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Economic Feasibility and Sensitivity Analysis of Carbon Capture and Utilization in Indonesian Coal-Fired Power Plants

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ABSTRACT

This study explores the economic feasibility of implementing Carbon Capture and Storage (CCS) and carbon capture, utilization, and storage (CCUS) technologies in Indonesian coal-fired power plants (CFPPs). CCS/CCUS is seen as crucial to achieving net-zero emissions by capturing carbon dioxide (CO_2) and either storing it underground or utilizing it for enhanced oil recovery (EOR). However, the application of these technologies results in a significant increase in the levelized cost of electricity (LCOE) due to higher capital and operational expenses. The study compares CFPPs without CCS, with CCS, and with CCUS, analyzing key financial indicators like net present value (NPV), internal rate of return (IRR), payback period (PP), and benefit-cost ratio (BCR). Additionally, sensitivity analyses on carbon tax, electricity prices, and EOR benefit-sharing are conducted to assess the conditions under which these technologies become financially viable. The findings suggest that while CCS technology is economically challenging, CCUS, particularly when integrated with EOR, shows better economic performance. For Indonesia to achieve net-zero targets, a carbon tax of at least \$107.3/ton CO_2 and electricity prices above \$0.18/kWh are recommended to make CCUS economically competitive.

Keywords: Economic Feasibility, Carbon Capture and Storage, Coal-Fired Power Plants
JEL Classifications: Q40, Q42, Q48, Q51, Q54, H23

1. INTRODUCTION

Carbon Capture Utilization and Storage or CCS/CCUS is a method for capturing carbon dioxide (CO_2) from fossile power plants, factories, and even the atmospheric air itself. This captured CO_2 is then either stored and sealed underground for a long time or utilize it to difference objective. For CCUS method, instead stored underground, the captured CO_2 can be used for enhanced oil recovery or even transforming it into another useful products (Shen et al., 2022; Ssebadduka et al., 2020). In the past, CCS/CCUS wasn't widely used, but now it's seen as essential for reducing greenhouse gas emissions and reaching net zero emissions (NZE) target (Matyushok et al., 2024). Basically, CCS/CCUS is becoming a more and more important tool in the fight against climate change (Pongthanaisawan et al., 2023; Wang, 2024).

Based on publicated data, there are about 196 CCS/CCUS projects as of the end of 2022 in the world. Many of the recently planned or implemented projects worldwide have a capacity of 3 million tons per year or higher (Wang, 2024). Meanwhile, In Indonesia, there are approximately 16 CCS/CCUS projects in the oil and gas sector, all of which are still in the study and/or preparation phase, with a target to be operational before 2030 (IESR, 2023). Meanwhile, in the electricity sector, PT. PLN (the state-owned electricity company) plans to implement CCS at the Indramayu coal-fired power plant (PLTU) and the Tambak Lorok gas-fired power plant (PLTGU). The utilization of CCS/CCUS technology in power plants offers a promising solution for Indonesia's NZE, especially on coal-fired power plant (CFPP) phase-down program. By capturing and storing CO_2 emissions, CCS/CCUS technology can significantly reduce the environmental impact of CFPPs while supporting the country's energy security and NZE goals.

There are three main method to capture CO_2, which is capturing it after burning fuel (called post-combustion) is the most popular choice right now. This method uses chemicals to absorb the CO_2 and works well with existing power plants in the near future (Shao et al., 2024). The addition of CCS/CCUS units will consume heat and also need auxiliary electricity from the power plant, resulting in reduced power output and, consequently, an increase in electricity production costs (Matin and Flanagan, 2022) (Eviani et al., 2021) (Hong, 2022). Nevertheless, captured CO_2 can be utilized for other purposes, such as enhancing oil production from depleted fields chemical and material production, or even transforming it into synthetic fuels, which offers benefits from the implementation of CCUS (Bajpai et al., 2022). Therefore, prior to formulating additional policies or technology development guidelines, it is crucial to perform a economic assessment of CCS/CCUS.

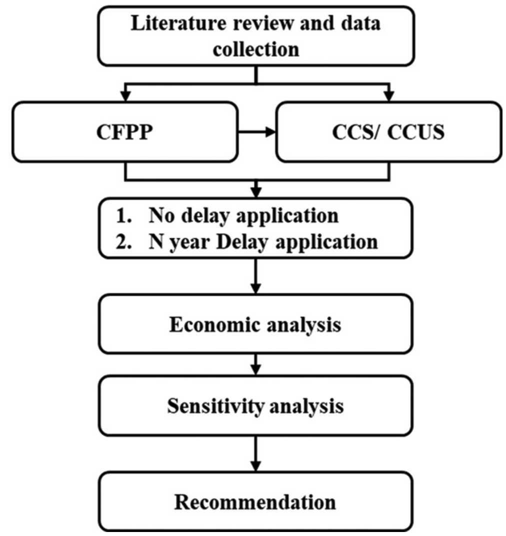
A review study has been conducted to investigate the general technology readiness, system performance, energy requirements, and cost of CCS (Hong, 2022). Another review evaluated the economic viability and long-term viability of CCS/CCUS technologies, aiming to pinpoint the obstacles hindering the commercialization of these innovative solutions (Gowd et al., 2023). Other researchers have conducted studies on the technical aspects of CCS/CCUS application in fosile power plants and oil/gas refineries (Adisasmito et al., 2023; Cousins et al., 2012; Eviani et al., 2021; Knudsen et al., 2009; Matin and Flanagan, 2022; Qvist et al., 2020). Meanwhile, other scholars have conducted studies related to the impact of carbon taxes on CCS implementation (Sun and Chen, 2022; Zhao et al., 2023), the influence of CCS installations on thermal power plants' levelized cost of electricity (LCOE) (Afsahi et al., 2021; Fan et al., 2019; Shao et al., 2024; Sugihardjo et al., 2017), and qualitative evaluation of the potential revenues earned through utilization of CFPP's captured CO2 for Enhanced Oil Recovery (EOR) (Sugihardjo et al., 2017).

The technical discussion on CCUS has been extensively conducted by researchers. However, most of the economic studies conducted tend to evaluate only one aspect of the process: Either Carbon Capture and Storage alone or Utilization alone. There has not yet been a comprehensive study that addresses the entire CCUS process. Therefore, this study aims to compare the economics between coal-fired power plants without CCS, coal-fired power plants with CCS, and coal-fired power plants with CCUS. This study is expected to provide recommendations regarding how to apply competitive CC technology.

2. METHODOLOGY AND DATA

The study was conducted utilizing a flowchart as illustrated in Figure 1. This study started with a review of the literature and data collection on Carbon Capture (CC) technology and it impementation, the cost estimation of CFPP and CC technology. The estimated cost can be used to calculate the LCOE from CFPP and CFPP+CC technology. Economic analysis is performed by

Figure 1: Method of study



comparing the LCOE NPV IRR PP and BCR of CFPP and CFPP with CC technology application.

The study also applied two scenarios for applying Carbon Capture technology (CCS/CCUS) to CFPP: No-delay application and N-year-delay application. With a no delay application the power plants construction will coincide with the application of CC technology (built it together). By contrast an application for N-year delay indicates that CC technology will not be implemented until the power plant has achieved its payback period. Both of the scenarios above are used to determine the optimal timing for implementing CC technology. Determining how many years the CC technology application is delayed comes from the results of the payback period calculation from the CFPP.

Sensitivity analysis was carried out for several economic parameters, they are carbon tax, electricity price and share of benefit of EOR product. A simple and economical method of reducing climate change is through carbon pricing particularly when implemented as a tax on greenhouse gas emissions or carbon tax (Abel et al., 2023; Sun and Chen, 2022; Zhao et al., 2023). The impact of carbon taxes on the economic indicator should be studied.

An understanding of how the selling price of electricity affects economic indicators is essential because it is a power plants revenue stream (Rokhmawati et al., 2023).

Another parameter of sensitivity that needs to be considered is the profit sharing of EOR products. Understanding the percentage of profit distribution between CFPP that implement CCUS and the well owners or oil companies is crucial for the economic viability of CFPP adopting CCUS technology.

The recommendations of CC technology implementation potential for economic use in Indonesia is ascertained by conducting an implementation strategy analysis based on the findings of the economic analysis.

The plant operation's economic viability will be evaluated using key economic indicators, including the levelized cost of electricity (LCOE), net present value (NPV), payback period (PP), internal rate of return (IRR), and benefit cost ratio (BCR)

2.1. LCOE

LCOE represents the generating cost of electricity, calculated by dividing all associated costs by the total electricity produced, adjusted to present value. This cost, measured in cost per kilowatt-hour (kWh), includes investment or capital construction costs, fixed and variable operation and maintenance costs, and fuel costs. The formula used to calculate LCOE in this study is shown in Eq. (1)

$$LCOE = \frac{\sum\left(I_t + M_t + F_t + CO_2Tax_t\right).\left(1+d\right)^{-(t-1)}}{\sum\left(MWh_t\right).\left(1+d\right)^{-(t-1)}} \quad (1)$$

LCOE refers to the average lifetime levelized generation cost per kWh. I_t refer to the investment cost in year *t*. M_t refers to operation and maintenance costs in year *t*. *F* refers to fuel costs in year *t*. CO_2Tax_t refer to carbon tax in year *t*. MWh_t refers to the production of electricity year *t*. *d* refers to the discount rate. $(1+d)^{-(t-1)}$ refers to Discount factor for year *t*.

2.2. NPV

Net Present Value (NPV) quantifies the difference between the present value of all profits and costs associated with a project. A positive NPV indicates a net profit, making NPV a valuable tool for assessing investment prospects. The NPV formula is given as shown in Eq (2).

$$NPV = \sum_t^n \left(NCF_t\right).\left(1+d\right)^{-(t-1)} \quad (2)$$

2.3. Payback Period

Payback period is a metric used to assess an investment prospect viability. It evaluates the number of years needed to recover the initial investments cash outlay. In order for the business to determine the actual cash inflow during that time the payback period is calculated by subtracting the annual cash inflow from the principle payment to the bank and the interest repayment.

2.4. IRR

The internal rate of return (IRR) represents the discount rate at which the present value of both costs and benefits' cash flows are equal, effectively making the project's net cost zero. This metric serves as an indicator for estimating investment profitability. When the IRR exceeds the discount rate, the net present value (NPV) becomes positive, suggesting a profitable investment. This indicates that the project is worth investing.

2.5. BCR

BCR is a ratio that compares an economic activitys costs and profits.

2.6. Data and Assumption

The technical and economic parameters of CFPP (base) and CC technologies, along with the assumptions used in this study, are presented in the following Table 1.

Table 1: Economic and technical parameter of study

Parameter	Description	Reference
CFPP base		
Unit capacity	300 MW	Internal source
Overnight cost	1.980 \$/kW	
Construction period	3 year	
Disbursement	1st year 20% 2nd year 50% 3rd year 30%	
O&M cost	0.13 \$/MWh	
Fixed cost	45.3 \$/kW	
Coal prices	70 \$/ton	
Calorific value	4,200 kcal/kg	
Net plant heat rate	2,560 kcal/kWh	
Load factor	75%	
CO_2 coefficient	1,031 ton/MWh	
Carbon tax	2.5 \$/ton	Law No. 7 year 2021
Plant life	30 year	assumption
Electricity price	0.1 \$/kWh	PLN
Carbon capture technology		
Invesment capture	150,890,000 \$	(Saimura et al., 2022)
Carbon transport	18,423,315 \$	
Carbon injection	264,360,000 \$	
O&M capture	31,320,000 \$/year	
Carbon transport	1,126,671 \$/year	
Carbon injection	26,520,000 \$/year	
Capture efficiency	90%	
Power consumption	30% of power output	
Enhanced oil/gas recovery prospect		
Crude oil price	71,43 \$/bbl	www.bloomberg.com
Natural gas price	2,51 \$/MMBTU	
Potential capacity and benefit of oil and gas lift in the area study		
Oil	49,200,000 bbl	(Ministry of Energy and Mineral Resources, 2016)
Gas	897,600 MMBTU	
Benefit from Oil and gas	130,244,777 \$/year	

3. RESULTS AND DISCUSSION

Table 2 shows the economic analysis of CC technology applications based on this study's paramenters. It is clear from the data that the use of CC technology in thermal power plants leads to a rise in LCOE, making it an unattractive option for financial standpoint. The NPV under various scenarios of implementing CC technologies shows poor estimates (negative), including low IRR and inadequate BCR.

The study has revealed that the LCOE for CFPP is 7.95 ¢/kWh. On the other hand the delayed CC plant scenario exhibits about 55% increase in LCOE compared to the base thermal power plant LCOE Conversely, the non-delayed CC scenario exhibits LCOE a significantly higher shown, with an impressive increase of 122%. The application of CC technology on CFPP which raises investment costs and O&M expenses related to the various CC technology equipments is the reason for the increase in LCOE.

The Payback Period calculation for CFPP is 9.3 years, so in the N year delay scenario, both CC technologies are built in the 11th year after the construction of CFPP. Meanwhile, the No-delay scenario as explained above is built simultaneously with the construction of the thermal power plant. The study shows that the PP CCS for both construction time scenarios is not achieved until the end of CFPP operation, while the PP CCUS no delay scenario shows a time of 31.1 years. The PP CCUS 11-year delay scenario shows a time of 23 years or 13 years after the PP CFPP is achieved. Figure 2 shows the cash flow, and the achievement of the PP on the CFPP base and all scenarios of CC technology application on CFPP.

Table 2 further illustrates that the IRR for the CFPP is 13.8%. However, the application of CCS for all construction time scenarios is unable to yield a return flow. On the other hand, the application of CCUS technology in both the no delay and the 11th year delay scenario yields a poor IRR value, i.e. 0.4% and 4.2% respectively. These values are significantly lower than both the IRR of the CFPP and the discount rate utilized in this study.

Table 2: LCOE payback period, NPV and IRR for CFPP baseline and CFPP+CC technology

Parameter	CFPP	No-delay		N-delay	
		CCS	CCUS	CCS	CCUS
LCOE (¢/kWh)	7.95	17.68		12.29	
Payback (year)	9.3*	-	31.1*	-	23*
NPV (10^6\$)	412	(2,151)	(739)	(819)	(157)
IRR (%)	13.8	-	0.4	-	4.2
BCR	1.26	0.39	0.77	0.70	0.94
CO_2 emmision (10^6 Ton)	61	6.1		24.4	
CO_2 Tax** (10^6\$)	152	15		61	

*After 1st year construction

**Accumulative for 30 year lifetime

And the last, BCR for all applications of CC technology show a value <1, indicating that they are not profitable, as the cash outflow exceeds the cash inflows of income.

However, from Table 2, it can be observed that, in general, the application of CCUS for all construction time scenarios result in better economic indicators than CCS application. This is primarily due to the fact that, in the case of CCUS, when coupled with EOR in this study, it not only reduces emissions but also contributes to revenue generation.

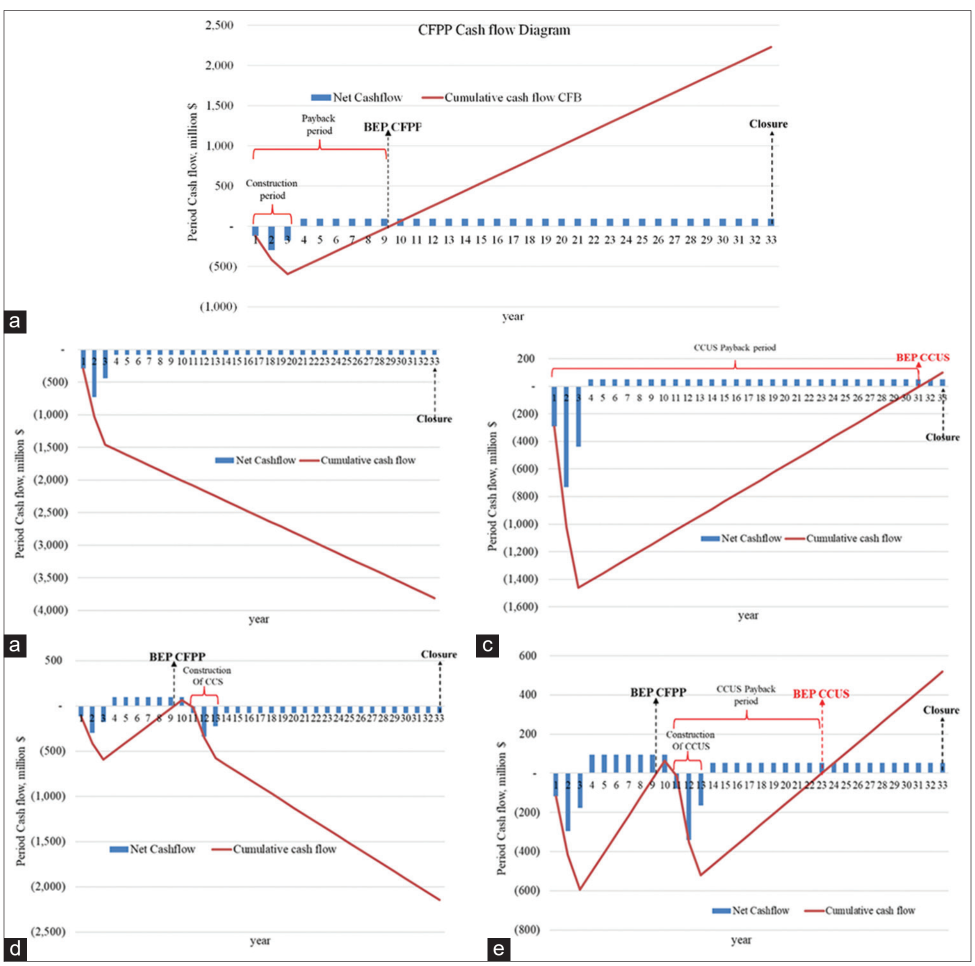
Meanwhile, from the environmental perspective, the no-delay CC technology construction scenario offers an advantage by rseult in the lowest total CO_2 emissions over the plant's lifetime compared to the 11-year delay scenario. The no delay scenario results in a reduction of CO_2 emissions by 90%, while the 11-year delay scenario yields a 60% reduction.

3.1. Sensitivity Analysis

3.1.1. Carbon tax

Generally, an increase in carbon taxes leads to higher LCOE. However, it is noteworthy that this rise in carbon taxes can render

Figure 2: Cash flow coal-fired power plants (CFPP) base and CFPP with carbon capture (CC) technology. (a) CFPP cash flow, (b) CFPP+ CCS no delay, (c), CFPP+CC, utilization, and storage (CCUS) no delay, (d) CFPP+ CCS 11 year delay, (e) CFPP+ CCUS 11 year delay



the LCOE for CC technologies competitive when compared to CFPP as the baseline. Figure 3 illustrates this relationship.

The study indicating that the LCOE for no-delay CC technology remains competitive when compared to CFPP based on a carbon tax above 107.29 \$/ton. Under this carbon tax rate, the LCOE for no-delay CC technology with a CFPP base stands at 18.76 ¢/kWh. Conversely, the 11th year-delay CC technology becomes competitive at a carbon tax price of 114.08 \$/ton, resulting in an LCOE of 19.46 ¢/kWh.

Its also clear from Figure 3 that carbon taxes have a greater impact on LCOE of CFPP. The reason for this is that CFPP release a substantial amount of CO_2 which raises the carbon tax payments that CFPP must make.

An increase in the carbon tax has a negative effect on the IRR even though it shows that CC technology applications and CFPP are competitively in term of LCOE, as mention above. Figure 4 report how increasing carbon taxes reduce the IRR for both CC technology applications and CFPP. This makes sense because higher carbon taxes will result in higher required carbon tax payments which will lower net cash flow and ultimately have an impact on the IRR.

Figure 3: The impact of variations carbon tax in levelized cost of electricity

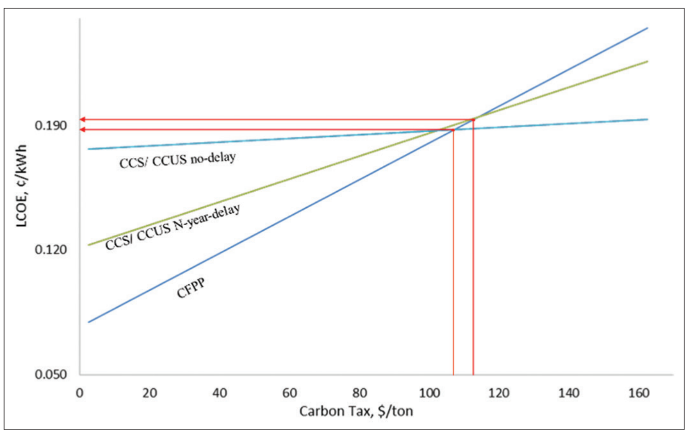
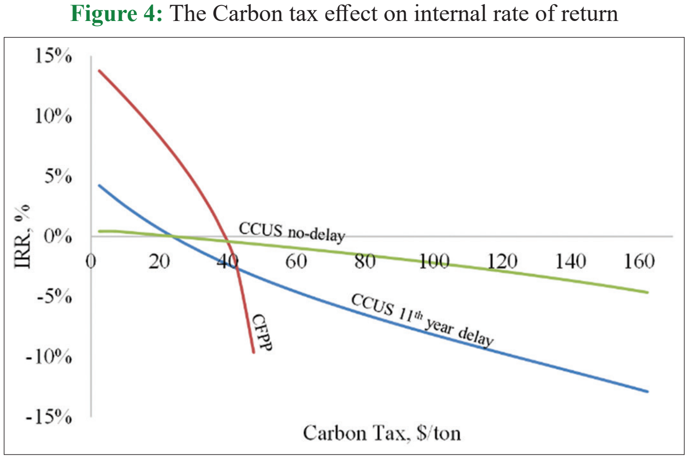


Figure 4: The Carbon tax effect on internal rate of return



The figure also shows that on the basis of parameters, the resulting IRR for the application of CC technology is unfavorable for all applied carbon taxes (lower than the project discount rate). For this reason, it is necessary to consider efforts to increase the IRR by increasing cash inflow, in this case from the electricity sales side and benefit of EOR product (as applicable).

3.1.2. Electricity price

For CFPP and every scenario of CC technology application, Figure 5 graphically illustrates the positive correlation between increases in electricity prices and the IRR. This is due to the direct results of higher cash inflows which are facilitated by higher electricity selling prices.

An increase in electricity prices of 10% will provide an attractive IRR in the CCUS implementation scenario of 11 years delay, while the non-delay CCUS and 11 year delay CCS scenario requires an increase of more than 50%.

3.1.3. Share of EOR benefit

The implementation of CCUS in CFPP provides additional cash flow beside electricity sales. The share of profits from EOR product sales between well owners and CCUS-equipped CFPPs significantly impacts the IRR. As showed in Figure 6, smaller share of EOR product sales for CFPPs will lead to a decrease in their IRR.

3.2. Formulation of Recommendation

The formulation of recommendations is prepared by simulating three parameters that have been tested on sensitivity analysis. The sensitivity analysis described above, specific values were chosen for the carbon tax and electricity price parameters, as well as the share EOR benefit (for CCUS). These parameter values were then simulated to obtain a LCOE and a favorable IRR for CC technology applications. Consequently, four cases were formulated, as outlined in the Table 3.

The base case utilizes the initial study parameters. Cases L_1 and L_2 employ a carbon tax parameter of 107.3 \$/CO_2, which represents the minimum value yielding competitive LCOE for CC technology applications in scenarios without construction delays. On the other hand, cases H_1 and H_2 utilize a carbon tax parameter of 114.1 \$/CO_2, which corresponds to the minimum value resulting in competitive LCOE for CC technology applications in scenarios with an 11-year delay. Additionally, the electricity price is set at 50% higher than the base electricity price, providing an attractive IRR for CC technology applications. Then, for cases L_1, L_2, H_1, and H_2, the electricity prices are 0.18, 0.19, 0.19, and 0.20 respectively.

The simulation of all cases and scenarios of CC technology applications, the results as shown in Table 3. The study show that

Table 3: Case for combined analysis

Case	base	L_1	L_2	H_1	H_2
Carbon tax \$/ton	2.5	107.3	107.3	114.1	114.1
Electricity price, \$/kWh	0.10	0.18	0.19	0.19	0.20

Table 4: Result of simulation

Case	Parameter	CFPP	Non delay		11 year delay	
			CCUS	CCS	CCUS	CCS
Base	LCOE	0.080	0.177		0.123	
	NPV	412.18	(819.78)	(2,150.87)	(157.02)	(739.32)
	IRR	13.75%	0.40%	-	4.23%	-
	BCR	1.26	0.77	0.40	0.94	0.70
L_1	LCOE	0.188	0.188		0.190	
	NPV	(152.82)	90.60	(1,240.49)	(104.11)	(706.27)
	IRR	4.67%	8.12%	−7.53%	6.40%	−10.35%
	BCR	0.96	1.02	0.67	0.97	0.82
L_2	LCOE	0.188	0.188		0.190	
	NPV	48.62	231.61	(1,099.48)	72.01	(532.63)
	IRR	8.32%	9.06%	−3.75%	8.28%	−4.48%
	BCR	1.01	1.06	0.71	1.02	0.86
H_1	LCOE	0.195	0.188		0.195	
	NPV	(92.60)	217.49	(1,113.60)	(15.98)	(620.62)
	IRR	5.84%	8.97%	−4.04%	7.33%	-5.63%
	BCR	0.98	1.06	0.71	1.00	0.84
H_2	LCOE	0.195	0.188		0.195	
	NPV	108.83	358.49	(972.60)	160.15	(446.98)
	IRR	9.29%	9.87%	−1.60%	9.20%	−1.53%
	BCR	1.03	1.09	0.74	1.04	0.89

Figure 5: Impact of electricity selling price to internal rate of return

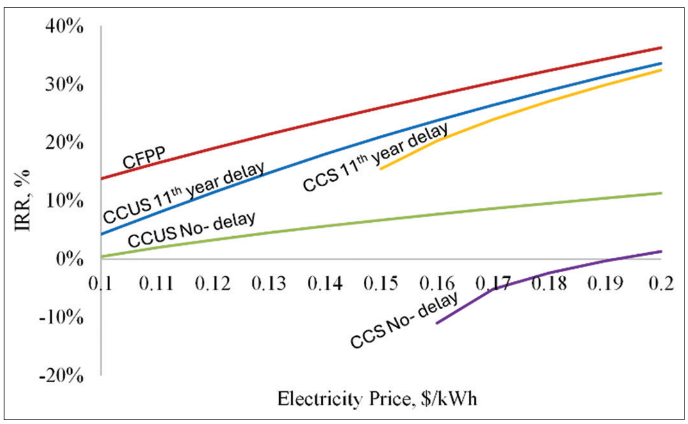
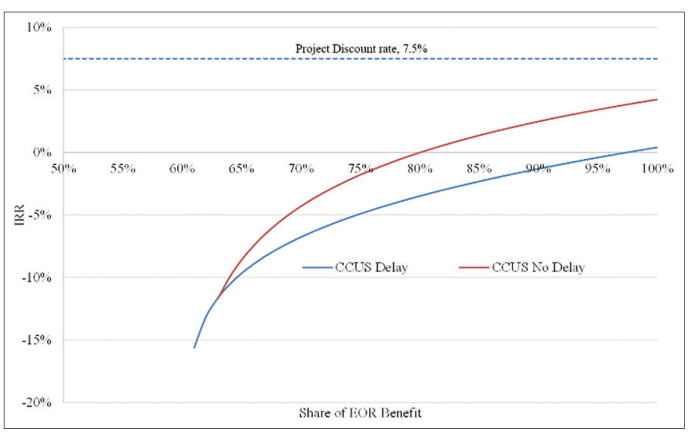
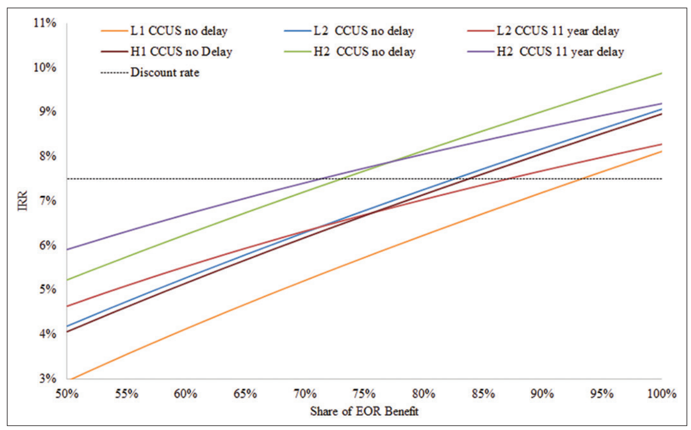


Figure 6: The impact of share of enhanced oil recovery benefit to internal rate of return



the implementation of Carbon Tax starting at 107.3 \$/ton CO_2 and electricity tariffs beginning at 0.18 \$/kWh, the non-delayed CCUS application will be competitive with CFPP across all analysis parameters. Meanwhile, the 11 year delay CCUS application,

Figure 7: Share of enhanced oil recovery Benefit impact on internal rate of return for carbon capture, utilization, and storage all scenarios



considering a carbon tax of 107.3 \$/ton CO_2 and an electricity tariff of 0.18 \$/kWh, demonstrates attractive economic parameters, although its LCOE remains slightly higher than that of CFPP. This scenario demonstrates competitiveness against CFPP when applying a carbon tax starting at 114.1 \$/ton CO_2 and electricity tariffs beginning at 0.20 \$/kWh. In contrast, for CCS across all construction scenarios, it does not shows attractive values, even though in some cases, its LCOE competitive with that of CFPP.

Further investigation, the minimum share of EOR benefit between the CCUS-applied CFPP and the oil and gas company can be seen in Figure 7 and Table 4. The study reveals that a minimum profit share of 93.20% and 83.70% must be allocated to no delay CCUS applicants to make it economically attractive on the L_1 and $H_{1\ case}$ respectively. However, under the L_1 and H_1 condition, the CCUS 11-year-delay scenario does not yield positive results even with a 100% profit share. In case L_2, it is shown that the profit share for CFPP should above 82.60% for applied CCUS with no delay, and 87.10% for 11-year delay scenario. Meanwhile, in case H_2, profit shares above 73.10% for no delay and 71.20% for 11-year delay would also be economically attractive.

4. CONCLUSION AND POLICY RECOMMENDATION

The current economic viability of CC technology applications in CFPP is poor. This is evidenced by high LCOE, negative NPV, low IRR, and a BCR <1. However, despite these economic challenges, the implementation of CC technology has a favorable environmental impact. Specifically, it significantly reduces CO_2 emissions in both the no-delay and 11-year-delay scenarios for CCS/CCUS technology applications.

The study also provides information that an increase in carbon tax value can drive competitive LCOE for CC technology applications. However, this will have a negative impact on the IRR. On the other hand, an increase in electricity selling price and large share of EOR Benefit (for CCUS) will positively affect the IRR.

Based on the results, this study provides policy recommendations as follows:

- The Indonesian government should introduce a carbon tax of at least \$107.3/ton CO_2 to drive the economic viability of CCUS technology, which aligns with achieving the country's net zero emissions (NZE) targets. The tax can incentivize industries to adopt cleaner technologies by making CCUS applications more competitive.
- Adjust electricity tariffs to a minimum of \$0.18/kWh, particularly for coal-fired power plants utilizing CCUS technology. This adjustment can generate the necessary cash inflows to offset the high initial investment and operational costs associated with CCUS.

Encourage the integration of CCUS with EOR by creating policies that ensure favorable revenue-sharing agreements between power plants and oil companies. This could involve setting a minimum profit share of 80% for CCUS-equipped CFPPs to make the projects economically attractive.

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