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MERCURY REDUCTION AT INDONESIAN COAL PLANTS

MINAMATA COMPLIANCE STRATEGY

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SUSTAINABLE CARBON

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PREFACE

This report has been produced by the International Centre for Sustainable Carbon (ICSC) and is based on a survey and analysis of published literature and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own and are not necessarily shared by those who supplied the information, nor by our member organisations.

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The overall objective of the International Centre for Sustainable Carbon is to continue to provide our members, the International Energy Agency (IEA) Working Party on Fossil Energy and other interested parties with definitive and policy relevant independent information on how various carbon-based energy sources can continue to be part of a sustainable energy mix worldwide. The energy sources include, but are not limited to coal, biomass, and organic waste materials. Our work is aligned with the UN Sustainable Development Goals (SDGs), which includes the need to address the climate targets as set out by the United Nations Framework Convention on Climate Change (UNFCCC). We consider all aspects of solid carbon production, transport, processing, and utilisation, within the rationale for balancing security of supply, affordability, and environmental issues. These include efficiency improvements, lowering greenhouse and non-greenhouse gas emissions, reducing water stress, financial resourcing, market issues, technology development and deployment, ensuring poverty alleviation through universal access to electricity, sustainability, and social licence to operate. Our operating framework is designed to identify and publicise the best practice in every aspect of the carbon production and utilisation chain, so helping to significantly reduce any unwanted impacts on health, the environment and climate, to ensure the well-being of societies worldwide.

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BACKGROUND

This technical report represents the results from the first phase of a significant project undertaken by the IEACCC (now the ICSC) on behalf of the US Department of State, Agreement Number: SLMAQM19CA238: *‘Capacity building in Southeast Asia to reduce mercury and other pollutant emissions from the coal combustion sector’*.

The project comprises two major lines of effort to reduce emissions from the coal-fired power sector: one in Indonesia focusing on mercury emissions; and the second in India which addresses additional pollutants (SO₂ and NO_x) as well as mercury.

The work will inform the development of Indonesia’s national implementation plan under the Minamata Convention, creating the basis for policy for the coal utility sector in Indonesia.

The Indonesia project is divided into three working phases:

- **Phase 1** – analysis of mercury emissions from the entire Indonesian coal fleet and ranking of plants according to mercury emissions – the report from this Phase is available from: <https://www.sustainable-carbon.org/>
- **Phase 2** – capacity building for mercury monitoring and control at three of the top-ranked plants in Indonesia – materials from three workshops in Indonesia are available from: <https://www.sustainable-carbon.org/>
- **Phase 3** – reaching out to identify how to move potential mercury reduction projects and strategies into action in Indonesia.

This report summarises the work completed under Phase 3 of the Indonesia project.

ABSTRACT

Indonesia ratified the UN Minamata Convention on Mercury in September 2017 and must now take action to comply with the aims of the Convention. For the coal sector, this means producing an inventory of mercury emissions and using these data to determine the most cost-effective and appropriate means to reduce mercury. The report from Phase 1 of this project ranked the Indonesian coal fleet according to mercury emissions over the remaining plant lifetimes. It also identified three plants for closer study to determine mercury reduction strategies that would be appropriate for the Indonesian challenge.

This report aims to assist the Indonesian government in the development of a national compliance strategy to reduce emissions of mercury from the coal utility sector. It focuses on technical solutions noting, where possible, how applicable they are to the Indonesian challenge. The report concludes with a selection of commercial emission reduction systems provided by international vendors who believe that their technologies would be appropriate for Indonesian coal-fired units.

ACRONYMS AND ABBREVIATIONS

ACI	activated carbon injection
ACT	accelerating coal transition
ADB	Asian Development Bank
AEA	Atlantic Energy Associates
BAT	best available technology
BAU	business-as-usual
BCRC	Basel Convention Regional Centre for Asia
BEP	best environmental practice
CCS	clean combustion system, CastleLight Ltd
CCUS	carbon capture utilisation and storage
CEM	continuous emissions monitor
CIF	Climate Investment Fund
CV	calorific value
EIA	Environmental Impact Assessment
EMMS	Environmental Management and Monitoring Scheme
EPA	Environmental Protection Agency, USA
ESP	electrostatic precipitator
ERM	Energy Transition Mechanism
FGD	flue gas desulphurisation
GEF	Global Environment Fund
GEM	Global Energy Monitor
GHG	greenhouse gas
GMSCS	Gore mercury and SO ₂ control system
GOI	Government of Indonesia
GWh	gigawatt hours
HELE	high efficiency low emissions
HHV	higher heating value
ICSC	International Centre for Sustainable Carbon
iPOG	interactive process optimisation guidance tool
LNB	low NO _x burner
LOI	loss on ignition
MIA	Minamata Impact Assessment
MOEF	Ministry of Environment and Forestry, Indonesia
MEMR	Ministry of Energy and Mineral Resources, Indonesia
NZE	net zero emissions
NAP	National Action Plan
NDC	Nationally Determined Contributions
PET	plant efficiency toolbox
PLN	Perusahaan Listrik Negara, Indonesian Government-owned electrical utility
PM	particulate matter

ppb	parts per billion
RUKN	Rencana Umum Ketenagalistrikan Nasional, General National Electricity Plan
RUPTL	Rencana Usaha Penyediaan Tenaga Listrik, Electricity Supply Business Plan
SCR	selective catalytic reduction
SWFGD	seawater flue gas desulphurisation
UN	United Nations
USDOE	United States Department of Energy
USDOS	United States Department of State
UNEP	United Nations Environment Programme
USEPA	United States Environmental Protection Agency
WFGD	wet flue gas desulphurisation
WLSFGD	wet limestone flue gas desulphurisation

Note: all monetary values are in United States dollars (\$) unless otherwise stated.

UNITS

/y	per year
/d	per day
/min	per minute
/s	per second
dscm	dry standard cubic metres
g	gramme
Gt	gigatonne
GW	gigawatt
GWh	gigawatt-hour
k	kilogramme
kJ/g	kilojoule per gramme
L	litre
MW	megawatt
MWe	megawatt-electric
MW/h	megawatt per hour
mg/m ³	milligrammes per cubic metre
t	tonnes, metric (unless otherwise stated)
TWh	terawatt-hour
µg/m ³	microgrammes per cubic metre

CHEMICALS

CaCO ₃	limestone
CaS	calcium sulphide
CO	carbon monoxide
CO ₂	carbon dioxide
HCN	hydrogen cyanide
Na ₂ S	sodium sulphide
N ₂	nitrogen (gas)
NO _x	total nitrogen oxide and nitrogen dioxide
O ₂	oxygen
SO ₂	sulphur dioxide
SO _x	oxides of sulphur (SO ₂ , SO ₃)

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1 INTRODUCTION

Coal is intrinsic to the Indonesian economy and is currently vital for economic development. Indonesia planned to double the capacity of coal-fired plants between 2019 and 2028 and, as coal use increases, so will emissions of pollutants such as mercury, unless action is taken. Indonesia has ratified the United Nations (UN) Minamata Convention on Mercury and so has an obligation to determine the best means to ‘control and where feasible reduce’ emissions of mercury from both new and existing coal plants. The Government of Indonesia must create an inventory of emissions from its coal fleet and then determine emission reduction strategies accordingly, to achieve this aim. As part of this work, the ICSC developed an emission inventory for the Indonesian coal sector, on behalf of the US Department of State (USDOS) and in conjunction with the Indonesian Ministry of Minerals and Energy Resources (MEMR) and Ministry of Environment and Forestry (MOEF). The report (Sloss and others, 2021) ranked mercury emissions from the Indonesian coal fleet according to the assumed remaining lifetime of each unit.

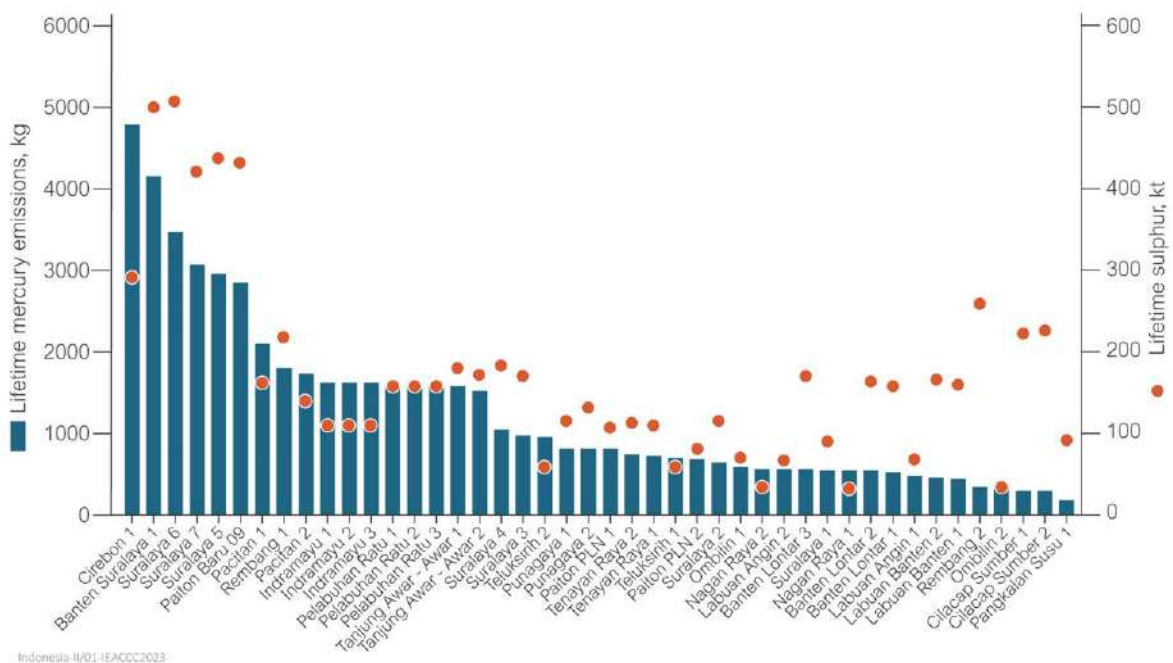


Figure 1 Emissions of mercury and SO₂ over the remaining lifetime of the plant (Sloss and others, 2021)

Figure 1 summarises the results, highlighting that the top 10 emitting units in Indonesia together could be responsible for over 40% of the mercury emissions from the entire predicted fleet lifetime. These results suggest that a strategic approach, targeting specific high-emitting plants first, could significantly accelerate emission reduction from the Indonesian fleet in a cost-effective manner.

The previous work also identified three plants of specific interest as they comprise different plant configurations which represent similar challenges within the Indonesian fleet. The plants selected were:

- an inefficient plant with high-intensity emissions, due for imminent refurbishment – OMBILIN 1;
- a typical high-capacity Indonesian coal plant, representing plants likely to upgrade and/or retrofit in the near future – SURALAYA 6; and
- a plant with seawater flue gas desulphurisation (SWFGD) installed for sulphur control, to investigate means to reduce potential increased mercury deposition to marine areas – PAITON 1 Unit 2.

This document provides guidance to MEMR and MOEF on mercury emission reduction strategies and technologies which will be most appropriate (effective and cost-effective) for the three identified plants and also across the remaining fleet.

Chapter 2 considers the requirements and obligations of Indonesia under its commitment to the UN Minamata Convention on Mercury and the associated national emission limits which have been set. This includes a discussion of the basic requirements to identify the best available techniques or technologies (BAT) and best environmental practice (BEP). Chapter 3 briefly considers significant changes in the coal sector which may arise due to obligations under other international agreements such as the Paris Agreement on Climate Change. Chapter 4 then focuses on the improvement of power plant performance through boiler changes, which includes upgrading the boiler, improving plant efficiency, and fuel modification, including cofiring of materials such as biomass and ammonia. It includes a review of how emission control systems for particulate, NO_x and SO₂ emissions, whether already in place or being installed in the future, can be optimised for mercury control at little or no cost. Chapter 5 provides information on commercially available technologies which have been identified as being applicable to the Indonesian challenge. More information on these commercial systems is included in the extensive Appendix to this report.

2 OBLIGATIONS UNDER THE MINAMATA CONVENTION

Indonesia ratified the UN Minamata Convention on Mercury in September 2017 (MC, 2020) and is therefore bound to comply with its aims. There are two main requirements under the Convention which relate to the evaluation and control of mercury from stationary sources such as coal-fired power plants:

- to create an inventory of emissions; and
- to create a national action plan outlining the proposed means to control these emissions.

2.1 INVENTORY OF EMISSIONS

Article 8 of the Minamata Convention states that parties shall adopt guidance on the methodology for preparing emissions inventories (MC, 2020).

‘EACH PARTY SHALL ESTABLISH, AS SOON AS PRACTICABLE AND NO LATER THAN FIVE YEARS AFTER THE DATE OF ENTRY INTO FORCE OF THE CONVENTION FOR IT, AND MAINTAIN THEREAFTER, AN INVENTORY OF EMISSIONS FROM RELEVANT SOURCES’

Indonesia has published its Minamata Initial Assessment (MIA) (RI, 2022a) which concludes that the greatest source of mercury emissions to the environment in Indonesia is gold and silver extraction, leading to over 102,223 kg/y of mercury released into the air. By comparison, as shown in Figure 2 below, emissions from the coal combustion sector were estimated to be significantly lower at 5370 kg/y for large power plants and 2385 kg/y for industrial boilers. Emissions from coal combustion were also lower than those from other metal extraction (amounting to almost 20,000 kg/y) and waste incineration (over 22,000 kg/y)

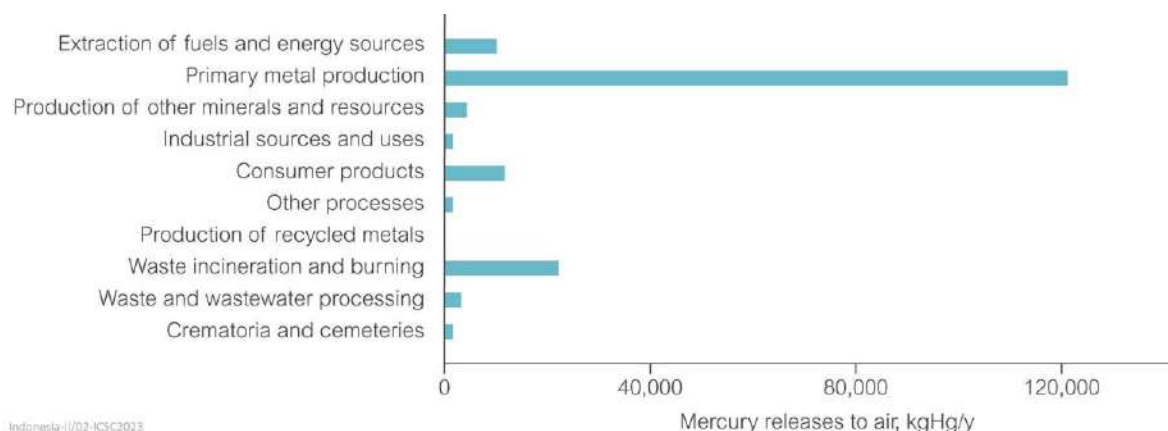


Figure 2 Mercury releases to air in Indonesia, as reported in the Minamata Initial Assessment (RI, 2022a)

The Indonesian MIA concluded that more information and accuracy was needed for most of the sectors, especially for materials production and use (for example batteries and light switches). The data for the coal sector are regarded as relatively accurate. In the MIA, estimates from each of the 141 coal-fired power plant units in Indonesia were calculated on a plant-by-plant basis. The values were produced by using a single emission factor for coal combined with the coal use for each plant. The presence of emission controls (electrostatic precipitators (ESP) flue gas desulphurisation (FGD) and low NO_x burners) were accounted for using basic mercury retention factors for each technology.

The ICSC study (Sloss, 2021) produced an emission inventory for the Indonesian coal fleet. Emission estimates were provided on a unit-by-unit basis, but, unlike the MIA, calculated plant-specific emission factors based on coal type, plant configuration and more specific information on control systems. This produced an inventory which provides significantly more insight into mercury behaviour on a unit-by-unit basis and will also facilitate more plant-specific emission reduction strategies. It is reassuring to note that the emission estimates from the national inventory and from the ICSC study are largely in agreement. However, it is also necessary to emphasise that the ICSC study did not produce an estimate of total fleet emissions as this could potentially compound assumption errors from individual plant estimates. But together the data from the MIA and the ICSC study provide a comprehensive and complementary analysis of the Indonesian coal fleet which will help inform a credible compliance strategy.

2.2 NATIONAL PLAN

Article 8 of the Minamata Convention also specifies ‘controlling and, where feasible, reducing’ emissions of mercury and mercury compounds. To this end, it recommends the production of action plans to address emissions from major source categories in each country.

‘A PARTY WITH RELEVANT SOURCES SHALL TAKE MEASURES TO CONTROL EMISSIONS AND MAY PREPARE A NATIONAL PLAN SETTING OUT THE MEASURES TO BE TAKEN TO CONTROL EMISSIONS AND ITS EXPECTED TARGETS, GOALS AND OUTCOMES’
(MC, 2020)

Currently, Indonesia has only produced a National Action Plan (NAP) relating to mercury emissions from artisanal gold mining (RI, 2022b). Since the emissions from this sector are more than an order of magnitude greater than those from the coal sector (*see* Figure 1), it is appropriate that gold mining take priority. However, since coal combustion is included in Annex D as a relevant source, a national action plan for coal should also be produced.

Article 8 of the convention also requires action to be taken within five and ten years of ratification.

Within five years of ratifying the convention (by 2023), Indonesia should:

- Provide information on emissions measures taken (to control or where feasible reduce); and
- Apply BAT/BEP to ‘new’ sources.

Within ten years of ratifying the convention (by September 2027), Indonesia should implement at least one measure into the National Plan:

- A quantified emissions goal and emission limit values;
- Apply BAT/BEP (to all sources, both new and existing);
- Apply a multipollutant control strategy; and
- Propose alternative measures to reduce emissions.

For Indonesia, the definition of new and existing units is determined by the date of ratification:

- ‘*New sources*’ – those coming online at least one year after the ratification date for Indonesia, that is plants that became operational after September 2018; and
- ‘*Existing sources*’ – those that were in operation before September 2018.

According to Global Energy Monitor (GEM), an 82% share of the country’s total coal utility fleet has been operating for less than 20 years (Figure 3), suggesting that most plants are only around halfway through their design lifetime (assuming a life expectancy of around 40 years). Therefore, an emission reduction plan for the existing fleet could include consideration of reducing reliance on (grandfathering) older or high-emitting units and the application of multipollutant emission control technologies to younger units where the payback period for retrofitting will be longer.

Based on the ratification requirements, Indonesia must define and apply BAT to all new sources (since 2023) and must define a NAP for the existing coal fleet by 2027.

Figure 3 shows the age range of the fleet and the proportion of the fleet of each age bracket. The Indonesian fleet is relatively young compared to coal plants in Europe and the USA, the majority of which are over 40 years old.

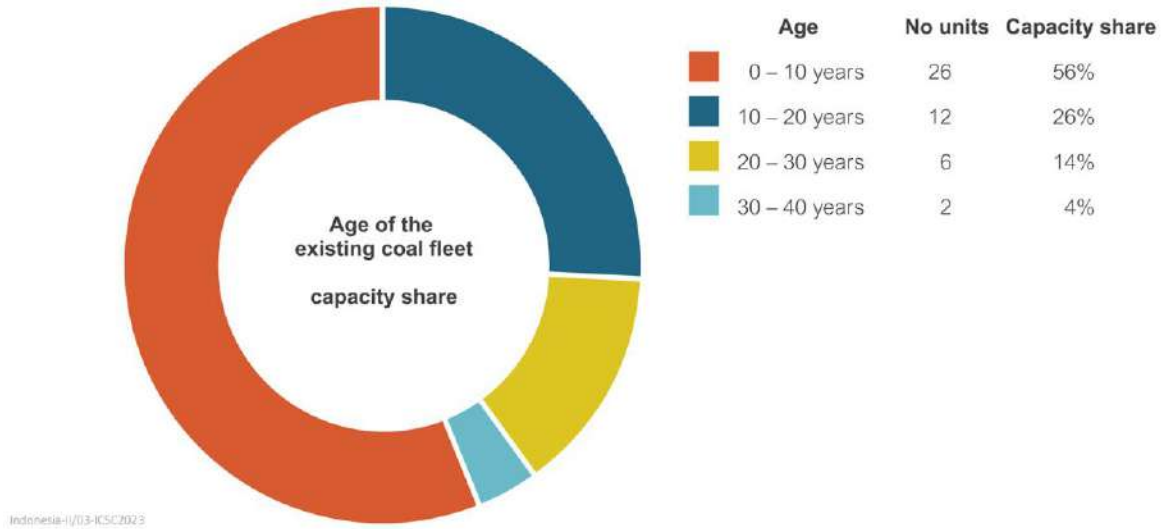


Figure 3 Age of the existing Indonesian coal fleet, GW (GEM, 2023)

2.2.1 BAT for ‘new’ plants

Most if not all ‘new’ plants in Indonesia (online after September 2018) are state-of-the-art coal-firing technologies (supercritical and ultrasupercritical) with efficient boilers. Many of these plants are being built with flue gas controls installed which will ensure co-benefit mercury reduction. Thus, these are high efficiency low emission (HELE) plants. It can be argued, therefore, that most of these ‘new sources’ in the Indonesian coal sector are already being built with BAT/BEP for mercury in place. However, it would be prudent for the relevant governmental stakeholders to evaluate the extent of mercury control to confirm this line of reasoning, going forward. This should be based on the considerations noted in the box below.

PROPOSED BAT FOR MERCURY CONTROL FOR NEW COAL UTILITY PLANTS IN INDONESIA:

- All new plants should be fitted with emission monitors to ensure that emissions comply with applicable emission limits.
- All new plants should be at least supercritical, although ultrasupercritical would be superior.
- All plants should be installed with particulate control – ESP, baghouses or equivalent and the ash produced should be used where possible. If enhanced mercury control is required in new build plant, then baghouses would be preferable to ESP due to their higher mercury capture rate.
- All plants should have control strategies to reduce NO_x emissions, such as low NO_x burners or selective catalytic reduction (SCR). If the latter is used, then the selection process should consider the potential for enhanced mercury reduction with appropriate catalyst materials.
- All plants should have sulphur emission control, ideally wet FGD or equivalent. Waste materials (such as gypsum) should be used where possible. If SWFGD is used, planning for installation should include evaluation of potential issues with mercury discharge in liquid effluent (see Chapter 5).
- Even if mercury-specific control is not installed, the plant planning process should still consider the potential for enhanced mercury co-benefit reduction based on the proposed design of the plant. This could mean selecting baghouses over ESP systems, selecting SCR systems for NO_x based on additional potential for mercury control, leaving plant footprint space for potential retrofitting of sorbent injection systems or for other advanced flue gas cleaning options, including carbon capture, utilisation, and storage (CCUS).

2.3 BAT FOR ‘EXISTING’ PLANTS

The challenge for ‘existing sources’ is significantly greater, as these plants are older, and many were not designed and built with emissions control as a major consideration. For these plants, emission control strategies must be identified and applied retrospectively. The definition of BAT/BEP for any coal plant varies with many factors, including coal characteristics, plant configuration and the presence of flue gas cleaning technologies. The BAT/BEP guidance produced under the Minamata Convention (UNEP, 2019) is a large and multifaceted document which acknowledges the complexity of mercury control. It does not provide prescriptive instructions on how to control mercury. Rather the document lists all the options available for mercury control, from coal treatment to bolt-on flue gas treatment systems without promoting one over the other. It promotes the use of expert advice to determine BAT/BEP requirements on a plant-by-plant basis, taking economic considerations into account.

This report aims to provide some expert guidance to help Indonesian stakeholders determine the most appropriate BAT/BEP approaches for the existing Indonesian fleet. Since plants are not required to implement any Minamata compliance strategy until 2027, in the first instance, BAT/BEP technologies and techniques recommended to ensure that plants comply with the current emission limits are discussed below.

2.3.1 National emission limits

One of the options listed in Article 8 to reduce emissions from existing coal plants is the establishment of emission limits. Emission limits for coal-fired plants in Indonesia were initially introduced in 2008, as shown in Table 1.

Pollutant	Old emission limit, mg/m ³ (2008)		New emission limit, mg/m ³ (2019)	
	Plants operating pre-December 2008	Plants operating post-December 2008	Existing plants (operating pre-April 2019)	New plants (post-April 2019)
Particulate matter	150	100	100	50
SO ₂	750	750	550	200
NO _x (as NO ₂)	850	750	550	200
Mercury	n/a	n/a	0.03	0.03
n/a – not applicable				

The 2008 limits were relatively lax compared to those set in North America and Europe. In 2019, the emission limits were tightened significantly. Those for particulates, SO₂ and NO_x are now in line with North American and European standards. However, the emission limit for mercury (30 µg/m³) is still around an order of magnitude more lenient than in Europe and North America (Sloss, 2015; 2017).

Emission reporting and compliance with the emission limits are under the jurisdiction of the local agency or city government (Bhati and others, 2017). Emissions are also controlled under the environmental licence of the plant which, in turn, is defined by an Environmental Impact Assessment (EIA) or Environmental Management and Monitoring scheme (EMMS). Regional authorities (such as the Governor, the Mayor or the local council) in Indonesia have the power to cancel or suspend licences and permits should a plant be found not to be compliant. Fines and imprisonment can be applied following repeated offences. There is therefore an established mechanism whereby specific emission control requirements can be applied to individual plants, an option which may be cost-effective when considering mercury reduction.

2.3.2 Monitoring for compliance

In order to ensure compliance with the emission limits, the Indonesian government created ‘Permen LHK No 15’, a regulation that includes the requirement that total mercury be monitored at all coal-fired power plants over 25 megawatts (MW) capacity (GOI, 2019). Reporting is required as a five-minute average which can only be achieved with continuous emission monitoring (CEM) systems. These systems can report data directly, and in real-time, to the regulator. To date (October 2023), only around five or fewer CEM systems are believed to be operational on coal-fired units although a similar number of new units were bought in 2022-23. Therefore, it may be several years before the emission limit can be fully policed and before an emission inventory can be produced which is based on validated measured plant emission data. However, these mercury CEM systems will be beneficial to confirm mercury emissions, to monitor compliance and, most importantly with respect to this study, to determine the efficacy of emission control strategies installed.

Currently, Tekran, a US company, is supplying the majority of continuous emission monitors into Indonesia (Ricci and Binangkit, 2023):

- Four Tekran 3400 systems have been installed at the PT PLN (Persero) Tanjung Jati B plant;
- Two Tekran 3400 systems have been installed at the PLTU Amamapare Port Power Station;
- Twelve Tekran 3400 systems have been installed across Sinar Mas pulp and paper plants in Java and Sumatra Island.

Continuous emission monitoring of mercury can be expensive and complex to operate (over \$200,000 per unit to install). A cheaper and simpler alternative would be the use of sorbent traps (USEPA, 2017). This method, developed by the US Environmental Protection Agency (USEPA) is accepted as a standard appropriate for compliance monitoring in the USA. In sorbent traps, four simultaneous samples are drawn from the flue gas into tubes containing treated activated carbon. The different sections of sorbent separate the different species of mercury and, following laboratory analyses (which can take place weeks or even months later as the samples are stable) will provide average measurement data for mercury from the source. Since coal-fired plants commonly operate in a stable manner with consistent fuel input, the mercury emissions are likely to remain relatively constant. In Europe and the USA, plants that can demonstrate consistent operation are only obliged to supply mercury emission data to regulators on an annual basis, saving significantly on the cost and complexity of operating a mercury continuous emission monitor. In the USA, Ohio Lumex is the main provider of sorbent traps for mercury monitoring (OH, 2023).

THE INDONESIAN GOVERNMENT'S REQUIREMENT FOR MERCURY CEM ON ALL PLANTS MAY BE OVERLY COMPLEX AND EXPENSIVE FOR SOME PLANTS. THOSE PLANTS WHICH CAN DEMONSTRATE CONSISTENCY OF OPERATION AND FUEL SUPPLY COULD BE OFFERED THE OPTION FOR ANNUAL TESTING WITH SORBENT TRAPS

2.4 COMMENTS

Indonesia has ratified the Minamata Convention, committing to reducing mercury emissions from all sectors, including coal power. 'New' Indonesian coal plants (online after September 2018) are likely to already be compliant with the common BAT/BEP mercury control requirements. This is due to the comprehensive move towards HELE coal technologies and the more stringent emission standards for these units. However, it would be prudent for these new plants to evaluate the extent of co-benefit mercury control being achieved in practice and to maximise it where possible. This will become easier as monitoring systems are rolled out across the fleet.

For 'existing' plants, compliance with the Minamata Convention will be a greater challenge as the definition of BAT/BEP and the target for reduction is open to national interpretation. However, due to the lower efficiency of these plants, the large number of units, and the lack of emission control technologies currently in place, the existing coal fleet should be a priority for emission reduction. The remainder of this report assists with this interpretation process.

Whilst the requirement for continuous emissions monitoring of mercury at all coal units will highlight any exceedances of the emission limit, it may be an expensive burden for plants that operate consistently with a steady coal supply – such plants could save time and money by reporting annually using sorbent trap measurement technology. However, CEM would remain appropriate for those plants where operation and coals vary and where emissions are known to be at or near the emission limit and thus require closer monitoring.

3 COAL PHASE-DOWN AND CARBON TAX

In addition to the Minamata Convention on Mercury, Indonesia also has commitments for emission reduction under international treaties such as the Paris Agreement on Climate Change. Although it is beyond the scope of this report to cover CO₂ reduction requirements, it is relevant to include details of requirements that will affect the energy mix in the future; for example, plans for early plant closure will affect mercury emissions from the existing coal fleet and will affect decisions on plant-specific action.

3.1 PRIORITISING PLANTS FOR CLOSURE UNDER PARIS AGREEMENT COMMITMENTS

Indonesia has ratified the Paris Agreement and is therefore obliged to produce an action plan for the implementation of the goals. The Government of Indonesia (GOI) published its draft implementation plan for Accelerating Coal Transition (ACT) under the Climate Investment Fund (CIF). Under its Nationally Determined Contributions (NDC), Indonesia plans to reduce emissions of CO₂ by 29% by 2030 relative to a business-as-usual (BAU) baseline total of 2.87 Gt/y (GOI, 2022). With international support, the GOI estimates that the reduction could be as high as 41% in the same time period with additional international support.

The GOI (2022) report outlines the plans for the transition of the energy sector in Indonesia in detail. This Chapter focuses on plant closures that could affect mercury emissions from the existing coal fleet (those which are covered under requirements of the Minamata Convention). Figure 4 summarises the preliminary plan for plant closure.

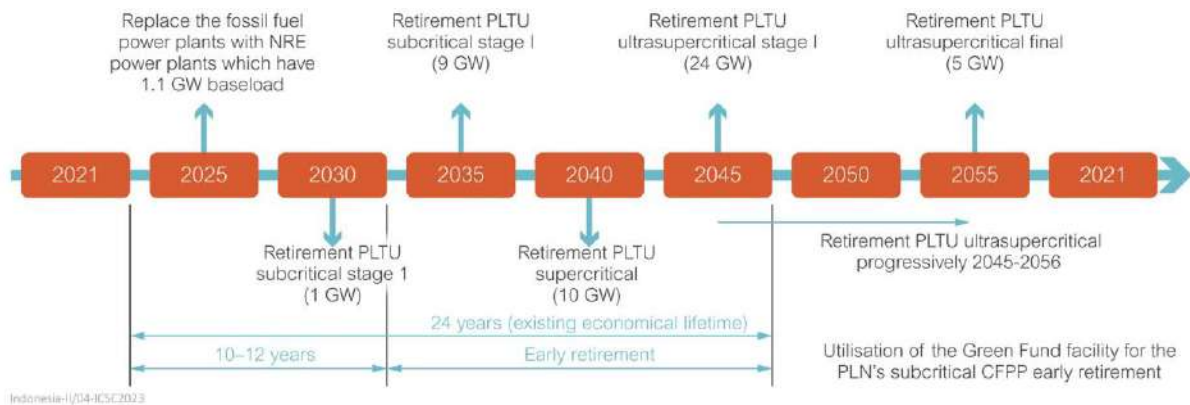


Figure 4 PLN pathway for early retirement of coal power plants in Indonesia (GOI, 2022)

PLN (the Indonesian state-owned power utility) plans to close 2–3 coal plants with a combined capacity of around 1 GW by 2030, 9 GW by 2035 and a further 49 GW by 2055. However, it is acknowledged that this is a goal that cannot happen without significant international financial support.

A task group was established which determined a list of plants that would be most appropriate for early retirement and the roadmap is summarised in Figure 5.

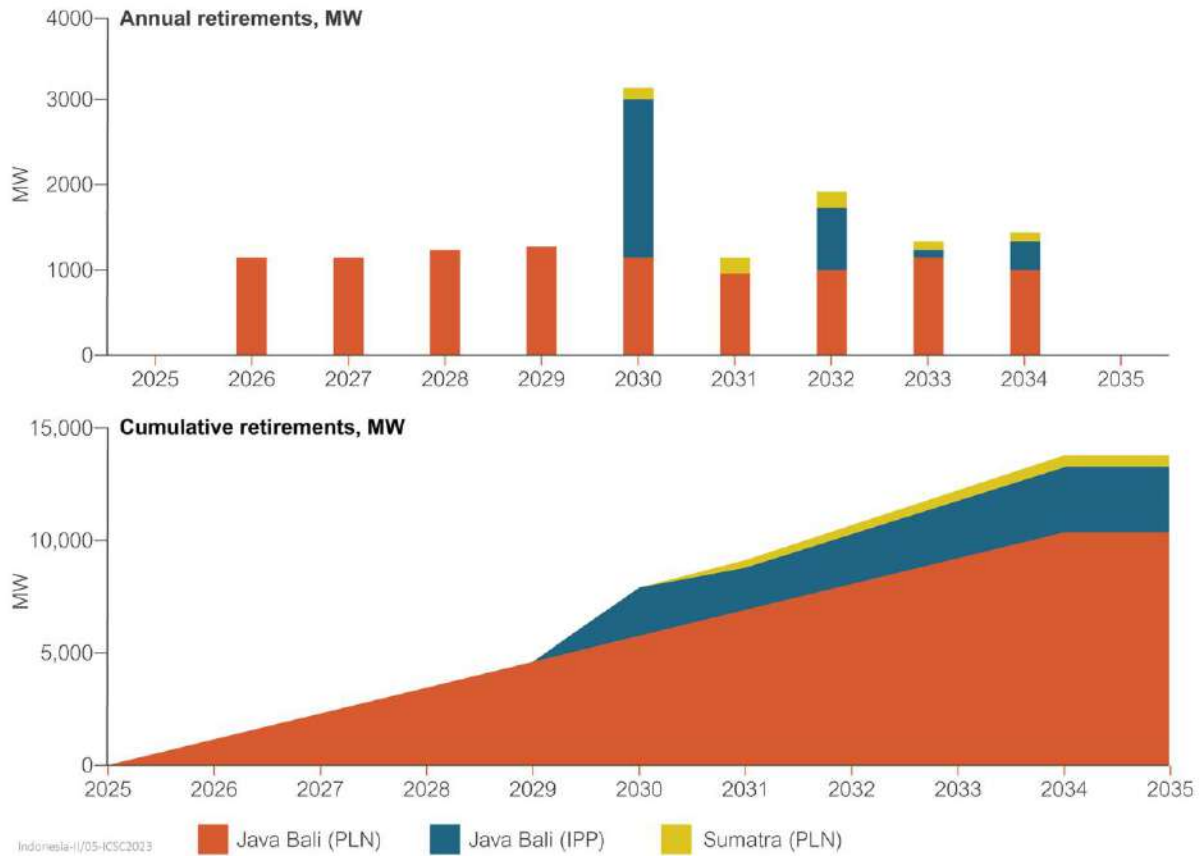


Figure 5 2025-2035 roadmap with 14 GW of early retirement (GOI, 2022)

The annual and cumulative plant retirements proposed are shown with the region and asset ownership. While this is still in discussion at the time of publication of this document (November 2023) the GOI has already named nine plants that are candidates for early retirement:

- Suralaya Units 1,2,5,6,7 and 8
- Paiton Units 1 and 9
- Adipala

It is important to note that Suralaya Unit 6 was selected as a target plant for closer study under this current project of work. The Paiton unit selected for early retirement above is not the same unit selected for this project of work (Sloss and others, 2021).

Since the draft GOI consultation was published in October 2022, the Asian Development Bank (ADB) has created an Energy Transition Mechanism (ETM) to accelerate the transition to renewable energy in SE Asia. The programme aims to refinance coal plants in the short term with the goal to then close them prematurely and replacing the capacity with cleaner energy. The first proposal is to retire a coal-fired power plant in Indonesia’s West Java. The 660 MW coal plant, Cirebon, will receive US\$300

million in funds but must close 10–15 years ahead of its 40–50-year design lifespan. According to Global Energy Monitor, Cirebon was due to retire by 2052, so retiring 10–15 years early (2037-2042) will align with the proposed time when the output from the plant will be replaced with 1.3 GW of wind and solar together with a 100 MW battery by 2042 (Rappler, 2022). Note that 2042 is actually 19 years from now, and therefore beyond the 15-year target date for the Cirebon closure. Shortening its lifespan will reduce total emissions from Cirebon. However, it also means that Cirebon, the country's highest emitting plant according to Sloss and others (2021) (see Figure 1) will continue to emit pollutants such as mercury at its current rate for the next almost two decades unless further investment is procured for retrofitting emission control technologies.

3.2 CARBON TAX

Indonesia has launched a carbon credit scheme to accelerate the country's moves towards net zero emissions (NZE). NZE refers to the balance between the amount of greenhouse gases (GHGs) produced and the amount removed from the atmosphere. It can be achieved through a combination of emissions reduction and emissions removal.

In Indonesia, the national carbon credit market could reach a value of over \$194 billion. Over 99 coal units will participate in the scheme, representing 86% of the coal fleet capacity. The first batch of credits was traded by the PT Pertamina Geothermal power plant. Since this is a non-fossil fuel plant, it represents carbon offsets rather than emission reductions. Currently trading credits are voluntary but the GOI has suggested that this may change to include a carbon tax (Carbon Credits, 2023). An Indonesian carbon tax, which would apply directly to emissions from coal on a tonne basis, has been postponed until 2025. Should a carbon tax be implemented in Indonesia and prove costly for existing coal plants, it will have a significant effect on the continued operation of less efficient plants.

Using such financial mechanisms will accelerate the closure of less efficient coal plants in Indonesia. However, it could potentially cause an increase in emissions from remaining plants which may have to increase output, potentially with lower efficiency, to ensure that capacity meets demand. As plants close – older plants may be used more, many of which may have an insufficient remaining lifetime to achieve payback for the cost of retrofitting emission controls. This means that some of the remaining fleet may be allowed to derogate on emission reduction requirements to ensure delivery of power. This may inadvertently cause a temporary but significant increase in emissions. This is discussed in more detail in the complementary ICSC report on financial challenges for coal projects (Sloss, 2023). It is imperative that the management of the Indonesian coal fleet includes consideration of all emissions under different future energy scenarios and is regularly updated to take into account any significant changes.

3.3 PRIORITISING PLANTS FOR ACTION

Determining which plants will close or be retrofitted under the various emission reduction commitments (Paris Agreement, Minamata Convention, and others) will be a complex decision that must also take energy security, operational costs, and the implications of stranded assets into account.

Considering just mercury, the Indonesian fleet can be prioritised according to annual emissions (kg/y), emission intensity (g/GWh mercury), or emissions over the remaining plant lifetime, as shown in Table 2.

Category A	Category B	Category C
Top emitters by kg/y	Top emitters by g/GWh	Top emitters by remaining lifetime, t
Suralaya 6	Banten Suralaya 1	Cirebon 1
Suralaya 5	Suralaya 7	Banten Suralaya 1
Suralaya 7	Suralaya 6	Suralaya 6
Cirebon 1	Suralaya 5	Paiton-III Unit 1
Banten Suralaya 1	Indramayu 1	Suralaya 7
Suralaya 2	Indramayu 2	Suralaya 5
Suralaya 3	Indramayu 3	Paiton Baru 09
Suralaya 4	Tanjung Awar – Awar 1	Rembang 1
Paiton-III No1	Tanjung Awar – Awar 2	Pacitan 2
Note: Ombilin identified as the highest emission intensity plant in the 2021 study but is not included as it is a small minemouth plant that has already undergone upgrading		

Sloss and others (2021) identified both Cirebon 1 and Suralaya 6 as high mercury emitting plants, having the highest cumulative emissions based on the remaining design lifetime and annual mercury emission rate (kg/y), respectively. It is not surprising that these large, high-demand plants, are also high emitters of CO₂ and are included in the list of priority plants above for early closure under the Paris Agreement commitments. Any national action plan for the existing fleet must include plant closure but, in doing so, it should ensure that the removal of existing capacity does not simply lead to increased emissions from the remaining plants which will be required to fill the missing supply.

3.4 COMMENTS

Indonesia faces a significant challenge in determining how to maintain and build electricity capacity under different international emission reduction commitments. In Indonesia's NDC for the Paris Agreement, the priority is coal plant closure, with the highest CO₂ emitters being closed first and their capacity being replaced by renewable energy and battery storage. To date, only one plant, Cirebon,

has been confirmed for early closure by 2042 but others are already being ranked by the Indonesian government to determine the most appropriate order for subsequent decommissioning.

With respect to mercury emissions, the common means for emission reduction is fuel or plant upgrading and retrofitting with emission reduction strategies. However, with Paris Agreement commitments taking priority to determine which plants will continue to operate, the decision-making process on how to strategise mercury reduction becomes more complex and the monitoring of the largest and most significant remaining sources must continue.

4 BAT OPTIONS FOR INDONESIAN COAL PLANTS

The ICSC's initial study of the Indonesian coal fleet (Sloss and others, 2021) identified three plants for closer analysis with respect to determining emission reduction strategies that could be replicated across the Indonesian fleet. Since this work began, the fate of these three plants has changed:

- Suralaya 6 has been flagged for potential early retirement under planned Paris Agreement commitments;
- Ombilin 1 has been upgraded (*see* Chapter 5); and
- Paiton-III SWFGD has been proposed as part of a new project of work looking at the fate of mercury in SWFGD systems (*see* Section 4.3).

Examples of technologies applicable to these units are included in Chapter 5. However, this chapter looks at how mercury reduction techniques and technologies could work on generic plant types across the Indonesian fleet and how each could form part of a BAT strategy.

With respect to emissions of all pollutants from coal-fired power plants, the most important factors are the efficiency of the plant (the less coal that is burnt per MW generated, the lower the emissions per MW) and the fuel characteristics (the quantity of pollutant or pollutant precursor entering the system). It is therefore possible to maximise coal plant performance to simultaneously reduce the emission of all pollutants, including mercury. Once the plant is optimised, further emission reduction can be achieved through additional flue gas treatment options. The following sections provide summaries of options for emission reduction as defined by the UN Guidance of BAT/BEP for coal plants (UNEP, 2017), focusing on the potential options specifically relevant to Indonesian coal plants.

4.1 BOILER UPGRADE

The more efficient a coal plant, the less coal is required to produce electricity and the lower the emissions. Any action taken to upgrade a boiler will therefore result in a reduction in emissions of mercury. As noted by Sloss and others (2021) the mercury emissions from different units in Indonesia vary significantly, with some plants producing an order of magnitude more mercury per GWh of electricity produced. For most of the fleet, this variation was slight and due to variations in coal mercury content, combustion chemistry and emission control systems in place, but there were several plants that had high emissions due almost entirely due to the low efficiency of the plant. The clearest example of this is the Ombilin plant which produced around 350 g/GWh of mercury compared to the fleet average of below 50 g/GWh, as shown in Figure 6.

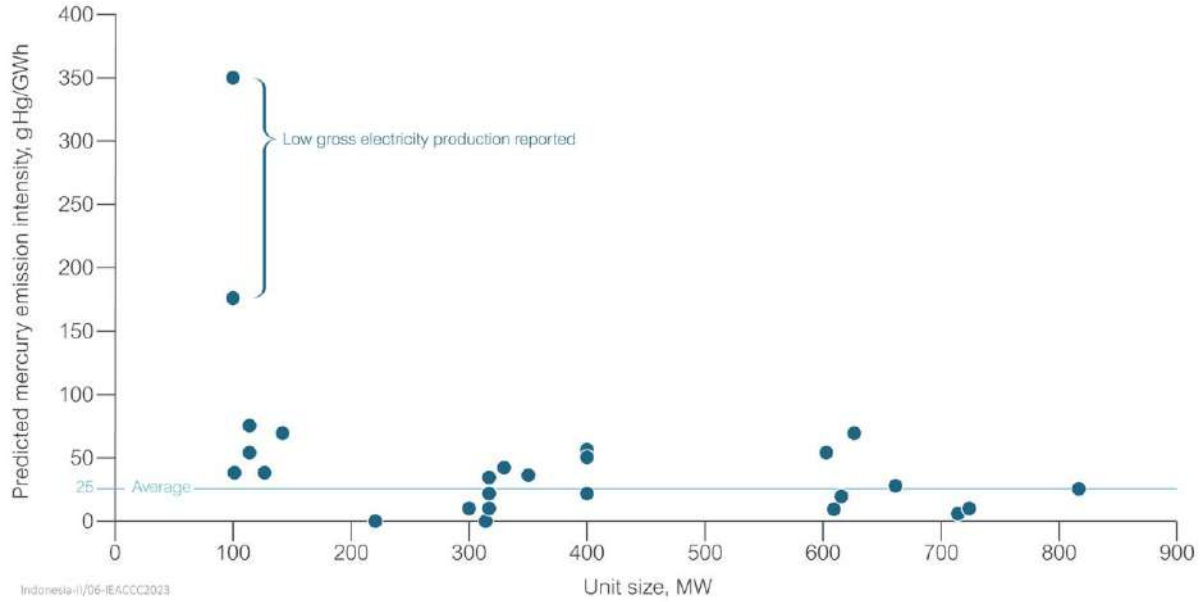


Figure 6 Mercury emission intensity versus unit size (Sloss and others, 2021)

The project identified units with 1000 kg or more mercury emissions each during their remaining lifetimes. Among these, there are 35 units 200 MW or larger with a total installed capacity of 15.15 GW and each with a gross efficiency below 34%. The average gross efficiency of these 35 units is 27%. The design efficiency of subcritical coal plants is commonly around 34%. To illustrate the effect of increased boiler efficiency on mercury emissions, (iPOG, interactive process optimisation guidance tool) analyses were carried out for a theoretical 433 MW unit (15,150 divided into 35) burning coal containing 100 ppb (parts per billion) of mercury and with a higher heating value (HHV) of 23.1 kJ/g. It is estimated from this that a 433 MW unit (equipped with an ESP for particulate control) operating with 27% gross efficiency would emit 201 kg/y of mercury. The same unit but operating with 34% gross efficiency was projected to emit 158 kg/y mercury, or 43 kg/y mercury less. These savings would translate into 1505 kg/y of mercury emissions saved across the whole fleet, over the remaining fleet lifetime.

A ROUGH CALCULATION SUGGESTS THAT MERCURY EMISSIONS ACROSS THE EXISTING INDONESIAN FLEET COULD BE REDUCED BY OVER 1.5 T/Y IF ALL THE PLANTS OPERATED AT DESIGN EFFICIENCY

The above analysis has been substantially simplified as actual gross efficiencies of units considered varied from 17–32%, unit sizes varied from 220–815 MW, and different coals were burned in these units. However, even this simplified analysis demonstrates a substantial decrease in mercury emissions resulting from the increased gross efficiency of boilers.

In theory, increasing the efficiency of the Indonesian coal fleet to design specifications could reduce the mercury emissions for the sector by between 1–2 t/y. Whilst this is a small fraction of the estimated 70 t/y for the entire fleet (Sloss and others, 2021), the increased efficiency will also mean less coal use, lower emissions of all pollutants, and economic savings for the plant which could be redirected to further pollution control strategies.

4.2 FUEL CHANGES

Burning less coal reduces emissions. This can be achieved by fuel cleaning and fuel switching strategies.

4.2.1 Coal washing

Coal washing is primarily designed to remove ash contained in the coal. Coal washing reduces the sulphur content and may reduce the mercury content of the coal. For mercury content to be reduced by coal washing, there must be a significant amount of pyrite, and the mercury must occur in this pyrite matrix (inorganic mercury). Organic mercury, within the carbon matrix of the coal, will not be removed to a significant extent. While mercury reduction by coal washing is possible, it is unlikely that this technology will be used solely for this purpose. Indonesian coals are typically low sulphur (less than 1%) and low ash and there will be no need for the deployment of coal washing to lower these parameters. Overall, coal washing is unlikely to play a major role in the development of mercury reduction strategies in Indonesia.

4.2.2 Fuel switching

Many coal plants worldwide are looking into either the replacement of coal with or the combination of coal with less carbon-intensive materials. In most cases, the reduction in mercury emission should be directly proportional to the reduction in coal use. However, as discussed below, there are some factors in cofiring that could have both positive and negative effects on mercury emissions.

Replacement of coal with **biomass** is becoming increasingly popular and some plants, such as Drax in the UK, are moving entirely from coal to biomass. The main reason for biomass cofiring is to reduce the use of fossil carbon as part of the move towards NZE. Cofiring biomass can be an appropriate option to take advantage of available biomass resources, often using materials that would otherwise go to waste. However, biomass production at large scale can require new national and international infrastructure and logistics to maintain consistent and reliable fuel supplies. These issues are addressed in numerous complementary reports from the ICSC (<https://www.sustainable-carbon.org/library/reports/>).

Indonesia has initiated trials of 1–5% biomass replacement at many of its plants. Under the biomass cofiring programme conducted by the state electricity company PNL, 3% to 5% biomass in the form of wood pellets or woodchips will be injected in 114 units of coal-fired power plants in 52 locations across the country by 2024 (IEEFA, 2021).

With respect to mercury emissions, the effect will be to reduce the mercury input that would arise from the coal. Since biomass contains trace or zero concentrations of mercury, the reduction in mercury input to the plant will be proportional to the amount of coal replaced by biomass – 5% cofiring will lead to a 5% reduction in mercury input. However, although this would imply a 5% reduction in emissions, there will be some variation due to several factors:

- The basis of replacement – weight of biomass versus volume will affect the absolute change in mercury input on an absolute basis.
- The calorific value of the biomass and the effect on the efficiency of combustion – if factors such as temperature or oxygen content of the combustion zone change then this could affect the efficiency of combustion.
- The combustion chemistry, and consequently the chemistry of the mercury in the plant, may change. If the biomass contains halogens (such as chlorine) or other oxidants, then more mercury may be oxidised which could enhance mercury capture. The presence of other materials, such as minerals, could also change the resistivity and ‘stickiness’ of the ash, which could affect the capture of mercury in downstream pollution control devices.

Thus, although the replacement of coal with biomass is likely to reduce emissions of mercury in proportion to the amount of coal removed, there may be some factors that increase or decrease this effect. The effect of biomass on mercury emissions from coal plants in Indonesia should therefore be monitored.

For the purpose of illustrating the potential for mercury reduction, it is possible to estimate gross values. The Indonesia MIA (2022) lists 144 units (including small units, likely not operated by PLN) burning 91.4 Mt/y of coal. Assuming that the amount of coal used by 114 units operated by PLN is 90 Mt/y, a 5% reduction in coal use equates to 4.5 Mt/y less coal fired. Further assuming the coal average mercury content to be 100 ppb, this reduction in coal consumption would correspond to a 0.45 t/y reduction in mercury input into 114 coal-fired units. Should 90% of mercury input in coal be released into the environment, 5% biomass substitution of coal would correspond to 0.41 t/y of mercury emissions saved.

As with biomass, the replacement of coal with **ammonia** will reduce mercury emissions. For ammonia, there will be no trace of mercury and so the mercury input to the plant will be reduced directly proportionally to the percentage of ammonia cofired. However, similar to the situation with biomass, the changes to combustion efficiency and combustion chemistry may have positive or negative effects on mercury speciation which could enhance or reduce mercury capture in downstream control devices. Again, this would need to be monitored.

Rough calculations suggest that:

- Bringing major emitters among Indonesian coal plants to 34% efficiency could reduce emissions by 1505 kg/y.
- Cofiring ammonia or biomass with coal will reduce mercury emissions proportionally to the amount of coal replaced. The 5% biomass or ammonia coal substitution proposed at PLN plants would correspond to 410 kg/y of mercury emissions saved.

It is important to note that these values are gross estimates. Further, the two options listed above may offset each other if applied together – the replacement of coal with ammonia will increase plant efficiency AND reduce fuel input mercury. However, the replacement of coal with biomass will reduce input mercury but could reduce plant efficiency slightly or cause issues with the performance of emission control systems which would raise mercury emissions again (although the total emitted would still be less due to the total mercury entering the plant being reduced).

ALTHOUGH IT IS NOT POSSIBLE TO PRODUCE ANYTHING MORE THAN GROSS ESTIMATES OF MERCURY REDUCTION POTENTIAL, BOTH IMPROVEMENTS IN PLANT EFFICIENCY AND COAL OFFSET WITH EITHER AMMONIA OR BIOMASS WILL REDUCE THE AMOUNT OF MERCURY PER GWH OF ENERGY PRODUCED AND THEREFORE, ALTHOUGH THE EFFECTS MAY BE SMALL, MERCURY EMISSION REDUCTIONS ARE GUARANTEED.

4.3 CO-BENEFIT EFFECTS

Control systems for particular matter (PM), SO₂ and NO_x are increasingly common in coal-fired plants and are the norm in many regions. Although these systems are not designed to capture mercury, they can be effective in reducing mercury emissions – this is called a co-benefit effect. Since this co-benefit effect for mercury control costs nothing, it is a cost-effective means of mercury control. In many situations, the co-benefit effect of mercury in these systems can be enhanced, by adding further, either free or inexpensive mercury control.

4.3.1 Particulate control systems

The Indonesia MIA lists 144 coal-fired units burning 91.4 Mt/y coal. This amount of coal corresponds to approximately 9 t/y of mercury input. All Indonesian units are equipped with ESP for PM control and a typical ESP can be assumed to remove around 5–10% of mercury input, depending on the operating conditions and on mercury speciation. This is equivalent to 450–900 kg/y mercury

reduction, as a co-benefit. For comparison, a typical baghouse (fabric filter, which captures particulates by sieving rather than electrostatics) can remove 20–30% of mercury input, or 1800–2700 kg/y mercury. Thus, in a theoretical scenario of all ESP in Indonesia being replaced with baghouses, the additional mercury removal could be more than doubled to 1350–1800 kg/y. While this total replacement is unreasonable to expect for any economy, the comparison of total emission reduction is indicative of reductions that could be achieved and could inform decisions on particulate controls to be installed on any future plants in Indonesia.

4.3.2 NO_x controls

Low NO_x burners, which maximise fuel-to-oxygen ratios to reduce emissions of NO_x, will have no effect on mercury emissions in Indonesia. SCR systems use catalysts to promote the conversion of NO_x to nitrogen (N₂). SCR systems do not remove mercury but can be effective in promoting mercury oxidation which, in turn, will promote substantial mercury removal in downstream equipment such as particulate controls (if the SCR is located upstream of these devices) and in FGD systems installed for SO₂ capture. The combined mercury removal in a unit equipped with SCR and FGD can be over 80%. SCR is not currently being considered for widespread installation in Indonesia. However, if such systems are installed in future, then their positioning and design should consider the potential to enhance co-benefit reduction (that is, high dust locations and mercury-effective catalysts).

4.3.3 FGD

According to the UNEP BAT/BEP guidance document (UNEP, 2017), dry FGD systems (spray dryer plus baghouse) can reduce mercury emissions significantly (40–60%) for high chlorine coals. Lower co-benefit capture is expected for low rank coals. Dry FGD systems are not expected to be installed to any significant capacity in Indonesia. Wet flue gas desulphurisation (WFGD) systems, which use limestone and produce gypsum as a by-product, can also reduce mercury emissions by 40–60%. Mercury reduction by WFGD of 80% or more has been reported, but the results are case-specific and not guaranteed.

Table 2 in Chapter 2 (repeated here for convenience) shows how the previous study (Sloss and others, 2021) identified the top emitting plants in Indonesia according to their annual mercury emissions, by intensity and over their remaining operating lifetime.

Category A	Category B	Category C
Top emitters by kg/y	Top emitters by g/GWh	Top emitters by remaining lifetime, t
Suralaya 6	Banten Suralaya 1	Cirebon 1
Suralaya 5	Suralaya 7	Banten Suralaya 1
Suralaya 7	Suralaya 6	Suralaya 6
Cirebon 1	Suralaya 5	Paiton-III Unit 1
Banten Suralaya 1	Indramayu 1	Suralaya 7
Suralaya 2	Indramayu 2	Suralaya 5
Suralaya 3	Indramayu 3	Paiton Baru 09
Suralaya 4	Tanjung Awar – Awar 1	Rembang 1
Paiton-III No1	Tanjung Awar – Awar 2	Pacitan 2
Note: Ombilin identified as the highest emission intensity plant in the 2021 study but is not included as it is a small, minemouth plant that has already undergone upgrading		

Considering the units listed in Category A (ranked by annual mercury emissions) or Category C (ranked by remaining lifetime emissions), each category equates to a collective annual mercury emission of around 700–750 kg/y as per a BAU scenario. Within groups A and C only Paiton-III No 1 is reported to be equipped with FGD technology. Based on the UNEP value of a 40–60% emission reduction efficiency for wet FGD systems (in combination with ESP), this would mean a potential annual emissions reduction of between 18–43% if all plants were equipped with FGD technologies (Categories A and C). Considering the units ranked by their mercury emissions intensity (gHg/GWh; Category B), annual emissions could be reduced between 20–47% (Table 3). The reason for a slightly higher collective emissions reduction for Category B is attributed to none of these plants having desulphurisation technologies installed, as opposed to Categories A and C which include Paiton-III No 1.

Category (as defined in Table 2)	Annual emissions (% of BAU value)	Lifetime emissions, t
Category A	18–43%	0.8–1.9
Category B	20–47%	1.7–4.0
Category C	18–43%	1.8–4.2

The values in Table 3 are based on large assumptions for which the variability and uncertainties around unit-specific performance of APCD technologies should be acknowledged. Moreover, the Suralaya Units 1–4 that are included in Category A are all proposed to retire by 2030, meaning that equipping

them with additional emission control technologies could create a significant risk of them becoming stranded assets. If Suralaya Units 1–4 do retrofit FGD, the collective annual emissions for all units in Category A will only be reduced between 12–28% by 2030. Therefore, the highest impact to reduce annual emissions would be to focus on units in Category B (ranked by emissions intensity), which will potentially produce a similar range of lifetime emissions reduction of around 2000–4000 kg as calculated for Category C (units ranked to their longest remaining lifetime). Again, it should be noted that Suralaya Unit 4, and Suralaya Units 5–7 are included in Category B and are proposed to retire by 2030 and 2037–2042 respectively, again suggesting a stranded asset risk for any FGD installation for these units. For this reason, the long-term vision should therefore be on the units in Category C by taking cumulative mercury emissions, and a longer remaining operating lifetime, into consideration.

An alternative to standard WFGD is SWFGD. In these systems, seawater is used rather than limestone to flush the SO₂ out of the flue gas. SWFGD units are deployed in coastal areas and predominantly, albeit not exclusively, in SE Asia countries of the Pacific basin. The S&P Global coal plant database (S&P Global, 2023) reports a total of 96 coal utility units, totalling 32 GW capacity in southeast Asia, including 5.2 GW in Indonesia. The McCoy Report (2023) lists around 6 GW of SWFGD installed in Indonesia. SWFGD is an attractive technology for the control of SO₂ emissions from coal-fired power plants because it has a lower capital expenditure than sorbent-based FGD. Since seawater is used rather than fresh or district water, there is no risk of reducing sources of potable water for local communities. Its operating expenditure is also lower since it does not require the addition of absorbent (such as limestone).

Depending on the flue gas properties and scrubber operational parameters, SWFGD may transfer up to about 85–90% of mercury from flue gas into the seawater. Our 2021 study suggested that this value is lower for Paiton due to the high proportion of elemental mercury from Indonesian coals. The spent/waste seawater laden with mercury is then collected and treated (through aeration) before being discharged directly back into the sea. Aeration basins are often shown as open troughs, making it possible for mercury to escape to air should oxidised mercury be reduced to elemental mercury in the aeration basin. A significant proportion of mercury captured by SWFGD units (not detected in stack flue gas) has been shown to be retained in seawater effluent from a scrubber (spent seawater), and with the lack of a mercury precipitation/separation step, it is possible that these facilities represent a significant source of mercury release to the marine environment (Liu and others, 2011).

The limited information on SWFGD systems suggests that any mercury captured is either rereleased to the air or released into the local water body, neither of which represents an appropriate reduction of mercury to the environment. It is therefore imperative that further investigation is carried out to determine the final fate of mercury from SWFGD systems to ensure that they do not create a new environmental issue. Technologies are available that could be designed to process and capture the

mercury being released from SWFGD. New projects are being proposed in this area by the USDOS and Macquarie University, Australia.

4.4 MERCURY-SPECIFIC BAT

Compliance with the current mercury standard in Indonesia (0.03 mg/m^3) is not a challenge for coal-fired power plants since it is around an order of magnitude more lenient than the limits for most plants in Europe and the USA. Based on our 2021 study, many plants in Indonesia are estimated to release mercury in the flue gas in concentrations of around $20 \text{ }\mu\text{g/m}^3$. Many Indonesian coal-fired power plants will therefore comply without any action being required. However, the current emission limit for mercury is likely to be tightened in Indonesia at some time in the future, to align with tighter emission limits set internationally.

Currently, mercury emissions are likely to be partly controlled because of the emission limits placed on other pollutants (co-benefit removal). However, the addition of halogens such as chlorine or bromine could build on co-benefit mercury control to bring emissions down almost to the emission limits set in Europe and the USA ($1\text{--}3 \text{ }\mu\text{g/m}^3$). Depending on the configuration of a power plant, halogens could be added for oxidation of mercury with removal of oxidised mercury downstream or as sorbents for adsorption of mercury and removal in a PM control device.

4.4.1 Oxidation

Oxidised mercury is sticky and soluble and significantly easier to capture in existing pollution control systems. The addition of halogens such as bromine to enhance mercury oxidation became relatively standard practice at units in the USA that could not otherwise meet the stringent emission limit (Sloss, 2014, 2017). The effectiveness of oxidation will vary with combustion conditions and plant configuration. Although oxidised mercury is easier to control than elemental mercury, the rate relies on an effective capture system, such as unburnt carbon, or an additional sorbent. The capture rate for oxidised mercury in an ESP can be low when there is little or no unburnt carbon. Capture in baghouses can be higher as the flue gas is in contact with the fly ash for longer, allowing more effective capture by any unburnt carbon present. If unburnt carbon is low, then sorbent addition is required to ensure the oxidised mercury is effectively captured and removed.

Since oxidation has not been trialled at any plant in Indonesia, it is only possible to estimate its effectiveness by using the iPOG emission estimation tool, as applied in the original study (Sloss and others, 2021). For guidance on using the iPOG, please refer to the 2021 report.

The iPOG was used to project mercury emissions from a fictitious 600 MW unit under different scenarios of mercury control:

- BAU** – the baseline was established first to illustrate the benefit of mercury oxidation on total mercury removal. A 600 MW unit with ESP only was assumed to use 100 ppb mercury coal. As shown in Figure 7, an ESP removes only a small fraction of the mercury, and the unit is projected to emit 29 g/h in the stack flue gas. This corresponds to around 20 $\mu\text{g}/\text{m}^3$ concentration for the 600 MW unit considered.

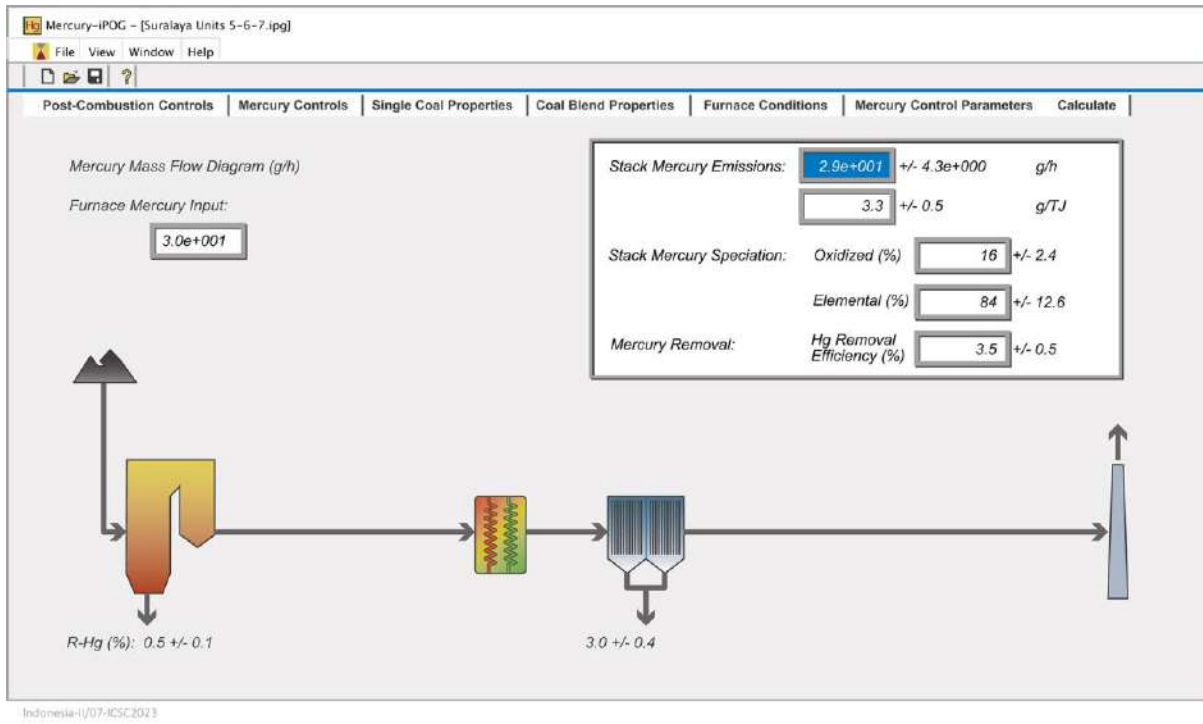


Figure 7 Mercury emissions from a 600 MW unit with ESP only

- ESP, WFGD** – according to the iPOG, the addition of WFGD would increase mercury capture to 17% with the resulting emissions of mercury reduced to 25 g/h (corresponding to a mercury concentration in the flue gas of $17 \mu\text{g}/\text{m}^3$). This relatively small improvement of mercury capture with FGD is the result of the low inherent chlorine content of coal (0.015%) and the resulting low content of oxidised mercury in the flue gas.
- ESP, wet FGD and bromine** – although bromine could theoretically be added to a plant fitted only with an ESP, this would never be a practical approach as mercury capture would still be limited by the ESP capture efficiency. A more common approach would be to add bromination to a plant with a wet FGD system in place. The iPOG calculation was adjusted to include the addition of 200 ppm by weight of brominating agent to the coal, with a wet FGD system present. It was estimated that the mercury emissions would decrease to 17 g/h in this scenario, as shown in Figure 8 (corresponding to mercury concentration in flue gas of $12 \mu\text{g}/\text{m}^3$).

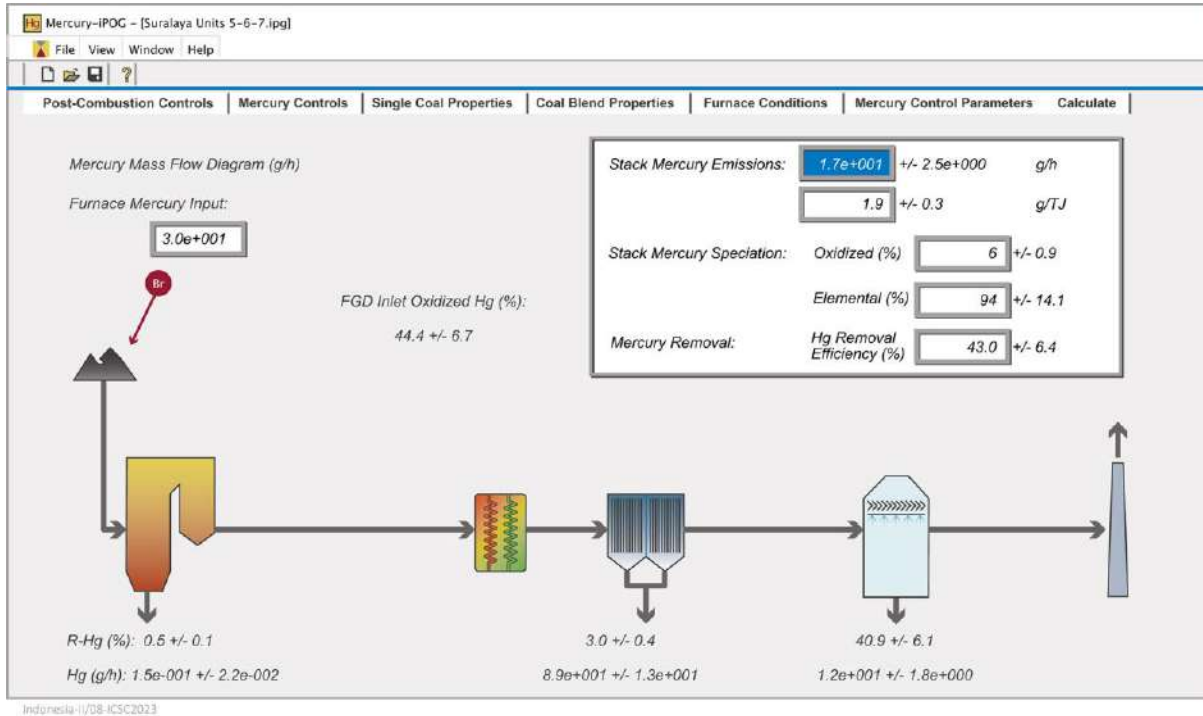


Figure 8 Mercury emissions from a 600 MW unit with ESP, wet FGD and the addition of bromine to the coal

The comparison of results shown in Figures 7 and 8 demonstrates 12 g/h mercury control with a bromine-FGD strategy, corresponding to 105 kg/y for just one 600 MW unit. It is important to note that the effect of bromine varies significantly with coal and flue gas characteristics so actual results may vary from the values suggested by the iPOG.

In theory, the combination of bromine and wet FGD on plants in Indonesia could achieve at least a 40% increase in mercury control over plants with only ESP installed.

4.4.2 Sorbent injection

Since some Indonesian coals are low in sulphur, wet FGD systems may not be applied across the fleet. An alternative to the bromine-WFGD combination described above could be the application of activated carbon upstream of the existing PM control system.

Again, assuming a fictitious 600 MW plant firing Indonesian coal, the iPOG was used to assess the potential for mercury reduction through the addition of activated carbon. Over 80% mercury removal was projected with the injection of 0.032 g/m³ of brominated activated carbon upstream of an ESP. This resulted in mercury emissions of 5 g/h, corresponding to a mercury flue gas concentration of 3.4 µg/m³ as shown in Figure 9.

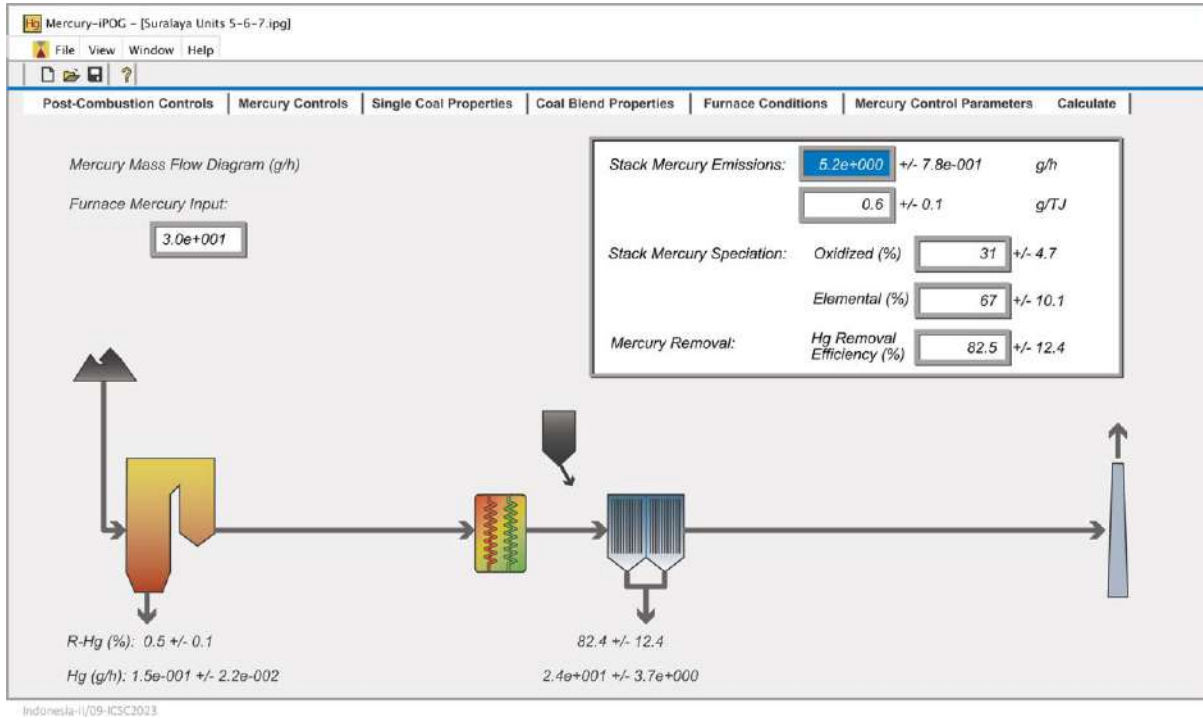


Figure 9 Mercury emissions from a 600 MW unit with ESP and brominated activated carbon injection (ACI)

The comparison of emissions shown in Figures 7 and 9, demonstrates that 24 g/h mercury could be prevented, an 82% reduction in total mercury. This number corresponds to 210 kg/y mercury emissions avoided from a single 600 MW unit. An 80% reduction in mercury emissions across the existing Indonesian coal fleet could mean a total reduction in emissions of over 50 t/y. This is a huge extrapolation and one which would be hard to realise in practice. However, this theoretical exercise emphasises that technical solutions such as activated carbon could offer significant mercury reduction potential in Indonesia if mercury reduction becomes a priority in the future.

4.5 TECHNICAL AND FINANCIAL CONSIDERATIONS

It is important to remember that the emission reduction projections discussed in Section 4.4 are based on estimates and modelling calculations. The values given are not intended to predict actual mercury reduction potential based on technology choices. The decision on which technology to implement for mercury control will come down to three factors:

- The amount of mercury to be reduced (defined by the emission limit or any future reduction strategy);
- The cost of installing controls and whether they can be feasibly recovered over the remaining lifetime of the plant; and
- The technical barriers that may exist (such as lack of plant footprint or inappropriate plant lay out).

Although dated, the information in Table 4, from a previous ICSC report (Sloss, 2017), summarises the relative installation and operational costs for different mercury control strategies, including enhanced co-benefit effects.

TABLE 4 MERCURY CONTROL OPTIONS			
Approach	Capital cost	O&M cost	Comments
Oxidation additives (see Section 2.4.1)	Very low	Low	Halogenated additives significantly increase Hg oxidation and capture (potential corrosion must be managed)
Re-emission control additives	Very low	Low	Potential for re-emission of Hg should be mitigated
SCR catalyst, with downstream FGD	Low	Low	(Cost estimate only refers to the prioritising of an Hg suitable catalyst). May require coal blending to maximise the effect. Additives may be required to prevent re-emission
ACI injection (see Section 2.4.2)	Low	Low to moderate	Preservation of ash quality sometimes an issue, but becoming less so with newer sorbents

While the USA has had significant experience and success with these strategies (Sloss, 2017), Indonesian coals and coal plants are different from those in the USA and so it remains to be demonstrated whether these strategies would be more or less effective in Indonesia. The 2017 report also includes a summary of new emerging technologies specifically for mercury control, such as the ReACT system, the Airborne Process, Neustream and others. However, since some of these technologies have only been deployed at one site or even only at a demonstration scale, they are not discussed further here.

The cost and effectiveness of mercury emission reduction strategies in Indonesia cannot be easily extrapolated from experience in Europe or North America since the coals and plant configurations are different. Rather, operators in Indonesia will need to monitor how mercury emissions change with imminent plant modifications, learning how to maximise co-benefit mercury control through experimentation and practice. As the fleet moves to modify plants – for example through cofiring and the installation of FGD on some units, the data from emissions monitoring should be collected, collated, and analysed to draw conclusions on mercury behaviour specifically in Indonesian coal plants. This work could then be used to inform potential copying of successful practices across the fleet.

4.6 COMMENTS

Mercury reduction at coal plants in Indonesia is currently below the emission limit of 30 µg/m³. However, the UN Minamata Convention requires signatory countries to ‘control and where feasible reduce’ emissions and provides guidance on best available practices to achieve this. Indonesia must therefore consider its own definition of how it might apply BAT to reduce mercury emissions from the existing fleet.

Based on gross estimates the following comments apply:

- Some Indonesian coal units are not running at design efficiency. If all plants were upgraded to their intended efficiency, mercury emissions could be reduced by around 1–2%.
- Cofiring biomass or ammonia with coal would reduce mercury emissions by around the replacement value; a 10% biomass mix could reduce mercury emissions by 10%. However, actual results will depend on combustion chemistry and the offset value cannot be assumed.
- With only ESP installed, and with assumed Indonesian coal chemistry, an average Indonesian coal plant will achieve around 5–10% mercury reduction.
- A theoretical switch from an ESP to a baghouse could increase mercury control to 20–30%. Although this is not a practical consideration for existing plants, it could be considered for new build.
- The installation of WFGD systems could reduce mercury emissions by 17%; this is dependent on the coal properties and could be significantly higher, especially for coals with higher inherent chlorine content. If bromine were added as an oxidant this would increase to over 40%, possibly up to 90%.
- The application of activated carbon sorbent could reduce mercury emissions at a standard Indonesian plant installed with ESP by 80% or more, in conjunction with bromine.

Although advanced options such as activated carbon could have significant success on the Indonesian coal fleet, a cost analysis would have to be performed to determine whether it is a necessary and cost-effective approach.

Current emissions from coal plants in Indonesia are below the 30 $\mu\text{g}/\text{m}^3$ limit and the majority of plants in Indonesia burning ‘typical’ coal can meet it without any additional mercury-specific measures. However, if the limit were to drop to the 3 $\mu\text{g}/\text{m}^3$ limit of Europe and North America, a number of Indonesian plants may need to consider mercury-specific options and, based on the iPOG analyses, this could mean the addition of oxidant and/or activated carbon. As shown in Figure 9, the addition of 0.032 g/m^3 of brominated activated carbon could lower the mercury concentration in flue gas to 3.4 $\mu\text{g}/\text{m}^3$. A slight increase in the injection rate of brominated activated carbon would be capable of bringing mercury concentration in flue gas below the assumed 3 $\mu\text{g}/\text{m}^3$ emission limit.

5 COMMERCIAL OPTIONS APPROPRIATE FOR INDONESIAN PLANTS

As part of this project, a call-for-proposals was distributed to relevant stakeholders to collect and collate potential techniques and technologies to reduce mercury emissions in Indonesia. Several companies submitted information on how their technologies could be appropriate under the Minamata Convention compliance strategy for Indonesia. Full details of their proposals are included in the appendix to this report. However, a short summary of each technology is given here, including where possible, an indication of how well they may work on specific Indonesian coal plants.

The ICSC and the USDOS cannot and do not endorse any of these systems. Trials would need to take place to determine whether the expected emission reduction is achievable in practice. The information below is therefore intended to provide an overview of commercial companies who have already initiated work in Indonesia or who are willing and ready to talk to Indonesian stakeholders further on potential collaboration and demonstration projects.

5.1 BOILER UPGRADING

Many Indonesian plants are not running at design specification and could improve their operating efficiency by several percentage points, as mentioned in Chapter 4. By taking this action they would increase their electricity output whilst reducing coal consumption and related costs. Improving plant efficiency can be costly but can have a short payback period as more income is generated from more power output from less coal. Further, increases in plant efficiency will reduce all emissions including mercury and CO₂. As Indonesia plans to introduce a carbon tax in 2025, any increase in plant efficiency will yield savings on this impending tax through lower CO₂ emissions.

The following sections include examples of upgrading options suited specifically for coal plants in Indonesia, notably Ombilin and Suralaya.

5.1.1 Ombilin case study – Greenbank/Ammegen

Sloss and others (2021) identified the Ombilin plant as having the highest mercury emissions per GWh of energy produced. This was largely due to Ombilin, a small (100 MW) minemouth plant, running at low efficiency. The plant has now undergone an upgrade to improve its performance.

Greenbank and Ammegen completed work to balance the fuel-air distribution at the plant (Savarianadam and others, 2023; *see* Appendix). The project identified several issues at Ombilin relating to fuel and combustion imbalances and excursions from design specifications. The combustion

zone was mapped and modelled to allow the combustion conditions to be stabilised. This involved the modification of piping, the mill-to-burner flow system, and the air flow system with the commercial systems CoalFlo®, VARB®, and Control Gate®, as shown in Figure 10.

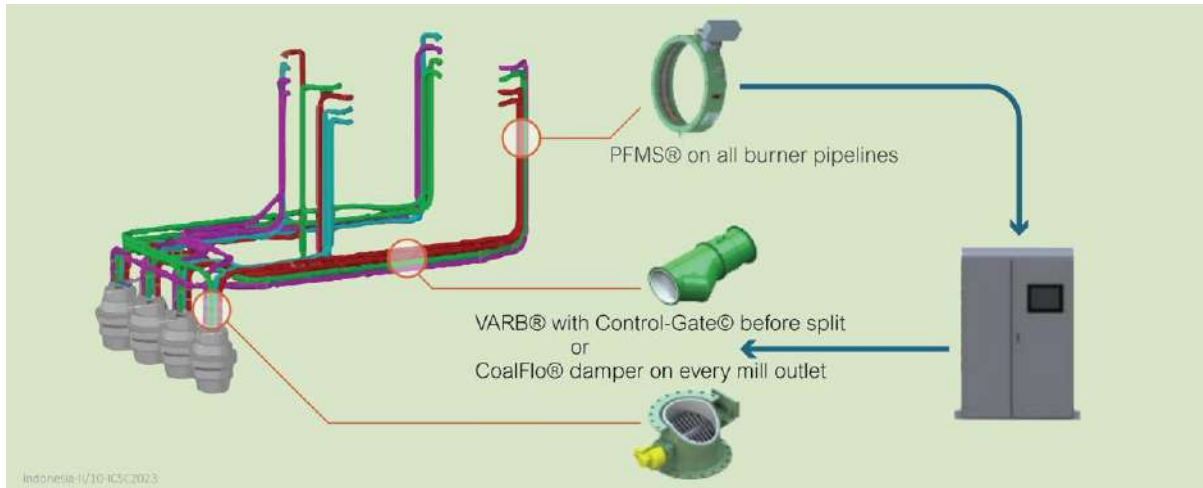


Figure 10 Dynamic balancing system applied at Ombilin power plant (Savarianadam and others, 2023)

Ombilin had a design rating of 100 MWe but was operating at 70 MWe due to low-grade, high-moisture fuel. It was producing ash which contained high concentrations of unburnt carbon which made it unsuitable for sale to the cement industry. By optimising the fuel and air flow through the plant, the carbon in ash was reduced from over 12% to under 8%, allowing the ash to be sold.

The effects of the recent project at Ombilin will be quantified after the first year of operation. However, for reference, a similar study at the Longannet coal-fired plant in the UK reduced the carbon in ash from 9.5% to 6.5%, created 225,000 £/y savings in efficiency, saving 45–48 t/d coal (equivalent to a further 815,000 £/y in plant costs). It is predicted that the upgrade work at Ombilin will provide a return on investment in under 5 years with a 2% saving in coal consumption.

At this stage, it is not possible to say how much mercury will be reduced at the Ombilin plant, but it is likely that the elevated mercury emissions (an order of magnitude greater than the rest of the Indonesian fleet; see Figure 5) are likely to be reduced and be more in alignment with those from other plants.

5.1.2 Suralaya case study – PET/ThermaChem FS12

Warga (2023) has developed a Plant Efficiency Toolbox (PET) which combines several factors:

- heat transfer maximisation using dedicated online heat transfer software;
- boiler tuning;
- anti-wall deposit technology; and
- an online application to ascertain the impact of wall deposits on coal usage.

Together the system enables coal power plants to compare how much more coal is burned and CO₂ emissions emitted compared to the plant design specification (see Appendix). The PET approach does not require capital investment or boiler stoppages to implement and provides significant economic and environmental gains.

A preliminary UN-funded project initiated in 2016 carried out boiler tuning at a 600 MW Suralaya unit. Based on the results, it has been suggested that tuning the plant with the PET knowhow and software alone could achieve:

- a reduction in coal use of 0.225 Mt/y;
- CO₂ emission reductions of 0.43 Mt/y;
- SO_x reduction potential of 3,070 t/y.

In addition to the tuning of the eight plant boilers, the project proposal includes the use of an additive – Therma-Chem’s FS12, a proprietary alkaline nitrate solution –which mitigates wall deposits that are known to reduce boiler efficiency. The additional use of Therma-Chem FS12 is predicted to:

- reduce coal use at Suralaya by 0.48 Mt/y
- reduce CO₂ emissions by 0.9 Mt/y

It is proposed that the application of this approach across Indonesia could reduce total coal use (from the existing fleet) by 8.3 Mt/y and lower CO₂ emissions by over 15 Mt/y. A previous four-year study carried out under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC) in Europe suggests that utilisation of FS12 can reduce plant CO₂ emissions by over 10% as a result of increased efficiency and reduced fuel consumption. Although the approach is not designed for mercury reduction, a decrease in coal use will result in a concomitant decrease in mercury emissions. Warga (2023) suggests that the savings in fuel would provide a rapid return on investment (within months) and could increase plant revenue, especially if a carbon tax is introduced in Indonesia. Savings from lower requirements for coal and reduced payment of carbon taxes could be invested in control systems to reduce other pollutants, including mercury. More details on this methodology are included in the Appendix.

5.1.3 Ombilin and Suralaya case studies – Sootaway

Sootaway, a treatment marketed by Johnsen Chemicals, has been used in plants in Poland, India, and Indonesia. Sootaway is a proprietary combustion catalyst based on a manganese complex that enables complete combustion at lower oxygen levels. Incomplete combustion means inefficient combustion and therefore more emissions from a higher consumption of coal (15–20% more).

Vebeenstad (2023) proposed the effectiveness of the Sootaway system (solution applied at 1 litre of Sootaway per tonne of coal) at the Ombilin plant. Although Ombilin has already been upgraded (see Section 5.1.1), it was predicted that the use of Sootaway could deliver:

- coal consumption reduced by 12%
- SO₂ emissions reduced by 57%
- NO_x emissions reduced by 39%
- PM emissions reduced by 20%

Assuming that the reduction in emissions of mercury would be directly related to the reduction in coal use, this could also mean at least a 12% reduction in mercury emissions. It is also suggested that Sootaway could lower coal use at Suralaya by 2–3% and reduce emissions significantly too, in the same order of magnitude as Ombilin.

As Indonesia moves towards requiring biomass cofiring at all plants, it is important to note that Sootaway can be used to reduce the slagging associated with cofiring, meaning reduced production of bottom ash and fewer shutdowns for cleaning.

5.1.4 Generic Indonesian coal unit – CastleLight Energy Corp

CastleLight Energy proposes a Clean Combustion System (CCS) as an option for older Indonesian coal plants; it is a field-demonstrated coal-fired plant retrofit technology (see Figure 11). The CastleLight approach includes options such as limestone addition to the boiler, boiler optimisation and sorbent (activated carbon) injection. The upgrades proposed for each plant would be determined on a case-by-case basis.

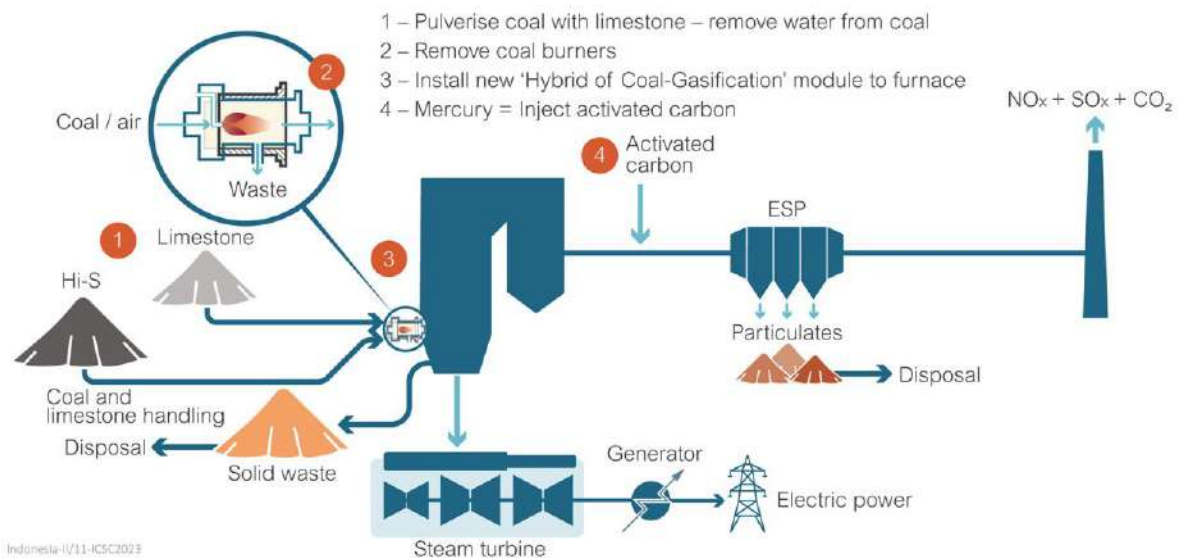


Figure 11 CCS conversion proposal for an Indonesian coal plant (Moore, 2023)

The CCS approach is designed:

- To address plant efficiency improvements (3% to 6%); reducing fuel cost and CO₂ emissions;
- To meet Indonesia's SO₂ and NO_x (550 mg/m³) pollution emission regulations;
- To modify a plant's coal pulveriser(s) with an additional fast, safe coal drying step to increase coal HHV and reduce fuel cost;
- To replace existing coal burners with what the suppliers define as a 'hybrid-of-coal gasification' (modules fit within boilers footprint); limestone (CaCO₃) is the only chemical required;
- To eliminate furnace wall ash deposition; no carbon in fly ash; LOI < 1%;
- To potentially retrofit all boiler types – wall-fired, tangential and cyclone designs; and
- To rework the plant's rotating turbine and machinery for improved plant efficiency – estimated at around 4%.

The plant start-up, operation and turn-down do not change as a result of these modifications and so still familiar to operators.

Table 5 shows the estimated cost of using the CastleLight CCS approach (boiler upgrade with activated carbon) rather than the standard retrofitting of FGD and SCR.

TABLE 5 EMISSION CONTROL COSTS FOR A 600 MW PLANT USING CASTLELIGHT CCS				
Estimate to add emissions control for 600 MW wall-fired power plant – Powder River Basin coal				
Control technology	Retrofit cost, \$/kW	Fuel cost, \$/y	+ Variable O&M cost, \$	Operating cost, \$/kWh
FGD + SCR + baghouse	1,102	80,000,000	24,000,000	0.0200
CCS w/existing ESP + ACI	425	70,000,000	11,000,000	0.0154
Delta Savings	61%	14%	54%	23%

Cost savings are predicted to be significant with retrofit costs being less than half that of standard emission control retrofits. Operation and running costs are also predicted to be significantly lower. More information can be found at: www.Castle-Light.com.

5.2 SORBENTS AND OXIDANTS

Sorbents and oxidants are additives which can enhance the capture of mercury from coal combustion. The combination of oxidants and sorbents could be the most effective means of reducing mercury emissions from Indonesian coal plants should they in, due course, need to meet the emission limits of Europe and the USA (*see* Chapter 4). There has been no testing of any oxidants or sorbents on Indonesian coal plants to date and so the following information is based on proposals which companies believe will work in Indonesia. More information on each of these systems can be found in the Appendix.

5.2.1 Bromine addition – Vosteen

Bromine is the most effective and appropriate oxidant for mercury oxidation in coal combustion. Chlorine is less effective. Although halogens can be corrosive to plant operation, the volumes used are low and the application processes (in addition to the fuel, to the boiler, or the flue gas) are designed to keep corrosion to a minimum. The use of bromine use has been patented in Europe by Vosteen Consulting Ltd and it is increasingly being used in coal plants there. The most recent application is ongoing at the Belchatów lignite power plant in Poland.

The addition of bromine can be cost-effective for mercury reduction at plants where fabric filters and/or FGD systems are already in place, as there is little or no requirement for structural change other than the bromine delivery systems (hoses, jets, or pumps). In plants where fabric filters or FGD are not installed, some retrofitting will be necessary. Bromine is a simple and cost-effective method that can be adapted and maximised to achieve the emission reduction required.

5.2.2 ME2C SEA© sorbent enhancement

SEA© is a sorbent enhancement additive that was developed in partnership with the US Department of Energy's (DOE) National Energy Technology Laboratory (NETL). The SEA technology is being applied at plants throughout the USA and Canada and has provided control for over 10 years. The SEA additive can be applied to sorbents, enhancing mercury absorbency, but it can also enhance the capture of fine particulates, SO₂, SO₃ and ammonia. Mercury reduction could be as high as 90% but will vary with coal and plant-specific factors and would therefore have to be determined on a plant-by-plant basis. The cost of the equipment is generally less than 10 \$/kW and the operating cost of the two-part system varies from 0.10–0.75 \$/MWh. MEC2C has proposed plant-specific suggestions for pollutant reduction at the three plants selected in Indonesia (see Appendix).

5.2.3 Lanxess Geobrom© oxidant

In the LANXESS treatment, a combination of oxidant and sorbent can be used for both SO₂ and mercury control, replacing the need for a wet FGD system. The capital and running costs of the technology are significantly lower than wet FGD or standard sorbent injection and can achieve over 90% SO₂ control. The company would perform pilot testing before designing and installing a unit-specific solution.

5.2.4 Thief Process – Mobotec/NETL

The Thief Process uses fly ash from the plant itself as the sorbent for mercury capture. It avoids the need to add to plant consumable costs. Testing is necessary to set up the fly ash processing to maximise the mercury capture potential. The Thief Process was developed by the USDOE NETL and licensed first to Mobotec, and then to Nalco Mobotec. It has been demonstrated at large scale. The technique is

notable as one of the lowest cost methods of manufacturing activated carbons. The method may have great application in countries where 80–90% mercury removal from coal flue gas is required.

5.2.5 Lehigh University fly ash-based sorbent

Lehigh University, PA, USA also proposes a means whereby the chemistry of the flue gas and the fly ash at the plant are modified to maximise co-benefit mercury reduction. A full balance-of-plant project would consider the existing plant configuration and emission control systems and work to maximise mercury capture at minimum cost. The Lehigh technology is carried out in two stages:

- **stage one:** the boiler and back-end components are optimised for mercury capture;
- **stage two:** the technology employs a portion of the fly ash collected from the ESP, treats it, and reintroduces it into the flue gas flow using multiple nozzles where it acts as a sorbent to capture mercury.

5.2.6 Oxidant and sorbent – Technical University of Ostrava

The VSB Technical University of Ostrava, Czechia, proposes to investigate the specific plant configuration and flue gas characteristics to determine the most appropriate combination of sorbent and additives to maximise mercury control. The capture of the mercury-laden sorbent would be in two stages – a cyclone filter followed by a baghouse. This allows separation of the sorbent from the fly ash which will ensure the fly ash remains saleable.

5.3 FURTHER MERCURY-SPECIFIC RETROFITS

5.3.1 Gore™ GMSCS

GORE™ has developed a Mercury and SO₂ Control System (GMSCS) based on catalyst/sorbent composite material. The modules can be placed directly into the flue gas to continuously capture gas phase mercury without requiring any reagent. Each module can last over 10 years. The modules contain a catalyst that converts SO₂ into sulphuric acid which is collected as a liquid for potential beneficial use. The captured mercury would need to be disposed of separately.

5.4 COMMENTS

Numerous commercial systems are available which could be of importance in Indonesia as part of a pro-active mercury emission reduction strategy. Systems which optimise plant performance and efficiency will be most cost-effective as they will reduce fuel costs whilst increasing power production. Emissions of all pollutants will be reduced simultaneously. Most of these systems would be ideal for Indonesia where many of the plants do not run at design efficiency. The initial investment in plant or boiler upgrading commonly has a short pay-back period and could mean significantly increased revenue for the plant in the future.

For mercury-specific control, the most common options are oxidants and/or sorbents. However, these are normally only considered when mercury emissions need to be targeted specifically. This is not currently the case in Indonesia but, should the country move to match the emission limits of Europe and North America, oxidants and sorbents may be required.

6 CONCLUSIONS AND RECOMMENDATIONS

A compliance strategy is required for the Indonesian coal fleet to control, and where feasible reduce mercury emissions. The fleet is divided into two sectors – new plants and existing plants. Each sector will have a distinct approach.

PROPOSED BAT STRATEGY FOR MERCURY CONTROL AT NEW INDONESIAN COAL UNITS:

- All new plants should be at least supercritical, although ultrasupercritical would be superior.
- All plants should be installed with PM control – ESP, baghouses or equivalent. For new build plant, baghouses would be preferable to ESP due to their higher rate of mercury capture.
- All new plants should have control strategies to reduce NO_x emissions. If SCR is used, then optimal mercury reduction should be included when selecting catalyst materials.
- All plants should have sulphur emission control, ideally wet FGD or equivalent. If seawater FGD is used, planning for installation should include evaluation of potential issues with mercury discharge in liquid effluent (*see Chapter 5*).
- All new plants should include mercury control in the planning process and, even if mercury is not specifically targeted, plant footprint space should be set aside for potential retrofitting of sorbent injection systems or for other advanced flue gas cleaning options, including carbon capture and storage (CCUS).

For existing plants, the challenge is greater. The Indonesian government should continue to consider emission reduction as a plant-specific strategy rather than a standardised requirement across the fleet. Targeted emission reduction at high-emitting plants will be more cost-effective. The approach will have to remain open to change as other requirements become relevant, such as selected plant closure, cofiring requirements, and so on.

The annual fleet inventory should be updated to include changes in plant lifetimes (such as early closure for Cirebon), changes in fuel (such as biomass and ammonia cofiring) and retrofits (FGD). This will ensure a coordinated approach to address the current and relevant challenges in the changing fleet. The government requirement for cofiring biomass and/or ammonia will lead to a slight reduction in emissions, largely due to the replacement of coal with fuel that does not contain mercury. However, overall, mercury reduction from cofiring will be minimal.

The most cost-effective method for mercury reduction for many older Indonesian plants could be through plant upgrading. Improving plant efficiency guarantees not only emission reduction but also increased electricity output from less fuel – a return on investment is then followed by years of increased revenue.

Mercury-specific control is not necessary since the current emission limit is still relatively lenient. However, it is likely that, like other regions, the emission limit will tighten in the future. It will then be necessary for Indonesian plants to identify the most appropriate methods of mercury reduction. There are factors that will affect the choices made:

- Indonesian coals produce mercury largely in the elemental form – inherent co-benefit reduction will be low.
- Oxidants such as bromine make mercury easier to capture but plants will still need to consider upgrading ESP to baghouses, the addition of sorbent injection and capture systems, and/or the application of FGD to actually capture the mercury.
- SWFGD systems will be lower cost and effective for SO₂ control but may create a new issue in terms of mercury release to local water bodies and this should be a major consideration in any future SWFGD system installation.

The Minamata Convention mercury compliance strategy for the existing Indonesian coal fleet will therefore have to be considered and specific, with a unit-by-unit approach. This would be best managed by building on the unit-by-unit spreadsheet provided by Sloss and others (2021). The spreadsheet should be updated annually at least, to take into account plant closures and plant retrofits. This will allow stakeholders to monitor continually the largest remaining sources and make informed decisions on future closures and retrofits.

**PROPOSED BAT STRATEGY FOR MERCURY REDUCTION AT EXISTING
INDONESIAN COAL UNITS:**

- Maintain and updated the unit-by-unit emission inventory to ensure that the identification of the most important long-term emission sources is up-to-date, and the emission reduction strategy adjusted accordingly (remove closed units and modify data for retrofitted plants).
- When possible, use emission data from the emission monitors being installed across the fleet to increase the accuracy of the emission estimates and to identify or confirm the sources of greatest concern.
- Continue to identify, and focus on, plants with the highest capacity and longest remaining lifetimes as these plants will be responsible for the greatest emissions overall and therefore are the most appropriate targets for cost-effective action.
- Maximise cost-effective co-benefit mercury reduction with flue gas technologies in place – oxidants could be applicable.
- When emission control retrofits are being considered for other pollutants (PM, SO₂, NO_x), mercury co-benefits should be maximised from the planning stage.
- Take expert guidance. Indonesian coals and coal utilities differ from those where mercury control strategies were developed. This document provides a list of international experts and vendors which could be useful. However, this is not an endorsement of these companies or their technologies.
- Share experience between plants and projects. There will be a period of trial and error to determine which systems work best so sharing this experience can accelerate effective strategies across the fleet.

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APPENDIX

The Appendix includes information from each of the commercial suppliers included in this report as it was originally provided by each organisation/company. Inclusion of these details here does NOT signify any recommendation or endorsement by the authors of this report, by the ICSC nor by the USDOS. Contact details of each organisation are included and interested parties are encouraged to contact these organisations for further information.

The following information on commercial suppliers is provided according to the order these technologies were discussed in the main report.

A1 GREENBANK/AMMEGEN

The Ombilin case study was described in Chapter 7.

Contact Ammegen Ltd: Hartshorne Road, Woodville, Derbyshire, DE11 7GT UK.
Tel: +44(0)845 0707 097, web: <https://www.greenbankgroup.com/ammegen.htm>

A2 PLANT EFFICIENCY TOOLBOX (PET) INCLUDING THERMA-CHEM FS12

The Suralaya case study was described in Chapter 7. The following is additional material from the technology provider.

Warga (2023) has developed a plant efficiency toolbox (PET) which comprises the following main constituents:

- Boiler heat transfer software (www.boilerdesignsoftwareonline.com);
- Boiler operational tuning, to increase boiler efficiency;
- Therma-Chem FS12 boiler anti-wall deposit technology (Therma-Chem: <https://therma-chem.com/>);
- Boiler wall deposit impact assessment online Utility (www.coalminder.co.uk)

The heat transfer software is designed to be user-friendly, comprehensive, and rapid. It can predict the impact in boiler performance which may arise due to changes in fuel composition, operating parameters, and internal geometry. The root of the problem is that existing boiler heat transfer modelling software tends to be complex to operate requiring dedicated personnel and is also not

publicly available. Consequently, power plants don't profit from it as they could. The software fits requirements for daily use by engineers, handles all existing power boiler designs and delivers accurate results quickly and is available online.

As discussed in Chapter 3, the potential for the PET process has been investigated at Suralaya within the framework of a United Nations-sponsored project. Perhaps the most effective alternation to the plant would be the application of Therma-Chem's unique FS12 alkaline nitrate additive, which reduces wall deposits and thus increases heat transfer rates and plant efficiency:

- Wall deposits plague coal-fired boilers;
- Heat transfer is reduced;
- Steam is wasted in the deposit removal process;
- Coal use and emissions increase;
- Mitigation techniques with limited effect;
- Wall deposits' effect on coal usage and CO₂ emissions is largely unknown;
- Effect of wall deposit removal on coal usage and CO₂ reduction is largely unknown.

Therma-Chem FS12 targets and reduces/eliminates wall deposits while the unit remains online. The boiler heat transfer efficiency is increased, reducing fuel usage and emissions. The generation design capacity is restored increasing revenue. Finally, corrosion is prevented, reducing maintenance costs.

Unlike oxidants, the FS12 chemical is not a fuel additive but instead is applied directly into the combustion chamber of the boiler using a simple injection system. At the beginning of treatment, the solution will be applied several times a day for 60–90 days at a rate of 3 L/MW/day. The plant would then move to maintenance dosing, twice a day at 2 L/MW/day.

FS12 has been utilised at a plant in Europe as part of a UNFCCC Joint Implementation project between the Danish and Romanian governments. The results reported an average of between 24 and 36 kt/y CO₂ reduction at the plant – equivalent to over 10% reduction in CO₂ emissions – as can be seen in Table A1 below.

Year	Baseline emissions before Therma-Chem (t/CO ₂ -eq)	Emissions after Therma-Chem (t/CO ₂ -eq)	Emissions reduction with Therma-Chem (t/CO ₂ -eq)	Emissions reduction with Therma-Chem (%)
1	375,778	339,283	36,495	9.71
2	259,843	234,590	25,253	9.72
3	269,001	239,900	29,101	10.82
4	233,273	208,712	24,561	10.53
Total	1,137,895	1,022,485	115,410	10.14

The utility online tool called CoalMinder allows for the assessment of coal-fired power plant boiler wall deposits' impact on fuel usage and CO₂ emissions. Moreover, it also tracks the effect of the wall deposit removal technique on fuel usage and CO₂ emissions reduction. Results are written in an Excel file, which contains a procedure explanation. This way operators now have a way to become aware of the wall deposits-related waste extent, prompting action.

Although the PET approach is not specifically designed for mercury control, a reduction in fuel use will result in a concomitant reduction in mercury emissions. Further, as Warga (2023) stresses, the fuel savings and increased revenue from electricity production, and potentially from Indonesia's proposed carbon tax, could result in a rapid return on investment whilst delivering economic and environmental benefits for plants.

Contact: Dr Zeljko Warga: Slovenia. Tel: +38640800276, email: zeljko.warga@gmail.com, Skype: wzeljko, web: <https://zeljkowarga.wixsite.com/coalpower>, www.coalminder.co.uk, www.boilerdesignsoftwareonline.com

Contact 2: Therma-Chem: 52 Crossgates, Bellshill, ML4 2EE, Scotland, UK. Tel: +441698 767575, email: info@therma-chem.com, web: <https://therma-chem.com>

A3 SOOTAWAY

Sootaway is a proprietary combustion catalyst for solid fuel that enables complete combustion at a lower level of oxygen. Rather than targeting the removal of high emissions from flue gas, Sootaway aims to solve the issues that cause these problems. Efficiency is increased through:

- Reduction in the creation of carbon monoxide (CO);
- Reduction in unburnt carbon in fly ash, bottom ash, and sediments;
- Increased heat transfer through reduced sediments on the heat exchanger.

Emissions of CO, CO₂, PM, hydrogen cyanide (HCN), NO_x, and SO₂ will be reduced, and with lower levels of SO₂ and HCN in the boiler, corrosion will also be reduced. This will provide cost savings in terms of maintenance and repair.

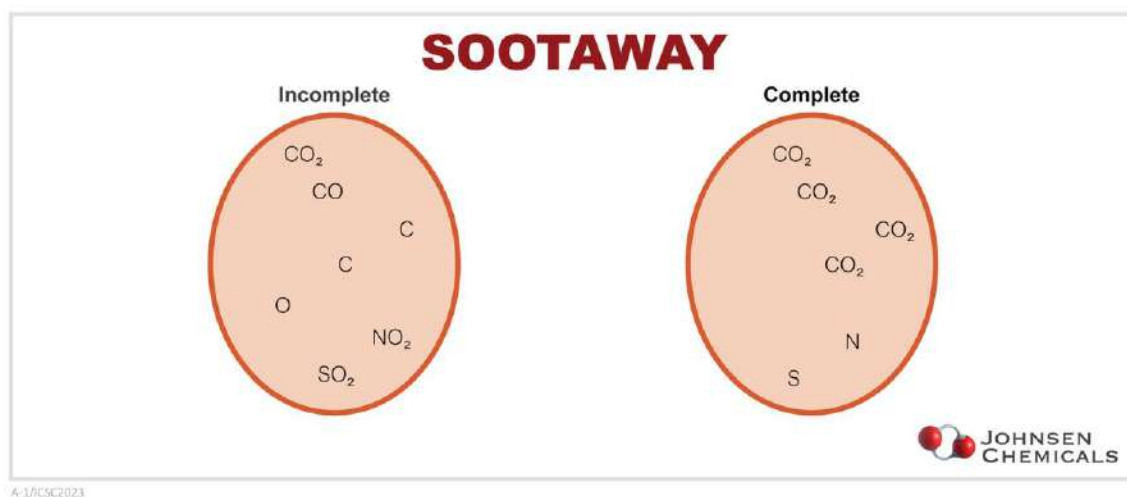


Figure A-1 Combustion chemistry affecting corrosion

A demonstration study at a coal plant in Dongamahua, India reported:

- 60% lower CO emissions;
- 31% lower SO₂ emissions;
- 11% lower NO_x emissions;
- 10% less coal use.

Based on the success of Sootaway applications in India and Poland, it is estimated that it could successfully reduce coal use and emissions from both Ombilin and Suralaya.

In addition to reduced coal consumption per MW of power produced, because Sootaway effectively reduces the creation of many pollutants, it can save or offset plant costs for ammonia (by avoiding the need for SCR), limestone (by avoiding the need for, or improving the efficiency of, FGD) and will also reduce the time and cost needed for shutdown and cleaning of the plant.

Contact: Leif Vebenstad: Tel: +47 91331089, email: Leif@johnsenchemicals.com, web: <http://johnsenchemicals.com/sootaway-en>

A4 CASTLELIGHT

The submission by CastleLight is summarised here. The full presentation can be found at <https://www.sustainable-carbon.org/workshop/strategies-for-emission-reduction-agenda/>

Existing Indonesian fleet of coal-fired electric generating units (>100 MW):

- 15 newer units with ESP + SO₂ control (WFGD): 6.75 GW;
- 46 older units (seeking higher efficiency and pollutant emissions control): 19.80 GW;
 - 21 wall-fired units w/ ESP particulate control: ~11.00 GW;
 - 15 tangential-fired units w/ ESP: ~5.10 GW;
 - cyclone-fired units w/ ESP: ~850 MW.

Program to improve fleet efficiency/heat rate: The most important factor for the Indonesian coal fleet is to improve efficiency. The average gross efficiency of older Indonesian coal-fired plant is 27%. Also expressed as Heat Rate = ~12,600 (3421/27%). Modern HELE plants report heat rates from 9500 [36%] to 8500 [40%]. Heat rate is like a golf score – ‘the lowest number wins’.

Under the Paris Agreement Indonesia has committed to reduce CO₂ (compared to BAU) emissions by 29% by 2030. Additionally, Indonesia has launched a carbon credit scheme to accelerate the country’s move towards net zero. The national carbon credit market could reach a value of over \$194 billion. Over 99 coal units will participate in this scheme, representing 86% of the coal fleet capacity.

Programme to address fleet pollution emissions: The challenge to address pollution emissions for ‘existing sources’ is significant, as older plants were not designed and built with emissions control as a major consideration. Indonesian units are already equipped with the ESP to control fly ash particulates (100 mg/m³). The plant sites have no room to add conventional flue gas cleaning equipment.

Under guidance from the UN Minamata Convention (UNEP, 2019), Indonesia is expected to meet the stack emission limits for SO₂ and NO_x of 550 mg/m³. The emission limits for mercury of 30 µg/m³ are defined by EMMS. CEMs will also be needed to provide the plant’s emission data.

CastleLight Energy ‘Clean Combustion System (CCS)’ for retrofit of coal-fired electric generating plants: The CCS technology evolved at Rockwell International from fundamental combustion research developed for the US Moon rocket program. Proprietary R&D sponsored by a consortium of US and Canadian utilities (SC Edison, Houston L&P, Niagara Mohawk, and Wisconsin P&L developed a practical Hybrid of Coal Gasification to replace a steam boiler’s coal burners. To date, there are some \$60 million in R&D, Field Demonstrations & Commercial US Utility / USDOE peer-reviewed programmes.

CCS Technology: The CCS fires pulverised coal with some powdered limestone (CaCO₃) in a simple (fuel-rich) staged combustion process. Under these high temperature conditions, carbon is oxidised to CO, sulphur binds with calcium to form calcium sulphide (CaS) and NO_x is reduced to nitrogen. Both SO₂ and NO_x emissions are controlled in the combustion step. The high combustion temperatures melt the coal ash and encapsulate the sulphur forming a liquid ash (slag) that drains to a water quench

tank. The clean hot fuel-rich gas then enters the boiler furnace to generate steam. Additional overfire air (OFA) completes the combustion of CO to CO₂ and hydrogen to H₂O. The furnace walls remain clean and free of slag deposits, improving boiler efficiency. The plant's existing ESP controls any fine particulates. If needed, mercury flue gas emissions may be controlled by ACI before the ESP.

CCS Coal Preparation: A coal-fired plant retrofit with the CCS uses the plant's existing coal pulveriser(s) and the plant's hot (inert – no O₂) flue gas as a sweep gas to pulverise the coal. The dry powdered coal and limestone and wet sweep gas are directed to a small baghouse to collect the coal. The wet sweep gas is piped around the boiler to the ESP. Coal is then metered from the baghouse to the CCS gasifier.

CCS Coal Moisture Removal: Indonesian coal includes about 30% moisture. In a CCS, the moisture is removed from the coal in about one second, improving the coal's HHV energy values. For the operation of PLTU Suralaya Plant number 1 to number 7, we estimate CCS coal drying results in a 6.2 % CO₂ reduction (12,900 t/y) with significant coal savings of 437,000 t/y (~\$ 87 million).

CCS Demonstration: TransAlta Utilities sponsored a one-year Pilot Scale program in Cold Lake, Alberta, Canada. Firing a low-sulphur, high moisture Highvale coal (similar to Indonesian subbituminous coals) w/limestone, emissions of SO₂ – 0.2 lb./MBtu (250 mg/m³) and NO_x – 0.15 lb./MBtu (184 mg/m³) meet Indonesia stack emissions requirement of 550 mg/m³. Note also <0.1 % carbon in fly ash (see Figure A2).

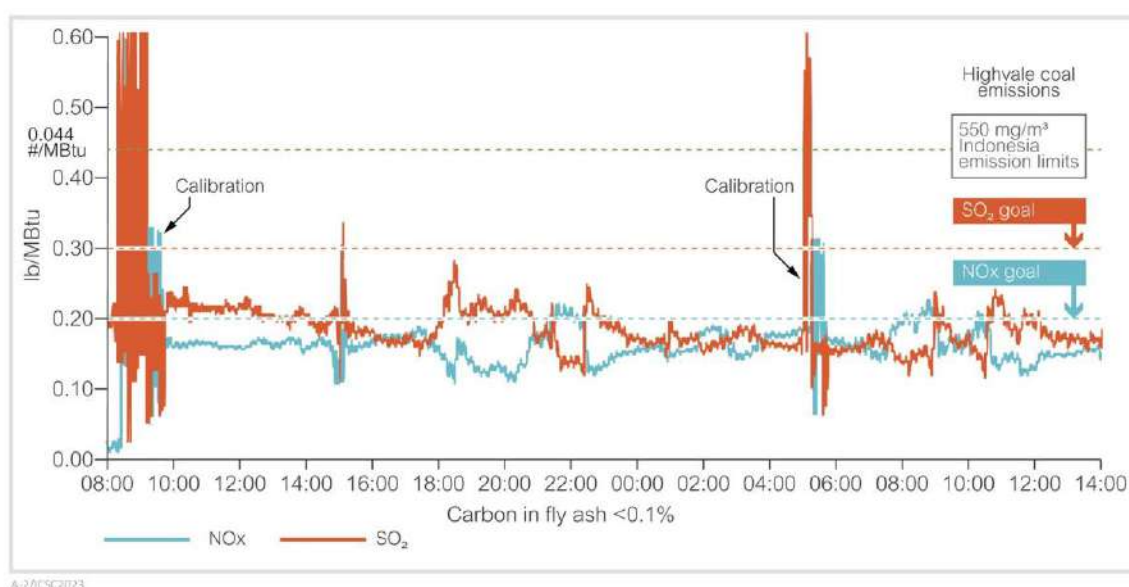


Figure A-2 CAP facility SO₂ and NO_x emissions

The potential for CastleLight technology to increase plant performance and reduce emissions in Indonesia was summarised in Section 5.1.4. For more information:

Contact: Keith Moore CEO: CastleLight Energy Corp. Tel: 805-551-0983, email: keith@castlelight.com, web: www.castlelight.com

A5 BROMINE – VOSTEEN

The following figures are included as provided by Bernhard Vosteen.

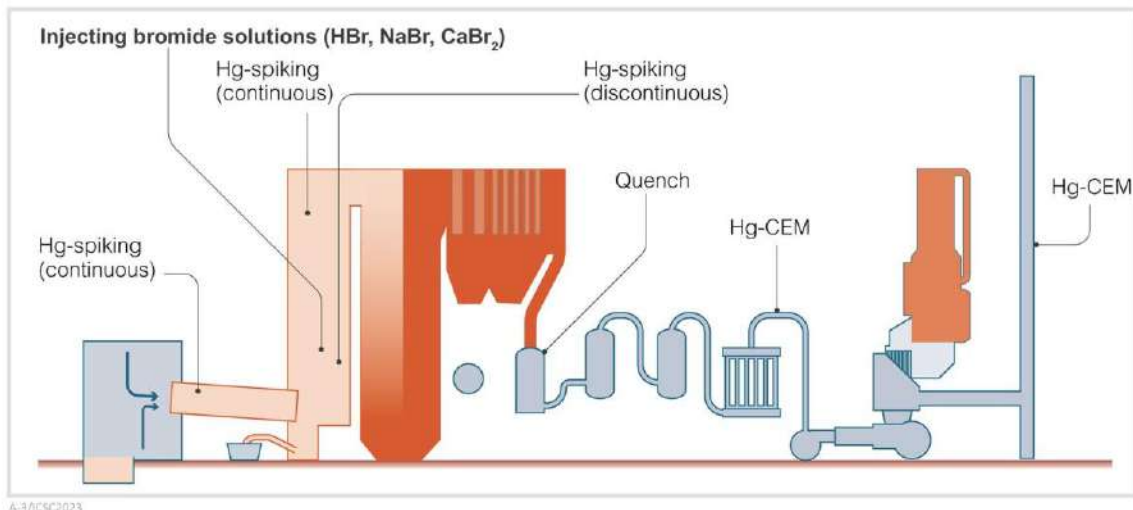


Figure A-3 Site of oxidant injection pre-boiler

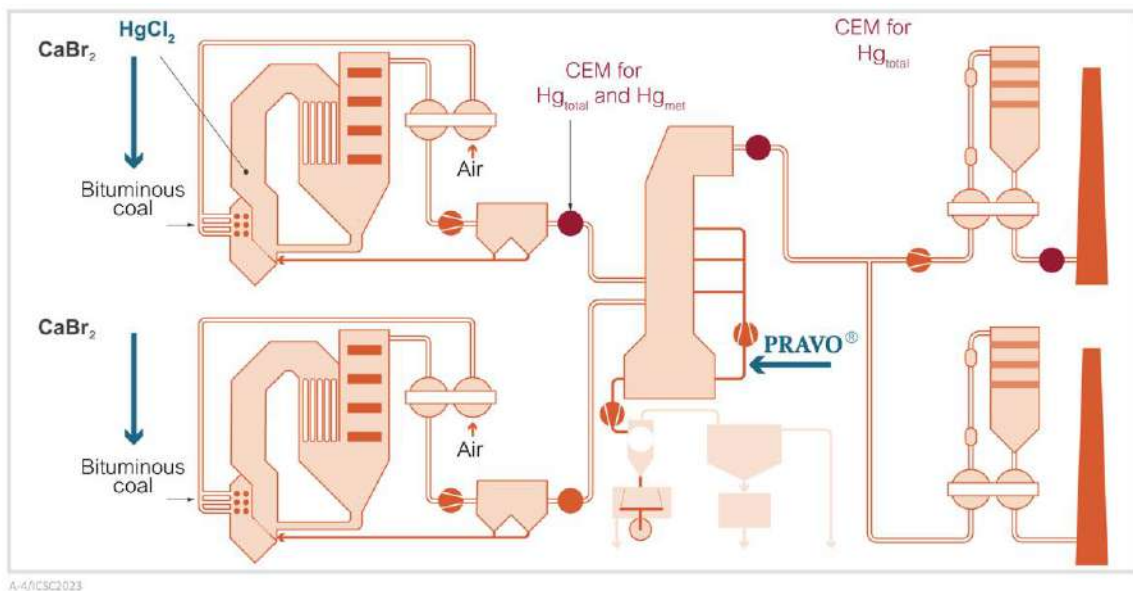


Figure A-4 Potential sites for oxidant injection

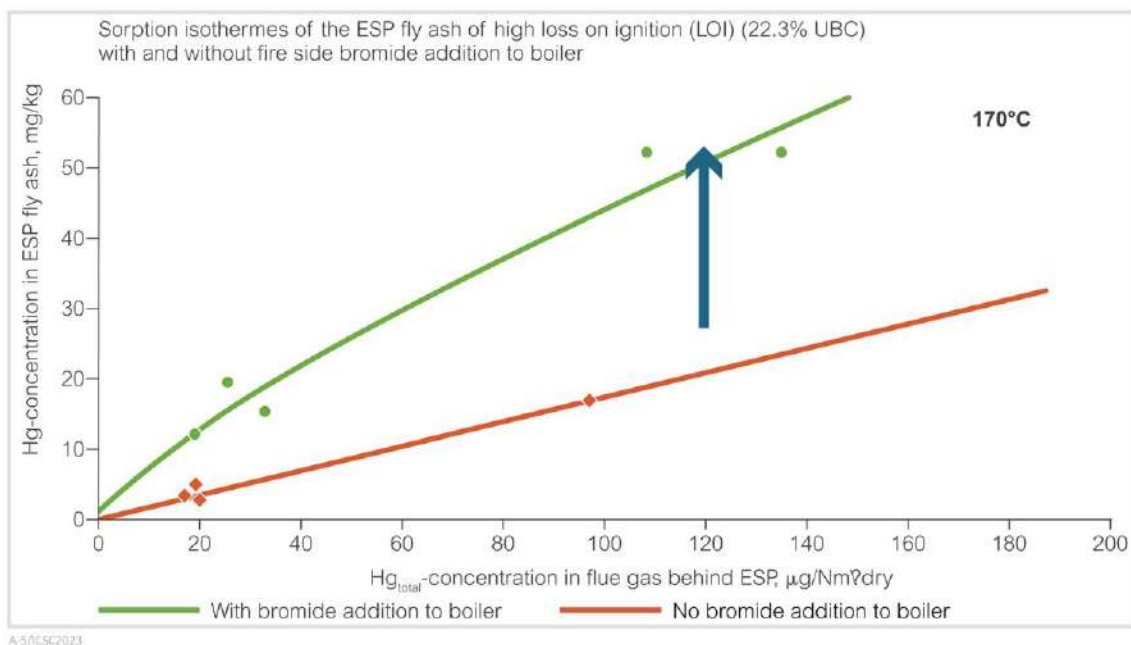


Figure A-5 Effect of bromine addition on mercury capture on ESP fly ash

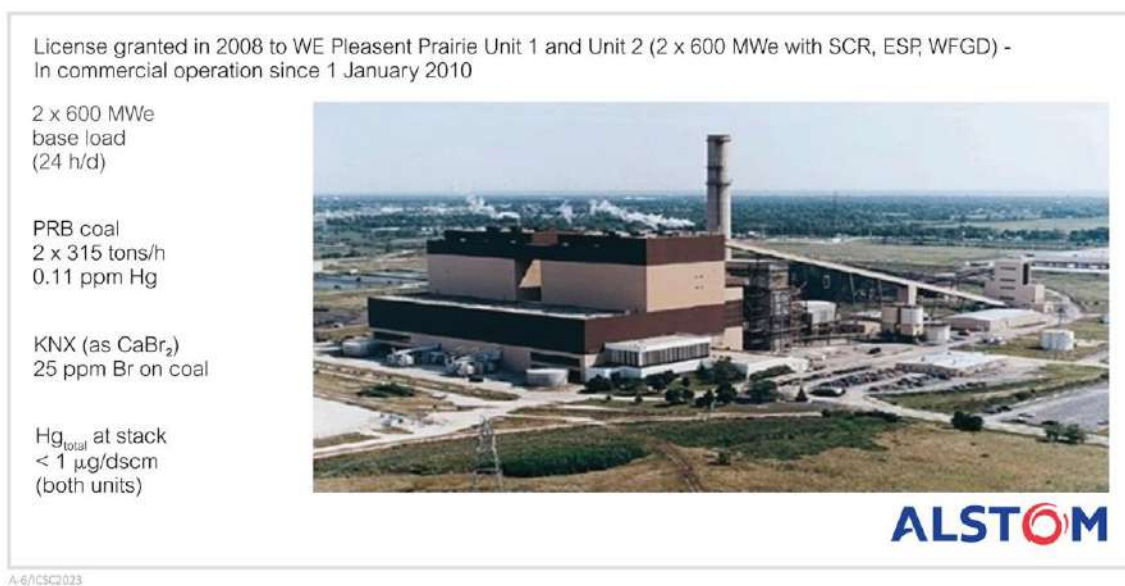


Figure A-6 Pleasant Prairie coal plant, USA – site of bromine testing

Since 2001 Vosteen's Bromine-Enhanced-Mercury-Oxidation-technology using Bromide solutions (BEMO-technology) has been successfully applied at a multitude of coal- and lignite-fired power plants as well as at waste-to-energy plants proving to be a most effective, though simple, and inexpensive retrofit method to promote dry and/or wet mercury removal from flue gases. Large-scale tests of the BEMO-technology at the huge Belchatów site in Poland (12 units, summing up to in total 5100 MWe) and its subsequent commercial application there, were reported. Precipitation agents such as our inorganic PRAVO®200 are used in large power plants as liquid wet-FGD additive to suppress Hg re-emissions and to stabilise the dissolved mercury bromide as solid (water-insoluble) mercury

sulphide. The success of the BEMO-technology has been acknowledged as a BAT within both European BREFs on large combustion plants and likewise waste-to-energy plants. Also, during full load, the oxygen content in the firing 'should not be too low'. Otherwise, the mercury oxidation will become insufficient (any Deacon reaction needs oxygen).

Contact: Prof Dr Bernhard W Vosteen: Vosteen Consulting GmbH, Cologne (Germany).
Tel: 0049 221 68009822; fax: 0049 221 68009824, mobile: 0049 1601912401, email: info@vosteen-consulting.de

A6 ME2C

ME2C Environmental is a global leader in mercury reduction technologies but also has the personnel and expertise to address a wide array of pollution control equipment and strategies. ME2C can work with a utility to identify and address specific reduction/control needs that meet targeted or required emission limits. ME2C can assist through the entire process, including technology selection, procurement, design and construction, commissioning, optimisation, and normal operation.

ME2C Technology Applied to Indonesian Coal Plants: The ME2C mercury control technology, SEA® (Sorbent Enhancement Additive), is a very flexible platform that is easily customised for a specific plant or unit to maximise mercury emission reductions at a competitive, and often the lowest, cost. This is achieved by using a two-part system that includes tailoring both a front-end material added to the coal or directly into the furnace and a back-end material injected upstream of a particulate control device. Even though the materials are different, the equipment needed is relatively simple and has been designed and perfected over time by ME2C to work reliably and efficiently.

Indonesia's ongoing commitment to coal-fired power generation requires emission reductions to their fleet to improve air quality around the country. ME2C believes that simplicity and flexibility are key factors that will enable emission reductions while also allowing for rapid changes as the power needs of Indonesia change. Below are brief emission reduction strategies for the three plants of interest, which can be applied broadly to other plants in Indonesia. Further specifics and details can be discussed in the future with ME2C, if interested.

Suralaya Unit 6, 600 MW: There are three options for Indonesia to consider for Suralaya Unit 6, each ranging in cost and benefits:

- **Highest Level, Long-Term Pollution Reduction:** The long-term, most expensive control option is to upgrade the plant with the installation of a WFGD system and low NOx burners. This will achieve significant SOx and NOx reductions and will also reduce PM and mercury emissions through capture in WFGD.
- **Moderate Pollution Reduction:** Shorter term and less expensive control options include an ESP upgrade to reduce PM emissions and increase mercury capture. The installation of a

ME₂C mercury control system, including a tailored sorbent for the Suralaya units, will reduce mercury emissions and improve reductions in PM emissions by conditioning the ESP.

- Minimal Pollution Reduction: A low-cost option to consider would be a boiler tune-up to improve overall plant/unit efficiency and lower NO_x levels.

Paiton (II), 610 MW: Paiton is equipped with a full suite of emissions control equipment and could potentially benefit from lower NO_x and improving efficiency from a boiler tune-up and optimisation. To lower mercury emissions, ME₂C suggests providing an additive product that would be added to the coal and/or furnace which would increase mercury capture across the system. The equipment required is very simple and low cost. Additional mist eliminators and/or spray level optimisation in the WFGD may also increase SO_x capture and further reduce mercury and PM emissions.

Ombilin 100 MW: Due to the small size, extremely low efficiency, and general operations, the recent boiler upgrade should represent a significant improvement for the plant. A boiler tune-up should be considered to ensure that the boiler is operating as efficiently as possible which would further assist in lowering SO_x, NO_x, and PM emissions. ME₂C can provide a fairly low-cost system to reduce mercury emissions.

Proven experience – Case study

ME₂C has provided mercury control systems to numerous large utilities for over 10 years. The case study presented here is a 550 MW plant equipped with an ESP only that burns a subbituminous fuel. The plant initially used SO₃ injection (3 to 9 ppm) to control opacity, which makes mercury control very challenging. To meet a 20% opacity (6 minutes) requirement and a mercury emission limit of 1.2 lb/trillion Btu (>90% mercury removal), the plant had to operate at a 200 MW derate (200 MW below full load). Attempts to increase MW output resulted in either opacity limit excursions or the inability to stay below the regulated mercury emission limit. This load reduction significantly affected the operability and profitability of the plant and its position with respect to load dispatch. Due to the poor ESP performance and SO₃ injection, mercury control injection rates were very high, even with the plant operating at 200 MW below full load. ME₂C was tasked with the challenge of maintaining mercury compliance and opacity (PM) compliance while achieving as high of a load as possible, and ideally returning to full load.

ME₂C conducted a demonstration test with its two-part system which included adding a material upfront of the boiler along with a variety of ME₂C tailored back-end sorbents. The material added upfront was added directly into the boiler furnace and the material on the back-end was injected into the flue gas ahead of the air preheater using the existing lances and distribution system. Using this technology combination, mercury and opacity compliance were demonstrated and maintained all the way up to full load, and compliance costs were lowered by 50%. The technology provided by ME₂C worked so well for opacity that the plant shortly thereafter removed their SO₃ injection system as it

was no longer needed, even at full load. Since installing the ME₂C technology in 2016, the plant has operated at full load while maintaining control of mercury and opacity below the required regulated emissions limits.

SEA® Technology, a proven ‘BACT’ for mercury emissions reduction: The SEA technology commercialised by ME₂C Environmental is internationally recognised as a ‘Best Available Control Technology’ developed in the early 2000s under a research project partnership overseen by the USDOE, Office of Fossil Energy’s NETL. An overview of this early development is published in a 2008 NETL report.

ME₂C introduced the patented SEA technologies to coal-fired power plants across North America beginning in 2011, and since that time, has significantly reduced mercury emissions and improved plant operations for numerous, major utilities. The SEA technology is believed to be used by more than 40% of the US fleet. ME₂C has been providing mercury control equipment and solutions for over 10 years and has over 35 patents on mercury control solutions for coal-fired power plants.

ME₂C’s website (<https://www.me2cenvironmental.com/>) provides an overview of the SEA technology, information on our patented sorbents and emissions control services, and our sorbent product data sheets.

Mercury control costs:

- The cost of the equipment for the 2-part system that ME₂C routinely provides for mercury control is generally less than 10 \$/kW.
- The operating cost of the 2-part system varies from plant to plant depending on the type of fuel that is combusted, the plant configuration, the emissions control equipment that is installed, the load profile and capacity factor, and the target level of removal of mercury.
- Generally, the operating cost for mercury control (which includes the additive/sorbents provided by ME₂C) varies from 0.10 \$/MWh to 0.75 \$/MWh.

Contact: Dr Nicholas Lentz: Field Technical Manager. Tel: (614) 505-6115, email: nlentz@me2cenvironmental.com


A7 THIEF PROCESS – USDOE

The Thief Process is a cost-effective variation to ACI for the removal of mercury from coal-fired utility flue gas. Partially combusted coal from the furnace of a pulverised coal power generation plant is extracted by a lance and then re-injected into the ductwork downstream of the air preheater. The Thief Process can be very helpful to industry, especially with recent projections indicating future shortages of activated carbon for coal-burning utilities. Recent results on a 500-lb/h (227 kg/h) pilot-scale combustion facility show similar removals of mercury for both the Thief Process and ACI. The tests conducted to date at laboratory, bench, and pilot scales demonstrate that the Thief sorbents exhibit capacities for mercury from flue gas streams that are comparable to those exhibited by commercially available activated carbons.

The Thief sorbents are significantly cheaper than commercially available activated carbons; exhibit excellent capacities for mercury and; the overall process holds enormous potential for reducing the cost of mercury removal from flue gas. The Thief Process was licensed first to Mobotec, and then to Nalco Mobotec in May 2005. The Process was successfully demonstrated at large-scale at the commercial coal-burning utility SaskPower.

In addition to the licenses to industry, the Thief Process won the R&D 100 award in 2009 and spawned dozens of similar technologies as shown in the US and international patent literature. The technique is notable as one of the lowest cost methods for manufacturing activated carbons. The method may have great application in countries where 80–90% mercury removal from coal flue gas would be acceptable.

2. GP-254 Process




- Alternative to ACI developed
- Sensitised oxidation of mercury
- Irradiation of flue gas with 254 nm light
- 99% oxidation achieved at laboratory scale
- 91% oxidation attained at bench-scale
- FLC Tech Transfer Award 2005
- Tests: DOE, Powerspan, Canmet, University of Florida
- Low parasitic power (less than 0.35%)
- Potential full-scale demonstrations

A-7/ICSC2023


Figure A-7 Summary of the development process for Thief sorbents

Background: GP-254 Process



Discovery


- Sorbent development
- UV measurement of mercury
- AFS
- Unwanted red-brown stains
- Mercuric oxide
- Serendipity



A-8/ICSC2023

Figure A-8 Development stages of the Thief process

What is quenching



- Intensity of fluorescent emission diminished
- Energy transfer due to collisions
- Function of size, shape, and reactivity
- Primed for chemical reaction (activation)
- Interferes with ultraviolet spectroscopy

$\text{Hg} + 253.7 \text{ nm light} \rightarrow \text{Hg}^*$	$\text{Hg } 6 (^3\text{P}_1)$
$\text{Hg}^* \rightarrow \text{Hg} + 253.7 \text{ nm light}$	Fluorescence
$\text{Hg}^* + \text{M} \rightarrow \text{Hg} + \text{M}^*$	Quenching

A-9/ICSC2023

Figure A-9 Explanation of quenching effect on mercury measurement

Photochemical oxidations

NATIONAL ENERGY TECHNOLOGY LABORATORY

- First described in 1926 by Dickenson & Sherrill (O₂)
- Gunning discovered others in 1950s (HCl, H₂O, CO₂)

Relevant overall reactions

Hg + 2 O ₂ + 253.7 nm light	→	HgO + O ₃
Hg + HCl + 253.7 nm light	→	HgCl + 1/2 H ₂
Hg + H ₂ O + 253.7 nm light	→	HgO + H ₂
Hg + NO ₂ + 253.7 nm light	→	HgO + NO
Hg + CO ₂ + 253.7 nm light	→	HgO + CO
Hg + SO ₃ + 253.7 nm light	→	HgO + SO ₂

- Interferes with UV-based CEMs
- Removal method

A-10/ICSC2023

Figure A-10 Photochemical oxidation reactions relevant to mercury behaviour in combustion

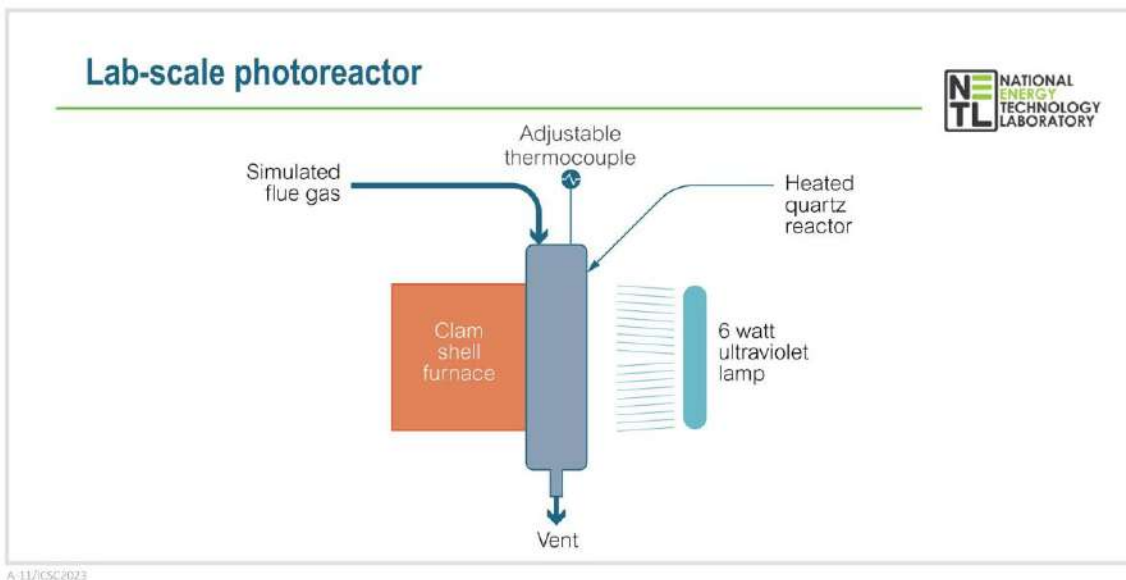


Figure A-11 Diagram of laboratory scale system used to measure mercury



Figure A-12 Examples of applications where the Powerspan system has been demonstrated

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Contact: Evan J. Granite: Program Manager, United States Department of Energy. Fossil Energy & Carbon Management, email: evan.granite@hq.doe.gov

A8 LANXESS – GEOBROM® TECHNOLOGY

Pollution control testing for low sulphur coal combustion was conducted to reduce SO₂ emissions, oxidise mercury for downstream capture, and control acid at, or below, baseline levels to minimise corrosion and possibly lower post-combustion dew point temperatures. The project was the joint development of LANXESS and Enerchem, an independent business partner, and relates to patented technology exclusively licensed to LANXESS by Enerchem.

The technology tested achieved 90%+ SO₂ reduction while meeting the other pollution control objectives. The technology utilises bromide derivatives with micronised metal alkali sorbents in the combustion zone to chemically convert SO₂ to species efficiently captured by micronised alkali sorbents. The technology also reduces sorbent use versus typical DSI performance.

LANXESS would like to conduct further full-scale plant tests and believes that this technology will benefit coal and carbon combustion facilities that require additional emission control but also require low capital expense, competitive operation costs, and robust and sustainable performance.

LANXESS would be interested in further discussions with interested parties and can share additional details with those provided in this presentation with the completion of a non-disclosure agreement.

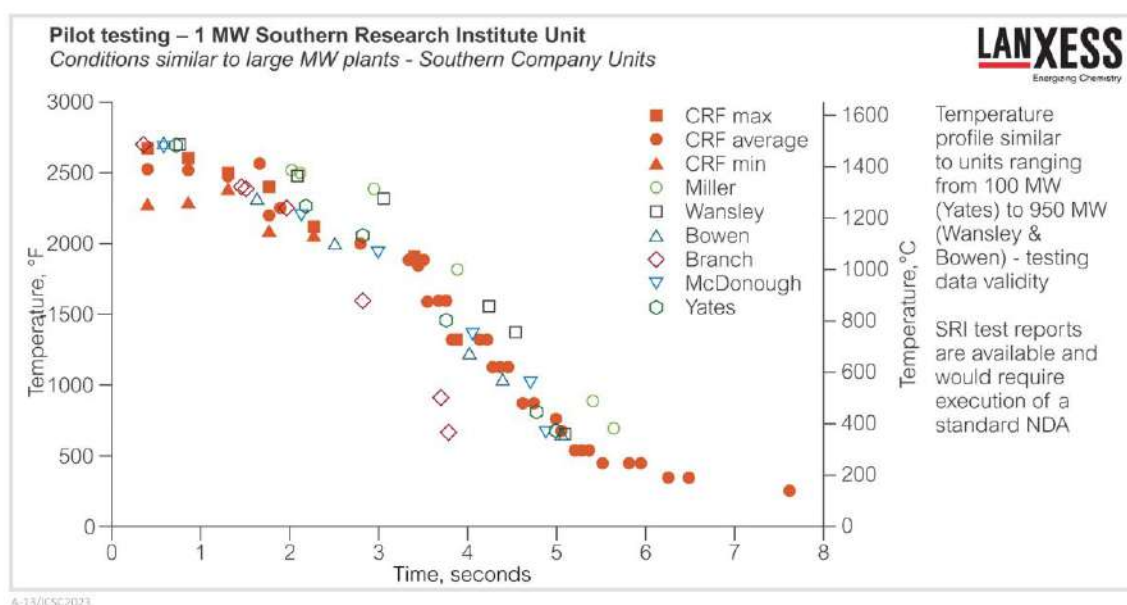



Figure A-13 Temperature profiles at pilot testing for the Lanxess process

Benefits - Capex, Opex and Performance




Capex	Opex	Performance
<ul style="list-style-type: none"> • Capex much lower than WFGD – Simple addition systems and off-the-shelf design • Low cost to complete testing and short time-frame to test and install full-scale unit • Flexibility for chemical use – combustion zone addition 	<ul style="list-style-type: none"> • Reduced sorbent vs typical DSI – 90+% reduction of SO₂ vs 75% w/DSI alone using 25+% less sorbent • Acid gas control reduces equipment and maintenance cost – potential for lower post-combustion dew point temperatures • Lower energy use vs other APC technologies 	<ul style="list-style-type: none"> • Acid gas control, lower SO₂ by 90+%, and mercury oxidation • Fast unit response with condition changes – steady state reached quickly in flue • Parametric and optimisation testing completed – confirmed results and robustness

Testing will help determine plant configuration impacts – low-cost test and unit installation

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Figure A-14 Benefits of the Lanxess process

Testing concepts summary



Two sets of tests to complete proof of concept – acid and SO₂

- Test burn PRB coal – dry basis (21.98% moisture): 0.41% sulphur, 6.83% ash, 11,602 Btu/lb
- First tests demonstrated high SO₂ reduction – broad ranges / minimal combinations
 - > Focus individual ADDITIVE impacts and trends and performance
 - > 90+% SO₂ reduction possible – similar to WFGD efficiency
 - > Total acid results not ideal, optimisation planned for second round
 - > Combination of ADDITIVES could reduce usage of both
- Second test protocol focused on optimisation and interaction of ADDITIVES
- Combination of two additives gave best results – second sorbent not further optimised
 - > Varying addition conditions did not improve sorbent performance
 - > Conditions for successful results confirmed and reproduced
- Varied conditions achieved 90+% SO₂ reduction and kept acid at baseline or below
- Both test runs also demonstrated that technology performs with normal addition variations

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Figure A-15 Summary of testing concepts for application of the Lanxess process

INTERNATIONAL CENTRE FOR SUSTAINABLE CARBON
MERCURY REDUCTION AT INDONESIAN COAL PLANTS – MINAMATA COMPLIANCE STRATEGY

70

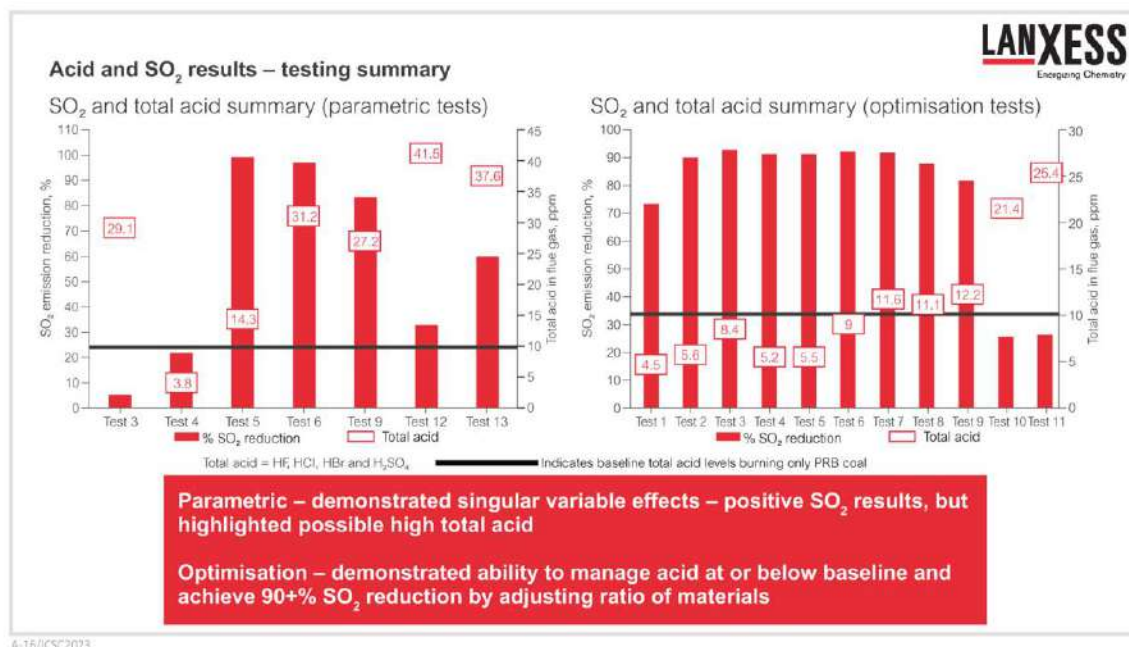


Figure A-16 Results of testing to manage SO₂ and Hg behaviour

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A9 GORE™ MERCURY AND SO₂ CONTROL SYSTEM (GMSCS) FOR COAL-FIRED POWER

GORE is a materials science company focused on product innovation and has developed several techniques and technologies for emission reduction.

Simple low operating cost multi-control system utilising sorbent/catalyst modules: Operators of coal-fired power plants in Indonesia are facing future tighter emissions limits including mercury and SO₂ while maintaining a desire to minimise operating costs and simplify operation. The GORE™ Mercury and SO₂ Control System (GMSCS) is ideally suited for this market as a multipollutant control system. The GMSCS is based on catalyst/sorbent composite material configured into low-pressure drop modules. Placed directly in the flue gas, these modules continuously capture gas phase mercury without requiring any reagent – and due to the high capacity for mercury capture, the modules are often projected to last over 10 years before needing to be replaced (Figure A17). In addition, the modules contain a catalyst that converts SO₂ into sulphuric acid where it is collected as a liquid for potential beneficial use.

GMSCS has been successfully deployed in over 30 installations around the world since 2013, in applications including coal-fired power, incineration, and metals/minerals applications. There are

different installation approaches possible depending on the needs and existing pollution controls at a given power plant.

For power plants that have wet FGD already installed (limestone or seawater), the GMSCS modules can be installed inside existing absorber vessels in a zero-footprint installation approach (see both diagrams in Figure A-17).

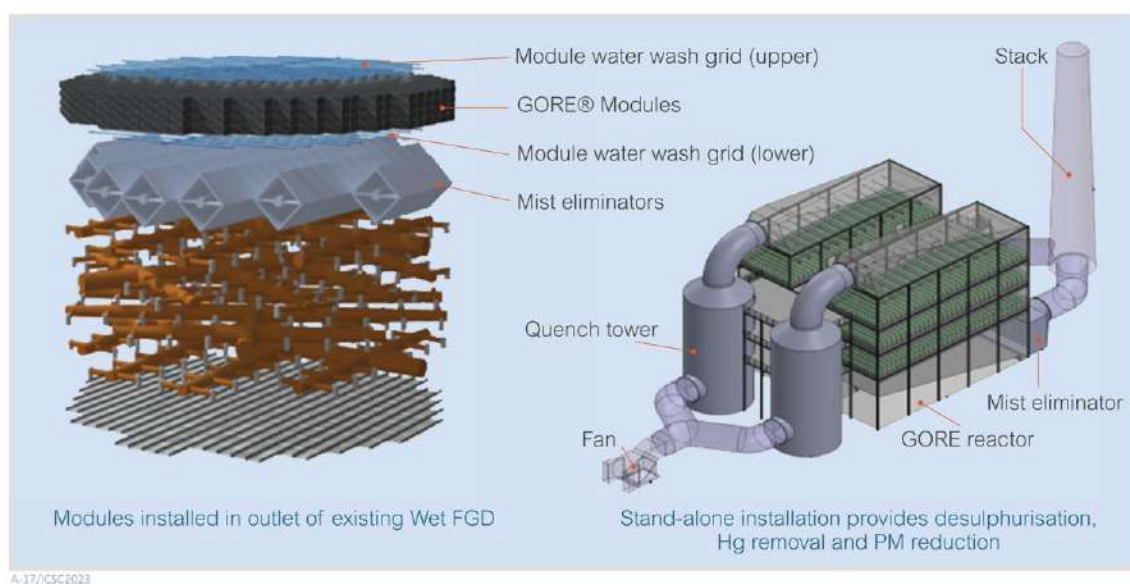


Figure A-17 Diagram of GORE modules for multipollutant control

In this case, there are no moving parts, and operation is exceedingly simple, as the passive modules will control mercury emissions (oxidised as well as elemental mercury) and provide additional SO₂ polishing. Mercury is not transferred to the liquid phase (seawater discharge in a seawater scrubber) and is instead chemisorbed by the sorbent material.

For plants without FGD controls, the GMSCS can be installed as a stand-alone unit (see right-hand image in Figure A-17, where the system will reduce SO₂ emissions to the required limits while simultaneously capturing gas phase mercury. In this configuration, there can be significant revenue generated from the sulphuric acid by-product, which has uses in many industries such as fertiliser production. This by-product combined with the fact that no reagents are required results in the lowest operating cost solution for this market. Additional benefits include low parasitic power consumption and a lack of solid waste generation. Furthermore, the catalytic reaction of SO₂ to sulphuric acid does not involve additional CO₂ generation.

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https://www.gore.com/news-events/press-release/hindalco-awards-contract-for-flue-gas-desulphurization?from=%5B%22content_type%3APress+Release%22%2C%22language%3Aen%22%5D

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A10 SORBENTS FROM FLY ASH – LEHIGH UNIVERSITY

This proposal involves capturing mercury using mildly modified fly ash from the power plant. While researchers and commercial enterprises have put forth several technologies aimed at capturing mercury from coal-fired power plants, only a limited set of these approaches prove to be economically viable. Certain methods place an additional strain on power plants, while others come with high costs.

Our strategy for achieving practical mercury capture from flue gases of coal-fired power plants will involve a two-stage process. In the initial phase, we will enhance the oxidation of elemental mercury through combustion tuning. Subsequently, the oxidised mercury will be captured using slightly modified fly ash from the plant.

In this methodology, we will implement combustion modifications, including adjustments in excess air and combustion staging, to optimise the transformation of elemental mercury into its oxidised state. Additionally, if the plant is equipped with an SCR catalyst, we will investigate the effects of ammonia injection on mercury oxidation, alongside other relevant parameters. This comprehensive assessment will involve approximately two weeks of field testing, providing an opportunity to gain insights into mercury speciation specific to the utility in question. An online stack-mounted mercury analyser will be employed to monitor mercury emissions under different boiler operating conditions and across various coal types. For power plants outfitted with WFGD systems, an online ORP (oxidation reduction potential) probe will be utilised to enhance scrubber operation, achieving the highest level of mercury reduction.

During the subsequent stage, a fraction of the fly ash collected from the power plant's ESP is modified and will be reintroduced into the flue gas stream through multiple nozzles. This investigation encompasses factors such as the optimal location within the flue gas stream (temperature considerations), the quantity of fly ash employed, and the condition of the fly ash (including

temperature, particle size distribution, and levels of unburnt carbon). Re-injected fly ash might lead to a slight increase in particle loading within the ESP or baghouse. Nevertheless, this challenge can be effectively addressed by enhancing the dust collection equipment's collection capacity, and this can be achieved with a reasonable investment cost. This approach presents a promising and cost-effective technology not only for power plants in Indonesia but also for those worldwide.

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A11 DEHG TECHNICS - TECHNICAL UNIVERSITY OF OSTRAVA

The effectiveness of mercury capture is determined by the chemical form. During the cooling of the flue passing through the combustion chamber to the heat exchanger system of a boiler, partial adsorption of mercury takes place on solid fly ash particles. This particle-bound mercury can be captured in downstream dedusting equipment such as ESPs or bag filters. The following sections explain how mercury species can be targeted for control:

- 1) **Oxidation of mercury:** The principle is to oxidise the mercury from Hg^0 to water-soluble Hg^{2+} compounds in the flue gas such as mercury chloride ($HgCl_2$). Oxidation can take place homogeneously (gas-gas) or heterogeneously (gas-solid). The oxidised mercury can be removed in wet scrubbers, typically in an FGD. The oxidation of mercury can be also promoted by the catalysts within the SCR

systems used for the reduction of nitrogen oxides – the degree of oxidation depends on the actual flue gas temperature. One issue is the potential for reformation and re-emission of oxidised mercury to Hg⁰ in the scrubbers, particularly in wet FGD systems. This can be inhibited by adding precipitants which convert the mercury into an insoluble precipitate. For this, there are many commercial (industrial) treatment options:

- Precipitants name TMT 15 – EVONIK Industries – <http://corporate.evonik.com/en>
- Nalco – <https://en-la.ecolab.com/pages/contact-us>
- Kurita – Kurita Europe GmbH – <https://www.kurita.eu/>
- Net (Netflock SMF-1) – NET GmbH – <http://www.netgmbh.de/netfloc>
- PanChemie – <http://www.panchemie.com/en/pravo-4/>
- Sodium sulphide, Na₂S – is injected into several lignite and coal power plants.

The product of these treatments is stable insoluble mercury sulphide which is captured on the gypsum where it remains insoluble and nontoxic. Sodium sulphide (Na₂S) has been applied at several power plants for mercury capture in this way.

2) **Adsorption of mercury:** A solid sorbent can be used in order to adsorb mercury into its porous system. Activated carbon can be injected either into the flue gas upstream of the ash separator or before the wet or semi-dry FGD process. Activation of the sorbents by bromides or iodides increases the adsorption capacity. The capture efficiency of the modified active carbon with bromide is higher than 80%, based on standard flue gas parameters and injection technology. For industrial applications is possible to use commercially available activated carbon. Suppliers are listed below.

TABLE 6 EXAMPLES OF SORBENT SUPPLIERS AND THEIR CONTACT DETAILS

Sorbent	Company	Contact
Power Pac Premium®	ADA Carbon Solutions	http://www.ada-cs.com/
Power Pac Premium Plus™	ADA Carbon Solutions	http://www.ada-cs.com/
BASF Mercury sorbent HX™	BASF	https://www.basf.com/cz/cz.html
Calgon HGR-LH™	Calgon Carbon Corporation	https://www.calgoncarbon.com/contact/
FLUEPAC®	Calgon Carbon Corporation	https://www.calgoncarbon.com/contact/
FLUEPAC® STH	Calgon Carbon Corporation	https://www.calgoncarbon.com/contact/
FLUEPAC® STH	Calgon Carbon Corporation	https://www.calgoncarbon.com/contact/
FLUEPAC® MC	Calgon Carbon Corporation	https://www.calgoncarbon.com/contact/
FLUEPAC® LMC	Calgon Carbon Corporation	https://www.calgoncarbon.com/contact/
DARCO® Hg	CABOT	http://www.cabotcorp.com/solutions/products-plus/activated-carbon/powdered
DARCO® Hg-LH	CABOT	http://www.cabotcorp.com/solutions/products-plus/activated-carbon/powdered
DARCO® GL	CABOT	http://www.cabotcorp.com/solutions/products-plus/activated-carbon/powdered
DARCO® Hg FGL	CABOT	http://www.cabotcorp.com/solutions/products-plus/activated-carbon/powdered

The dosing of sorbents is important, as well as the distribution system in order to ensure homogeneity in the flue gas. With poor homogenisation, even activated carbon modified with bromide has a low efficiency.

There are several alternative sorbents for mercury capture, for example, modified aluminosilicate and modified natural zeolite. These sorbents are still to be proven at coal-fired power plants but, for industrial applications, sorbents based on aluminosilicate modified with bromide are already in use, for example from Absory – <https://www.absory.cz/>

3) **Separation of mercury by membranes:** Specifically developed membranes are designed to bind not only the oxidised form of mercury but also elemental mercury. For example, Gore (<https://www.gore.com/products/gore-mercury-control-systems>) has developed membranes based on fluoropolymer. The technology is installed at several power plants but is currently regarded as expensive, with the modules being difficult to recycle.

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