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Implementation Analysis of Emission Reduction System for SO_2, NO_2, and Hg Emission Reduction Equipment in Coal-Fired Power Plants

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Abstract. Coal-Fired Power-Plants (CFPP) have four main emission parameters: SO_2, NO_2, particulate matter, and Hg. Currently, many existing CFPP have yet to install emission reduction equipment for SO_2, NO_2, and Hg emission. This study aims to evaluate the technical and economic impacts of implementing emission reduction equipment in existing CFPP with capacities between 50 and 1000 MW. This study is conducted using SteamPro–Thermoflow, a well-known software in the thermal power plant industry for heat and mass balance analysis. The simulations show that Selective Catalytic Reduction (SCR) achieves 80% NO_2 reduction efficiency, higher than Selective Non-Catalytic Reduction (SNCR) at 40%. For SO_2 reduction, Wet and Sea Water Flue Gas Desulfurization (WFGD and SWFGD) reach 95%, while Semi-Dry FGD (SDFGD) achieves 90%. Activated Carbon Injection (ACI) for mercury (Hg) reduction achieves 60%, and up to 85% when combined with FGD. For auxiliary power consumption, at 0.01–0.03% of gross power for NO_2 reduction, 0.25–0.50% for SO_2 reduction, and 0.17–0.22% for Hg reduction. Investment costs are 50–120 USD/kW for SNCR, 5–20 USD/kW for SCR, 10–35 USD/kW for ACI, and 32–110 USD/kW for FGD. The study results are expected to guide emission reduction policies in power generation sector.

Keywords: *CFPP, SO_2 Emission, NO_2 Emission, Mercury Emission, Net Zero Emission*

1 Introduction

Economic growth, population increase, and technological development have driven the rising energy demand in Indonesia [1]. Energy is a vital component in supporting national development and achieving the vision of Indonesia Emas 2045 [2]. According to the Electricity Supply Business Plan (RUPTL) 2021–2030, electricity demand is projected to grow at an average rate of 4.9% per year. The RUPTL also states in that by the end of 2020, the total installed power generation capacity in Indonesia had reached 62.45 GW, with coal-fired steam power plants (CFPP) contributing the largest share at 51% [3]. Although the government has set a target of Net Zero Emission (NZE) by 2060, coal-fired power plants (CFPP) still play a crucial role in the national electricity system [4].

One of the main challenges is the high level of flue gas emissions such as SO_2, NO_x, and Hg, which contribute to environmental pollution. Most coal-fired power plants in Indonesia are still not equipped with air emission control technologies, particularly for pollutants such as SO_2, NO_x, and Hg [5].

The government has established emission quality standards through regulations issued by the Ministry of Environment and Forestry, which are expected to become increasingly stringent in the future to support the NZE target. The emission quality standards regulation for coal-fired power plants (CFPP) was first issued by the Ministry of Environment and Forestry in 2008, under Regulation Number 21 of 2008 [6]. In 2019, an updated version was introduced Regulation Number 15 of 2019 which imposed more stringent parameter limits [7]. There are four emission parameters for coal-fired power plants, as presented in **Table 1**.

Table 1 Emission Quality Standard in Indonesia (2019) [7]

No	Parameter	CFPP Built Before This Regulation	CFPP Built After This Regulation
		Maximum Limit (mg/Nm^3)	
1.	Sulfur Dioxide (SO_2)	550	200
2.	Nitrogen Oxide (NO_x)	550	200
3.	Particulate Matter (PM)	100	50
4.	Mercury (Hg)	0.03	0.03

Emission quality standards in other countries can be seen in **Table 2**. It can be observed that several countries even have stricter emission limits for coal-fired power plants. Considering the emission standard parameters applied in various countries and Indonesia's commitment to achieving Net Zero Emissions, it is inevitable that Indonesia may introduce revised emission standard regulations with more stringent requirements in the future.

Table 2 Emission Quality Standard for CFPP in Various Countries [8] [9] [10] [11] [12] [13]

No	Parameter (mg/Nm^3)	China	United States	Europe	India	South Korea
1.	Sulfur Dioxide (SO_2)	35	60	75	100	229
2.	Nitrogen Oxide (NO_x)	50	99	85	100	164
3.	Particulate Matter (PM)	10	13	5	30	18
4.	Mercury (Hg)	0.03	0.0005	0.004	0.004	0.03

As the national electricity provider, PLN is responding to this challenge through various strategies, including the implementation of Clean Coal Technology (CCT), such as the installation of emission control equipment [14]. For SO_2 emission control, three high-efficiency post-combustion technologies are commonly used: Wet Flue Gas Desulfurization (WFGD), Semi-Dry Flue Gas Desulfurization (SDFGD), and Sea Water Flue Gas Desulfurization (SWFGD) [15]. These technologies are installed after the combustion process in the furnace. For NO_x emission control, two commonly used post-combustion technologies are Selective Catalytic Reduction (SCR) [16] [17] and Selective Non-Catalytic Reduction (SNCR) [18] [19]. Additionally, a widely applied pre-combustion method is the use of Low-NO_x Burners [20]. To reduce mercury emissions in flue gas, Activated Carbon Injection (ACI) is commonly employed [21]. This method involves injecting activated carbon into the flue gas stream, where mercury is captured through an adsorption process. During this process, mercury adheres to the surface of the activated carbon particles and is subsequently removed by particulate matter reduction equipment such as Electrostatic Precipitators (ESP) or Fabric Filters (FF) [22].

Therefore, this study aims to analyze the technical effectiveness and economic cost of implementing SO_2, NO_x, and Hg emission control technologies in coal-fired power plants, using the STEAMPRO software by Thermoflow. The findings of this study are expected to provide a valuable reference for policy considerations in emission reduction efforts within the power generation sector.

2 Methodology

To obtain technical and economic data, this study uses STEAMPRO software by Thermoflow as a tool to develop a model that based on heat and mass balance analysis.

2.1 Dependent Variables

The dependent variables used in this study are as follows:

1. The CFPP is already equipped with particulate emission reduction equipment, namely an Electrostatic Precipitator (ESP).
2. CFB-type CFPP will be equipped with NO_2 and Hg emission reduction technologies, while PC-type CFPP will be equipped with SO_2, NO_2, and Hg emission reduction technologies.
3. There are two types of coal specifications: coal with a calorific value of 4300 kcal/kg and coal with a calorific value of 5800 kcal/kg, as detailed in **Table 3**.

Table 3 Coal Specifications between Low Rank Coal (4300 kcal/kg) and Medium Low Rank Coal (5800 kcal/kg)

Analysis	Coal-4300		Coal-5800	
	Value	Unit	Value	Unit
Heating Value				
Low Heating Value	3935	kcal/kg	5486	kcal/kg
High Heating Value	4300	kcal/kg	5800	kcal/kg
Ultimate Analysis				
Moisture	32.78	%	14.7	%
Ash	6.56	%	6.7	%
Carbon	44.86	%	60.33	%
Hydrogen	3.34	%	4.38	%
Nitrogen	0.57	%	1.71	%
Chlorine	0	%	0.05	%
Sulfur	0.18	%	0.7	%
Oxygen	11.71	%	11.43	%
Total	100	%	100	%
Proximate Analysis				
Moisture	32.78	%	14.7	%
Ash	6.56	%	6.7	%
Volatile Matter	33.25	%	34.5	%
Fixed Carbon	27.41	%	44.1	%
Total	100	%	100	%
Other Properties				
Mercury Content [23]	0.19	mg/kg	0.19	mg/kg

2.2 Independent Variables

The independent variables used in this study are as follows:

1. Type of Power Plant: CFB (Circulating Fluidized Bed) CFPP and PC (Pulverized Coal) CFPP.
2. Plant Capacity Class: 50 MW, 100 MW, 200 MW, 600 MW, or 1000 MW.
3. SO_2 Emission Reduction Equipment: WFGD, SDFGD, or SWFGD.
4. NO_2 Emission Reduction Equipment: SCR or SNCR.
5. Hg Emission Reduction Equipment: ACI.

2.3 Output Variables

The output variables generated in this study are as follows:

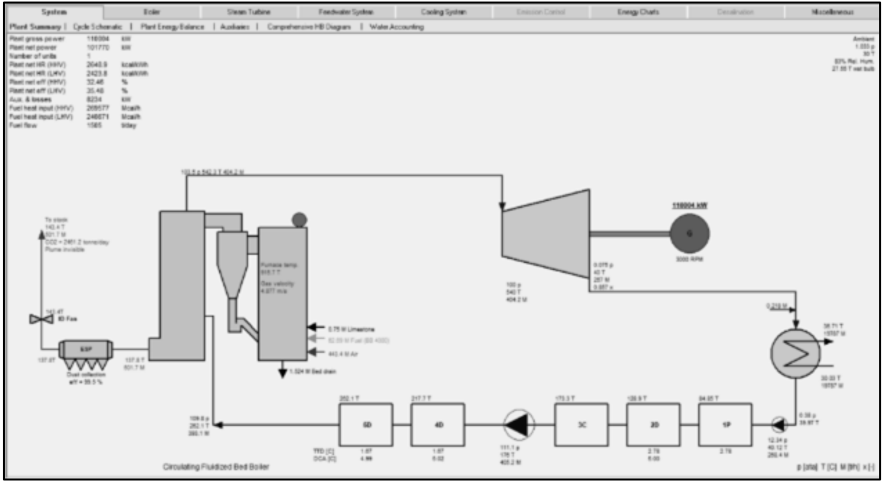
1. Emissions produced by the coal-fired power plant (CFPP).
2. Auxiliary power required for the installation of each emission reduction technology or combination of technologies.
3. Investment cost required for the installation of each emission reduction technology or combination of technologies.

3 Results and Discussion

Based on the variables used in this study, a total of 17 models will be developed, as follows:

1. CFB-4300 Only
2. CFB-4300 (50MW & 100MW Class) + SCR + ACI
3. CFB-4300 (50MW & 100MW Class) + SNCR + ACI
4. PC-4300 Only
5. PC-4300 (200MW, 600MW, & 1000MW Class) + SCR + ACI + WFGD
6. PC-4300 (200MW, 600MW, & 1000MW Class) + SCR + ACI + SDFGD
7. PC-4300 (200MW, 600MW, & 1000MW Class) +SCR + ACI + SWFGD
8. PC-4300 (200MW, 600MW, & 1000MW Class) +SNCR +ACI + WFGD
9. PC-4300 (200MW, 600MW, & 1000MW Class) +SNCR+ACI +SDFGD
10. PC-4300 (200MW, 600MW, & 1000MW Class) +SNCR+ACI+SWFGD
11. PC-5800 Only
12. PC-5800 (600MW & 1000MW Class) + SCR + ACI + WFGD
13. PC-5800 (600MW & 1000MW Class) + SCR + ACI + SDFGD
14. PC-5800 (600MW & 1000MW Class) + SCR + ACI + SWFGD
15. PC-5800 (600MW & 1000MW Class) + SNCR + ACI + WFGD
16. PC-5800 (600MW & 1000MW Class) + SNCR + ACI + SDFGD
17. PC-5800 (600MW & 1000MW Class) + SNCR + ACI + SWFGD

An example of the modeling result using SteamPRO software for one model can be seen in **Figure. 1**.



Plant gross power	118004	kW
Plant net power	101770	kW
Number of units	1	
Plant net HR (HHV)	2648.9	kcal/kWh
Plant net HR (LHV)	2423.8	kcal/kWh
Plant net eff (HHV)	32.46	%
Plant net eff (LHV)	35.48	%
Aux. & losses	8234	kW
Fuel heat input (HHV)	269577	Mcal/h
Fuel heat input (LHV)	246671	Mcal/h
Fuel flow	1585	t/day

Figure 1 Modelling Result for one model (case) using SteamPRO software

3.1 Emission Reduction in the CFPP

Based on the modeling results, it was found that there were changes in emissions after the installation of emission reduction equipment in the CFPP. These emission changes are presented in **Table 4**.

Table 4 Stack Emission of NO_2, SO_2, and Hg (Corrected to 7% O2) for Various Boiler and Coal Type Combinations with different Emission Control Equipment Configurations

Boiler Type – Coal Type	Equipment Combination	Stack Emissions (Corrected to 7% O_2) (mg/Nm^3)		
		NO_2	SO_2	Hg
CFB-4300	CFB Only	200	55.63	0.0125
	CFB + SCR + ACI	40	55.63	0.005
	CFB + SNCR + ACI	120	55.63	0.005
PC-4300	PC Only	350	550	0.013
	PC+SCR+ACI+WFGD	70	27.67	0.002
	PC+SCR+ACI+SDFGD	70	55.37	0.002
	PC+SCR+ACI+SWFGD	70	27.67	0.002
	PC+SNCR+ACI+WFGD	210	27.67	0.002
	PC+SNCR+ACI+SDFGD	210	55.37	0.002
	PC+SNCR+ACI+SWFGD	210	27.67	0.002
PC-5800	PC Only	350	1549.2	0.0115
	PC+SCR+ACI+WFGD	70	77.35	0.002
	PC+SCR+ACI+SDFGD	70	155	0.002
	PC+SCR+ACI+SWFGD	70	77.35	0.002
	PC+SNCR+ACI+WFGD	210	77.35	0.002
	PC+SNCR+ACI+SDFGD	210	155	0.002
	PC+SNCR+ACI+SWFGD	210	77.35	0.002

For a CFB-type CFPP using coal with a calorific value of 4300 kcal/kg, the initial NO_2 emission was 200 mg/Nm^3. After the installation of an SCR system, the emission was reduced to 40 mg/Nm^3. When using an SNCR system, the emission decreased from 200 mg/Nm^3 to 120 mg/Nm^3. This indicates that SCR has a higher reduction efficiency than SNCR. This is because SNCR only involves spraying ammonia into the flue gas without any catalytic process, whereas SCR not only involves ammonia injection but also includes a catalyst that facilitates the capture of NO_2. In terms of efficiency, SCR achieves a reduction of 80%, while SNCR achieves 40%. For mercury (Hg) emissions, the use of Activated Carbon Injection (ACI) technology reduced the initial emission from 0.0125 mg/Nm^3 to 0.005 mg/Nm^3, indicating a reduction efficiency of 60%.

For a PC-type CFPP using coal with a calorific value of 4300 kcal/kg, the initial NO_2 emission was 350 mg/Nm^3. After the installation of a Selective Catalytic Reduction (SCR) system, the emission decreased to 70 mg/Nm^3. When using a Selective Non-Catalytic Reduction (SNCR) system, the emission decreased from

350 mg/Nm^3 to 210 mg/Nm^3. In percentage terms, SCR achieves a reduction efficiency of 80%, while SNCR achieves 40%. For SO_2 emissions, three post-combustion technologies were evaluated: WFGD, SDFGD, and SWFGD. When WFGD was applied, SO_2 emissions were reduced from 550 mg/Nm^3 to 27.67 mg/Nm^3. Using SDFGD reduced emissions to 55.37 mg/Nm^3, while SWFGD also reduced emissions to 27.67 mg/Nm^3. This indicates that WFGD and SWFGD offer higher removal effectiveness compared to SDFGD. In percentage terms, both WFGD and SWFGD have an efficiency of 95%, whereas SDFGD achieves 90%. For mercury (Hg) emissions, the use of Activated Carbon Injection (ACI) combined with Flue Gas Desulphurization (FGD) technologies reduced Hg emissions from 0.013 mg/Nm^3 to 0.002 mg/Nm^3. The FGD process also contributes to mercury removal, thereby increasing the overall efficiency of mercury reduction from 60% to 84.6%.

For a PC-type CFPP using coal with a calorific value of 5800 kcal/kg, the initial NO_2 emission was 350 mg/Nm^3. After the installation of a Selective Catalytic Reduction (SCR) system, the emission was reduced to 70 mg/Nm^3. When using a Selective Non-Catalytic Reduction (SNCR) system, the emission decreased from 350 mg/Nm^3 to 210 mg/Nm^3. In percentage terms, SCR achieves a reduction efficiency of 80%, while SNCR achieves 40%. The SO_2 emissions produced by this power plant are higher than those of the PC-4300 CFPP. This is due to the higher sulfur content by weight in the 5800 kcal/kg coal compared to the 4300 kcal/kg coal. Therefore, during the combustion reaction, the amount of SO_2 formed in the PC-5800 CFPP is also higher. For SO_2 emissions, three technologies were evaluated: WFGD, SDFGD, and SWFGD. With WFGD, SO_2 emissions were reduced from 1149.2 mg/Nm^3 to 77.35 mg/Nm^3. With SDFGD, emissions decreased to 155 mg/Nm^3. Using SWFGD also reduced SO_2 emissions to 77.35 mg/Nm^3. In percentage terms, WFGD and SWFGD achieved a removal efficiency of 95%, while SDFGD achieved 90%. For mercury (Hg) emissions, the use of Activated Carbon Injection (ACI), combined with Flue Gas Desulphurization (FGD) technology, reduced Hg emissions from 0.0115 mg/Nm^3 to 0.002 mg/Nm^3. Since FGD technology also contributes to mercury reduction, its application increases the overall mercury removal efficiency from 60% to 82.6%.

3.2 Auxiliary Power Consumption of Emission Reduction Equipment

The data in **Table 5** is obtained by dividing the auxiliary power from the simulation results by the gross power of the power plant.

Table 5 Auxiliary Power Requirements as a Percentage of Gross Power for NO_2, SO_2, and Hg Reduction Systems accros different CFPP Capacities and Coal Types

Boiler Type – Coal Type	CFPP Class (MW)	Gross Power (MW)	Auxiliary Power as a Percentage of Gross Power					
			NO_2 Reduction		Hg Reduction	SO_2 Reduction		
			SCR	SNCR	ACI	WFGD	SDFGD	SWFGD
CFB-4300	50	55	0.014%	0.010%	0.212%	-	-	-
	100	110	0.014%	0.010%	0.206%	-	-	-
PC-4300	200	214	0.022%	0.016%	0.204%	0.265%	0.453%	0.290%
	600	645	0.021%	0.015%	0.192%	0.277%	0.418%	0.321%
	1000	1075	0.021%	0.015%	0.189%	0.265%	0.409%	0.304%
PC-5800	600	645	0.021%	0.015%	0.178%	0.417%	0.436%	0.470%
	1000	1075	0.020%	0.014%	0.175%	0.402%	0.430%	0.448%

Based on the calculation results, it was found that SO_2 emission reduction equipment (all types of FGD) has relatively high additional power consumption (>0.25%) compared to NO_2 or Hg reduction equipment (SCR, SNCR, and ACI), especially in large-capacity units. While auxiliary power in kilowatts increases with plant capacity, its percentage relative to gross power tends to remain stable or slightly decrease. This indicates the presence of an economy of scale, where larger-capacity CFPP have proportionally better efficiency in their supporting systems. The increase in auxiliary power consumption may also reduce the net plant efficiency, and thus should be compensated through operational optimization, boiler efficiency improvements, or energy recovery measures.

3.3 Investment Cost of Emission Reduction Equipment

The data in **Table 6** is obtained by dividing the Capital Expenditure (CAPEX) from the simulation results by the gross power of the power plant.

Table 6 Investment Cost (USD/kW) for implementing NO_2, SO_2, and Hg Emission Reduction Technologies across Various CFPP Capacities and Coal Types

Boiler Type – Coal Type	CFPP Class (MW)	Gross Power (MW)	Investment Cost USD/kW					
			NO_2 Reduction		Hg Reduction	SO_2 Reduction		
			SCR	SNCR	ACI	WFGD	SDFGD	SWFGD
CFB-4300	50	55	118.038	19.071	33.883	-	-	-
	100	110	95.210	14.584	24.687	-	-	-
PC-4300	200	214	87.482	10.866	18.454	163.933	159.051	149.614
	600	645	67.151	7.038	13.466	104.860	118.452	90.439
	1000	1075	61.980	5.789	10.681	97.830	101.456	86.428
PC-5800	600	645	57.652	6.819	12.883	114.467	112.075	91.035
	1000	1075	53.070	5.609	10.230	102.096	101.059	85.951

Based on the calculation results, it was found that the investment cost of equipment in USD/kW tends to decrease. For NO_2 emission reduction technologies, the investment cost of SCR is higher than that of SNCR for the same plant type and capacity. This indicates that achieving higher removal efficiency comes with a higher investment cost. For Hg emission reduction technologies, the larger the plant capacity, the lower the investment cost required, indicating an economy of scale, where larger units benefit from proportionally better efficiency in supporting systems. For SO_2 emission reduction technologies WFGD, SDFGD, and SWFGD, the differences in investment cost for the same plant type and coal quality are relatively small. However, from a purely cost perspective, SWFGD can be considered a more economical option, as it has a lower investment cost in USD/kW compared to WFGD and SDFGD.

4 Conclusion

The conclusions generated from this study show that the SCR system achieves the highest NO_2 emission reduction efficiency at 80%, compared to 40% for SNCR. For SO_2 control, WFGD and SWFGD systems achieve 95% efficiency, surpassing SDFGD at 90%. Mercury (Hg) removal reaches 60% using ACI alone and improves up to 85% when combined with FGD systems. Auxiliary power consumption increases with plant capacity, with SNCR exhibiting the lowest demand for NO_2 control (0.01–0.03% of gross power), ACI for Hg control (0.17–0.22% of gross power), and WFGD for SO_2 control (0.25–0.50% of gross power). Investment costs decrease as plant capacity increases; for example, SCR investment drops from 118.038 USD/kW at Class 50 MW scale to 57.070 USD/kW at Class 1000 MW, while WFGD cost declines from 163.933 USD/kW at Class 200 MW to 102.096 USD/kW at Class 1000 MW. Among SO_2 reduction options, SWFGD offers the lowest cost at large scales, reaching 85.951 USD/kW at Class 1000 MW. Overall, SCR, ACI, and WFGD/SWFGD are recommended for large-scale (>600 MW) plants, while SNCR, ACI, and SWFGD are suitable for mid-scale (200–400 MW) units, and SNCR-ACI combinations are preferable for small-scale (<200 MW, CFB) facilities, balancing emission compliance and economic feasibility. These findings can provide valuable insights for policy decisions and support the practical implementation of emission control strategies within Indonesia's energy transition roadmap, particularly through retrofitting existing coal-fired power plants to support the achievement of Indonesia's Net Zero Emissions (NZE) 2060 target.

5 Nomenclature

ACI = Activated Carbon Injection
CAPEX = Capital Expenditure

CFB = Circulating Fluidized Bed
CFPP = Coal-Fired Power Plant
ESP = Electrostatic Precipitator
FGD = Flue Gas Desulfurization
FF = Fabric Filter
Hg = Mercury Emissions
NO_2 = Nitrogen Dioxide
NSR = Normal Stoichiometric Ratio
NZE = Net Zero Emission
OPEX = Operational Expenditure
PC = Pulverized Coal
SDFGD = Semi-Dry Flue Gas Desulfurization
SCR = Selective Catalytic Reduction
SNCR = Selective Non-Catalytic Reduction
SO_2 = Sulfur Dioxide
SWFGD = Seawater Flue Gas Desulfurization
WFGD = Wet Flue Gas Desulfurization

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