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Techno-Economic Feasibility Study of CCUS Implementation and Biomass Co-Firing System for Teluk Balikpapan Coal-Fired Power Plant (CFPP)

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Abstract. This research aims to evaluate the technical and economic feasibility of implementing Carbon Capture, Utilization, and Storage (CCUS) technology as well as biomass co-firing systems at the Teluk Balikpapan 2×110 MW Steam Power Plant (PLTU). CO_2 capture simulations were performed using a post-combustion approach with amine solvents, comparing the efficiency between MEA/PZ and MDEA/PZ mixtures. The simulation results show that the MEA/PZ solvent achieved a CO_2 capture efficiency of up to 92.4%, with a lower regeneration energy requirement compared to MDEA/PZ. Co-firing with biomass (wood bark and palm kernel) affects the flue gas characteristics, increasing the energy consumption of the CO_2 capture system, but still results in a CO_2 purity of 99.2%. The economic analysis indicates that this CCS project is financially viable with an IRR of 10.02%, an LCOE of IDR 2,400.51 /kWh, and an investment payback period of 6.96 years. These findings confirm that integrating CCUS and biomass co-firing in an existing power plant can serve as a sustainable energy transition strategy to reduce carbon emissions in Indonesia.

Keywords: *CCUS, Biomass Co-Firing, Balikpapan CFPP, Technical Optimization, Economic Analysis, Carbon Capture*

1 Introduction

Climate change has become a global issue affecting various aspects of life, including the environment, economy, and society. One of the main causes is the increase in carbon dioxide (CO_2) emissions resulting from human activities, such as fossil fuel-based power generation. In an effort to reduce these emissions, various mitigation strategies have been developed, one of which is Carbon Capture, Utilization, and Storage (CCUS) technology. This technology aims to capture, utilize, and store carbon dioxide emissions to minimize their impact on the environment. As part of Indonesia's commitment to achieving Net Zero Emissions (NZE) by 2060, PT PLN (Persero) has incorporated the CCUS program into its 2021–2030 Electricity Supply Business Plan (RUPTL). This program aligns with the global goal of limiting the average global temperature rise to below 1.5°C as outlined in the Paris Agreement. Within the RUPTL, PLN targets to increase the share of renewable energy (RE) to 23% by 2025, while also adopting low-carbon technologies, including CCUS, to reduce emissions from fossil fuel-based power plants.

CCUS technology is particularly relevant in Indonesia due to the prevalence of coal-fired power plants (CFPPs), which significantly contribute to carbon emissions. Given the relatively high CO_2 concentrations in fossil-fuel-based power plants, CCUS can be efficiently implemented to capture emissions directly from major sources. In addition, the potential use of CO_2 in industrial sectors such as for the production of synthetic fuels or for enhanced oil recovery (EOR) in the oil and gas sector—adds economic value to this technology. This study aims to assess the technical and economic feasibility of implementing CCUS at one of Indonesia's power plants, namely the Teluk Balikpapan CFPP. The research is not only relevant to climate change mitigation efforts but also serves as a strategy to support the national energy transition towards sustainability, in line with the RUPTL policy, GHG Inventory report, and Indonesia's commitments under its Enhanced Nationally Determined Contribution (ENDC).

Teluk Balikpapan CFPP, with a capacity of 2 × 110 MW, is located in East Kalimantan and operated by PT PLN Nusantara Power. It utilizes low-rank coal with a calorific value of approximately 4,134 kCal/kWh. This type of coal has a high sulfur content, which can damage power plant components, particularly boiler tubes. To address this challenge, the Teluk Balikpapan CFPP employs a Circulating Fluidized Bed (CFB) boiler, which offers several advantages such as fuel flexibility, high combustion efficiency, effective sulfur absorption, low NOx emissions, and a smaller furnace heating process.

With the superior characteristics of the CFB boiler and the availability of biomass waste such as Palm Kernel Shell (PKS) in Riau, the Teluk Balikpapan CFPP holds strong potential for implementing co-firing methods using PKS biomass.

2 Methodology

2.1 Location

A coal-based power plant in Teluk Balikpapan CFPP East Kalimantan, Indonesia was chosen for the location of CO2 capture simulation.

2.2 Data Collection

The data was obtained from a confidential third-party report that surveyed properties of flue gas in coal-based power plant, East Kalimantan

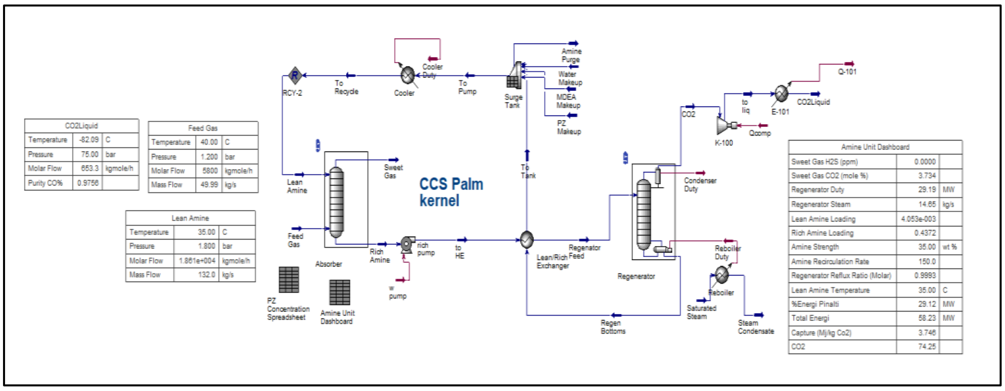
Table 1. Raw Material Flue Gas Emission Data Woodbark (PLN. 2022)

Fuel Composition	O_2 %	CO_2 (Mg/Nm3)	CO (Mg/Nm3)	NOx (Mg/Nm3)	Molar Flow (Kgmole/hr)	Temperature (°C)	Pressure (bar)
100% Coal (0% Biomass)	2.4	17.7	0.7	285	5800	40	1.2
97% Coal + 3% Woodbark	2.7	17.3	0.3	307	5626	40	1.2
95% Coal + 5% Woodbark	2.9	17	0.17	321	5510	40	1.2

Table 2. Raw Material Flue Gas Emission Data Palm Kernel (PLN. 2020)

Fuel Composition	O_2 (%)	CO_2 (%)	CO (Mg/Nm3)	NOx (Mg/Nm3)	SO_2 (Mg/Nm3)	Molar Flow (Kgmole/hr)	Temperature (°C)	Pressure (Bar)
100% Coal (0% Biomass)	16.3	14.7	4	55.1	362.2	5800	40	1.2
97% Coal + 3% Palm Kernel	15.8	15.5	4.52	64.7	342.3	5626	40	1.2
95% Coal + 5% Palm Kernel	15.4	16.8	4.80	68.6	312.1	5510	40	1.2

2.3 Flowsheet Simulation



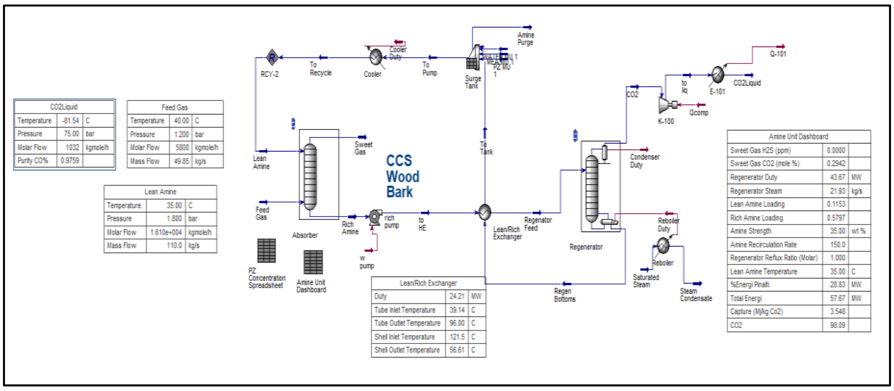
CO2Liquid		
Temperature	-82.09	C
Pressure	75.00	bar
Molar Flow	653.3	kgmole/h
Purity CO%	0.9756	

Feed Gas		
Temperature	40.00	C
Pressure	1.200	bar
Molar Flow	5800	kgmole/h
Mass Flow	49.99	kg/s

Lean Amine		
Temperature	35.00	C
Pressure	1.800	bar
Molar Flow	1.861e+004	kgmole/h
Mass Flow	132.0	kg/s

Amine Unit Dashboard		
Sweet Gas H2S (ppm)	0.0000	
Sweet Gas CO2 (mole %)	3.734	
Regenerator Duty	29.19	MW
Regenerator Steam	14.65	kg/s
Lean Amine Loading	4.053e-003	
Rich Amine Loading	0.4372	
Amine Strength	35.00	wt %
Amine Recirculation Rate	150.0	
Regenerator Reflux Ratio (Molar)	0.9993	
Lean Amine Temperature	35.00	C
%Energi Pinalti	29.12	MW
Total Energi	58.23	MW
Capture (Mj/kg Co2)	3.746	
CO2	74.25	

Figure 1. Process flow diagram and modelling CO2 capture for raw material Palm Kernel



CO2Liquid		
Temperature	-81.54	C
Pressure	75.00	bar
Molar Flow	1032	kgmole/h
Purity CO%	0.9759	

Feed Gas		
Temperature	40.00	C
Pressure	1.200	bar
Molar Flow	5800	kgmole/h
Mass Flow	49.85	kg/s

Lean Amine		
Temperature	35.00	C
Pressure	1.800	bar
Molar Flow	1.610e+004	kgmole/h
Mass Flow	110.0	kg/s

Lean/Rich Exchanger		
Duty	24.21	MW
Tube Inlet Temperature	39.14	C
Tube Outlet Temperature	96.00	C
Shell Inlet Temperature	121.5	C
Shell Outlet Temperature	56.61	C

Amine Unit Dashboard		
Sweet Gas H2S (ppm)	0.0000	
Sweet Gas CO2 (mole %)	0.2942	
Regenerator Duty	43.67	MW
Regenerator Steam	21.93	kg/s
Lean Amine Loading	0.1153	
Rich Amine Loading	0.5797	
Amine Strength	35.00	wt %
Amine Recirculation Rate	150.0	
Regenerator Reflux Ratio (Molar)	1.000	
Lean Amine Temperature	35.00	C
%Energi Pinalti	28.83	MW
Total Energi	57.67	MW
Capture (Mj/kg Co2)	3.548	
CO2	98.09	

Figure 2. Process flow diagram and modelling CO2 capture for raw material Woodbark

The carbon capture process illustrated in this flowsheet represents a standard post-combustion carbon capture configuration based on amine absorption. In this system, flue gas from a combustion process such as a biomass boiler in a palm kernel plant is directed into an absorber column to capture the carbon dioxide (CO_2) content. The inlet gas stream (feed gas) enters at a temperature of 40 °C and a pressure of 1.2 bar, with a molar flow rate of 5,800 kmol/h. Within the absorber, the flue gas comes into counter-current contact with a lean amine solution at 35 °C and 1.8 bar, consisting of a mixture of monoethanolamine (MEA) and methyldiethanolamine (MDEA) [1].

Inside the absorber, CO_2 from the flue gas chemically reacts with the circulating amine solution, forming intermediate compounds that effectively bind CO_2 in the liquid phase. The use of a blended MEA and MDEA solvent allows for efficient CO_2 capture at relatively low operating temperatures (30–60 °C). This absorption process is exothermic, releasing heat into the system. As a result, the outlet stream from the absorber is a sweet gas with a very low CO_2 concentration of 3.734 ppm, while the amine solution becomes rich in CO_2, with a CO_2 loading of 0.4372 mol/amine.

The rich amine is then pumped to a lean/rich heat exchanger, where it is preheated using the thermal energy from the lean amine stream. This heat integration strategy is implemented to reduce the overall energy consumption of the system [2]. The preheated rich amine is subsequently fed into a regeneration column, where it is heated by saturated steam supplied to the column base via a reboiler, consuming approximately 23.99 MW of thermal energy. The heating process drives the desorption of CO_2 from the amine solution, releasing CO_2 gas from the top of the column. This CO_2 is partially condensed (with a condenser duty of

0.1167 MW) and sent to a compressor (K-100), where it is compressed to a high pressure (75 bar) and temperature (82.09 °C) to be liquefied. The final CO_2 product has a purity of 97.66% [3].

The remaining amine solution, now stripped of CO_2 and known as lean amine, is cooled and recycled back to the absorber column. The system maintains an amine concentration of 35 wt% and a lean amine CO_2 loading of 0.4035 mol/mol. This indicates that the absorption reaction is operating near the solvent's maximum loading capacity while retaining a sufficient margin for circulation efficiency [4].

The CO_2 capture performance of this system varies based on the choice of amine solvent. When using a MEA/PZ (piperazine) blend, the CO_2 capture efficiency reaches 92.4%, reflecting highly effective CO_2 removal from the gas stream. This is consistent with the known characteristics of MEA/PZ, which offers high reactivity with CO_2 and better thermal stability than pure MEA [4].

Conversely, with a MDEA/PZ blend, the capture efficiency is 74.26%. Although lower than the MEA/PZ system, this efficiency is still considered satisfactory for MDEA-based processes, as MDEA offers advantages such as lower energy requirements for regeneration and minimal solvent degradation [5]. This difference highlights the trade-off between absorption rate and regeneration energy demand, emphasizing the importance of solvent selection in the design and operation of carbon capture units.

In conclusion, MEA/PZ is better suited for applications requiring maximum CO_2 capture efficiency, while MDEA/PZ is preferable in systems that prioritize energy efficiency and long-term solvent stability.

3 Results and Discussion

The capture of carbon dioxide (CO_2) from the flue gas of fossil fuel combustion is currently one of the most promising technologies for climate change mitigation. Among the various approaches, chemical absorption using amine-based solvents is the most widely applied method, where CO_2 is captured in an absorber column and subsequently released in a stripper column through a solvent regeneration process. The energy required for regeneration is a key parameter in evaluating the efficiency and economic viability of carbon capture systems. In the context of energy efficiency, both the type of solvent and the composition of the fuel significantly influence the total regeneration energy demand.

In this study, two modified solvent systems were employed namely a mixture of 30% monoethanolamine (MEA) + 5% piperazine (PZ), and 30% methyldiethanolamine (MDEA) + 5% PZ. MEA is known for its high reactivity with CO_2 but suffers from limitations in thermal stability and relatively high regeneration energy consumption. Conversely, MDEA offers advantages in terms of lower energy consumption but has slower reaction kinetics. The addition of PZ as a kinetic promoter is intended to overcome the limitations of each solvent, with the aim of enhancing the overall efficiency of the CO_2 capture process (Rochelle, 2009) [6].

Tabel 3. Investigation of regeneration energy

Concentration Solvent (wt%)	Variasi Flue Gas	Regeneration Energy (MJ/kg CO_2)
30% MEA + 5 % PZ	100% Coal (0% Biomass)	3.548
	97% Coal + 3% Woodbark	3.596
	95% Coal + 5% Woodbark	3.687
30% MDEA +5 % PZ	100% Coal (0% Biomass)	3.746
	97% Coal + 3% Palm Karnel	3.796
	95% Coal + 5% Palm Karnel	3.838

Based on the data presented in Table 3, this study evaluates the regeneration energy requirements of two types of solvents—namely a mixture of 30% monoethanolamine (MEA) + 5% piperazine (PZ) and 30% methyldiethanolamine (MDEA) + 5% PZ—under various flue gas fuel compositions, specifically 100% coal and coal co-fired with biomass in the form of wood bark and palm kernel. The results indicate that both the solvent type and the proportion of biomass in the fuel significantly influence the energy required for CO_2 absorption and desorption processes.

Overall, the MEA + PZ solvent exhibited lower regeneration energy demands compared to MDEA + PZ. For instance, under conditions without biomass (100% coal), the MEA + PZ solvent required only 3.548 MJ/kg CO_2, while MDEA + PZ required 3.746 MJ/kg CO_2. This finding is consistent with Monteiro et al. (2016), who reported that MEA has a higher CO_2 absorption capacity and faster reaction kinetics than MDEA, although the presence of PZ enhances regeneration efficiency in both solvent systems [7,8]

When biomass is introduced into the fuel mixture, an increase in regeneration energy demand is observed. For the MEA + PZ solvent, the addition of 3% and 5% wood bark raised the regeneration energy to 3.596 and 3.687 MJ/kg CO_2, respectively. In contrast, for the MDEA + PZ solvent, the addition of 3% and 5% palm kernel increased the energy requirement to 3.796 and 3.838 MJ/kg CO_2, respectively. This trend indicates that higher biomass proportions in the fuel mixture lead to greater regeneration energy demands. This phenomenon can be attributed to the higher moisture and volatile compound content in biomass, which alters the flue gas composition and increases the thermal load on the solvent regeneration unit [9, 10].

Under 100% coal conditions, the regeneration energy requirement tends to be lower due to the more stable flue gas composition and lower water vapor content compared to biomass mixtures. This results in more consistent interactions with the solvent and reduces the energy needed for CO_2 desorption. These findings align with the study by [11] which found that flue gas sources with more homogeneous compositions can improve the efficiency of CO_2 absorption and regeneration systems [12].

In conclusion, the choice of solvent and fuel type plays a critical role in determining the efficiency of carbon capture processes. The MEA + PZ-based solvent demonstrates better potential for reducing regeneration energy demands, particularly under conditions without biomass, although the inclusion of biomass still presents thermal efficiency challenges.

3.4 CO_2 Capture Process Result

The performance evaluation of a carbon dioxide (CO_2) capture system is not limited to the solvent regeneration energy efficiency, but also includes other operational indicators such as the purity of the captured CO_2, total energy consumption, and the energy penalty resulting from integrating the capture system into the power plant.

Tabel 4. CO2 Capture proses result

Variasi	Purity of CO2 Product (%)	Total Energi (MW)	% Energy Pinalty
100% Coal (0% Biomass)	99.5	58.23	29.12
97% Coal + 3% Biomass	99.5	58.44	29.22
95% Coal + 5% Biomass	99.5	58.48	29.29

Table 4 presents the simulation results of CO_2 capture for three fuel variation scenarios: 100% coal, and coal co-fired with 3% and 5% biomass. The objective of this evaluation is to assess the extent to which biomass co-firing influences CO_2 product quality, operational energy requirements, and the percentage of energy penalty imposed on the power generation system. The incorporation of biomass as an alternative fuel offers environmental benefits in the form of reduced net carbon emissions; however, the resulting changes in flue gas characteristics have the potential to affect the performance of the CO_2 capture system, particularly in terms of thermodynamics and process efficiency [13]

In addition to regeneration energy, the overall performance evaluation of a CO_2 capture process also includes parameters such as product CO_2 purity, total energy consumption, and the associated energy penalty resulting from the integration of the capture system. In this context, the energy penalty (% energy penalty) refers to the reduction in power plant efficiency due to the implementation of carbon capture technology. This efficiency loss arises from the additional energy required to operate the absorber, stripper, CO_2 compressor, and solvent circulation system [14,15].

According to the results presented in Table 4, the purity of the captured CO_2 remained consistent at 99.5% across all fuel variations, including 100% coal combustion and co-firing with up to 5% biomass. This indicates that the fuel composition does not significantly affect the CO_2 purification performance, provided that solvent operating conditions and desorption processes are optimally controlled. These findings align with the study by [16], which reported that amine-based capture systems can maintain high CO_2 purity as long as solvent-to-gas ratios and residence times are properly managed [17].

However, fuel variations do influence total energy consumption and energy penalties. Under 100% coal conditions, the energy consumption of the capture system was 58.23 MW, with an energy penalty of 29.12%. When biomass was co-fired at 3% and 5%, energy consumption increased slightly to 58.44 MW and 58.48 MW, respectively, with corresponding energy penalties rising to 29.22% and 29.29%. Although the differences are relatively small, this trend indicates that higher biomass proportions in the fuel mix tend to increase the energy load of the capture system.

This increase can be attributed to changes in the characteristics of the flue gas generated from biomass combustion, which typically contains higher moisture levels and a more diverse gas composition. These factors contribute to increased thermal loads on the desorption unit and CO_2 drying system prior to compression, thus affecting the overall system efficiency. This observation is supported by [18] who reported that biomass co-firing leads to elevated moisture and additional gaseous components such as SOx and NOx, which complicate flue gas treatment processes [19].

Overall, while co-firing coal with biomass does not compromise the purity of captured CO_2, it does introduce increased energy demand and energy penalties that must be considered in system design. Nonetheless, the increase remains within an acceptable range to preserve the environmental benefits of utilizing biomass as a low-carbon fuel source.

4 Economy Analysis

The implementation of Carbon Capture and Storage (CCS) technology in the power generation sector requires not only technical and operational considerations, but also a thorough economic assessment to ensure that the investment delivers long-term financial and environmental benefits. Economic analysis is a critical component in determining the feasibility of CCS projects, especially given the high capital and operational costs associated with this technology [21]. The evaluation includes various parameters such as capital expenditure, annual operating costs, tax rates, and financial metrics like the Levelized Cost of Electricity (LCOE), Internal Rate of Return (IRR), and Net Present Value (NPV), which provide insight into the project's potential profitability and risks.

Table 6. Sensitivity Analysis of LCOE Impact on Project Economic Indicators

Senitivity	Harga	IRR	NPV	B/C Ratio	Payback Period
1.00	1,467.00	#NUM!	(5,501,448,037.00)	0.67	-
1.05	1,540.35	#NUM!	(5,081,310,161.90)	0.70	-
1.10	1,613.70	#NUM!	(4,661,172,286.79)	0.72	-
1.15	1,687.05	#NUM!	(4,241,034,411.69)	0.75	-
1.20	1,760.40	#NUM!	(3,820,896,536.58)	0.78	-
1.25	1,833.75	#NUM!	(3,400,758,661.48)	0.80	-
1.30	1,907.10	#NUM!	(2,980,620,786.37)	0.83	-
1.35	1,980.45	#NUM!	(2,560,482,911.27)	0.85	-
1.40	2,053.80	-6%	(2,140,345,036.16)	0.88	-
1.45	2,127.15	-1%	(1,720,207,161.06)	0.90	-
1.50	2,200.50	3%	(1,300,069,285.95)	0.93	17.66
1.55	2,273.85	5%	(879,931,410.85)	0.95	12.76
1.60	2,347.20	8%	(459,793,535.74)	0.97	9.98
1.65	2,420.55	10%	(39,655,660.64)	1.00	8.20
1.70	2,493.90	11%	380,482,214.47	1.02	6.96
1.75	2,567.25	13%	800,620,089.57	1.04	6.04
1.80	2,640.60	14%	1,220,757,964.68	1.07	5.34
1.85	2,713.95	16%	1,640,895,839.78	1.09	4.78
1.90	2,787.30	17%	2,061,033,714.89	1.11	4.33
1.95	2,860.65	19%	2,481,171,589.99	1.13	3.96
2.00	2,934.00	20%	2,901,309,465.10	1.15	3.64

Table 6. Economy Analysis

No	Description	Unit	Value	Remarks
1	CCS Investment Cost	Thousand IDR	2,481,141,249.51	APEA

No	Description	Unit	Value	Remarks
2	O&M/Year	Thousand IDR	301,741,814.37	APEA
3	Discount Rate	%	9.7	WACC RKAP 2024–2025
4	Income Tax (PPH)	%	22	Government Regulation
5	LCOE	IDR/kWh	2,400.51	
6	Carbon Tax	IDR/tonCO₂	796,229	
7	IRR	%	10.02	> Discount Rate
8	NPV	MVAR	380,482,214.47	> 0 (positive)
9	B/C Ratio		1	> 1 Time
10	Payback Period	IDR/USD	6.96	
	Conclusion		**Feasible**	

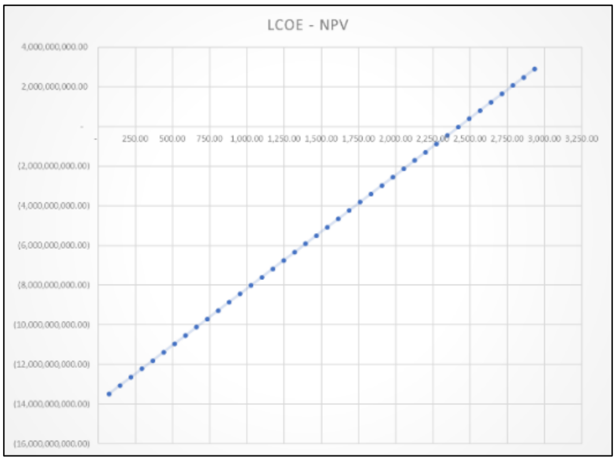


Figure 3. Graph of the relationship between changes in LCOE and NPV

Economic analysis is a crucial step in evaluating the feasibility of implementing carbon capture and storage (CCS) technology in fossil fuel-based power plants. In addition to technical aspects such as energy efficiency and CO_2 capture performance, investment costs, operational expenditures, and the potential return on investment play key roles in determining the commercial viability of CCS deployment. Table 5 presents the main economic parameters used to assess the feasibility of this CCS project.

The initial capital investment for the installation of the CCS system is recorded at IDR 2,481,141,249.51 while the annual operation and maintenance (O&M) cost amounts to IDR 301,741,814.37. These relatively high figures reflect the complexity and large scale of the carbon capture system integrated into an existing power generation facility. However, in the long term, this investment can be offset by the potential for carbon tax avoidance and the environmental value generated from reduced carbon emissions [22].

Feasibility was assessed using standard economic indicators, including the discount rate, corporate income tax rate, Levelized Cost of Electricity (LCOE), and financial performance metrics such as Internal Rate of Return (IRR), Net Present Value (NPV), and Benefit-Cost (B/C) ratio. In this simulation, the discount rate was set at 9.7%, based on the Weighted Average Cost of Capital (WACC) in the 2024–2025 business plan, while the tax rate of 22% follows current government regulations.

The resulting LCOE is IDR 2,400.51 /kWh, indicating that despite the increased electricity production costs due to CCS integration, the value remains within an economically acceptable range—especially when compared to the external costs of unmanaged carbon emissions. The additional carbon tax burden of IDR 796,229 per ton of CO_2 further strengthens the argument that CCS systems can help mitigate the future cost impacts of environmental regulations (Rubin et al., 2015) [23].

In terms of profitability, the IRR of 10.02% exceeds the discount rate, indicating that the project is financially viable. This is supported by a positive NPV of more than IDR 380 trillion, demonstrating that the project is expected to generate a net present profit. The B/C ratio of 1 also indicates that the expected benefits are at least equal to the costs incurred, while the Payback Period of 8.2 years is considered moderate for large-scale energy projects, suggesting that the investment can be recovered within a commercially reasonable timeframe [24].

In conclusion, all economic indicators show that the implementation of CCS technology in this scenario is both financially and technically feasible, offering long-term benefits from both economic and environmental perspectives. These findings provide a strong foundation for considering CCS adoption as part of the energy transition strategy toward a sustainable low-carbon energy system.

5 Conclusion

This research demonstrates that the implementation of Carbon Capture, Utilization, and Storage (CCUS) technology and biomass co-firing at the Teluk Balikpapan Steam Power Plant is technically and economically feasible. From a technical perspective, the use of the MEA/PZ solvent provides the highest CO_2 capture efficiency of 92.4%, with a lower regeneration energy requirement compared to MDEA/PZ. Co-firing with wood bark and palm kernel biomass has been proven to be applicable without reducing the CO_2 capture purity (97.5%), although it slightly increases energy consumption and system energy penalties.

From an economic standpoint, the project is considered feasible based on key economic indicators, such as an IRR of 10.02%, an LCOE of IDR 2,400.51 /kWh, and a payback period of 8.2 years. Therefore, the combination of CCUS and biomass co-firing can serve as a strategic approach to support the low-carbon energy transition in the coal-based power generation sector, while also contributing to the achievement of Indonesia's Net Zero Emission.

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