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)

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).

[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

<table>
<tr><th>Objective to Be Protected</th><th colspan="2">Category Endpoint</th><th colspan="2">Objective of Damage Function Calculation</th></tr>
<tr><td rowspan="5">Human health</td><td rowspan="5">Respiratory disorder</td><td>Chronic death</td><td>✓</td><td>Increase of chronic death (converted into DALY)</td></tr>
<tr><td>Acute death</td><td>-</td><td>Already taken into consideration as a part of chronic death</td></tr>
<tr><td>Lower respiratory tract symptom</td><td>✓</td><td rowspan="3">Increase of disorder affected individuals (converted into DALY)</td></tr>
<tr><td>Chronic bronchitis</td><td>✓</td></tr>
<tr><td>Use of bronchodilator</td><td>✓</td></tr>
</table>

[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

[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.

[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.

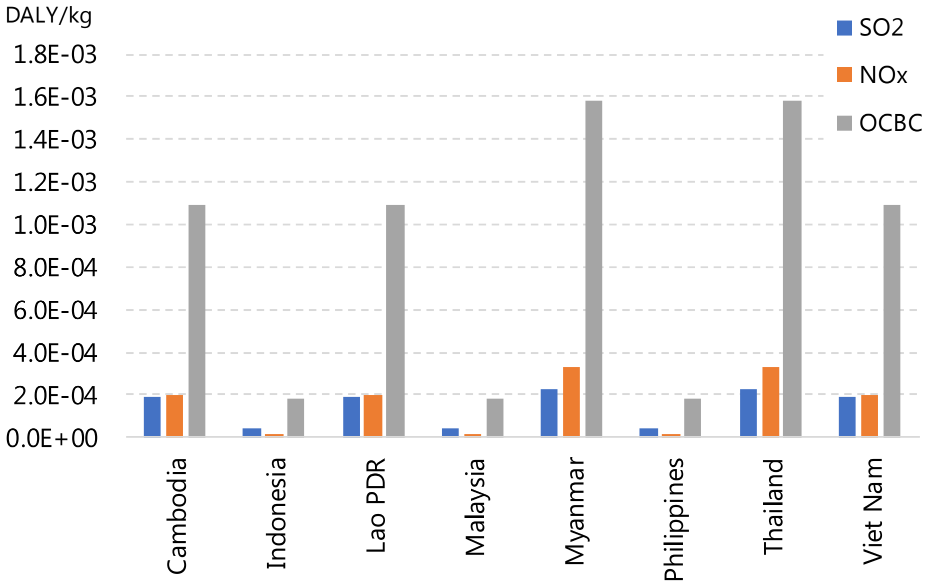
In impact analysis, the concentration response function (CRF) obtained in an epidemiological study is used to calculate the increase of health risk due to a PM 2.5 concentration increase. The CRF of mortality represents the change rate of PM 2.5 concentration and chronic mortality, which are examined 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.

[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

[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

[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)

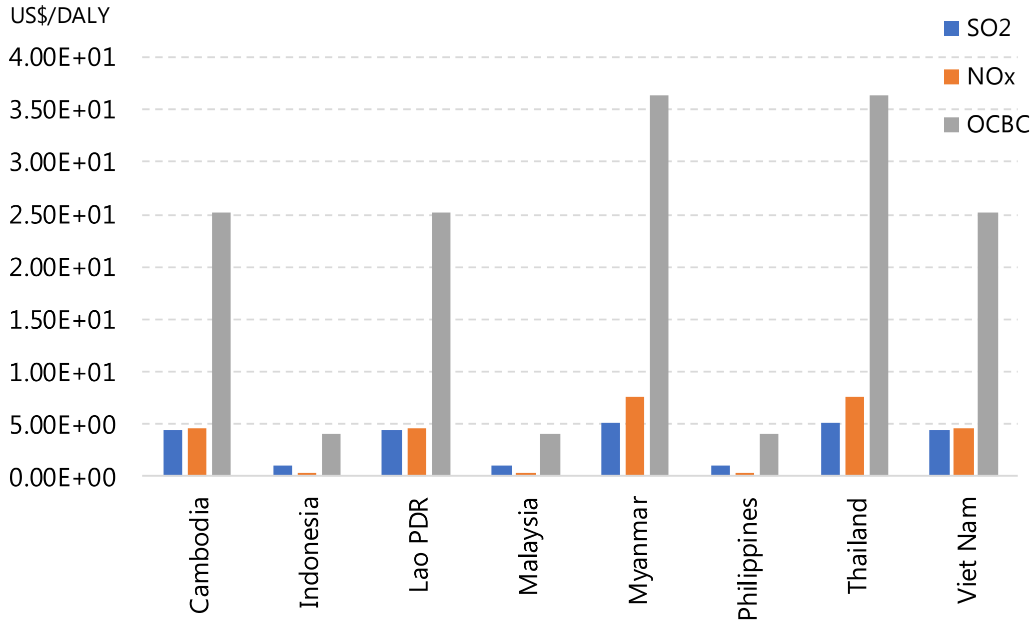
β_p: Preference strength for monetary attribute (p)

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%.

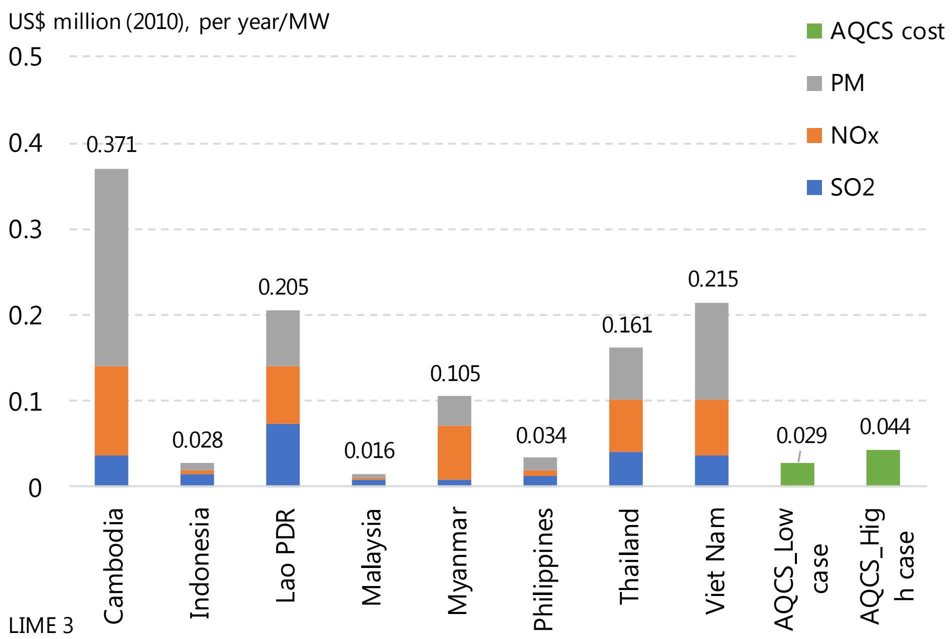
In LIME 3, OCBC is mentioned as primary particulates. The Emissions Database for Global Atmospheric Research (EDGAR) of the European Commission mentions fine PM (PM 10 and PM 2.5 and carbonaceous speciation [BC, OC]) as primary particulates. Therefore, the substance referred to as OCBC in LIME 3 is treated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

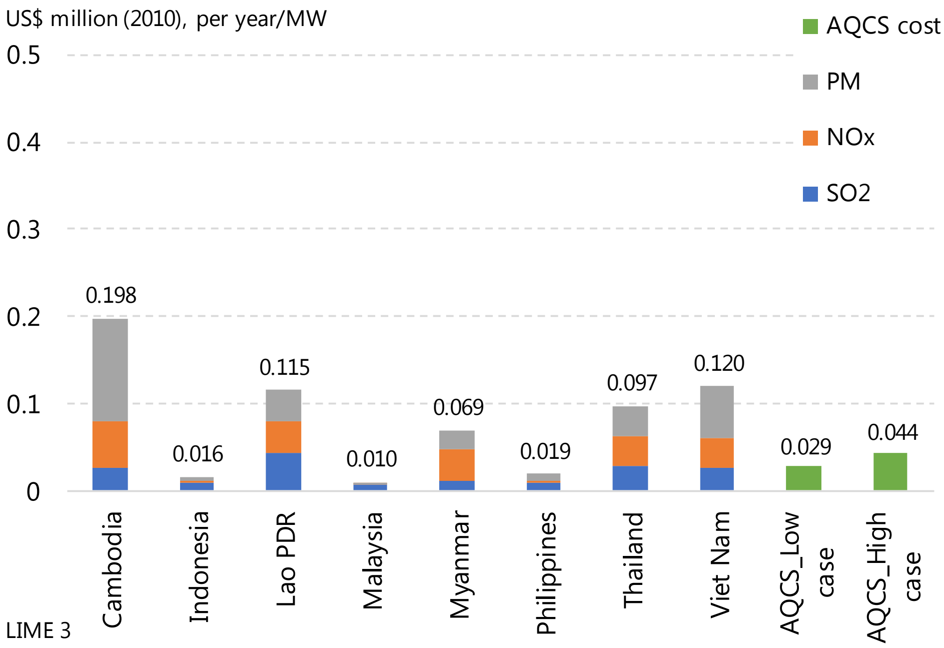


AQCS = air quality control system, Lao PDR = Lao People's Democratic Republic, NOx = nitrogen oxides, PM = particulate matter, SOx = sulphur oxides.

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

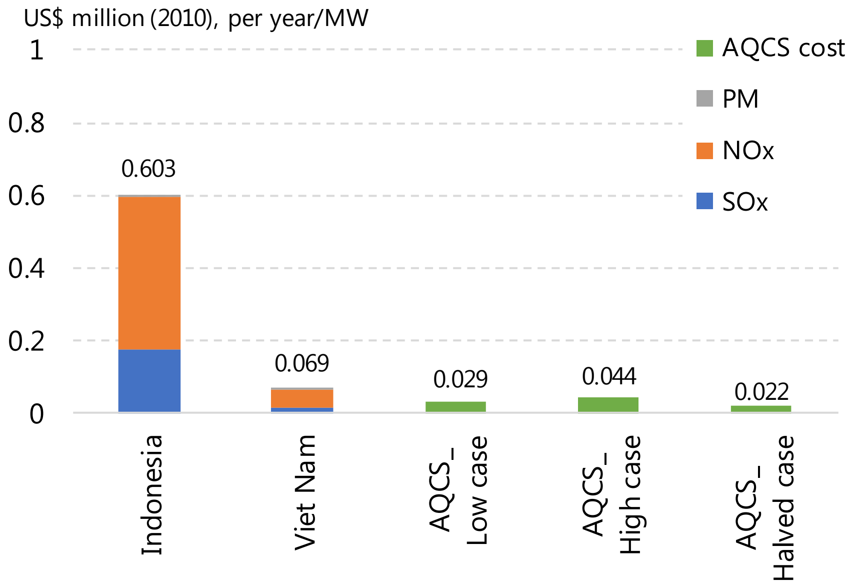
	SOx (mg/m^3)	NOx (mg/m^3)	PM (mg/m^3)
For existing plants	200/600 (more than 500MW / less than 500 MW)	200/600 (Start operation after 2013/ before 2013)	50/100 (Start operation after 2013/ before 2013)
For new plants	100	100	30

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.

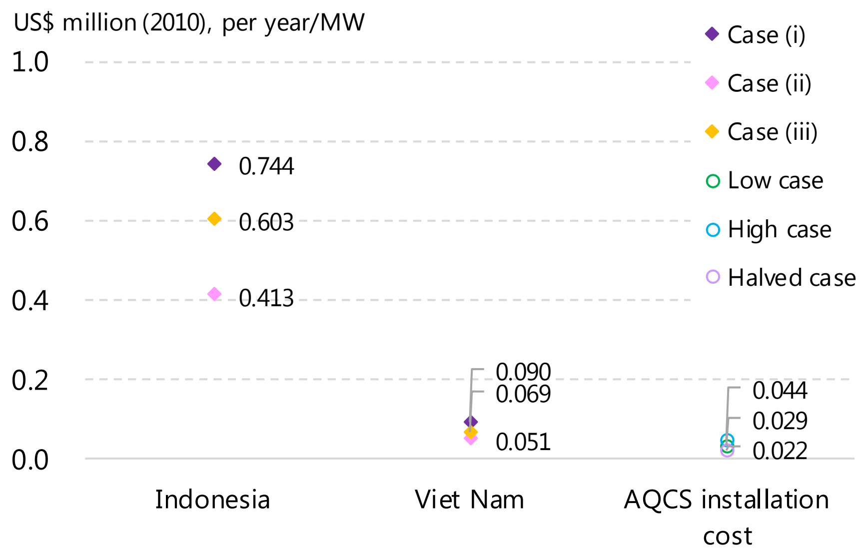
Figure 2A: Results of Additional Calculation



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.