Available online at www.HighTechJournal.org

HighTech and Innovation Journal

ISSN: 2723-9535

Vol. 6, No. 2, June, 2025

Techno-Economic Evaluation of Carbon Capture and Storage for Combined Cycle Power Generation

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Received 23 December 2024; Revised 14 May 2025; Accepted 18 May 2025; Published 01 June 2025

Abstract

Carbon dioxide (CO_2) is a major driver of greenhouse gas emissions, which lead to an increase in Earth's temperature and subsequently drive climate change. CO_2 is primarily produced from fossil fuel-based power generation. Carbon capture and storage (CCS) is a CO_2 capture technology that can be added to fossil fuel power generation. This study evaluates the he technological, financial, and ecological impacts of upgrading CCS technology on a Natural Gas Combined Cycle (NGCC) power generation with three blocks. Amine-based post-combustion capture technology is applied in this study. Simulations were performed employing the Integrated Environment Control Model software. The addition of CCS significantly reduces net power output across all blocks. For Block 1, net power declines from 133 MW to 97.6 MW, a 27% reduction, while Block 2 drops by 17%, from 441.7 MW to 368.1 MW. Block 3 shows a 13% decrease, with net power falling from 441.9 MW to 385.5 MW. Thermal efficiency also declines with the installation of CCS. Corresponding efficiency losses are also notable: Block 1 falls from 40.85% to 30%, Block 2 from 45.24% to 37.69%, and Block 3 from 53.89% to 46.79%. The levelized cost of electricity increases considerably alongside CCS implementation, rising by 80% for Block 1 (0.0843 to 0.1522 USD/kWh), 47% for Block 2 (0.0761 to 0.1114 USD/kWh), and 42% for Block 3 (0.06618 to 0.0874 USD/kWh). Sensitivity analysis indicates that LCOE competitiveness with the national weighted average is achievable when carbon prices exceed 145 USD/t CO_2 for Block 1, 90 USD/t CO_2 for Block 2, and 45 USD/t CO_2 for Block 3. These findings emphasize the trade-offs between power generation efficiency, costs, and carbon capture, providing essential insights for future energy policy and CCS adoption strategies.

Keywords: Carbon Capture and Storage (CCS); Carbon Price; Integrated Environment Control Model (IECM); Net Power Output, Natural Gas Combined Cycle (NGCC); Thermal Efficiency.

1. Introduction

CO_2 is a significant driver of increasing greenhouse gas concentrations in the Earth's atmosphere. Its continuous emission, primarily from fossil fuel combustion and deforestation, accelerates global warming and worsens ecological issues. Greenhouse gases (GHGs) contribute to the greenhouse effect by trapping heat in the atmosphere, leading to rising global temperatures and climate change [1, 2]. In 2023, global CO_2 emissions totaled 39 billion tons, with the

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http://dx.doi.org/10.28991/HIJ-2025-06-02-04

power industry being the largest contributor, responsible for 38.24% of these emissions [3]. Fossil fuels continue to dominate electricity generation, with coal accounting for 35.5% and natural gas contributing 22.5% of global electricity production in 2023 [4].

In Indonesia, CO_2 emissions increased from 0.295 billion tons in 2000 to 0.692 billion tons in 2022, more than doubling over two decades. These emissions account for 1.8% of global CO_2 emissions [5]. The power and heat generation sectors contributed 45% of Indonesia's CO_2 emissions in 2022 [6], with the electricity sector alone emitting 260.79 million tons of CO_2 in 2021 [7]. The dominance of fossil fuels in the energy mix drives these emissions, with coal generating 67% of electricity and natural gas 19% in 2023 [8, 9].

As electricity demand fluctuates, power plants require flexible load management. NGCC power plants are highly efficient and versatile, making them suitable for both load-following and peaking applications. These plants combine gas and steam turbines, utilizing waste heat from the gas turbine to enhance thermal efficiency, which typically ranges between 50–60% [10, 11]. However, the CO_2 emission factor for NGCC plants remains significant at 0.370 tCO_2 equivalent/MWh [12]. Their performance and efficiency are also strongly influenced by ambient temperature, which poses challenges in tropical climates [12, 13].

Reducing CO_2 emissions in NGCC power plants involves several strategies, including enhancing thermal efficiency through advanced turbine technologies, integrating carbon capture systems, and co-firing with hydrogen or biogas. Additionally, optimizing operations and maintenance practices can contribute to significant emission reductions [14–16]. Carbon capture implementation is carried out through either Carbon Capture and Storage (CCS) or Carbon Capture, Utilization, and Storage (CCUS) technologies. While both technologies aim to prevent CO_2 release into the atmosphere, CCUS also enables the captured CO_2 to be used in industrial applications, such as urea production for fertilizers or enhanced oil and gas recovery through injection techniques. This dual functionality of CCUS supports a circular carbon economy and enhances sustainability in industrial practices [17].

To mitigate emissions in the power sector, the Indonesian government prioritizes expanding renewable energy and adopting environmental control technologies like CCS and CCUS. These technologies play a key role in Indonesia's decarbonization strategy, particularly in the oil and gas industry and the power sector [18, 19]. In the oil and gas sector, CO_2 captured from production facilities can support Enhanced Oil Recovery (EOR) and Enhanced Gas Recovery (EGR) at locations such as Gundih, Tangguh, Arun, and Ramba. In the power sector, captured CO_2 from coal-fired power plants is transported via pipelines to oil and gas fields for storage or EOR/EGR applications. Various studies have explored this approach, particularly in sub-critical and ultra-supercritical coal power plants [20–22].

Globally, CCS capacity continues to expand, increasing from 0.120 Gtpa of CO_2 in 2013 to 0.360 Gtpa in 2023, demonstrating growing recognition of CCS as a critical technology for reducing greenhouse gas emissions [23]. Among CCS deployment strategies, network-based CCS systems gain prominence due to economies of scale and reduced operational risks, improving cost-effectiveness [23]. Several large-scale projects highlight the feasibility of CCS/CCUS in power generation, such as the SaskPower Boundary Dam plant in Canada, which has removed 1 Mtpa of CO_2 since 2014. Similarly, China National Energy's Guohua Jinjie and Taizhou plants capture 0.15 Mtpa and 0.5 Mtpa of CO_2, respectively, with the captured CO_2 either stored in geological formations or used for EOR [23–25].

Technology Readiness Level (TRL) measures the advancement of a technology. TRLs with higher maturity, such as those at the demonstration and commercial levels, are classified within levels 7 to 9 [26]. Carbon capture technologies at the demonstration phase (TRL 7) include oxy-fuel combustion, pre-combustion, direct air, and post-combustion capture using adsorption. Meanwhile, technologies at the commercial level (TRL 9) include post-combustion capture with amine [27–29]. Post-combustion carbon capture achieves over 90% CO_2 separation efficiency but requires substantial energy and incurs high operating costs [27, 30, 31]. Comparisons of capture technologies show that post-combustion offers high efficiency but lower CO_2 capture rates, whereas oxy-combustion achieves nearly 100% capture and delivers the highest net efficiency and power output when capture rates exceed 92% [32]. Studies indicate that higher CO_2 concentrations improve capture plant performance but also increase flooding risks, leading to slight increases in electricity costs but significantly reducing CO_2 avoidance costs [16]. While CCS and CCUS significantly reduce emissions, their high costs underscore the need for incentives to maintain economic competitiveness [22, 30, 33].

The implementation of CCS in natural gas combined cycle (NGCC) power plants involves both technical, economic, and geographical trade-offs. A 440 MWe NGCC plant using monoethanolamine (MEA) for carbon capture experiences reduced thermal efficiency and increased Levelized Cost of Electricity (LCOE), with fuel costs and currency exchange rates being key influencing factors [34]. The LCOE is projected to rise by $22−40/MWh, with a carbon price of at least $125/t CO_2 needed to make CCS economically viable [35]. Geographical conditions further impact CCS performance; in Mexico, as ambient temperatures increase from 15°C to 45°C, NGCC power plant efficiency drops from 50.95% to 48.01%, with supplementary firing restoring power output but further reducing efficiency [36]. Similarly, in Nigeria, CCS retrofitting significantly lowers CO_2 emissions but raises the LCOE to $84.44/MWh, with CO_2 avoidance costs reaching $60.02 per ton [33]. From an environmental perspective, MEA-based post-combustion capture reduces CO_2 emissions by 70% per unit of electricity and mitigates climate change potential by 64%, but it also intensifies acidification, eutrophication, and toxicity impacts, highlighting broader sustainability concerns [37].

Despite extensive studies on CCS implementation in NGCC power plants, significant research gaps remain. Previous studies have primarily focused on technical aspects, such as the decline in performance or efficiency, and economic impacts, particularly the increase in LCOE, while neglecting comprehensive assessments of environmental trade-offs and geographical influences. This study examines the implementation of CCS technology in established NGCC power generation through technical, economic, and ecological assessments. It includes an analysis of performance and efficiency, additional investment requirements, and the impact on LCOE due to CCS installation, as well as the reduction in CO_2 emissions. Furthermore, the study considers geographical factors, particularly Indonesia's tropical ambient conditions, which influence power plant performance and CCS feasibility.

2. Method

Figure 1 illustrates the research process. This study analyzes the condition of NGCC power plants before and after implementing CCS technology. The analysis covers several key aspects, including performance, efficiency, the impact of ambient condition variability, CO_2 emissions, and sensitivity analyses on factors such as capacity factor, fuel costs, and carbon price policy.

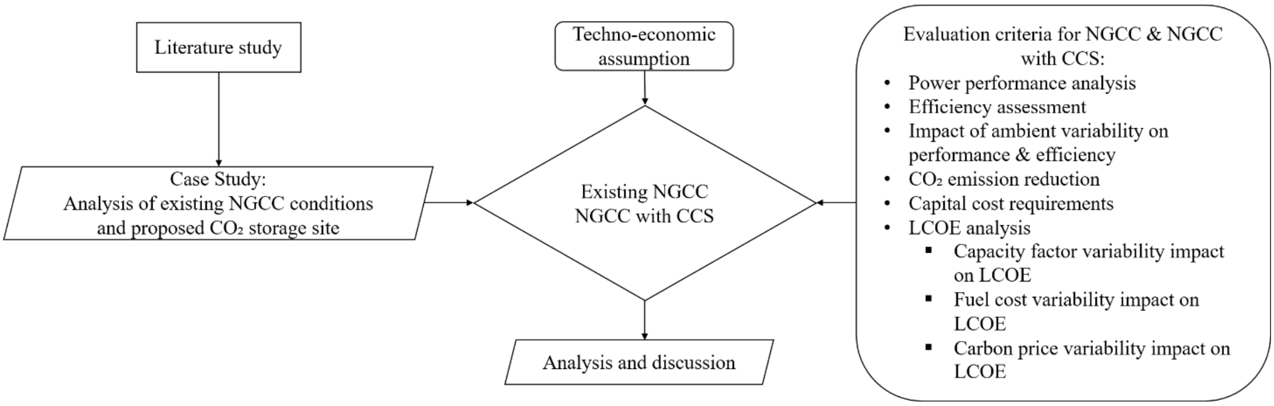

Figure 1. Research methodology flow diagram

2.1. Applied Study Overview

This assessment is conducted at the Grati Power Station in East Java, Indonesia, which has been in operation since 1996. The power station currently operates with a total capacity of 1,070 MWe, consisting of three NGCC blocks [38]. The station is located near the East Java Basin, which hosts numerous oil and gas production fields. In this case study, CO_2 generated by the Grati Power Station is transported to the Sukowati gas field via a pipeline approximately 175 km in length, as illustrated in Figure 2.

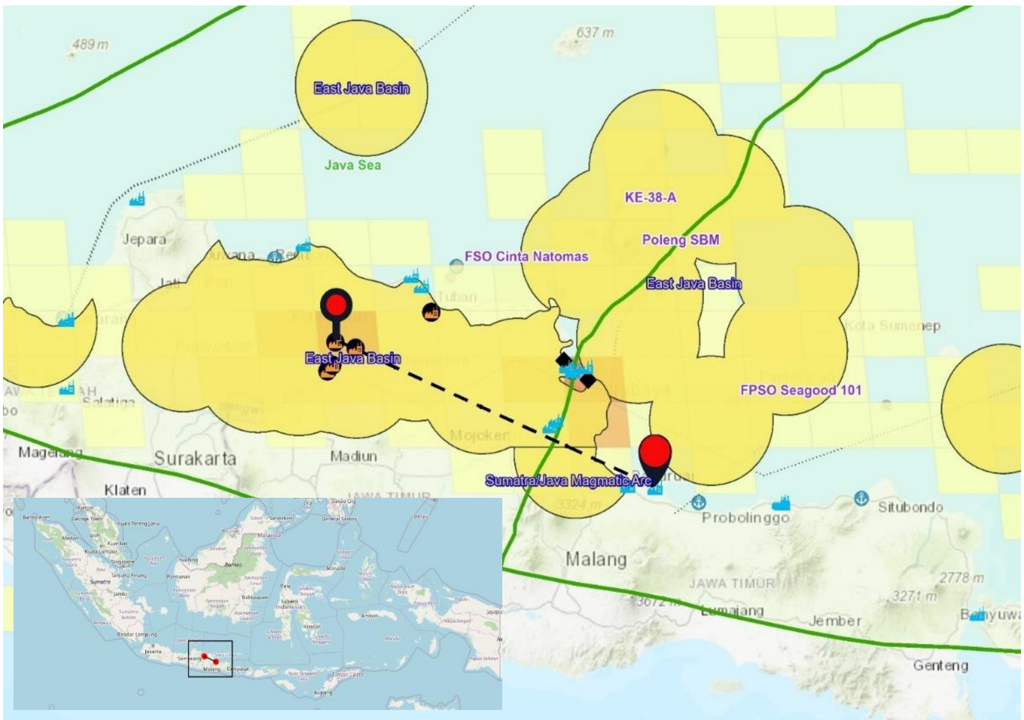

Figure 2. Position of the Sukowati gas field to the power station [39]

Table 1 presents the technical specifications of the NGCC units at Grati Power Station. The three blocks feature unique configurations, each designed to optimize performance. The energy conversion process in an NGCC system functions as follows: the gas turbine (GT) converts thermal energy from combustion into electrical power. The hot exhaust gases from the gas turbine are then directed to the heat recovery steam generator (HRSG), which uses this heat to convert water into steam. This steam is subsequently utilized by the steam turbine (ST) to generate additional power, enhancing the overall efficiency of the system. The key difference between open-cycle and combined-cycle systems is that an open cycle consists solely of the GT, while a combined cycle incorporates the HRSG and ST. Combined-cycle systems significantly improve energy conversion efficiency by utilizing the hot exhaust gases from the GT to heat water into steam, enabling additional power generation.

Table 1. Technical specifications of the NGCC Power Station at Grati

Metric	Dimension	Block 1	Block 2	Block 3
Gas Turbine				
Number of GT		1	3	2
Total GT Capacity	MWe	100	300	300
GT exhaust temperature	deg C	1150	1147	1250
Efficiency of GT	%	90	90	95
Electric generator efficiency	%	98	98	98
Pressure ratio of compressor	ratio	12	12	14
Compressor efficiency	%	87	87	88
HRSG & Steam Turbine				
HRSG outlet temperature	deg C	188	147	119
Steam cycle heat rate	kJ/kWh	12500	10000	8000
Steam turbine output	MWe	40	165	165
Power requirement	% MWe	5	5	5
Cooling system	type	Once-through	Once-through	Once-through
Total NGCC capacity	MWe	140	465	465

2.2. Emission Restriction Regulations

The Indonesian government does not impose limits on CO_2 emissions for power plants. However, specific emission standards are in place for SO_2, NOx, and particulate matter (PM), with limits set at 150 mg/Nm³ for SO_2, 400 mg/Nm³ for NOx, and 30 mg/Nm³ for PM. These standards apply to open-cycle as well as combined-cycle power generation systems. Similarly, coal and oil power plants are also not subject to CO_2 emission limits [40]. This results in power plants in Indonesia not being obligated to integrate environmental technologies into their operational systems.

2.3. Addition of CCS Technology

Figure 3 is a schematic diagram of Block 2, which includes 3 GT, 3 HRSG, and 1 ST. Block 1 uses a combination of 1 GT, 1 HRSG, and 1 ST. Block 3 has a configuration of 2 GTs, 2 HRSGs, and 1 ST. CO_2 capture is installed in the exhaust gas line after the HRSG. The carbon capture technology used is an amine-based post-combustion type, specifically using MEA, which has proven its effectiveness at a commercial scale and achieved a high TRL [27, 29]. The CO_2 removal efficiency of the absorber is measured to be 90%. Captured carbon dioxide is sent to the Sukowati Gas Field for EGR by pipeline. The Sukowati gas field is located in the East Java Basin.

The location map of this case study is shown in Figure 2. The Sukowati field has a CO_2 storage capacity of 8.6 billion tons of CO_2 [18, 41]. This research utilizes onshore CO_2 storage with a capability of 1-2 Mtpa CO_2 through two wells (assuming 1 Mtpa per well) at a depth of 2000 meters below the surface [20, 41].

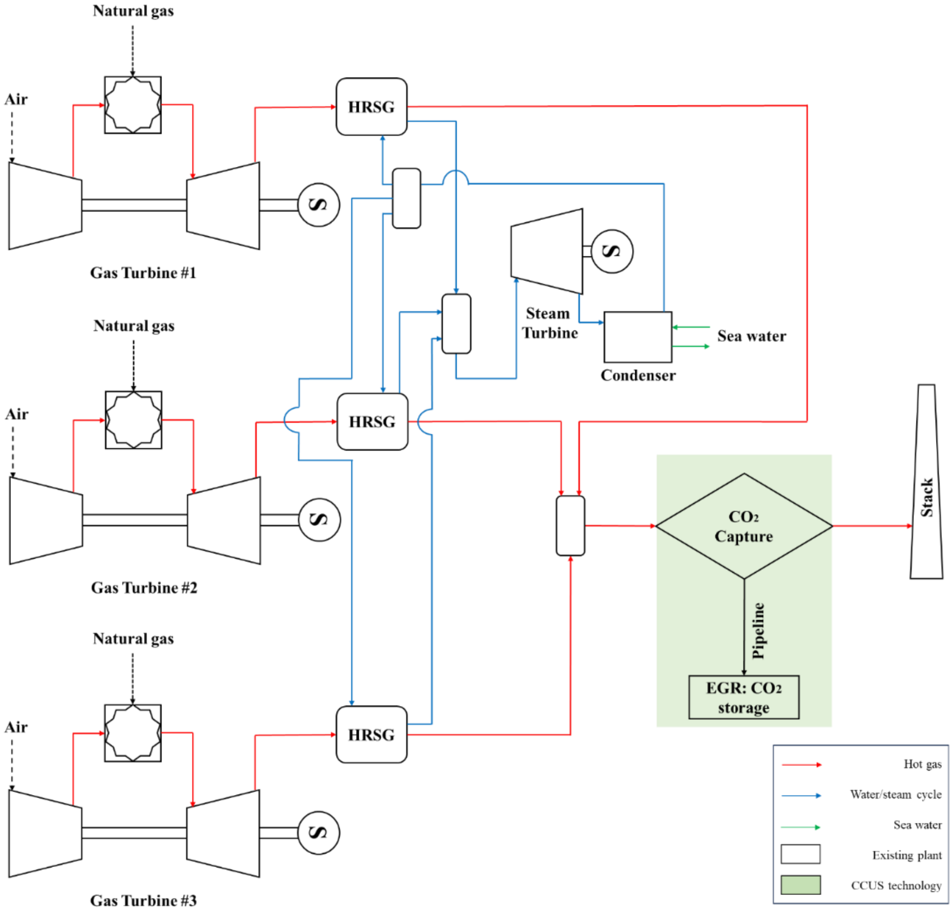

Figure 3. Schematic diagram of NGCC and CO_2 storage

2.4. Comprehensive Framework for Assessing Technical and Economic Viability

This study utilizes Integrated Environmental Control (IECM) version 11.5, the most recent publicly available 64-bit version. IECM serves as software designed for the initial design and evaluation of clean power generation technologies utilizing fossil fuels. It aids engineers, researchers, and policymakers in assessing the cost and efficiency of different power plant configurations and emission control strategies. The model encompasses various components, including power generation systems, pollution control technologies (for NOx, SO_2 , particulates, mercury, CO_2 , and H_2 S), water treatment, and waste management. Furthermore, it provides probabilistic analysis to evaluate uncertainties in system performance and economic outcomes [42, 43]. Validation of the IECM model is beyond the scope of this study; however, detailed information on its approach and structure is available on the official IECM site [43–45]. IECM's dependability has been demonstrated in prior economic and technical evaluations of energy facilities [33, 35, 46].

The IECM exhibits various constraints which must be taken into account while analyzing its outcomes. Its cost estimates for CO_2 transport and storage rely upon a restricted set of case studies while excluding factors such as pipeline routing, terrain complexity, or population density, which may substantially impact costs. While the models for EOR and aquifer storage provide broad estimates, they lack the precision of advanced, data-intensive models. Additionally, sparse data for aquifer storage projects limits their representativeness. As a result, the IECM is best suited for preliminary assessments, with more detailed tools needed for investment-grade analyses [44].

Table 2 presents comprehensive parameters included in the analysis. The IECM dataset and approach are leveraged for the financial analysis in this simulation, with particular customization focusing on Indonesia. The evaluations are adjusted into 2020 US dollars for accuracy and applicability. The Total Capital Requirement (TCR) includes a broad spectrum of investment costs, such as initial costs, design fees, reserve allowances, and financial expenses [47]. The adjustment parameters utilized in IECM are as follows: 1 for Equipment Costs, 0.979 for Material Costs, and 0.261 for Labor Costs. Labor demands for construction and seismic factors are adjusted using values of 1,874 and 1, respectively [48, 49]. The economic parameters used for the simulation are carefully outlined, incorporating fuel costs estimated based on the Cost, Insurance, and Freight (CIF) method.

This research investigates the impact of applying post-combustion CCS technology to power generation performance, focusing regarding net energy output and overall performance efficiency measured in high heating value (fuel energy basis). Viewed through an environmental perspective, it examines a reduction in CO_2 emissions attained via the implementation of post-combustion CCS. On the economic front, the analysis evaluates key cost parameters, including the LCOE, the additional expenses related to CCS technology, and the expense or cost per metric ton of CO_2 mitigated (avoided). Additionally, the study analyzes how ambient temperature variations influence the performance and economic aspects of NGCC plants with and without CCS.

Table 2. Technical and economic considerations within the IECM

Metric	Dimension	Amount	Ref.
Interest percentage	%	10	[50, 51]
Natural gas price (CIF) [1]	USD/MMBTU	7.5	[52]
Effective tax rate	%	22	[53]
Labor rate [2]	USD/hour	5	[54]
Shift schedule count	Shift frequency per day	3	[42]
NH_3 cost [3]	USD per metric ton	393	[55]
Amine cost [4]	USD per metric ton	1190	[56]
CO_2 transportation [5]	USD per metric ton	5.23	[57]
CO_2 storage [5]	USD per metric ton	10.88	[57]
Monetary unit	-	Inflation-adjusted USD	[42]
Publication year	year	2020	[42]

[1] Using the highest natural gas supply prices

[2] Calculated based on four multiples of the local baseline salary

[3] The peak price of NH3 (Ammonia) in the Southeast Asia (SEA) area in 2018

[4] The peak price of MEA in China in 2018

[5] Adjusted to 2020 USD

2.5. Key Parameters and Modeling Conditions

This study evaluates NGCC scenarios both without and with CCS, powered by natural gas. The calculations are based on an annual average surrounding temperature of 29°C, a humidity ratio of 78%, and an atmospheric pressure of 0.1014 MPa [58]. All NGCC blocks, whether operating without or with CCS, are considered to operate with a capacity factor at 80%. As outlined in Table 2, this configuration acts as the reference point for evaluating the impact of CCS technology deployment. Incorporating CCS requires additional steam and auxiliary power. This demand reduces the plant's gross power production because of limitations in steam generation capacity. The expenses associated with carbon dioxide delivery and sequestration are carefully analyzed and converted to 2020 USD values for precision. The fuel used in this study consists of natural gas, featuring a calorific value amounting to 53,100 kJ/kg HHV (see Table A1).

3. Results and Discussion

3.1. Performance Analysis

The gross power values of NGCC without CCS (existing plant) and with CCS for each block are: Block 1 at 140 MW, Block 2 at 465 MW, and Block 3 at 465 MW. The installation of CCS does not result in a reduction in gross power output. But there is a significant reduction in net power for NGCC with CCS across all blocks. Specifically, the net power for Block 1 drops from 133 MW in the base plant to 97.6 MW with CCS (a 27% decrease); for Block 2, it decreases from 441.7 MW in the base plant to 368.1 MW with CCS (a 17% decrease); and for Block 3, it falls from 441.9 MW in the base plant to 385.5 MW with CCS (a 13% decrease). There is a significant difference in the net plant efficiency reduction among the three blocks due to the integration of CCS (Figure 4b). This variation is primarily caused by differences in the amount of CO_2 emissions captured by the CCS system in each block. CO_2 emissions are directly influenced by the fuel consumption of the power plant.

Block 1 has the lowest net plant efficiency, leading to higher fuel consumption. As a result, the amount of CO_2 emissions captured by the CCS system is also higher. Conversely, Block 2 has a higher net plant efficiency, which results in lower fuel consumption. Consequently, the CO_2 emissions captured by the CCS system in Block 3 are relatively lower. The reduction in net power output is primarily due to the energy requirements of the CCS system, particularly for operating the flue gas fan, CO_2 compressor, and sorbent regeneration process [35]. The less CO_2 mass captured in the CCS system, the smaller the reduction in net plant efficiency.

Net plant efficiency represents the proportion of net energy output compared to the total energy input. In the context of retrofitting CCS technology, there is a reduction in net power output, the decrease is driven by the power required to run the CCS setup. The efficiency loss or penalty refers to the extra power needed to operate a facility Including CO_2 capture, calculated based on overall operational effectiveness [59].

$$E_p = \frac{NPE_{ref}}{NPE_{ccs}} - 1 \quad (1)$$

where, E_p represents the energy penalty (%), NPE_{ref} denotes the net efficiency of the reference plant, and NPE_{ccs} indicates the net efficiency of the plant equipped with carbon capture and storage technology.

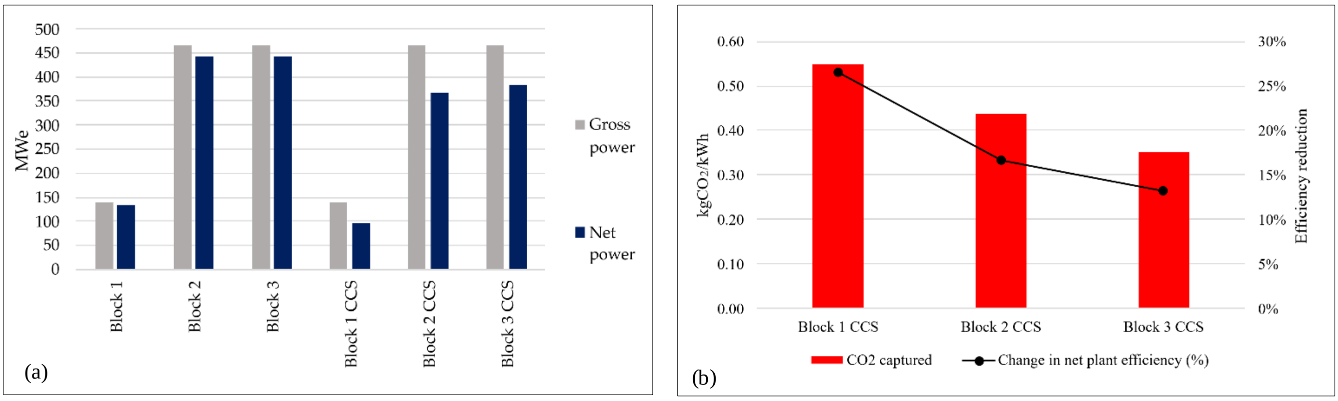

Figure 4. Comparison of NGCC and NGCC with CCS: (a) Performance, (b) Net Plant Efficiency Reduction

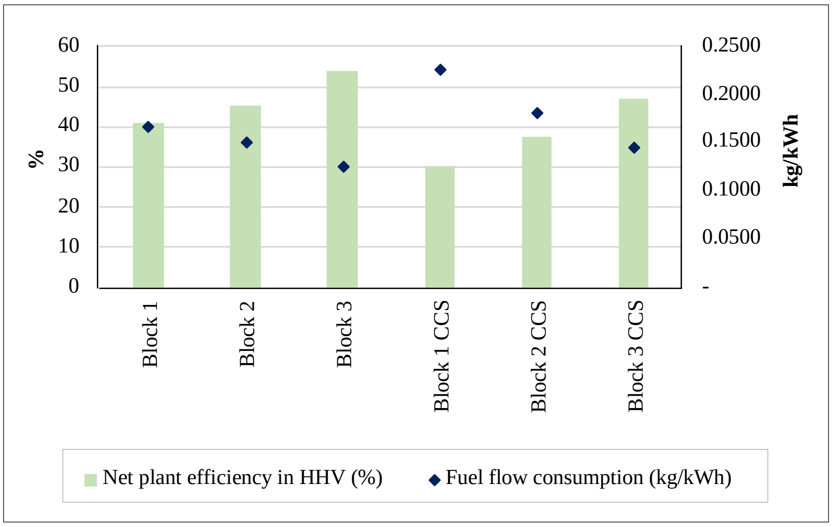

Figure 5. Comparison of efficiency and fuel flow rate of NGCC plants before and after CCS retrofitting

A decrease in net plant efficiency and an increase in fuel consumption compared to the existing facility are impacted by the installation of CCS. The efficiency reductions for each block are as follows: Block 1 drops from 40.85% to 30%, Block 2 decreases from 45.24% to 37.69%, and Block 3 declines from 53.89% to 46.79%. Fuel consumption increases correspondingly: Block 1 shifts between 0.166 kg/kWh and 0.2261 kg/kWh, Block 2 ranges between 0.1499 kg/kWh and 0.1799 kg/kWh, and Block 3 varies between 0.1258 kg/kWh and 0.1449 kg/kWh. This increase in fuel consumption is due to the reduced net plant efficiency resulting from the installation of CCS as shown in Figure 5.

The energy penalty for using CCS is as follows: Block 1 is 9.85%, Block 2 is 6.55%, and Block 3 is 6.10%. These values are within the acceptable range, below 15% [60]. Although Blocks 2 and 3 have the same NGCC capacity, the energy penalty required to run CCS on Block 3 is lower than that of Block 2. This is due to Block 3 being more efficient than Block 2 in its existing condition. Additionally, Block 2 has fewer configurations (2 GT - 2 HRSG - 1 ST) compared to Block 3 (3 GT - 3 HRSG - 3 ST). The greater variety of machine configurations impacts the incremental cost of electricity. This is caused by the extra energy needed to operate the CCS system. The higher energy demand increases operational costs and affects economic performance. One way to reduce the energy penalty in NGCC with CCS is by integrating exhaust gas recirculation (EGR) to increase CO_2 concentration, lowering capture energy demand. Additionally, waste heat recovery via dual-pressure ORC and LNG cold energy utilization improves power generation efficiency [61, 62].

3.2. Impact of Ambient Condition Variability

The increase in environmental temperature results in reduced gross power output for both existing NGCC and NGCC with CCS across all blocks. This reduction occurs in the GT, while the ST experiences only a minimal drop in power output. This is because higher environmental temperatures decrease air density, thereby diminishing the airflow entering the GT compressor. As a result, the turbine's power output, directly related to the airflow rate, diminishes, as illustrated in Figure 6 [36, 63].

Overall, there is a very slight decrease in net plant efficiency across all blocks for both existing NGCC and NGCC with CCS. This is illustrated in Figure 7. One of the most dominant factors affecting net plant efficiency is condenser pressure. In this simulation, the cooling system for the condenser uses once-through seawater. The condenser pressure is assumed to remain constant and unchanged throughout this simulation. This stability in pressure ensures that its impact on the system's overall performance is minimal. Consequently, any reduction in net power generation or plant efficiency is negligible and does not significantly affect the simulation results [36, 64]. In the future, further studies are needed to assess the extent of efficiency reduction due to changes in condenser pressure.

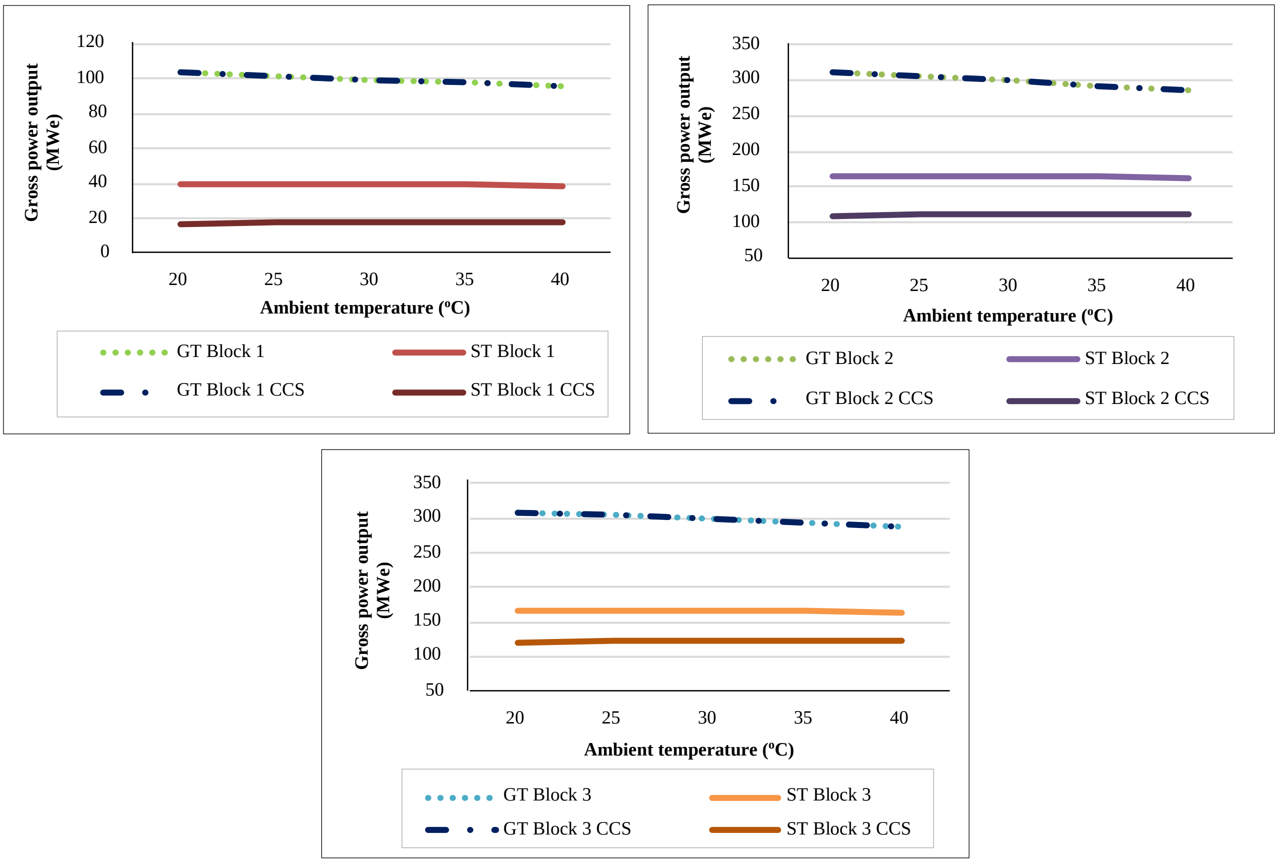

Figure 6. Impact of ambient temperature variability on gross power output: (a) Block 1; (b) Block 2; (c) Block 3

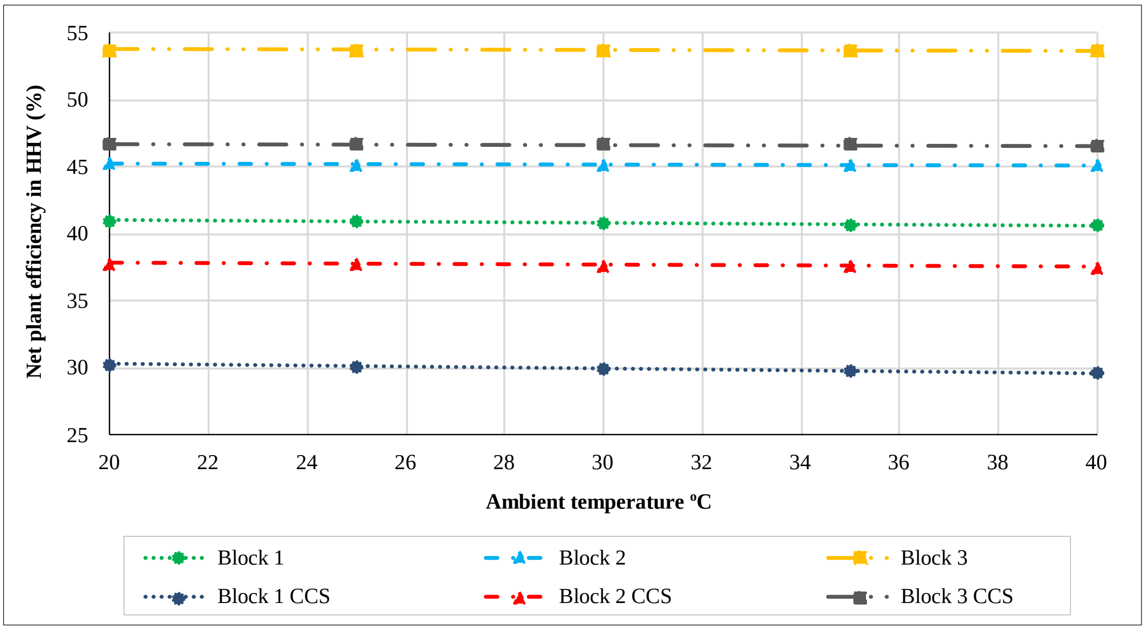

Figure 7. Impact of environmental temperature variability on net plant performance

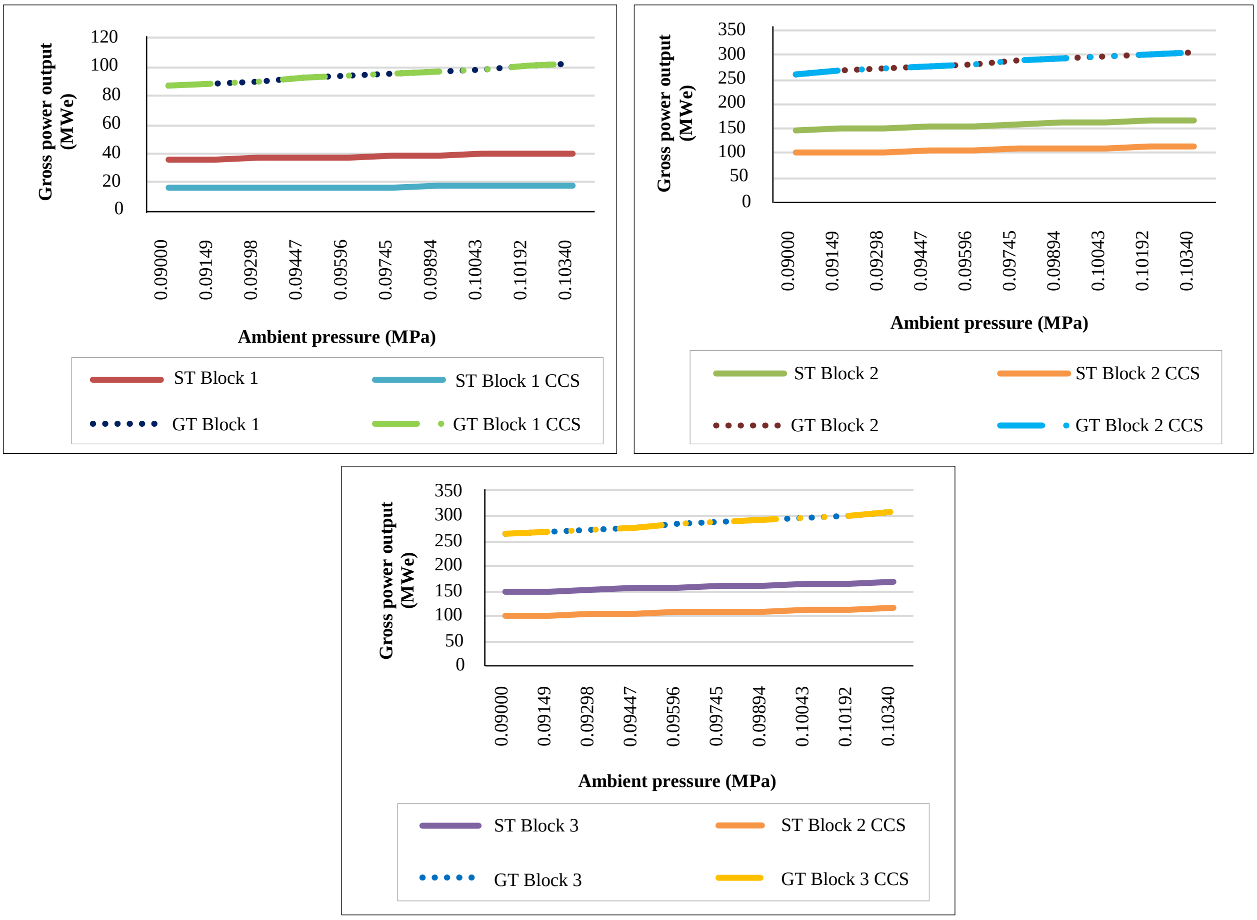

Figure 8. Impact of ambient pressure variability on gross power output: (a) Block1 (b) Block 2 (c) Block 3

In all NGCC blocks, higher environmental pressure causes an increase within the total power generation of GT, as illustrated in Figure 8. The elevated pressure enhances the density of air entering the compression system, improving the airflow during the combustion process. This allows more energy to be delivered to the GT, thereby increasing its power output. Consequently, the system's overall performance benefits from the enhanced efficiency of the GT under these conditions [12, 64, 65]. The overall power generation of the ST experiences a slight improvement. This occurs as a result of the greater flow rate of exhaust gases from the GT entering the HRSG. This additional heat transfer increases the energy content of the steam supplied to the turbine, thereby boosting its output. Figure 9 illustrates that elevated environmental pressure leads to a slight improvement in net plant efficiency.

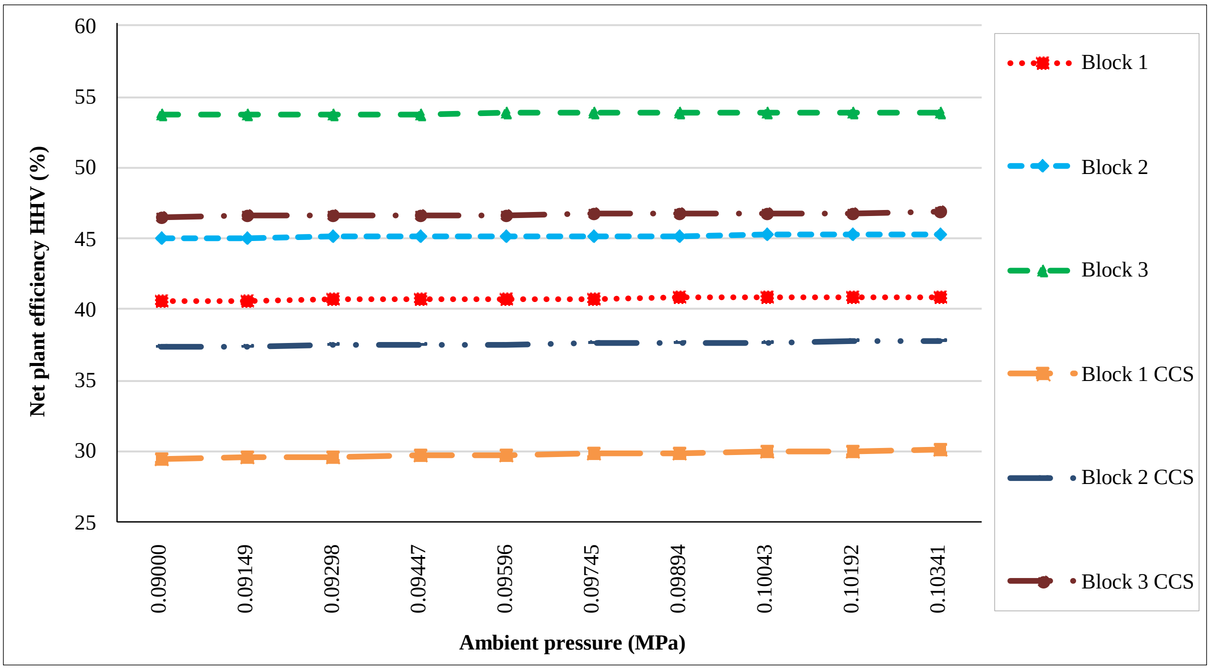

Figure 9. Implications of ambient pressure variability on net plant efficiency

3.3. Impact on CO_2 Emission

The implementation of CCS across all NGCC blocks demonstrates a substantial decrease in CO_2 emissions, as illustrated in Figure 10. The CO_2 emissions reduce as follows: Block 1 drops between 0.4470 kg/kWh (NGCC) and 0.06088 kg/kWh (NGCC CCS); Block 2 decreases from 0.4038 kg/kWh (NGCC) to 0.04845 kg/kWh (NGCC CCS); and Block 3 lowers between 0.3389 kg/kWh (NGCC) and 0.0390 kg/kWh (NGCC CCS). The percentage reduction in CO_2 emissions following CCS installation is 86% for Block 1, 88% for Block 2, and 88% for Block 3. This significant reduction highlights the performance of CCS technology in lowering carbon emissions produced by energy facilities.

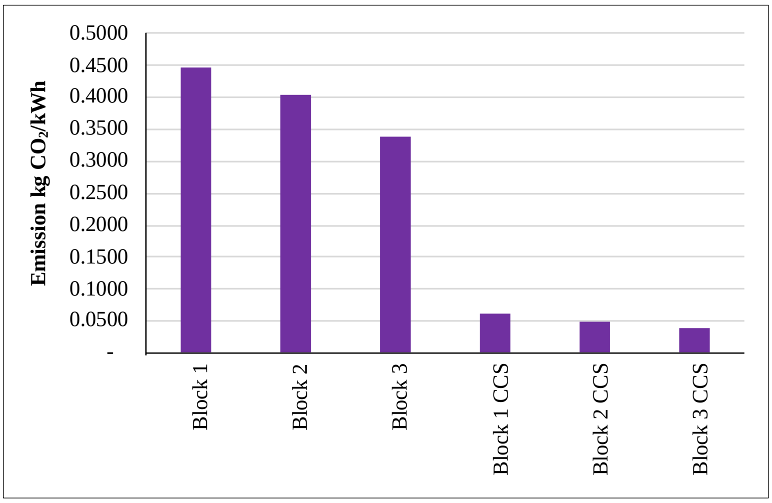

Figure 10. Comparison of CO_2 emissions from NGCC plants with and without CCS

3.4. Cost of Retrofitting CCS Technology

Figure 11 illustrates the total capital expenditure for the implementation of CCS across all NGCC blocks. The capital costs are as follows: Block 1 requires 135 million USD, Block 2 requires 250 million USD, and Block 3 requires 203 million USD. These capital expenditures are significantly influenced by the amount of CO_2 emissions produced by each block. Although Blocks 2 and 3 have the same gross power output, the required investment expenditure for CCS differs. The capital cost for implementing CCS in Block 3 is lower than in Block 2 because Block 3 has higher efficiency. Higher efficiency results in lower natural gas consumption and thus fewer CO_2 emissions.

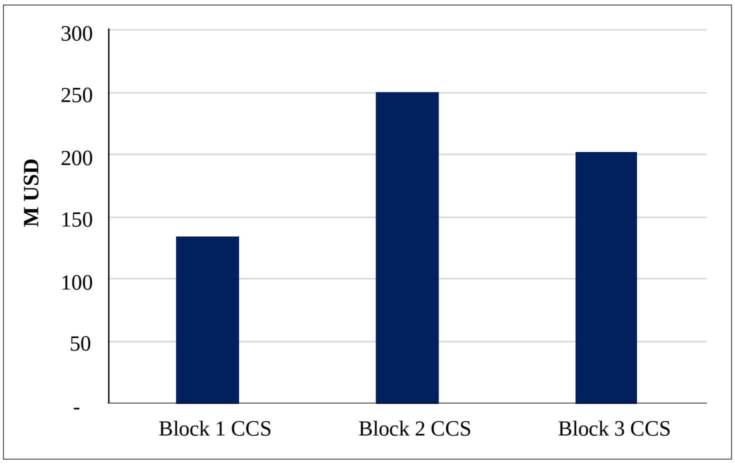

Figure 11. Capital required for CCS retrofitting technologies

3.5. Effect of CCS on LCOE

Equation 2, presented within the framework of the IECM analysis, describes the LCOE, in USD/kWh as a calculation involving the Total Levelized Annual Cost (TLAC, in million USD per year) divided by the multiplication of total yearly operational hours and the net power generation of the plant. This formula provides a comprehensive measure of the cost-effectiveness of electricity production, factoring in both operational and financial components [66]. The TLAC encompasses operational and maintenance (O&M) costs alongside the annualized capital expenditure, illustrating the overall expenditure necessary to generate electricity annually.

This formula accurately reflects the total economic load of electricity production, accounting for upfront capital investments in plant construction or modifications, such as CCS integration, as well as the recurring operational expenses. The LCOE metric plays a crucial role in evaluating the economic feasibility of diverse energy generation methods. It serves as an inclusive indicator, enabling comparisons between the cost-efficiency of different fuel types and technology configurations in electricity production.

$$LCOE\ (USD/kWh)\ = \left(\frac{TLAC\ (Million\ USD\ /year)}{total\ no.of\ hrs/yr*Net\ electric\ output\ (kW)*1000}\right) \tag{2}$$

An increase in LCOE across various NGCC blocks before and after CCS installation is illustrated in Figure 12. The LCOE increases as follows: Block 1 transitions between 0.0843 USD per kilowatt-hour (NGCC) and 0.1522 USD per kilowatt-hour (NGCC CCS); Block 2 shifts between 0.0761 USD per kilowatt-hour (NGCC) and 0.1114 USD per kilowatt-hour (NGCC CCS); and Block 3 ranges from 0.06618 USD per kilowatt-hour (NGCC) to 0.0874 USD per kilowatt-hour. The LCOE values for existing NGCC in this study are still close to the average range of LCOE for NGCC in Indonesia (2015-2021), which spans 0.0788 USD per kWh through 0.0960 USD per kWh [67]. As a result of CCS implementation, the percentage increases in LCOE are 80% for Block 1, 47% for Block 2, and 42% for Block 3. Carbon capture technology is the main contributor to the increase in LCOE. The higher the CO_2 capture capacity, the greater the required investment, leading to a rise in LCOE. This trend is illustrated in Figure 13.

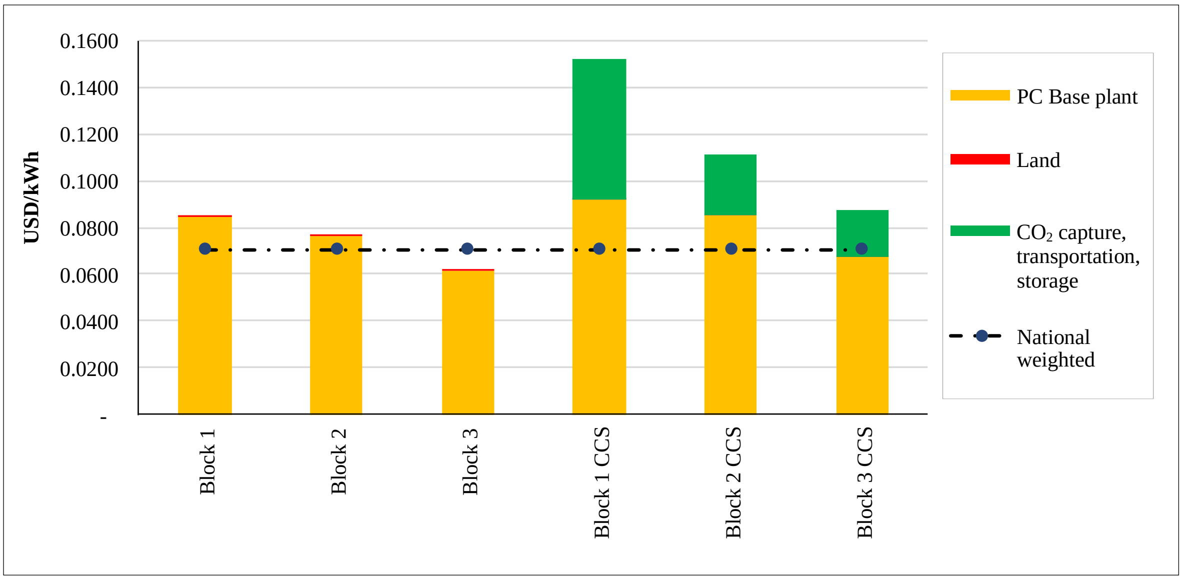

Figure 12. LCOE breakdown by component for different NGCC blocks, comparing scenarios with and without CCS integration

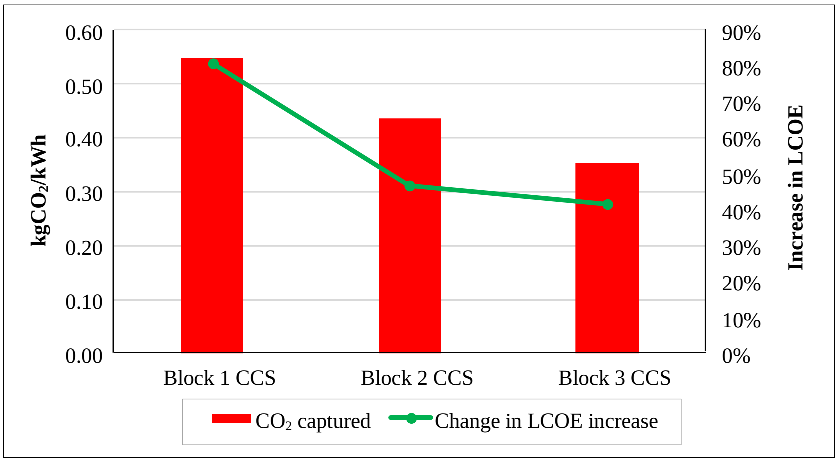

Figure 13. Percentage increase in LCOE

This increase is due to the reduction in net power output from each NGCC CCS block, leading to a rise in the base plant LCOE and the additional contribution from CCS operations. Compared to Indonesia's countrywide average LCOE, which is 0.0705 USD per kWh, blocks 1 and 2 of the existing NGCC have higher LCOEs, while Block 3 has a lower LCOE. Under the NGCC with CCS condition, all blocks exhibit higher LCOEs than the national average LCOE [52]. This significant increase in LCOE makes NGCC with CCS less competitive in terms of operational costs, despite offering substantial CO_2 emission mitigation.

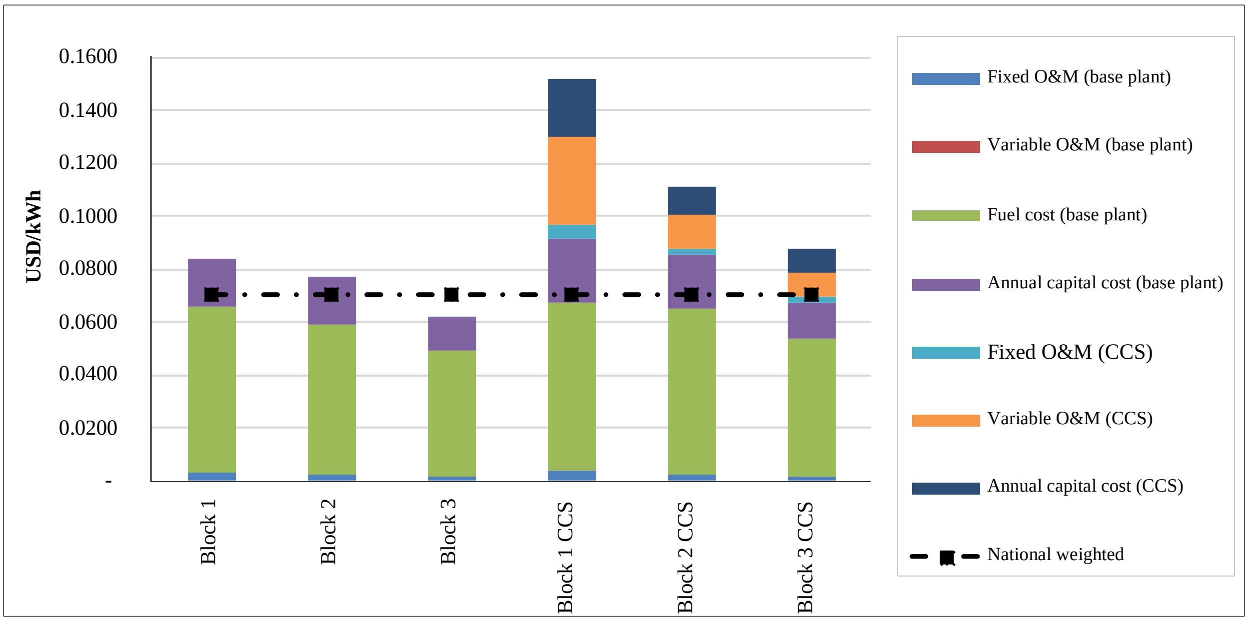

Figure 14. LCOE cost breakdown for various NGCC blocks with and without CCS retrofitting

Figure 14 shows the distribution of LCOE expenses for both current NGCC units and those retrofitted with CCS. In conventional NGCC plants, fuel costs dominate, accounting for approximately 74% to 77% of the LCOE. However, in NGCC plants equipped with CCS, this proportion decreases to 42%–59% due to reduced net power output caused by the additional energy required for carbon capture. Variable costs from CCS contribute between 11% and 22% of the LCOE, covering steam and auxiliary power needed for the capture process, along with energy for CO_2 compression, transport, and storage. Additionally, capital expenditures for CCS infrastructure play a significant role in increasing LCOE.

Opportunities for reducing carbon capture costs include scaling up capture capacity to 0.4–0.5 Mtpa, adopting modular construction approaches, utilizing low-cost energy sources such as waste heat, and leveraging financial incentives like tax credits and subsidies. We thank the reviewer for this valuable suggestion. The development of next-generation solvents with lower regeneration energy demands [68], higher CO_2 absorption capacities [69], and greater chemical stability [70] could significantly reduce the parasitic energy load associated with CCS processes. These advancements are expected not only to mitigate efficiency losses but also to lower the incremental LCOE resulting from CCS retrofitting in NGCC plants. Furthermore, continuous learning from operational projects, process optimizations, and the implementation of hybrid systems hold potential to further enhance energy integration and improve the overall economic viability of CCS deployment [71].

3.6. Cost of Carbon Avoidance and Carbon Capture

As demonstrated in equation 3, the expense of CO_2 avoidance serves as an essential measure for analysing CCS systems in energy facilities. This metric quantifies the investment needed to avert the discharge of 1 ton of CO2 while producing a single kilowatt-hour (kWh) of electricity. It is critical to measure both the financial and environmental practicality of CCS systems through assessing the extra costs required to lower CO_2 emissions in comparison to conventional energy production approaches. Essentially, this measure underscores the financial considerations in reducing GHG using CCS, providing a reference point to evaluate the efficiency of various carbon mitigation technologies and approaches within the energy industry [66, 72].

$$Cost\ of\ CO_2\ avoided = \left(\frac{(LCOE)_{ccs} - (LCOE)_{ref}}{(CO_2\ emission)_{ref} - (CO_2\ emission)_{ccs}}\right) \tag{3}$$

where: $LCOE_{ccs}$ is LCOE NGCC CCS (USD/kWh), $LCOE_{ref}$ is LCOE NGCC (USD/kWh) CO_2 $emission_{ref}$ is emission factor NGCC (t CO_2/kWh), CO_2 $emission_{ccs}$ is emission factor NGCC CCS (t CO_2/kWh).

The expense of CO_2 captured, as outlined in equation 3, serves as an important measure for analyzing the economical dimension of the carbon capture stage in CCS systems. It dedicated to quantifying the costs associated with capturing a single metric ton of CO_2, without including expenses tied to the transport and storage of the captured CO_2. This metric holds significant importance in assessing the economic viability and performance of various CCS systems by emphasizing the economic effectiveness of the capture mechanism individually.

Focusing solely on the capture cost allows stakeholders to better evaluate technology options depending on the economic impacts concerning every CCS alternative. This measure supports a thorough evaluation of capture technology efficiency, aiding in the identification of the most economical methods for minimizing CO_2 emissions in power generation and other manufacturing activities. It offers deeper insight into the financial hurdles and possibilities linked to different CCS approaches, improving the capacity to design and apply successful carbon mitigation strategies [66, 72].

$$Cost\ of\ CO_2\ captured = \frac{((LCOE)_{ccs} - (LCOE)_{ref})}{CO_2 captured\ in\ CCS\ technology} \tag{4}$$

where: $LCOE_{ccs}$ is LCOE NGCC CCS (USD/kWh), $LCOE_{ref}$ is LCOE NGCC (USD/kWh), The amount of CO_2 captured in CCS systems is calculated as the variation in CO_2 emissions observed prior to and following the implementation of the capturing process (t CO_2/kWh).

The expense of CO_2 avoided for Block 1 CCS is notably high, as indicated in Table 3. This high cost is influenced by the relatively high LCOE of Block 1 with CCS. Conversely, Block 3 CCS has the lowest cost of CO_2 avoided, which is supported by the relatively low LCOE for both the existing and CCS configurations of Block 3.

The characteristics of the carbon capture technology used are reflected in the cost, which is influenced by the amount of CO_2 captured. In this assessment, MEA-based post-combustion capture technology is applied across all blocks. The CO_2 capture costs for Blocks 2 and 3 fall within the typical range of carbon capture costs reported in various international studies, which ranges from $60 to $130 per ton of CO_2 [27, 71, 73]. Additionally, the CO_2 avoided cost (in 2020 USD) from multiple studies ranges between $70.4 and $108.1 per ton of CO_2, indicating that the costs for Blocks 2 and 3 are well within this established range [73].

Table 3. Expenses for CO_2 avoided and captured during the retrofitting of NGCC with CCS

Metric	Dimension	Block 1 CCS	Block 2 CCS	Block 3 CCS
Expanse for CO_2 avoided	USD per t CO_2	175.778	99.591	85.521
Expanse for CO_2 captured by CC	USD per t CO_2	123.917	81.202	73.031

3.7. Impact of Capacity Factor Variability

In general, the LCOE formula, as indicated in Equation 5, is influenced by various costs such as investment cost, O&M cost, fuel cost, decommissioning cost, electricity produced, and the discount factor. The capacity factor of a plant is a measure of how often a power plant operates at its maximum output over a given period [74, 75]. It is defined as the proportion (%) of the actual output produced during a given period to the maximum potential output if the plant operated at full capacity continuously. The capacity factor significantly impacts LCOE because it influences the overall amount of electricity generated, which in turn affects the distribution of fixed and variable costs over the generated output. The higher the capacity factor, the more the fixed costs are spread over a larger amount of electricity, leading to lower per-unit variable costs and increased revenue (due to higher electricity production).

$$LCOE = \frac{\sum_t \left(\frac{Investment_t + O\&M_t + Fuel_t + Decommisioning_t}{(1+r)^t}\right)}{\sum_t \left(\frac{Electricity_t}{(1+r)^t}\right)} \tag{5}$$

where: $LCOE$ is Levelized Cost of Electricity, $Investment_t$ is Investment costs in the year "t", $O\&M_t$ is Operation & maintenance costs in the year "t", $Fuel_t$ is Cost of fuel in year "t", $Decommisioning_t$ is Decommissioning costs in the year "t", $Electricity_t$ is Total electrical energy produced in the year "t", and r is Discount rate of $Electricity_t$.

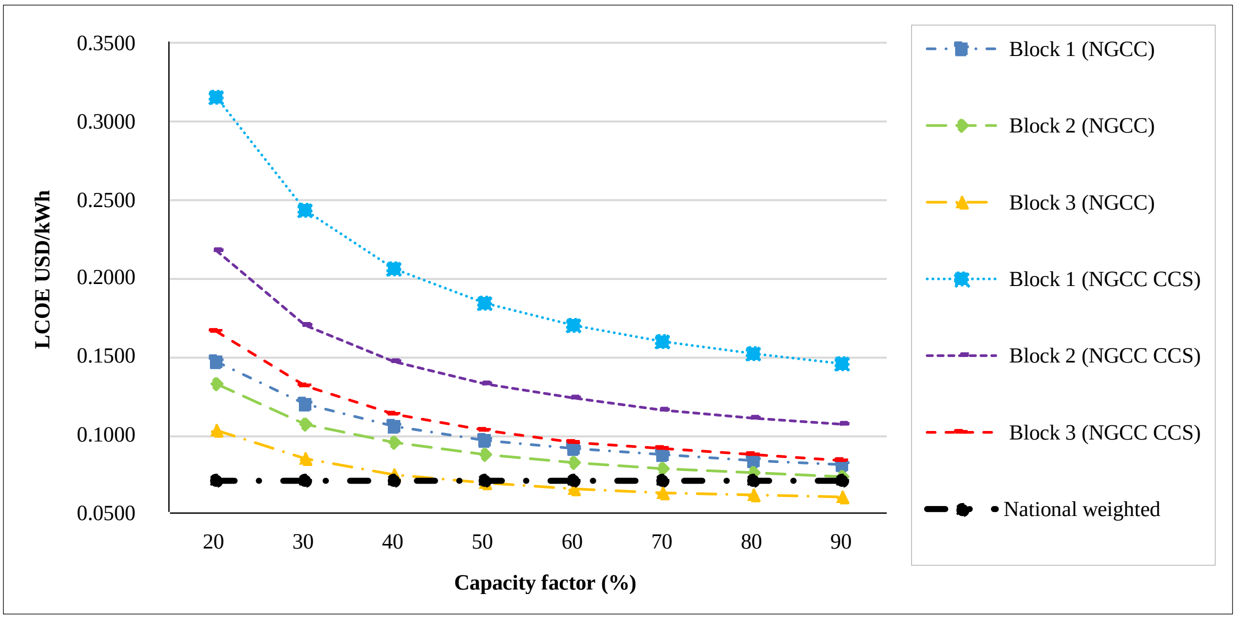

Figure 15. The effect of capacity factor variability on LCOE

As a result, a higher capacity factor leads to a lower LCOE, making the power plant more competitive. Figure 15 shows the LCOE values with various capacity factor variations. For all NGCC blocks (existing and with CCS), the lower the capacity factor, the higher the LCOE. Conversely, as the capacity factor increases, the LCOE decreases. Compared to the national weighted LCOE, Block 2 (existing condition) with a capacity factor of 90% has an LCOE value that is relatively similar to the national weighted LCOE. Block 3 (existing condition) can achieve a competitive LCOE, lower than the national weighted LCOE, if it operates at a minimum capacity factor of 50%. All NGCC CCS blocks have significantly higher LCOE values than the national weighted LCOE, even when operating at a capacity factor of 90%.

In power systems, several types of power plants are used to maintain quality, reliability, security, and cost-effectiveness. Based on flexibility, power plants are classified into three categories: base load, peaking, and load-following plants. Base load plants, such as coal and nuclear power plants, operate continuously with low ramping rates and cannot respond quickly to demand changes [76]. Peaking plants operate only during peak demand for short periods. Load-following plants adjust output to balance supply and demand fluctuations, such as hydro and gas turbine plants [77]. These generators have high ramping rates (>5%/min) to quickly respond to changes, making NGCC power plants highly versatile as they can operate as base load units and also adjust output rapidly for load-following and peaking roles, supporting grid stability alongside renewable energy sources [78, 79]. In Indonesia, many NGCC power plants operate with a capacity factor below 50% as they primarily function as peaking units or load-following plants [38, 80]. A low capacity factor reduces NGCC plant revenue and increases LCOE. NGCC with CCS faces the same challenge. Operating at low capacity factors leads to a significant rise in LCOE, affecting economic viability.

3.8. Impact on Fuel Cost Variability

Indonesia's average weighted LCOE is calculated at 0.0705 USD per kilowatt-hour. Under current conditions, each NGCC block can achieve a competitive LCOE with this national average if fuel prices are kept below 6 USD/MMBTU for Block 1, below 7 USD/MMBTU for Block 2, and below 9 USD/MMBTU for Block 3. With the integration of CCS technology, maintaining a competitive LCOE with the national average requires even lower fuel prices: below 2 USD/MMBTU for Block 1, below 3 USD/MMBTU for Block 2, and below 5 USD/MMBTU for Block 3. This relationship is depicted in Figure 16. To ensure the financial feasibility of NGCC with CCS, it is imperative to minimize fuel costs as much as possible. This presents a substantial challenge in the implementation of CCS technology.

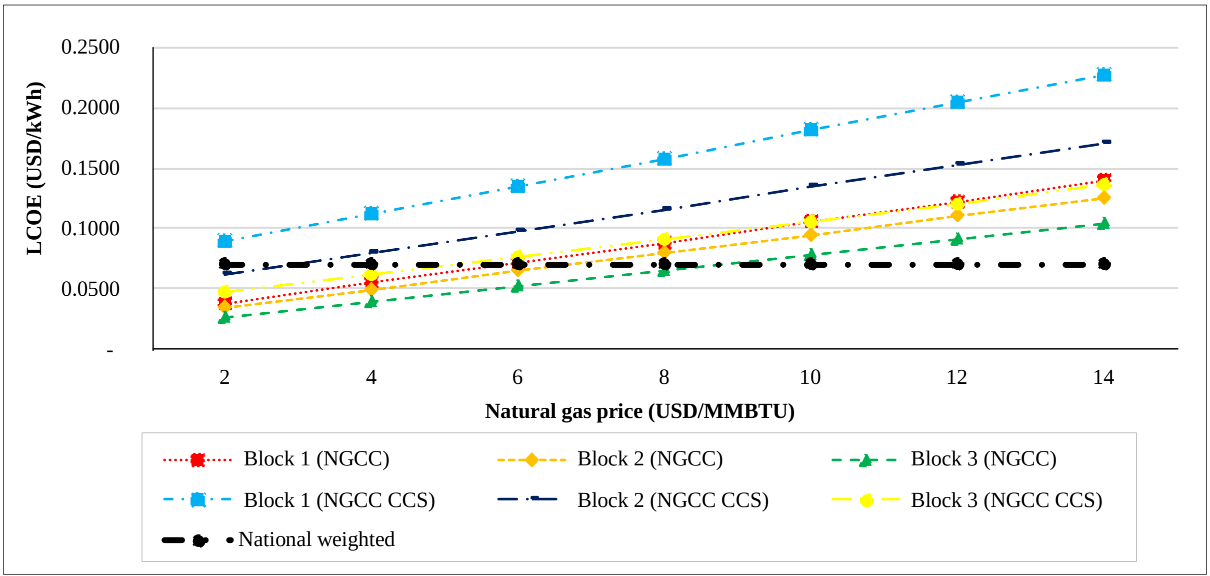

Figure 16. The impact of fuel price variability on LCOE

3.9. Carbon Price Variability and Policy Implication

One of the key policies for mitigating climate change is carbon pricing. Carbon pricing addresses the expenses incurred with minimizing GHG emissions and promotes the adoption of low-carbon technologies, particularly in managing CO_2 emissions. There are two primary mechanisms for implementing carbon pricing: carbon taxes and emissions trading systems (ETS) [81, 82]. ETS: This mechanism sets a cap on total emissions and allows the market to determine the price of emission allowances. By limiting the overall level of emissions, it creates a market for companies to buy and sell allowances as needed, incentivizing reductions where they are most cost-effective. These mechanisms are designed to internalize the external costs of carbon emissions, encouraging industries to adopt sustainable technologies and minimize their environmental impact. Carbon Tax: This approach sets a fixed price per ton of CO_2 emitted, directly pricing carbon to reflect its environmental cost.

The number of operational carbons pricing mechanisms, including carbon taxes and ETS, has been steadily increasing each year, growing from 33 in 2013 to 77 in 2023. As of 2024, numerous nations have introduced carbon taxes. For example, Uruguay imposes a tax of 167 USD per metric ton of CO_2, Switzerland applies a rate of 132 USD per metric ton of CO_2, and Sweden enforces a levy of 127 USD per metric ton of CO_2. In the Asian region, carbon taxes have been implemented in Singapore at 18 USD per ton of CO_2 and Japan at 2 USD per ton of CO_2 [83, 84]. In terms of market value, the European Union ETS has a size of 770 billion euros (88%), the United Kingdom's trading system is valued at 36.4 billion euros (4%), North America's at 71.4 billion euros (8%), and China's at 2.3 billion euros (0.3%). By 2024, the carbon prices covered by ETS in various regions are as follows: European Union at 61.3 USD/t CO_2, United Kingdom at 45.06 USD/t CO_2, Japan at 36.91 USD/t CO_2, China at 12.57 USD/t CO_2, and Australia at 21.9 USD/t CO_2 [85].

Indonesia's carbon pricing system is implemented via the harmonization of tax regulation laws and a presidential decree aimed at meeting NDC goals and managing greenhouse gas emissions [86, 87]. Two main mechanisms exist for carbon pricing: Cap-and-Trade and Carbon Tax. Under the Cap-and-Trade system, the government allocates emission permits within a defined limit. Companies exceeding this limit must buy additional allowances through carbon trading markets. Carbon Tax, Companies pay a tax on carbon emissions. The tax is initially imposed on power plant companies and may be expanded annually through government regulations.

The Carbon Tax applies to both individuals and companies involved in activities or purchasing goods that result in carbon emissions. The HPP Law specifies that the tax subjects can be either carbon purchasers or emitters, with detailed provisions to be outlined in government regulations [88]. Within the electricity sector, the Indonesian government has initiated the implementation of an ETS, representing a major milestone in aligning with international carbon reduction efforts [89, 90].

Figure 17 demonstrates that the LCOE for NGCC with CCS decreases with rising carbon prices. For each NGCC block, the LCOE becomes comparable to the nationwide LCOE average when the carbon price surpasses 145 USD/t CO_2 for Block 1, 90 USD/t CO_2 for Block 2, and 45 USD/t CO_2 for Block 3. Greater power plant efficiency reduces the carbon price needed for the LCOE to align with the national weighted LCOE.

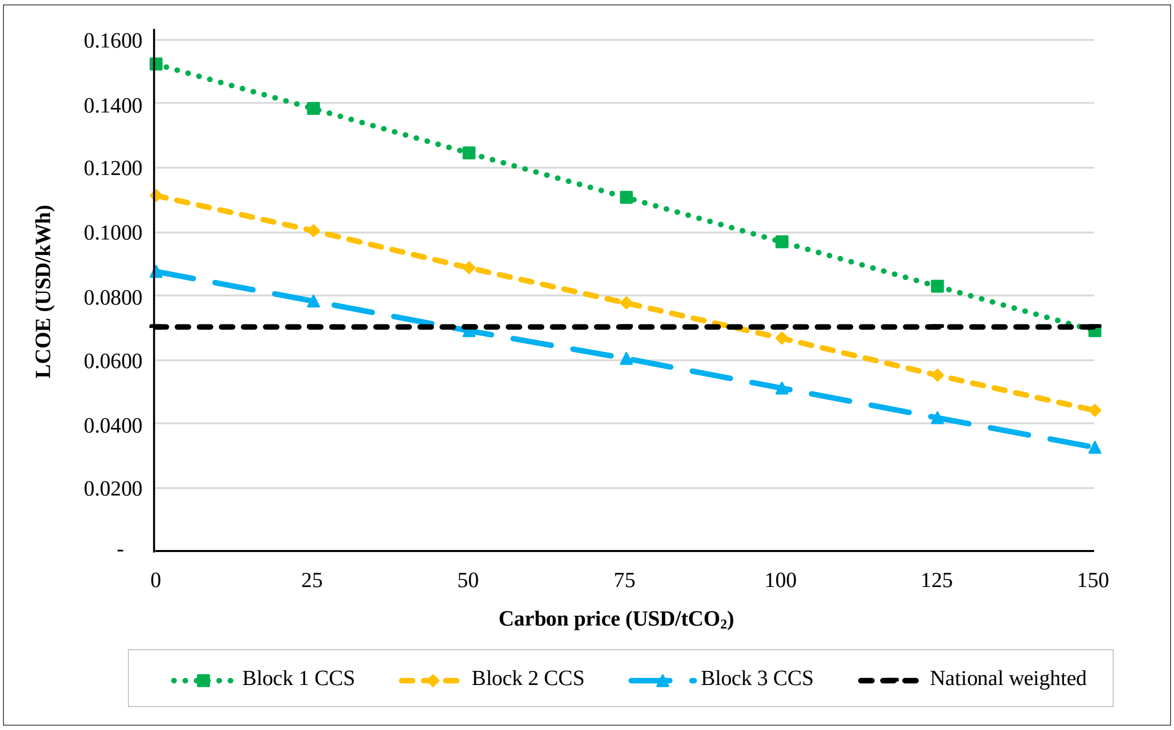

Figure 17. The impact of carbon price variability on LCOE

This connection highlights the significance of adopting effective strategies for pricing carbon to drive the use of CCS technology. By establishing suitable carbon price levels, policymakers can support the economic feasibility of efficient power plants while simultaneously lowering carbon emissions. Such measures encourage cleaner energy generation and play a role in international initiatives to mitigate climate change. Mechanisms like Cap-and-Trade or Carbon Tax are essential for accomplishing these objectives by factoring in the environmental costs of emissions and fostering investments in low-carbon solutions.

4. Conclusion

The retrofitting process includes the integration of amine-based post-combustion carbon capture technology, resulting in a decline in net power output: Block 1 transitions between 133 MWe (NGCC) and 97.6 MWe (NGCC CCS), Block 2 shifts between 441.7 MWe (NGCC) and 368.1 MWe (NGCC CCS), and Block 3 moves between 441.9 MWe (NGCC) and 385.5 MWe (NGCC CCS). This decrease is further associated with a drop in net efficiency (HHV): Block 1 shifts between 40.85% and 30%, Block 2 changes between 45.24% and 37.69%, and Block 3 varies between 53.89% and 46.79%. The simulation demonstrates that higher ambient temperatures cause a decrease in gross power output for both existing NGCC and NGCC with CCS across all blocks, with the gas turbine being primarily affected, while the steam turbine experiences only a minor reduction in power output.

The implementation of CCS technology significantly reduces CO_2 emissions. The reductions are as follows: Block 1 shifts between 0.4470 kg/kWh (NGCC) and 0.06088 kg/kWh (NGCC CCS); Block $_2$ changes between 0.4038 kg/kWh (NGCC) and 0.04845 kg/kWh (NGCC CCS); and Block 3 varies between 0.3389 kg/kWh (NGCC) and 0.0390 kg/kWh (NGCC CCS). The percentage reduction in CO_2 emissions is 86% for Block 1 and 88% for both Blocks 2 and 3.

The increase in LCOE for various NGCC blocks after CCS installation is significant. The LCOE shifts between the following values: Block 1 changes from 0.0843 USD/kWh (NGCC) and 0.1522 USD/kWh (NGCC CCS); Block 2 varies between 0.0761 USD/kWh (NGCC) and 0.1114 USD/kWh (NGCC CCS); and Block 3 ranges between 0.06618 USD/kWh (NGCC) and 0.0874 USD/kWh (NGCC CCS). For all NGCC blocks (both existing and with CCS), a lower capacity factor results in a higher LCOE, while a higher capacity factor reduces the LCOE. Compared to Indonesia's average LCOE, Block 2 in its current condition with a capacity factor of 90% has an LCOE value that is relatively similar to the national average. Block 3, in its existing state, can achieve a competitive LCOE, lower than the national average, if it operates at a minimum capacity factor of 50%. However, all NGCC CCS blocks have significantly higher LCOE values than Indonesia's average LCOE, even under maximum operational efficiency at a 90% capacity factor.

The LCOE for each NGCC block becomes competitive with Indonesia's average LCOE if the carbon price surpasses 145 USD/t CO_2 for Block 1, 90 USD/t CO_2 for Block 2, and 45 USD/t CO_2 for Block 3. Greater power plant efficiency reduces the carbon price needed for the LCOE to align with Indonesia's average LCOE.

In summary, this study has shown that implementing CCS technology significantly reduces CO_2 emissions. It also results in higher LCOE, which can be offset by increased carbon prices and enhanced plant efficiency. Further studies should prioritize optimizing these factors to strengthen the financial feasibility of CCS technologies for NGCC facilities. Employing life cycle assessment methods for NGCC CCS implementation can offer a detailed perspective on environmental impacts for upcoming research.

5. Declarations

5.1. Author Contributions

Conceptualization, M.A.R., N.C., and R.; methodology, M.A.R. and R.; software, M.A.R., N.C., and T.W.D.H.; validation, R., T.W.D.H., and M.T.; formal analysis, E.S. and M.T.; investigation, E.S.; resources, M.T.; data curation, N.C. and T.W.D.H.; writing—original draft preparation, M.A.R.; writing—review and editing, M.A.R, N.C., R., and T.W.D.H.; visualization, M.T.; supervision, N.C. and R.; project administration, M.T.; funding acquisition, E.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received financial support for the research and publication of this article from PT. PLN Research Institute.

5.4. Institutional Review Board Statement

Not applicable.

5.5. Informed Consent Statement

Not applicable.

5.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix I

Table A1. Typical characteristics of natural gas fuel for simulation

Parameter	Unit	Value
Methane (CH_4)	Vol %	94.1
Ethane ($C2H_6$)	Vol %	2.9
Propane (C_3H_6)	Vol %	1.46
Carbon Dioxide (CO_2)	Vol %	1.25
Oxygen (O_2)	Vol %	0
Nitrogen (N_2)	Vol %	0.29
Hydrogen Sulfide (H_2S)	Vol %	0
Total	Vol %	100
Natural gas density	kg/m^3	0.62
Caloric value (High Heating Value/HHV)	kJ/kg	53100