00837	0.00335	0.00729
WHO_most strengthen standard	0.14146	0.56206	0.01397
WHO_half of ext. standard	0.08732	0.29582	0.00748
AQCS installation cost	0.02860	～	0.04385

AQCS = air quality control system, LIME = Life-cycle Impact Assessment Method Based on Endpoint, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide, WHO = World Health Organization.

Source: Author.

Figure 3.25: Results for Thailand

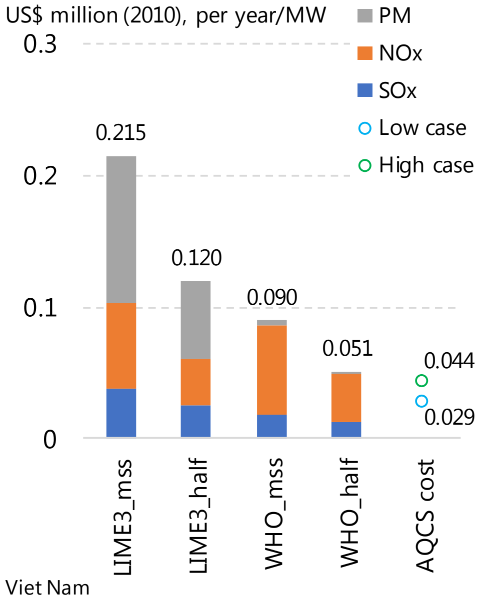


(US$ million, 2010)	SOx	NOx	PM
LIME 3_most strengthen standard	0.04161	0.06001	0.05971
LIME 3_half of ext. standard	0.02878	0.03451	0.03412
WHO_most strengthen standard	0.01165	0.02652	0.00094
WHO_half of ext. standard	0.00806	0.01525	0.00054
AQCS installation cost	0.02860	～	0.04385

AQCS = air quality control system, LIME = Life-cycle Impact Assessment Method Based on Endpoint, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide, WHO = World Health Organization.

Source: Author.

Figure 3.26: Results of Viet Nam



(US$ million, 2010)	SOx	NOx	PM
LIME 3_most strengthen standard	0.03724	0.06534	0.11209
LIME 3_half of ext. standard	0.02537	0.03539	0.05899
WHO_most strengthen standard	0.01768	0.06854	0.00366
WHO_half of ext. standard	0.01204	0.03713	0.00193
AQCS installation cost	0.02860	～	0.04385

AQCS = air quality control system, LIME = Life-cycle Impact Assessment Method Based on Endpoint, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide, WHO = World Health Organization.

Source: Author.

Chapter 4

Policy Implications

1. Economic Rationality of Tightening Air Pollutant Emission Standards of Coal-fired Power Plants

It is difficult to convert an environmental value into monetary terms. Environmental countermeasures for coal-fired power plants are sometimes considered a cost that does not generate any benefit and that plant operators may hesitate to implement. This study estimates the monetary value of good air quality, of which the benefits have rarely been quantified until now. We found that, in the countries surveyed, the potential benefit from tightening air pollutant emission standards often exceeds the cost of installing AQCS. Campaigns against new coal-fired power plants are escalating because of air pollution. In many ASEAN countries, tightening emission standards for coal-fired power plants and installing AQCS to conform to the standards are economically rational.

Installing AQCS, however, requires careful consideration of each country's circumstances. All coal-fired power plants to be constructed from now on must be equipped with appropriate facilities, but whether or not existing power plants should be so equipped must be studied. ASEAN countries utilise coal-fired power plants in different ways and the status of AQCS installation is different across countries. Each country may have its own plan for installing AQCS.

Coal-fired power generation is forecast to increase in ASEAN until 2040, and in BAU the ratio of coal-fired power generation to total generated electricity will increase to 57.2% in 2040 (38.0% in 2015). Coal-fired power generation continues to be a major energy source in each country.

ASEAN countries install AQCS in coal-fired power plants that started operation in or after 1990. The installed capacity of coal-fired power plants that started operation in or before 1989 is approximately 4.2 GW, and in or after 1990 approximately 59.6 GW. Although a power plant with large installed capacity requires a large amount of investment, existing power plants that are expected to operate long into the future should be prioritised for AQCS installation. It is possible to consider prioritising the installation of NOx control facilities, as their adoption rate is lower than those of SOx and PM. Because isolating the pollutant source of SOx and PM is easier,[7] however, and many control facilities have already been installed in many countries, it may be reasonable to prioritise facilities for SOx and PM to complete the countermeasures for all power plants.

Types of coal used in coal-fired power plants are different depending on the country or power plant. Some types of coal have low sulphur content. For example, coal produced by Adaro is classified as significantly low sulphur in Indonesia. If a power plant uses low-sulphur coal, it may be better to prioritise either NOx or PM control over SOx. The type of coal used by a power plant should be considered when planning to install AQCS.

2. Financing Issues

Criticism of coal-fired power plants is rapidly escalating mainly in Western Europe because of global warming. Since 2013, the World Bank Group and development banks in Europe (European Bank for Reconstruction and Development [EBRD], European Investment Bank [EIB]), amongst others, have announced policies to restrict coal-related investments and loans.[8] The World Bank Group excludes new construction of coal-fired power plants from the list of eligible projects for investment and loans, except in rare cases. The group considers supporting existing facility-related projects only when they improve efficiency. EBRD has removed coal-fired power generation projects, except in rare cases, from its list of eligible projects for investment and loans, and EIB has started to apply a CO_2 emission standard of 550 g/kWh.

As international and foreign-government financing becomes more difficult, the climate for domestic financing has worsened because of the increasing uncertainty of the prospects of coal-fired power generation. Two factors stand out: (1) the decline of the load factor of coal-fired power plants due to increased use of renewable energy, and (2) the risk that the

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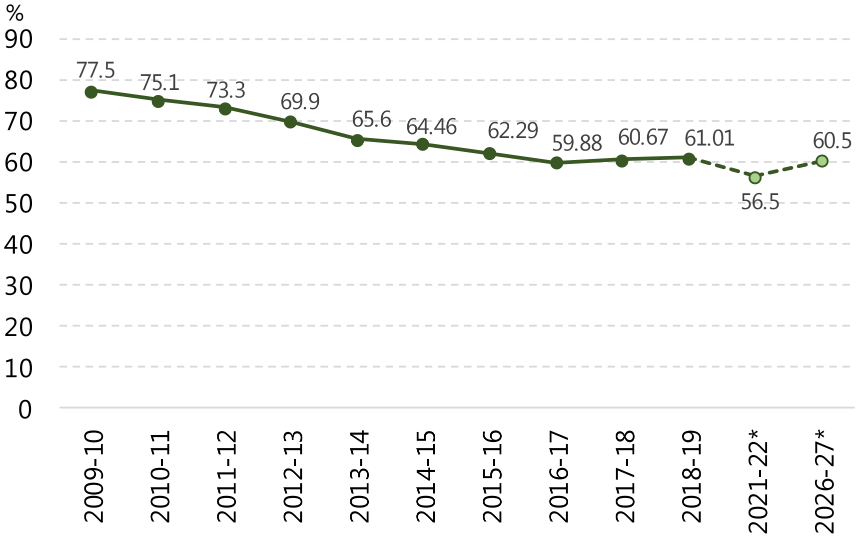
[7] Automobiles also emit NOx. Therefore, it is difficult to quantify the effect of countermeasures taken in power plants with reference to the total emission amount of NOx.

[8] Financial institutions operated mainly by non-OECD countries, including the Asian Infrastructure Investment Bank (AIIB), are not moving to restrict loans for and investments in coal-related projects. For example, the Asian Development Bank says that coal-fired power generation is necessary to fulfil energy demand and that it is prepared to support efficiency improvement (Super Critical, Ultra Super Critical, etc.). AIIB says it is prepared to consider loans for coal-related projects only when they are replacing facilities with low efficiency or are indispensable for reliability of an electric power network system.

share of coal-fired power generation will decrease in a low-carbon energy mix as a part of measures against global warming. The risk may not be too high because coal-fired power generation is expected to continue to be important in ASEAN. However, in BAU, the long-term forecast until 2040 suggests that the share of renewable energy in power generation will rapidly increase in some countries (e.g. Thailand). Thus, it is possible that political measures supporting a low-carbon energy mix may influence the prospects of coal-fired power generation.

Factor (1) is evident in India. During the COP 21 meeting, the government set a goal 'to achieve about 40 percent of installed capacity from non-fossil fuel-based energy resources by 2030 with the help of transfer of technology and low cost international finance' to reduce electric power sector–related greenhouse gas [GHG] emissions (Kumar, 2019). India has consistently worked to reduce GHG emissions, and the share of renewable energy in power generation (excluding hydropower), which was 0.5% in 2000, increased to 6.9% in 2016. The share of variable renewable energy such as solar and wind power generation increased from 0% in 2000 to 4% in 2016. Renewable energy power sources have generally low marginal costs and are often eligible for prioritised connection to power systems, causing a decline of the load factor of coal-fired power plants (Figure 4.1).

Figure 4.1: Coal Power Plant Load Factor, India



Source: Kumar (2019).

Coal-fired power plants are frequently required to operate in a standby capacity to absorb the output fluctuation of renewable energy–based power sources. A coal-fired power plant is suitable for operation at a constant output as a base load, whilst standby capacity needs the ability for frequent shutdowns or sharp ups and downs in output. The Central Electricity Authority forecasts that the installed capacity of power sources using renewable energy will reach 175 GW and is studying the performance of coal-fired power plants as a balancing power source.

Like India, ASEAN may experience a decline of load factor of coal-fired power plants, which may operate with ups and downs in output. If a coal-fired power plant needs to operate under such conditions, further efforts will be needed to improve the climate for financing for coal-fired power generation technology.

First, because overseas financing is no longer feasible, local financing should be procured. Local electric power companies' investment capacity and local financial institutions' strength are important. To create an environment where local government-affiliated and private financial institutions can adequately fund new coal-fired power plants and related technology such as AQCS, the government must declare that the plants and technology are important. By making every effort to reduce risks from possible policy changes, amongst others, the government may improve the investment climate.

Second, to enhance their investment capacity, local electric power companies must ensure that their management is sound. Subsidies must be eliminated. In November 2015, the leaders of the Asia-Pacific Economic Co-operation (APEC) economies reaffirmed their landmark 2009 commitment to 'rationalize and phase out over the medium term inefficient fossil fuel subsidies that encourage wasteful consumption whilst recognising the importance of providing those in need with essential energy services' (IEA, 2017: 8). Several APEC members have moved ahead with energy pricing reforms (IEA, 2017). Around 60% of total fossil fuel consumption subsidies in APEC economies are in the residential sector (for gas, electricity, and LPG) and reforms have been slow (IEA, 2017). Reforms are politically sensitive but can bring multiple benefits, including freeing up resources for government investment in infrastructure, for example. Recent reforms to reduce electricity subsidies in Indonesia, Malaysia, and Viet Nam should be continued, enhanced, and implemented in all ASEAN countries (IEA, 2017).

Last, some countries are liberalising or planning to liberalise their electricity markets. Fully liberalising not only the wholesale but also the retail electricity market will generally increase the uncertainty of electric power companies' profitability, making investment in large-scale infrastructure and facilities, including AQCS, difficult for the companies.

Investment in coal-fired power generation–related technology faces multiple political challenges such as liberalisation of the electricity market and environmental countermeasures to reduce air pollution and CO_2 emissions. In ASEAN countries where energy demand continues to increase along with their economic growth, however, coal-fired power generation will continue to be important because locally available resources can be utilised or fuel procurement costs are low. Such countries must study how to utilise coal-fired power generation in a sustainable manner, not only for their energy security but also for the health of their people. ASEAN policymakers will be required to tighten air emission standards for coal-fired power generation at the right time and on the right scale, and to promote installation of AQCS.

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Appendices

Appendix 1. Life-cycle Impact Assessment Method Based on Endpoint (LIME) 3: Methodology

I-1. LIME 3[9]

Life-cycle assessment (LCA) has developed rapidly through incorporation into international standards and government-led software development. In particular, the development of the Inventory Database, which is used to calculate the emission amount of substances such as CO_2 and NOx, has been promoted in countries such as China, the Republic of Korea, Thailand, and Malaysia, as well as Japan, European countries, and the United States (US). However, the current state of LCA research is not suitable for accurately assessing emerging countries because of the limited availability of an internationally acknowledged impact assessment method. Japan, Europe, and the US are proposing their own assessment methods, but these will not help until the issue of limited impact assessment is solved. LIME 3 was developed to fulfil demand for an impact assessment method that meets global standards and can reflect environmental conditions across the world, and to assess global-scale environmental issues under a single assessment system.

LIME 3 developed damage factor lists and an integration factor list. Impact can be assessed by multiplying these factor lists by inventory data calculated for each substance of concern. Features of the two lists disclosed by LIME 3 are listed in Table 1A.

Table 1A. Features of Damage and Integration Factor Lists Developed by LIME 3

	Damage Factor List	Integration Factor List
Underlying academic discipline	Knowledge on natural science, models are used	Analysis method of social science is used
Objective of assessment	Endpoint specific	Entire environment
Number of items of results	4 (human health, social wealth, biodiversity, primary production)	1 (chosen from either dimensionless index or economic index)

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[9] Unless otherwise noted, this section draws on Itsubo and Inaba (2018).

Principal use	Life-cycle assessment (LCA), company valuation, natural capital valuation	LCA, company valuation, environmental efficiency, full-cost assessment, cost–effect analysis, cost–benefit analysis, natural capital valuation
Advantage	Results can be obtained based on natural-science knowledge	No trade-off occurs, wide application range
Features of LIME 3	Global analysis can be conducted whilst considering local environmental conditions	Differences in environmental consciousness amongst countries are considered in assessment
Indication method of factor list	Classification into 193 countries, relation between the country generating environmental load and the country suffering therefrom	G20, developed countries, emerging countries, differences by country in environmental consciousness are presented

Source: Itsubo and Inaba (2018).

When an LCA of a coal-fired power plant is conducted, it usually covers the entire range of mining and transportation of coal, power generation, exhaust gas treatment, coal ash disposal, and landfilling. However, this study conducts only an impact assessment of air pollution at the power generation stage of a coal-fired power plant. Therefore, this study examines air pollution outside the influence areas. The assessment range of LIME 3 is in Table 1B.

Table 1B. Assessment Range of LIME 3

Influence Area	Endpoint[10]	Category Endpoint[11]
Climate change	Human health	Malnutrition, diarrhoea, cardiovascular illness, malaria, coast flood, inland flood
Air pollution	Human health	Chronic death, acute death, respiratory disorder
Photochemical oxidant	Human health	Chronic death, acute death, respiratory disorder
Water resource consumption	Human health	Water-bone infectious disease, malnutrition
Land utilisation	Biodiversity	Land area ecological system (vascular plants)
	Primary production[12]	Land area ecological system
Resource consumption (fossil fuel, mineral resource)	Social wealth[13]	Fairness to future generations
	Biodiversity	Land area ecological system (vascular plants)
	Primary production	Land area ecological system
Forest resource consumption	Biodiversity	Land area ecological system (vascular plants)
	Primary production	Land area ecological system
Waste	Social wealth	Fairness to future generations
	Biodiversity	Land area ecological system
	Primary production	Land area ecological system

Source: Itsubo and Inaba (2018).

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[10] A subject ultimately affected by an environmental impact.

[11] Type of damage that may be incurred on a specific endpoint (what suffers at the end of an environmental impact) during environmental load. There are multiple category endpoints for each influence area.

[12] Conversion of solar energy into organic substance by photosynthesis.

[13] Things that are regarded as valuable for human society and that continuously change human society from resource-related point of view.

I-2. Damage Factor[14]

In LIME 3, a model was developed to calculate the quantity of potential damage that the human and ecological systems will suffer when a unit quantity of environmental load is put on them. It is particularly applicable to things and events that cause severe damage on a global scale, such as (1) climate change, (2) air pollution, (3) photochemical oxidant, (4) water resource consumption, (5) land utilisation, (6) mineral resource consumption, (7) fossil fuel consumption, (8) forest resource consumption, and (9) waste.

The detailed calculation method for the damage factor of air pollution (particulate matter [PM] 2.5) for LIME 3 is described below.

PM 2.5 can be divided into primary and secondary particulates. In the case of primary particulates, an emitted substance directly causes a health impact. In the case of secondary particulates, a health impact is caused by an altered substance from an emitted substance. In LIME 3, the health damage factor is calculated for organic carbon (OC) and black carbon (BC) (forming one group – OCBC) as primary particulates, and for hydrosulphate and nitrate produced by emission of SO_2 and NOx as secondary particulates. Category endpoints taken into consideration in LIME 3 are listed in Table 1C.

Table 1C. Category Endpoints for Which Damage Function[15] Is Calculated

Objective to Be Protected	**Category Endpoint**		**Objective of Damage Function Calculation**	
Human health	Respiratory disorder	Chronic death	✓	Increase of chronic death (converted into DALY)
		Acute death	-	Already taken into consideration as a part of chronic death
		Lower respiratory tract symptom	✓	Increase of disorder affected individuals (converted into DALY)
		Chronic bronchitis	✓	
		Use of bronchodilator	✓	

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[14] Unless otherwise noted, the contents of this section are based on Itsubo and Inaba (2018).

[15] To make a quantitative correlation between inventory and category endpoint. Damage factors can be obtained by summation of damage functions for common endpoints.

		Days of restricted activity	✓	
		Respiratory system–related hospitalisation	✓	
		Stridor	-	No information on concentration–response of PM2.5 was obtained
		Chronic cough	-	
		Hospitalisation in emergency room	-	

DALY = disability adjusted life year, PM = particulate matter.

Source: Itsubo and Inaba (2018).

The calculation flow of damage factors follows:

1. Fate analysis. Estimate territory- and substance-specific increase in global concentration generated by 1 kg emission of PM 2.5
2. Impact analysis. Calculate an increase in global mortality and morbidity from the result of fate analysis.
3. Damage analysis. Calculate an increase in disability adjusted life year (DALY) from the result of impact analysis.

Damage factors are calculated for each of the 10 areas.[16] Health impacts on areas outside the emission area caused by cross-border transfer are also considered.

The damage factor considers the health impact due to death and disease. The death-derived health impact is calculated by multiplying an increase in mortality (R) by base mortality (M_c), population (P_i) and DALY (K_w) per death. The increase in mortality (R) is obtained by multiplying an increase in PM 2.5 concentration ($\Delta C_{s,r,i}$), which is created when the substance to be evaluated is increased by unit quantity, by concentration–reaction relation of chronic death. The disease-derived health impact is calculated by multiplying the increase in the number of disease cases (R_d) by population ($P_{d,i}$) and DALY ($K_{d,w}$) per disease. The increase in the number of disease cases (R_d) is obtained by multiplying the increase in PM 2.5

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[16] North America, South America, Europe, East Europe/Russia, Middle East/West Asia, Africa, India/South Asia, China/Southeast Asia, Oceania, and Japan.

concentration ($\Delta C_{s,r,i}$), which is created when the substance to be evaluated is increased by the unit quantity, by the concentration–reaction relation of the disease.

$$DF_{HH}(r,s) = D^{mortality}(r,s) + D^{morbidity}(r,s)$$
$$D^{mortality}(r,s) = \sum_i (\Delta C_{s,r,i} \times R \times M_c \times P_i \times K_w)$$
$$D^{morbidity}(r,s) = \sum_i \sum_d (\Delta C_{s,r,i} \times R_d \times P_{d,i} \times K_{d,w})$$

Where,

$DF(r,s)$: Damage factor (DALY/kg) of substance (s) emitted from area (r)

$D^{mortality}(r,s)$: Quantity of death-derived health impact (DALY/kg) due to substance (s) emitted from area (r)

$D^{morbidity}(r,s)$: Quantity of disorder-derived health impact (DALY/kg) due to substance (s) emitted from area (r)

$\Delta C_{s,r,i}$: An increase in yearly average PM 2.5 concentration ([μg/m^3]/kg) for each grid (i) caused by substance (s) emitted from area (r)

R: An increase in mortality due to an increase in PM 2.5 concentration (%/[μg/m^3])

M_c: Baseline mortality (case/cap) in the country (c) (case/cap)

P_i: Population (cap) of grid (i)

K_w: Lost life expectancy (set for each of 14 areas designated by the World Health Organization [WHO]) per death case (DALY/case)

R_d: An increase in occurrence rate of disease (d) ((case/cap) / (μg/m^3)) due to an increase in PM 2.5 concentration

$P_{d,i}$: Population subject to an impact of disease (d) in grid (i) (cap)

$K_{d,w}$: Lost life expectancy (set for each of 14 areas designated by the WHO) per case of disease (d) (DALY/case)

DALY was developed to quantitatively measure worldwide health damage, including in emerging countries. It is a health index developed by Murray et al. (1994, 1996) of Harvard University jointly with the WHO in the course of the study on the global burden of disease conducted on request of the World Bank. DALY is defined as follows and is used to calculate worldwide lost life expectancy:

DALY=YLL+YLD

$$=\int_{x=a}^{x=a+L} Cx\exp(-\beta x)\exp\{-r(x-a)\}dx + \int_{x=a}^{x=a+L_a} DCx\exp(-\beta x)\exp\{-r(x-a)\}dx$$

YLL means years of life lost due to premature mortality and YLD means corresponding years lived with a disability due to disorder, and DALY is obtained as a sum of the two. a is the age of death or onset of a specific disorder, L is the balance between expected life and age of death and $L_a{}'$ is a duration of disorder. C and β are constants – 0.1658 and 0.04, respectively. This definitional identity can be obtained by time integration of three items: (1) weighting of disorder, (2) weighting of age ($Cx\exp(-\beta x)$), and (3) time discount ($\exp\{-r(x-a)$). In LIME, (2) and (3) are not adopted; only (1) is adopted.

Fate analysis calculates an increase in PM 2.5 concentration in 10 areas when a unit quantity of air pollutant is emitted. The forecast of PM 2.5 concentration uses the MIROC-ESM-CHEM model (Watanabe et al., 2011), including the CHASER model and SPRINTARS model that can simulate the atmospheric chemistry process and aerosol process in the troposphere/stratosphere.[17]Horizontal resolution is approximately 2.8° X 2.8°, and the world is divided into 8,192 grids. Perpendicular direction is calculated with 32 layers of resolution, and concentration in the nearest layer to ground surface (approximately 500 m above the ground) has been adopted. For the purpose of the model, dust particles and sea-salt particles are considered PM 10 and hydrosulphate and particle sizes of hydrosulphate/nitrate produced from anthropogenic air pollutants and OCBC are both considered equivalent to PM 2.5. To estimate base concentration, data on the quantity of worldwide air pollutant emissions in 2000 (Lamarque et al., 2010) were used. To calculate the increase in PM 2.5 concentration, worldwide distribution of the base concentration of PM 2.5 as of 2000 was first calculated. Second, the emission quantity of substances to be evaluated was increased by 20% for all grids included in a particular area to estimate worldwide PM 2.5 concentration again. Last, the difference between the above two concentrates was divided by the total additional emission quantity of the area to calculate an increase per 1 kg in PM 2.5 concentration of the substance in the area.

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[17] CHASER is an atmospheric chemistry model in troposphere/stratosphere (chemical atmospheric general circulation model for study of atmospheric environment and radiative forcing). SPRINTARS means spectral radiation-transport model for aerosol species.

In impact analysis, the concentration response function (CRF) obtained in an epidemiological study is used to calculate the increase of health risk due to a PM 2.5 concentration increase. The CRF of mortality represents the change rate of PM 2.5 concentration and chronic mortality, which are examined mainly in a cohort study.[18] In LIME 3, the CRF of all factors in death estimated by Krewski et al. (2009) was adopted. Country-specific mortality based on all factors in death as of 2004 obtained from the WHO (2008) is adopted as base mortality. The CRF of epidemics represents an increase in incidence of disease relative to PM 2.5 concentration. In LIME 3, the CRF of diseases is recommended by *ExternE Report* (Bickel et al., 2005). CRF is considered to have area-based differences, including in medical care conditions. However, it is difficult to reflect such differences in evaluation, so the above-mentioned CRF is being applied worldwide.

In damage analysis, to calculate DALY from an increase in mortality and incidence in disease, population data and lost life expectancy per case of death or onset of disease (DALY/case) are required. Population data were compiled into 2.8° X 2.8° from data with a horizontal resolution of 2.5° X 2.5° provided in the Gridded Population of the World Version 3. As data on DALY/case, assuming that the relation in asthma in WHO (2008) between DALY and the number of incidences of the disease of each of the 14 areas can equally apply to other diseases, the proportion between lost life expectancy per one case of asthma (Hofstetter, 1998) (0.03 year) and area-specific lost life expectancy per case of asthma (WHO, 2008) (0.07 year in case of Africa D area) was multiplied by DALY/case of diseases other than asthma indicated by Hofstetter (1998). Because those assumptions are based on a big 'if', the accuracy thereof needs to be reviewed.

In LIME 3, the damage factors of SO_2, NOx, and OCBC are calculated for each of the 10 areas, and country-specific damage factors are calculated based on an assumption that the same value is applicable to all countries belonging to the same area. Damage factors of ASEAN countries are shown in Figure A1. Indonesia, Malaysia, and the Philippines, of which wide areas face oceans, have relatively low damage factor values because a large portion of air pollutants are transferred into the oceans.

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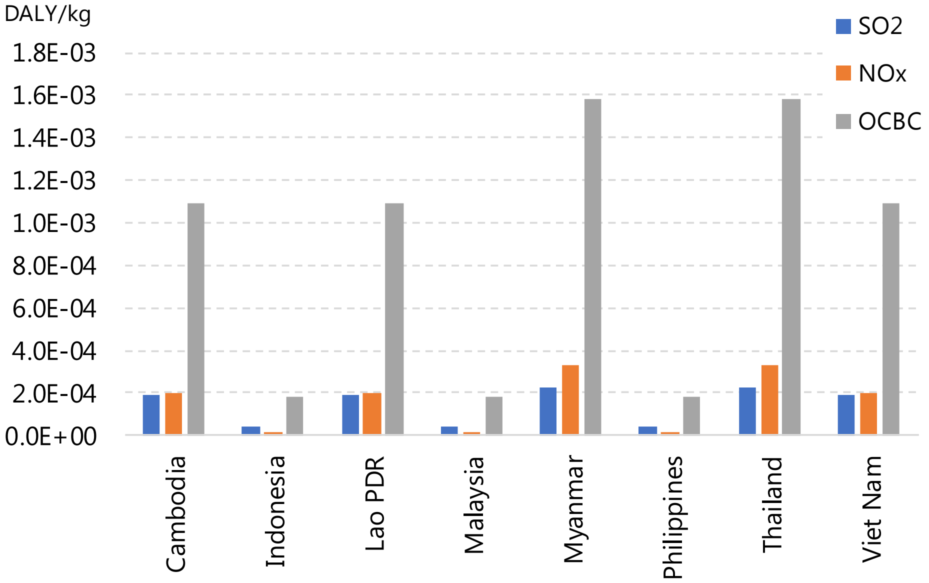
[18] An epidemiological study to trace a long-term process with regard to a specific cohort.

Figure 1A: Damage Factor of Air Pollution (PM 2.5) for Eight ASEAN Countries



NO_2 = nitrogen dioxide, OCBC = organic carbon and black carbon, SO_2 = sulphur dioxide.

Source: Itsubo and Inaba (2018).

I-3. Integration Factors[19]

Integration factors are obtained by multiplying the damage factor of each objective to be protected (human health, social wealth, biodiversity, primary production) by the weighting factor. The weighting factor represents the ratio of degree of importance amongst objectives to be protected and can be obtained from results of conjoint analysis.

Conjoint analysis is a method that has a long track record in environmental economics and is suitable for measuring attribute-specific value in a multi-attribute environment. In LIME 3 (as in LIME 1 and 2), selection-based conjoint analysis is adopted. It is a method in which a responder selects the most desirable option from multiple options. Because of the reduced burden to answer and limited possibility to create bias, it is the most popular survey method.

In LIME 3, a questionnaire survey was conducted in G20 member countries based on the same questions asked in all member countries. The surveyed countries were 19 belonging to G20 (8 developed [G8] and 11 emerging countries) and, for efficiency, the survey was conducted in the

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[19] Unless otherwise noted, the contents of this section are drawn from Itsubo and Inaba (2018).

city with the largest economy in the country. The survey method combined surveys through the Internet and interviews. To ensure that respondents could understand the questionnaire and to minimise bias, surveys in emerging countries were conducted by interview. Surveys in the developed countries were conducted by interview after a pre-test in which the difference in the results between surveys through the Internet and interviews was confirmed as small enough. In both cases, a random sampling method was adopted, with 200–250 samples from each emerging country and 500–600 from each developed country; 6,400 answers in total were gathered.

To determine an option set for conjoint analysis, in addition to the existing quantity level of environmental impact on each objective to be evaluated (i.e. to be protected), an imaginary level in case of changes in the said existing level was set. By setting a standard value (quantity of an environmental impact created through environmental burdens in a specific area during a certain period), which was calculated beforehand for each objective to be protected, as an existing level, scenarios to reduce environmental impacts to a certain level (one-half, one-quarter, and zero) were made for each case. In addition to four objectives to be protected, a yearly increase in direct and indirect taxes that has become necessary to reduce damage is set as an objective to be evaluated. Inclusion of such monetary attributes in the options may make it possible to estimate willingness-to-pay (WTP) for each objective to be protected based on data from the survey answers. Taxes are set between JPY10,000 and JPY30,000 per year. The amount of tax presented to respondents was converted to local currencies and fine adjustments were made based on results of interviews with surveyors.

To design an option set, the most commonly used orthogonal array method[20] was adopted. Eight patterns of option sets were prepared by using different orthogonal array methods and one pattern was randomly allocated to each respondent to avoid an order effect due to the constant appearance order of closed-ended questions.

Answers given through surveys on the Internet and interviews were analysed statistically to estimate weighting factors. The random parameter logit model, which was duly certified, was

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[20] A method developed in the field of experiment design to efficiently and substantially reduce the frequency of experiments (questions) necessary to obtain certain information. This is done by narrowing down the range of patterns by allocating levels (conditions) of different attributes to each orthogonal array.

adopted to obtain the preference strength of environmental attributes. By using the equation below together with such a parameter for estimated preference strength, weighting factors converted into monetary units can be calculated.

$$WF2(a,c) = MWTP_{a,c} = \frac{\beta_{a,c}}{\beta_{p,c}}$$

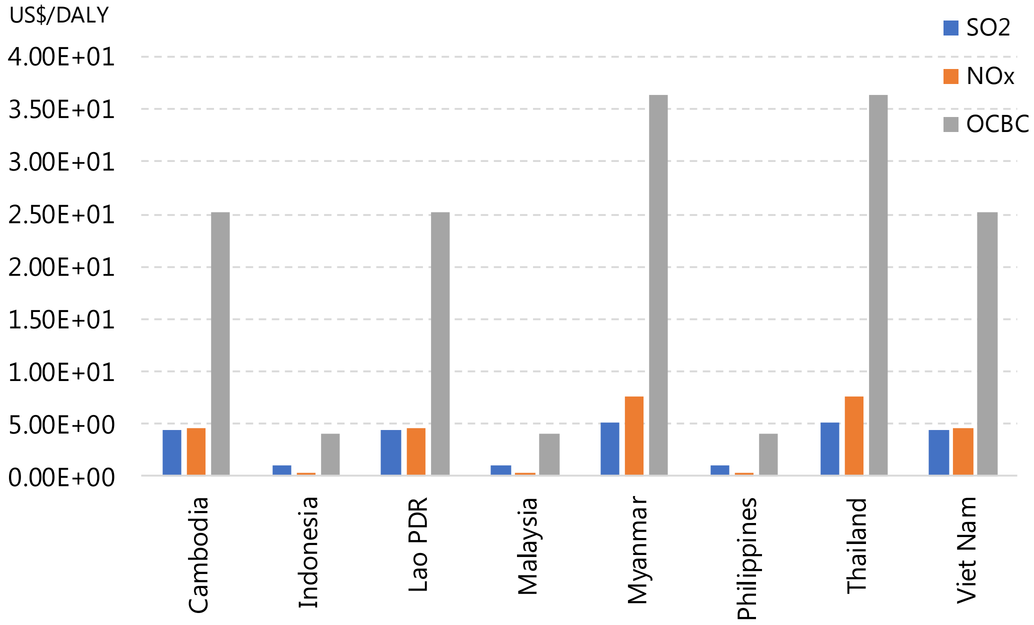
Where,
$MWTP_{a,c}$: Marginal WTP of the country (c) for each objective to be protected (a)
β_a: Preference strength for attribute (a)
β_p: Preference strength for monetary attribute (p)

For any objective to be protected, the more GDP per person decreases, the more WTP increases. The reason is that the preference strength for monetary attributes in developed countries such as the US and Japan is greater than that in emerging countries, whilst the preference strength for environmental attributes in developed and emerging countries remains in a similar value range.

As for WF2 of human health (WTP to avoid unit quantity of damage to human health [US$/unit quantity of damage, 1DALY herein]), the average value amongst G8 countries is approximately US$6,700 per year, whilst the average value amongst G20 countries except G8 countries is as high as approximately US$29,000 per year. The health impacts of environmental contamination in emerging countries are widespread and of very high urgency. In many developed countries, health impacts due to contamination have been controlled to a certain extent, which affect the results of examination of human health.

An integration factor can be obtained by multiplying such WF2 value by the damage factor.

Figure 1B: Integration Factors in ASEAN Countries (air pollution, human health)



NO_2 = nitrogen dioxide, OCBC = organic carbon and black carbon, SO_2 = sulphur dioxide.

Note: Values of other 11 countries (populations weighted) are quoted.

Source: Itsubo and Inaba (2018).

I-4. Application to This Study

Because the impact assessment is conducted only for air pollution caused at the stage of power generation in a coal-fired power plant, air pollution among various influence areas is the only subject we examine here. We adopted damage factors and integration factors based on an interest rate of 7%.

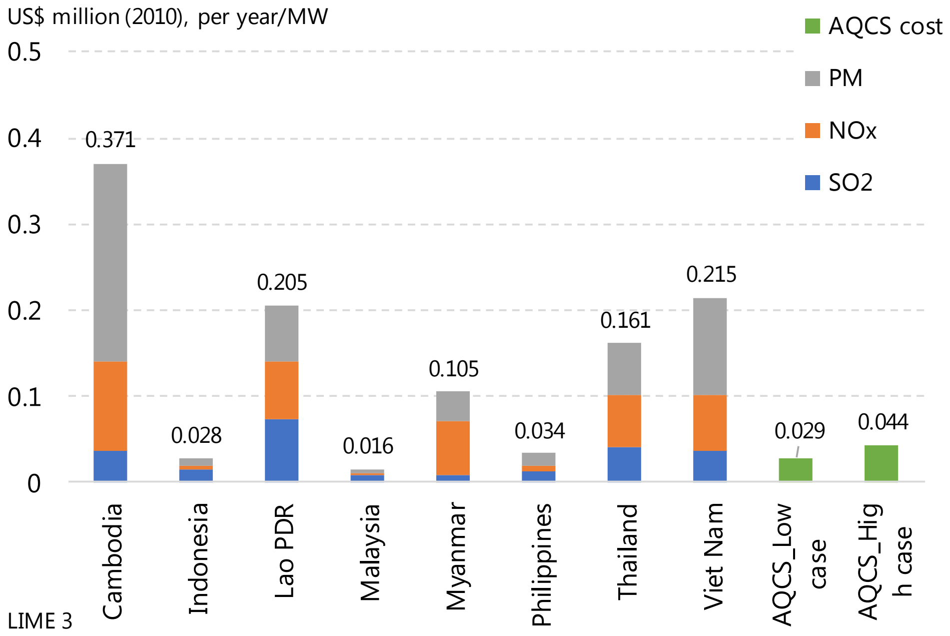
In LIME 3, OCBC is mentioned as primary particulates. The Emissions Database for Global Atmospheric Research (EDGAR) of the European Commission mentions fine PM (PM 10 and PM 2.5 and carbonaceous speciation [BC, OC]) as primary particulates. Therefore, the substance referred to as OCBC in LIME 3 is treated as PM.

An increase in external expenses to generate a unit quantity of environmental load can be calculated (US$/year/MW) by multiplying inventory data by integration factor (value based on 7% interest rate, US$/kg). Integration factors can be obtained by multiplying the damage factor (value based on 7% interest rate) by weighting factor (value of Other 11 [population weighted], i.e. value of emerging countries amongst G20 countries, except G8 countries, [damage to human health, US$/1DALY] is adopted as the weighting factor option). Because LIME 3 uses 2013 US dollar prices, they have been adjusted to the 2010 level by using the same deflator as the one used in WHO methodology.

In Indonesia, Malaysia, and the Philippines, sometimes the benefit from strengthening emission standards is lower than the cost thereof. Because a substantial portion of air pollutant transferred outside the area is absorbed by the oceans, the damage factor to the countries is relatively small. Thus, the values obtained from the estimation resulted in smaller values for those countries.

Although Cambodia, Lao PDR, Myanmar, Thailand, and Viet Nam show differences in emission levels of air pollutants in case (i) and case (ii), the study shows that tightening regulations would have an adequate benefit in both cases.

Figure 1C: Results of LIME 3 for Case (i)

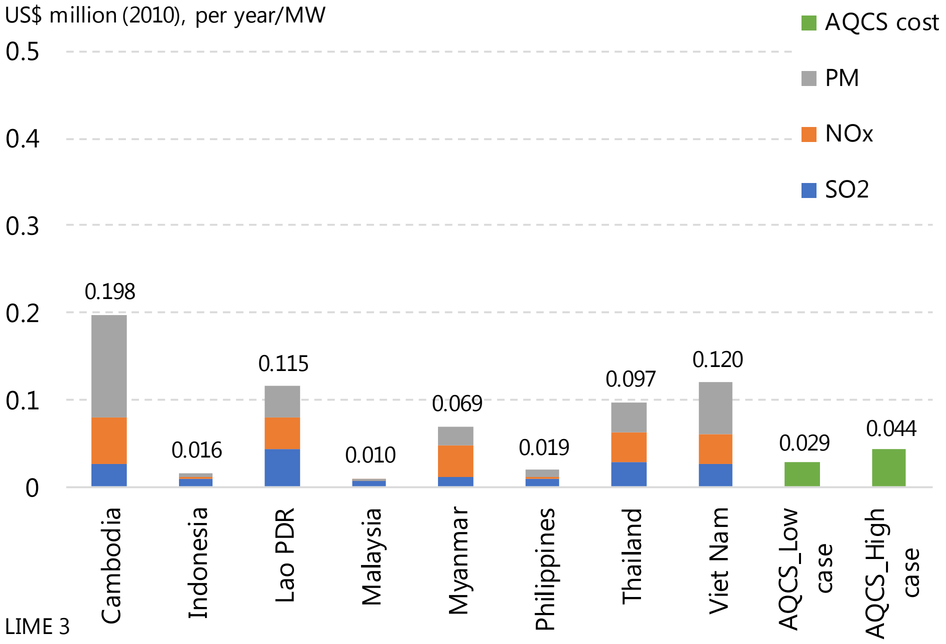


AQCS = air quality control system, Lao PDR = Lao People's Democratic Republic, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxides.

Note: Case (i) = most strengthened emission standard. Case (ii) = half of existing emission standard.

Source: Author.

Figure 1D: Results of LIME 3 for Case (ii)



AQCS = air quality control system, Lao PDR = Lao People's Democratic Republic, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxides.

Note: Case (i) = most strengthened emission standard. Case (ii) = half of existing emission standard.

Source: Author.

Appendix 2. Additional Calculation

Recently, some developing countries have been strengthening their emission standards for air pollutants. India is one of them. It enacted emission standards in 2015 for existing and new coal-fired power plants, and classified existing plants based on capacity and year operation started. It set emission standards based on capacity and on year operation started.

Table 2A: Emission Standards in India

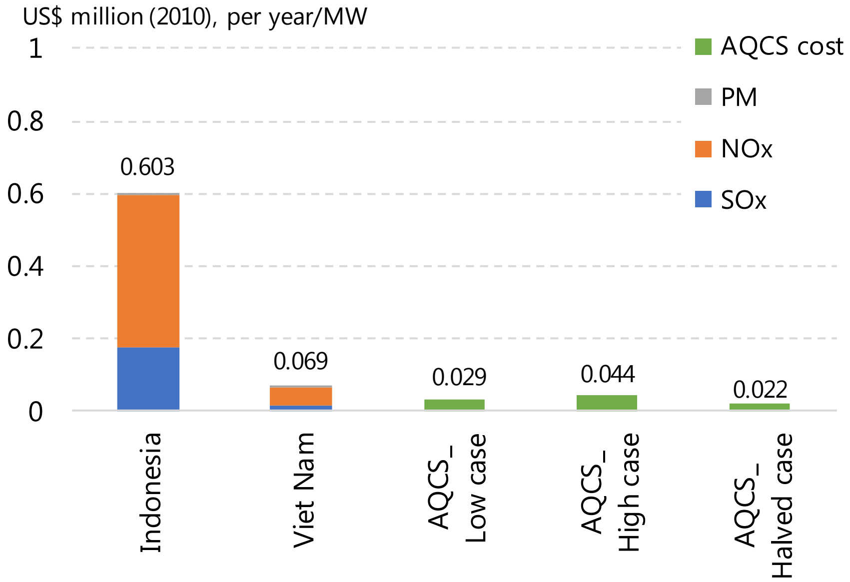
	SOx (mg/m^3)	**NOx (mg/m^3)**	**PM (mg/m^3)**
For existing plants	200/600 (more than 500MW / less than 500 MW)	200/600 (Start operation after 2013/ before 2013)	50/100 (Start operation after 2013/ before 2013)
For new plants	100	100	30

NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide.

Source: Government of India (2019).

Taking Indonesia and Viet Nam as examples, we also calculate the benefit of strengthening emission standards when two countries introduce the same level of standards as India. We use the standards for >500 MW existing plants that started operation after 2013. We chose Indonesia and Viet Nam for their high share of coal-fired power generation in total power generation output. For convenience, we refer to them as case (iii) in Figure 2B. The calculation is based on World Health Organization (WHO) methodology (Chapter 3, section 2 of this study). Air quality control system (AQCS) installation cost could be reduced by local procurement, for example, giving us a case where the capital expenditure (CAPEX) of the high case is halved.

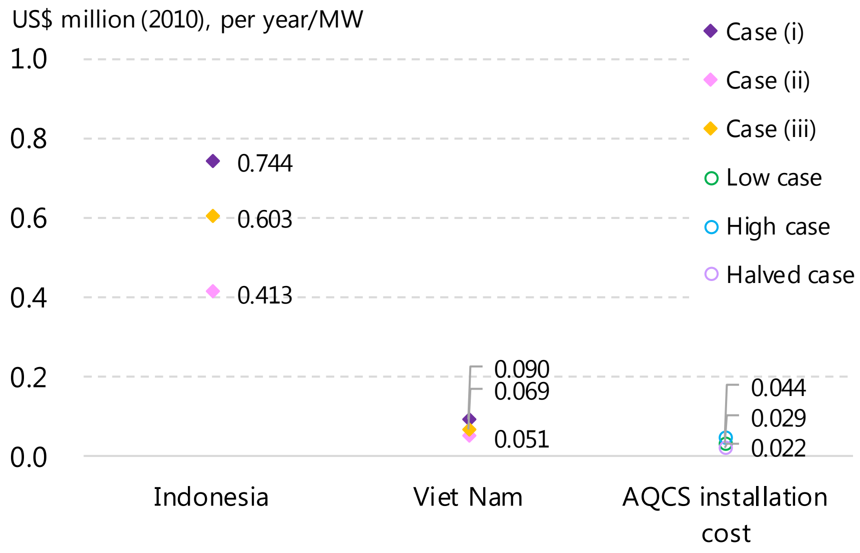
Figure 2A: Results of Additional Calculation



AQCS = air quality control system, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxide.

Source: Author.

Figure 2B: Results of Additional Calculation with Other Cases



AQCS = air quality control system.

Note: Case (i) = most strengthened emission standard. Case (ii) = half of existing emission standard. Case (iii) = same level of standards as India.

Source: Author.

Figure 2A shows that the benefit from strengthening emission standards to the same level as India’s exceeds the cost thereof in Indonesia and Viet Nam. More than other cases, strengthening emission standards to India’s level would bring much more benefit than halving existing standards. It might be difficult for both countries to raise their standards to the level of developed countries’, but it is economically rational to strengthen their standards to the level of India’s.