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Techno-Economic Analysis of CCS Implementation for Decarbonization at the Tidore Coal-Fired Power Plant

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Abstract. This study presents a techno-economic analysis of Carbon Capture and Storage (CCS) implementation at the Tidore Coal-Fired Power Plant (PLTU Tidore) using post-combustion technology with amine-based solvents. Two solvent formulations—30% monoethanolamine (MEA) with 10% piperazine (PZ) and 30% methyldiethanolamine (MDEA) with 10% PZ—were evaluated through process simulation in Aspen Plus to assess their technical performance and economic feasibility. The MDEA + PZ system demonstrated lower regeneration energy requirements (4.261 MJ/kg CO_2) compared to MEA + PZ (4.315 MJ/kg CO_2), with comparable CO_2 product purity of 99%. Despite MEA's higher absorption reactivity, MDEA showed superior energy efficiency and operational stability. Economic analysis revealed that the CCS investment cost reached IDR 139.17 billion, with annual O&M costs of IDR 65.74 billion. Under a carbon pricing scheme of USD 100/ton CO_2 and LCOE of IDR 2,486/kWh, the project achieved financial viability with a Net Present Value (NPV) of IDR 31 billion, Internal Rate of Return (IRR) of 9.79%, Benefit-Cost Ratio (B/C) of 1.00, and a payback period of 8 years. Additionally, scenario analysis demonstrated that increasing carbon pricing significantly lowers the required LCOE for breakeven, enhancing the attractiveness of CCS.

Keywords: CCS, MDEA, MEA, Piperazine, Coal-Fired Power Plant, Energy Penalty, Economic Analysis, LCOE.

1 Introduction

The Paris Agreement, signed by 196 countries in 2015, aims to limit global temperature rise to well below 2°C, with efforts to keep it below 1.5°C. Each participating country is required to develop action plans to reduce greenhouse gas (GHG) emissions from human activities to meet this critical goal. A key strategy involves shifting to renewable energy and reducing dependence on fossil fuels such as coal and crude oil.

The transition to renewable energy is a gradual process that cannot be accelerated abruptly. While fossil fuels remain a necessary energy source during this transition, Carbon Capture, and Storage (CCS) technology has emerged as a viable solution. CCS is designed to capture carbon dioxide emissions from fossil fuel use and industrial processes, either by reusing the CO_2 or storing it underground to prevent its release into the atmosphere. This technology plays a crucial role in achieving the objectives of the Paris Agreement and mitigating the effects of climate change.

PT PLN (Persero) has demonstrated its commitment to reducing greenhouse gas emissions by developing innovations and implementing programs aimed at emissions reduction. In 2023, the company succeeded in reducing 9.7 million tons of CO_2 emissions compared to the Business as Usual (BAU) scenario. PLN's initiatives to control GHG emissions begin with emission source inventorying, followed by periodic calculation and reporting of emissions. The company continues to systematically reduce emissions through various programs that show significant results [1].

As a "negative emission" technology, CCS is particularly relevant for fossil-fuel-based power plants such as coal-fired power plants (CFPPs). Global research trends indicate that CCS implementation not only aids in climate change mitigation but also provides opportunities to enhance energy efficiency and create new economic prospects. Although research on CCS implementation is extensive, limited studies focus on smaller power plants like PLTU Tidore, particularly in Eastern Indonesia.

The implementation of Carbon Capture, and Storage (CCS) by PT PLN is a strategic move to address carbon emissions in the energy sector. This technology offers an effective solution for reducing GHG emissions and aligns with PLN's goals of achieving Net Zero Emissions by 2060 and supporting the NDC target by 2030. The deployment of CCS is critical in strengthening PLN's commitment to environmental sustainability and clean energy transition in Indonesia, ensuring operational continuity and solidifying PLN's role as a leader in the national and international energy sector.

2 Methodology

2.1 Location

A coal-based power plant in PLTU Tidore, 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, PLTU Tidore.

Table 1. Flue Gas Emission Data (PLN. 2024)

Parameter	Unit 1	Unit 2
Temperature (°C)	162	168
Flow (kgmol/hr)	79.06	79.59
Pressure (mbar)	40	38
O_2 (mol fraction)	0.069	0.078
CO_2 (mol fraction)	0.135	0.127
CO (mol fraction)	0.1211	0.1244
NO_x (mol fraction)	0.1295	0.1395
SO_2 (mol fraction)	0.0155	0.0184
N_2 (mol fraction)	0.53	0.5127
Total	1.000	1.000

Table 1 shows the flue gas properties from two units of a coal-fired power plant (PLTU Tidore), based on data from a confidential third-party report. The flue gas temperatures are 162°C for Unit 1 and 168°C for Unit 2, with similar flow rates around 79 kgmol/hr and 311.2 kgmol/hr units operate at low pressures below 40 mbar.

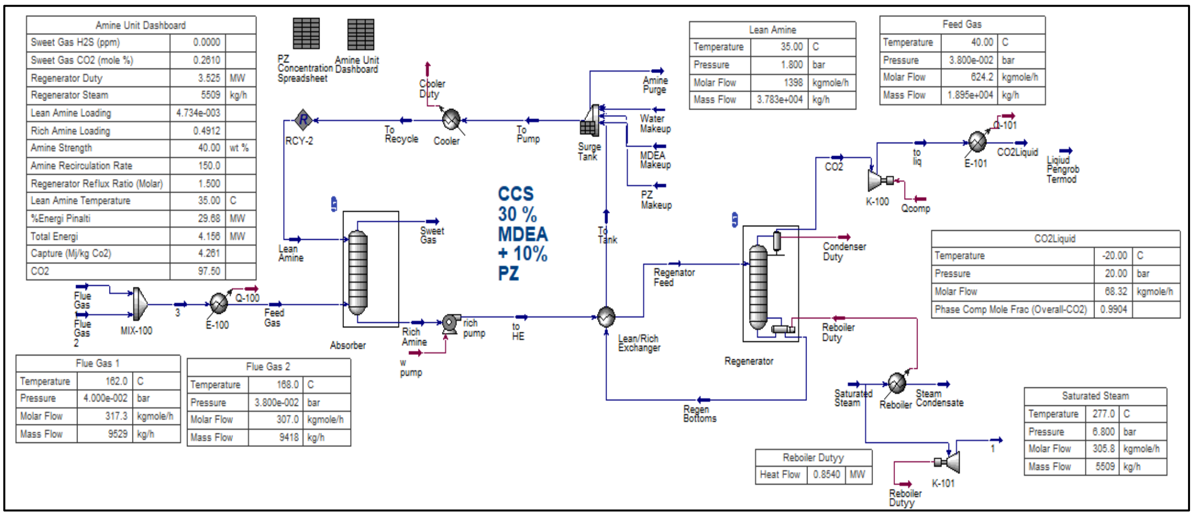
The main components of the flue gas are nitrogen (around 51–53%), carbon dioxide (12.7–13.5%), and oxygen (6.9–7.8%). Trace gases include carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur dioxide (SO_2), with NO_x reaching up to 13.95% mole fraction in Unit 2. These gas compositions are essential for evaluating CO_2 capture performance and solvent stability in the CCS system.

2.3 Flowsheet Simulation

The simulation displayed in this flowsheet represents a Carbon Capture and Storage (CCS) system based on post-combustion technology utilizing amine solvents. The primary objective of this process is to capture carbon dioxide (CO_2) from flue gas generated by the combustion of fossil fuels. In this system, two solvent variations are employed: a mixture of 30% monoethanolamine (MEA) with 5% piperazine (PZ), and a mixture of 30% methyldiethanolamine (MDEA) with 5% PZ. These combinations are based on prior research findings indicating that the addition of PZ enhances CO_2 absorption rates and reduces regeneration energy requirements, thereby providing a balance between process efficiency and performance [20].

The flue gas enters the system at a pressure of approximately atmospheric is first mixed and cooled to reach optimal conditions for CO_2 absorption by the amine solution. The gas is then directed into the absorber column, where CO_2 absorption occurs via a counter-current flow with the lean amine solution. Lean amine refers to fresh or regenerated solvent that still has the capacity to absorb CO_2. Within the absorber, gas and liquid phases interact through trays or packing material, allowing CO_2 in the flue gas to dissolve into the amine solvent. The overhead product from the absorber is referred to as sweet gas with reduced CO_2 content. In this simulation, the sweet gas shows a CO_2 mole fraction of 3.825% and 0 ppm H_2S, indicating effective absorption.

The CO_2-rich solution, known as rich amine, exits from the bottom of the absorber and is pumped to a lean/rich heat exchanger, where it is preheated by the cooled lean amine stream. This energy integration step reduces the heat duty required in the next stage the regenerator column. After passing through the heat exchanger, the rich amine is fed into the regenerator, where CO_2 is stripped from the amine solvent through steam-assisted heating in the reboiler. The released CO_2 rises to the top of the regenerator, where it is partially condensed in condenser K-100. The remaining liquid CO_2 is then liquefied and compressed by compressor Q-101. The final CO_2 product is in liquid phase at 20 bar, -20°C, with a purity of 99% and 98% suitable for injection into underground reservoirs or for use in various industrial applications [22].



Amine Unit Dashboard		
Sweet Gas H2S (ppm)	0.0000	
Sweet Gas CO2 (mole %)	0.2610	
Regenerator Duty	3.525	MW
Regenerator Steam	5509	kg/h
Lean Amine Loading	4.734e-003	
Rich Amine Loading	0.4912	
Amine Strength	40.00	wt %
Amine Recirculation Rate	150.0	
Regenerator Reflux Ratio (Molar)	1.500	
Lean Amine Temperature	35.00	C
%Energi Pinalti	29.68	MW
Total Energi	4.156	MW
Capture (Mj/kg Co2)	4.261	
CO2	97.50	

Lean Amine		
Temperature	35.00	C
Pressure	1.800	bar
Molar Flow	1398	kgmole/h
Mass Flow	3.783e+004	kg/h

Feed Gas		
Temperature	40.00	C
Pressure	3.800e-002	bar
Molar Flow	624.2	kgmole/h
Mass Flow	1.895e+004	kg/h

CO2Liquid		
Temperature	-20.00	C
Pressure	20.00	bar
Molar Flow	68.32	kgmole/h
Phase Comp Mole Frac (Overall-CO2)	0.9904	

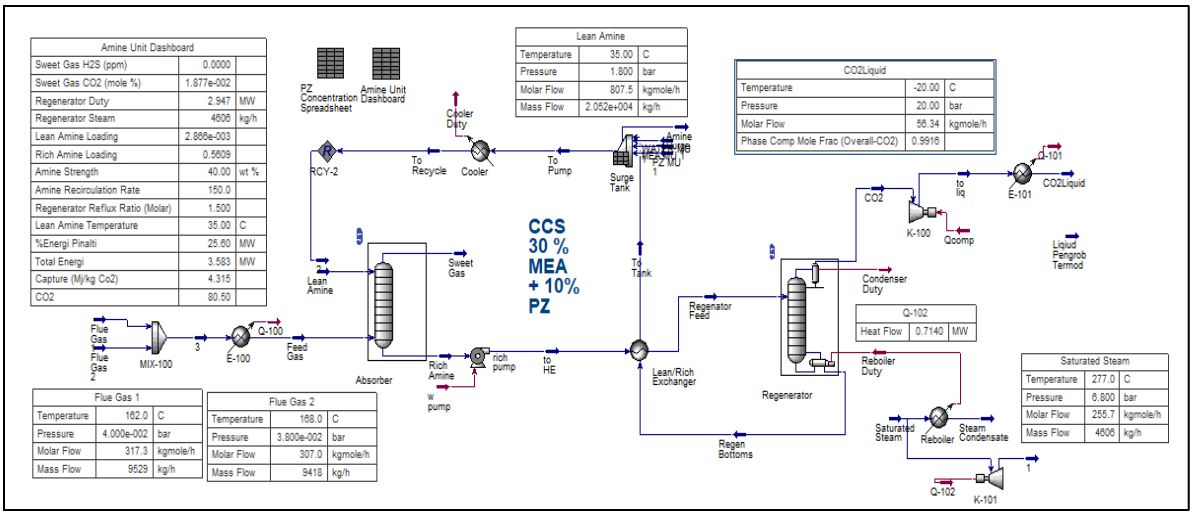
Flue Gas 1		
Temperature	162.0	C
Pressure	4.000e-002	bar
Molar Flow	317.3	kgmole/h
Mass Flow	9529	kg/h

Flue Gas 2		
Temperature	168.0	C
Pressure	3.800e-002	bar
Molar Flow	307.0	kgmole/h
Mass Flow	9418	kg/h

Reboiler Dutyy		
Heat Flow	0.8540	MW

Saturated Steam		
Temperature	277.0	C
Pressure	6.800	bar
Molar Flow	305.8	kgmole/h
Mass Flow	5509	kg/h

Figure 1. Process flow diagram and modelling parameter of CO2 capture 30%MDEA + 10% PZ



Amine Unit Dashboard		
Sweet Gas H2S (ppm)	0.0000	
Sweet Gas CO2 (mole %)	1.877e-002	
Regenerator Duty	2.947	MW
Regenerator Steam	4606	kg/h
Lean Amine Loading	2.866e-003	
Rich Amine Loading	0.5609	
Amine Strength	40.00	wt %
Amine Recirculation Rate	150.0	
Regenerator Reflux Ratio (Molar)	1.500	
Lean Amine Temperature	35.00	C
%Energi Pinalti	25.60	MW
Total Energi	3.583	MW
Capture (Mj/kg Co2)	4.315	
CO2	80.50	

Lean Amine		
Temperature	35.00	C
Pressure	1.800	bar
Molar Flow	807.5	kgmole/h
Mass Flow	2.052e+004	kg/h

CO2Liquid		
Temperature	-20.00	C
Pressure	20.00	bar
Molar Flow	56.34	kgmole/h
Phase Comp Mole Frac (Overall-CO2)	0.9916	

Q-102		
Heat Flow	0.7140	MW

Flue Gas 1		
Temperature	162.0	C
Pressure	4.000e-002	bar
Molar Flow	317.3	kgmole/h
Mass Flow	9529	kg/h

Flue Gas 2		
Temperature	168.0	C
Pressure	3.800e-002	bar
Molar Flow	307.0	kgmole/h
Mass Flow	9418	kg/h

Saturated Steam		
Temperature	277.0	C
Pressure	6.800	bar
Molar Flow	255.7	kgmole/h
Mass Flow	4606	kg/h

Figure 2. Process flow diagram and modelling parameter of CO2 capt0%MEA + 10% PZ

The regenerated amine, now lean, is recirculated through the lean/rich heat exchanger, then cooled in a cooler and temporarily stored in a surge tank before being pumped back to the absorber. To maintain system stability, an amine purge stream is provided to remove degradation products and contaminants, and a make-up amine stream compensates for solvent losses.

This simulation aims to evaluate the performance of both solvent variations in capturing CO_2, with emphasis on key parameters such as regenerator energy duty, CO_2 conversion, and capture efficiency. The regenerator energy duty in this system is 1.829 MW, with a total CO_2 capture rate of 97.5% and 80.5% a capture rate of approximately 48.31 kgmole/hr. These findings align with literature such as [2] which demonstrate that the addition of PZ to MEA or MDEA enhances the chemical reaction rate and increases solvent capacity for CO_2 absorption. Other studies have shown that MDEA offers benefits in terms of reduced reboiler energy demand due to its selective and easily regenerable nature, although it reacts more slowly than MEA [17]. Therefore, combining MDEA with PZ helps compensate for its slower reaction rate.

Overall, the simulation results demonstrate that amine solvent combinations with PZ activators provide strong performance in post-combustion CCS systems. Not only do they enable high absorption efficiency, but they also significantly reduce regeneration energy requirements. Such simulations are highly valuable for the design and optimization of industrial-scale CCS systems and contribute to the development of more economical and sustainable carbon emission reduction technologies.

3 Results and Discussion

This section presents a technical evaluation of the thermal energy requirements for solvent regeneration in post-combustion CO_2 capture systems. Regeneration energy, expressed in MJ/kg CO_2, quantifies the thermal duty required to desorb CO_2 from the rich amine solution after absorption. It represents a major energy sink in amine-based CO_2 capture. Therefore, minimizing this energy requirement is critical for improving overall process efficiency and economic viability in large-scale CCS implementations.

Tabel 3. Investigation of regeneration energy

Concentration Solvent (wt%)	Regeneration Energy (MJ/kg CO_2)
30% MDEA + 10 % PZ	4.261
30% MEA + 10 % PZ	4.315

This subsection analyzes the regeneration energy requirements of two different amine-based solvent formulations used in a post-combustion carbon capture system. Regeneration energy, measured in MJ/kg CO_2, is a key parameter reflecting the thermal energy needed to desorb CO_2 from a rich amine solution after absorption. Since the regeneration step typically accounts for 60–70% of the total energy demand in amine-based CO_2 capture processes, reducing this energy burden is essential to improve overall system efficiency and lower operational costs [5].

In this study, a simulation was conducted to compare the performance of two solvent systems: 30% methyldiethanolamine (MDEA) 10% piperazine (PZ) and 30% monoethanolamine (MEA) 10% PZ. The results show that the MDEA + PZ blend requires 4.261 MJ/kg CO_2 for regeneration, whereas the MEA + PZ blend consumes a higher energy of 4.315 MJ/kg CO_2. Although the difference may seem modest, a reduction of approximately 0.099 MJ/kg CO_2 translates into significant energy savings when applied at large-scale CCS facilities.

The observed performance can be attributed to the chemical and thermodynamic properties of the solvents. MDEA, a tertiary amine, has lower heat of reaction and slower kinetics, but it exhibits a higher CO_2 loading capacity. The addition of PZ, a cyclic diamine, enhances the kinetics of MDEA by accelerating the CO_2 absorption rate and improving the reversibility of carbamate formation during regeneration [6]. As a result, the MDEA + PZ system performs efficiently with relatively low energy input.

In contrast, MEA is a primary amine known for its fast reaction kinetics with CO_2, making it a popular solvent in industrial CCS applications. However, the strong carbamate bonds formed between MEA and CO_2 may demand more energy during the regeneration process. Furthermore, the combination of MEA with PZ might increase the thermal load due to the formation of more stable carbamate species that are harder to break at standard reboiler conditions [7].

These findings align with literature reports emphasizing that solvent regeneration energy is not only determined by absorption speed or CO_2 capacity but also by the ease with which CO_2 can be desorbed during regeneration [8]. A lower regeneration energy improves both the technical performance and economic viability of CCS systems, especially in scenarios where energy costs dominate operational expenses [9].

Therefore, under the simulated operating conditions, the MDEA + PZ mixture offers a more energy-efficient solution compared to the MEA + PZ blend. This makes it a promising alternative for large-scale CCS deployments, particularly where energy integration and cost optimization are priorities.

3.1 CO_2 Capture Process Result

Based on the results presented in Table 4, it can be concluded that the choice of amine solvent formulation has a significant impact on the performance of post-combustion CO_2 capture processes. Two solvent mixtures were evaluated: 30% MDEA 10% PZ and 30% MEA 10% PZ.

Tabel 4. CO2 Capture proses result

Variasi	**Purity of CO2 Product (%)**	**Total Energi (MW)**	**% Energi Pinalti**
30% MDEA + 5 % PZ	99	4.156	29.68%
30% MEA + 5 % PZ	99	3.583	25.60%

Based on the results presented in Table 4, the evaluation of post-combustion CO_2 capture using two amine solvent formulations — namely 30% MDEA 10% PZ and 30% MEA 10% PZ provides important insights into their technical performance and economic implications. These formulation differences not only affect the purity of the captured CO_2 but also the total energy consumption and energy penalty (percentage of power plant energy used for solvent regeneration).

Technically, the 30% MEA 10% PZ formulation yields a higher CO_2 purity of 99%, compared to 99% for the 30% MDEA 10% PZ formulation. This indicates that the MEA-based (Monoethanolamine) solvent system is more effective in capturing CO_2 at high purity levels. Such purity is crucial for downstream processes like transportation and storage (CCS), or in CO_2 utilization (CCU), as higher purity reduces the need for further purification [16,17].

However, the advantage in CO_2 product purity comes at the cost of higher energy consumption. The MDEA + PZ formulation requires 4.156 MW, which is higher than the 3.583 MW required by the MEA + PZ formulation. This result is somewhat counterintuitive, as MEA is typically known for its higher heat capacity and greater regeneration energy demand. Despite the enhancement in the CO_2 absorption rate due to the addition of PZ (Piperazine), solvent regeneration remains an energy-intensive step [10].

This difference is also reflected in the energy penalty, which refers to the portion of the power plant's output consumed by the CO_2 capture process. The MDEA + PZ system results in a higher energy penalty of 29.68%, compared to 25.60% for the MEA + PZ system. In the context of power generation, such an energy penalty directly impacts plant efficiency, as a significant portion of energy is diverted from electricity production to emission capture.

According to the IEA Greenhouse Gas R&D Programme, an energy penalty ranging from 25–35% is typical for MEA-based CO_2 capture systems, with potential reductions achievable through alternative solvent technologies such as MDEA + PZ. This performance discrepancy can be attributed to the intrinsic properties of each solvent. Monoethanolamine (MEA) is known for its high reactivity with CO_2, but its major drawbacks include high regeneration energy requirements and a greater tendency for thermal degradation [15]. On the other hand, Methyldiethanolamine (MDEA), a tertiary amine, has slower reaction kinetics but offers better thermal stability and lower energy consumption, especially when combined with a kinetic promoter like PZ [11,12].

The MDEA-PZ formulation is particularly attractive for applications involving biomass and natural gas co-firing, where the flue gas composition varies and can influence absorption efficiency. A study by [13] highlighted that the MDEA-PZ system provides higher thermal and chemical stability during long-term operation, making it a promising candidate for industrial-scale CO_2 capture under variable gas conditions. These findings are also consistent with the work of [14], which reported that while MEA exhibits faster initial absorption, MDEA combined with an activator can achieve comparable or even better efficiency under more energy-efficient operating conditions.

Considering energy efficiency, power penalty, and CO_2 product purity, the 30% MEA + 5% PZ formulation demonstrates technical and economic superiority for the proposed co-firing-based CO_2 capture system.

4 Economy Analysis

The economic feasibility of implementing a post-combustion CO_2 capture system is assessed in this section using key financial parameters. This evaluation aims to determine whether the proposed investment in Carbon Capture and Storage (CCS) technology is justifiable from a financial standpoint, considering both the capital expenditures and the operational costs involved. In addition to direct costs, the analysis also incorporates broader economic indicators such as the Levelized Cost of Energy (LCOE), Internal Rate of Return (IRR), Net Present Value (NPV), Benefit-Cost Ratio (B/C Ratio), and Payback Period. Furthermore, the potential economic benefits resulting from the application of a carbon tax policy are examined to reflect the growing emphasis on emissions reduction incentives, with carbon pricing also monitored as one of the key benefits. By integrating these variables, this analysis provides a comprehensive insight into the viability and sustainability of the CCS implementation under current and projected economic conditions.

Tabel 5. Economy Analysis

No	Description	Unit	Value	Remarks
1	CCS Investment Cost	Thousand IDR	139,186,969.75	
2	O&M/Year	Thousand IDR	65,742,916.41	
3	Discount Rate	%	9.7	WACC RKAP 2024–2025
4	Income Tax (PPH)	%	22	Government Regulation
5	LCOE	IDR/kWh	4,439.73	
6	Rupiah exchange rate	IDR/USD	16,000	
7	Project Lifetime	Year	23	

Based on the economic analysis presented in Table 5, the implementation of Carbon Capture and Storage (CCS) technology in the power generation system demonstrates both technical and economic feasibility. The initial investment required for CCS implementation is estimated at IDR 139.17billion, with annual operation and maintenance (O&M) costs amounting to IDR 65.74 billion. Although these investment and operational costs are relatively high, they remain justifiable when considering the long-term benefits, particularly in terms of carbon emissions reduction [19].

The analysis employs a discount rate of 9.7%, in line with the Weighted Average Cost of Capital (WACC) outlined in the company's 2024–2025 Corporate Work Plan and Budget (RKAP). An income tax rate of 22% has also been incorporated, in accordance with government regulations. One of the key indicators for evaluating project feasibility is the Levelized Cost of Energy (LCOE), which is calculated at IDR 4,439.73 per kWh following the implementation of carbon capture and storage (CCS). This represents a significant increase from the previous LCOE of IDR 2,488 per kWh when CCS was not applied. The increase in LCOE highlights the additional costs of integrating CCS technology, yet it also underscores the growing emphasis on sustainable energy solutions and long-term emissions reduction.

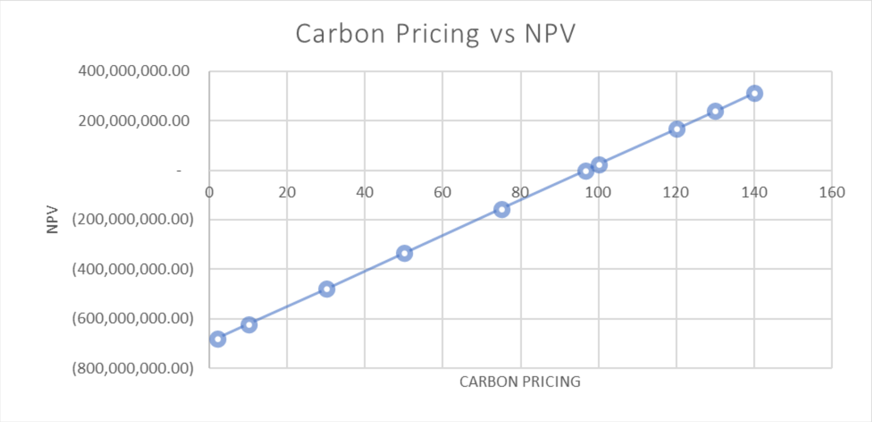


Figure 3. Impact of Carbon Pricing on CCS Project NPV

The economic feasibility of the CCS project is closely linked to the implementation of a carbon pricing mechanism. As illustrated in the updated graph, there is a strong positive linear relationship between carbon pricing and Net Present Value (NPV). Higher carbon pricing leads to a significant improvement in project viability.

With the Levelized Cost of Energy (LCOE) maintained at IDR 2,486 per kWh, the project yields negative NPV values when carbon pricing is below USD 100 per ton of CO_2, indicating financial infeasibility in that range. However, at a carbon price of USD 100 per ton, the project reaches the financial breakeven point, with the NPV turning positive at approximately IDR 31 billion. This milestone also corresponds to an Internal Rate of Return (IRR) of 9.79%, a Benefit-Cost (B/C) ratio of 1.00, and a payback period of 8 years.

These values mark the minimum threshold at which the project becomes financially feasible, making USD 100 per ton of CO_2 a critical benchmark. Therefore, in order to support the implementation of CCS technology without increasing electricity tariffs, a carbon pricing policy of at least USD 100 per ton of CO_2 is essential.

This analysis emphasizes the importance of carbon pricing not only as a climate policy instrument but also as a key enabler of investment in carbon capture solutions.

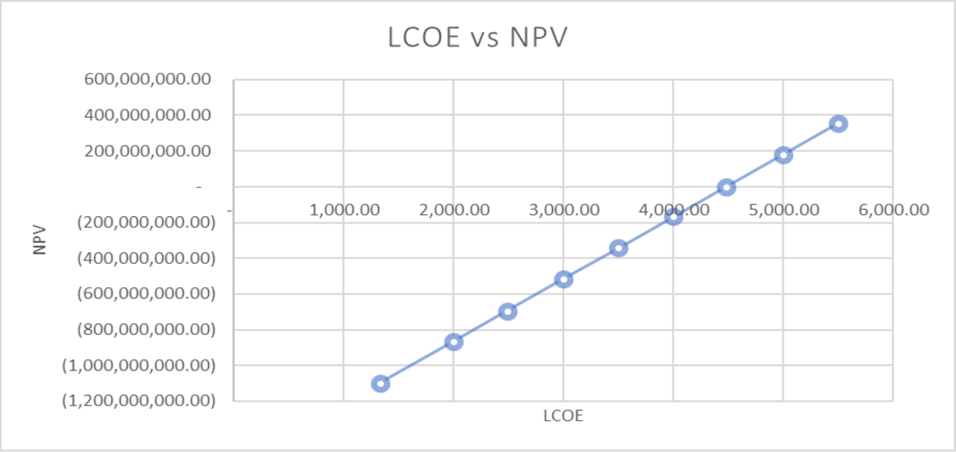


Figure 4. Impact of LCOE on CCS Project NPV

Figure 4 illustrates a strong positive correlation between the Levelized Cost of Energy (LCOE) and the Net Present Value (NPV) of the CCS project under the assumption of zero carbon pricing. The graph shows that at lower LCOE values—especially below IDR 3,500 per kWh—the project yields significantly negative NPV, indicating it is not financially feasible in that range. As the LCOE increases, the NPV improves in a near-linear manner. The financial breakeven point occurs when the LCOE reaches approximately IDR 4,390 per kWh, where the NPV becomes positive at around IDR 42.7 billion. At this point, the Internal Rate of Return (IRR) reaches 9.70%, the Benefit-Cost (B/C) ratio equals 1.00, and the payback period is approximately 8.06 years. This breakeven point defines the minimum LCOE required for the CCS project to be financially viable without any support from carbon pricing mechanisms. Thus, in the absence of carbon pricing incentives, the project would require an electricity selling price of at least IDR 4,390 per kWh to become economically attractive

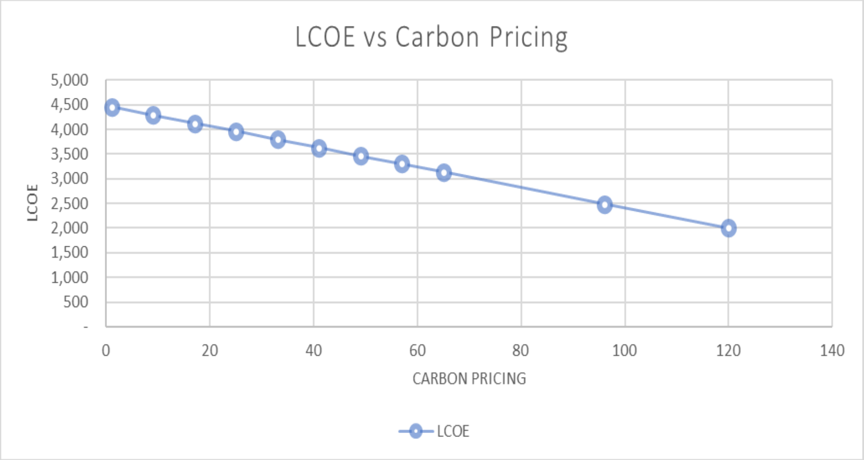


Figure 5. Impact of Carbon Pricing on LCOE for CCS Feasibility

Figure 5 illustrates the inverse relationship between carbon pricing and the Levelized Cost of Energy (LCOE) required to achieve a Net Present Value (NPV) of zero and an Internal Rate of Return (IRR) of 9.70%, representing the breakeven condition for project feasibility. As carbon pricing increases from USD 0 to USD 120 per ton of CO_2, the required LCOE decreases significantly from IDR 4,390 per kWh to IDR 2,486 per kWh. This trend highlights that higher carbon pricing enables the CCS project to remain financially viable even at lower electricity tariffs. The implementation of a carbon pricing mechanism thus plays a dual role: it promotes emissions reduction while alleviating the financial burden of CCS integration. Higher carbon prices increase the economic value of avoided emissions, reducing the need for elevated energy prices to ensure profitability. Under the assessed scenarios, the project meets standard economic feasibility criteria—NPV ≥ 0, IRR ≥ 9.70%, and a Benefit-Cost Ratio (B/C) ≥ 1.00—while maintaining a payback period of approximately 8 years, which is considered reasonable for long-term energy infrastructure investments. Therefore, the combination of robust carbon pricing and optimized LCOE levels supports both the financial and environmental viability of the CCS project. In conclusion, the integration of carbon pricing not only enhances the attractiveness of CCS from an investment perspective but also aligns with broader sustainability goals by making low-carbon power generation economically competitive.

5 Conclusion

The results of this study demonstrate that the implementation of Carbon Capture and Storage (CCS) technology at the Tidore Coal-Fired Power Plant (PLTU Tidore) is not only technically feasible but also economically viable. Simulation of post-combustion CO_2 capture using two amine-based solvent formulations 30% MDEA 10% piperazine (PZ) and 30% MEA 10% PZ—reveals that the MDEA + PZ system offers better energy efficiency, requiring 4.261 MJ/kg CO_2 for solvent regeneration, compared to 4.315 MJ/kg CO_2 for MEA + PZ. Although the CO_2 purity obtained with MDEA + PZ (99%) is slightly higher than that of MEA + PZ (99%), the lower energy penalty (25% and. 29%) demonstrates improved process efficiency.

The technical advantage of the MDEA + PZ combination lies in its lower regeneration energy requirement and superior long-term operational stability, making it a promising option for medium-scale facilities like PLTU Tidore.

From an economic perspective, the CCS project yields favorable indicators. With an initial investment of IDR IDR 139.17billion billion and annual operation and maintenance costs of IDR IDR 65.74 billion, the project achieves a positive Net Present Value (NPV) above zero and an minimum Internal Rate of Return (IRR) of 9.7%. A Benefit-Cost Ratio (B/C) of 1.00 and a payback period of 8.06 years indicate that the project reaches breakeven within a reasonable timeframe. The introduction of a carbon pricing mechanism combined with an adjusted Levelized Cost of Energy (LCOE) strengthens the project's financial viability, positioning CCS as a strategic solution in support of Indonesia's Net Zero Emissions target by 2060 and its Nationally Determined Contributions (NDCs) by 2030. This alignment of policy incentives and energy economics highlights the importance of integrating carbon pricing frameworks to ensure the feasibility of low-carbon technologies.

In conclusion, this study supports the deployment of CCS technology as an effective and sustainable approach to carbon emission reduction in coal-based power generation. The use of MDEA + PZ as a solvent blend in a post-combustion system offers a practical balance of energy efficiency, operational reliability, and economic competitiveness, positioning it as a viable solution for clean energy transition in Eastern Indonesia.

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