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The Role of Carbon Capture and Storage (CCS) Technology in Coal-Fired Power Plants in Supporting Zero-Emission Policies and National Energy Security

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Abstract

Coal-fired power plants remain the backbone of Indonesia's national energy security despite their significant contribution to carbon dioxide (CO_2) emissions. In line with the national Net Zero Emission (NZE) 2060 target, the Indonesian government promotes low-carbon technologies such as Carbon Capture and Storage (CCS). This study discusses the role of CCS in coal power plants in supporting zero-emission policies and national energy security, focusing on implementation effectiveness as well as the driving and inhibiting factors for its adoption in Indonesia. Based on recent literature (2019–2025), CCS demonstrates a strong potential to reduce up to 90% of CO_2 emissions while maintaining reliable domestic energy supply. Key driving factors include extensive geological storage potential, emerging regulatory support, and institutional readiness. However, several obstacles persist, such as high capital costs, regulatory uncertainty, limited infrastructure, and low public acceptance. Therefore, accelerating CCS implementation in Indonesia requires strengthening the regulatory framework, enhancing technical capacity, increasing transparency in storage data, and developing attractive business models. Through these efforts, CCS can serve as a strategic bridge toward a sustainable, low-carbon energy transition.

Keywords: Carbon Capture and Storage, Coal Power Plant, Zero Emission, Energy Security.

INTRODUCTION

Coal-fired steam power plants (PLTU) remain the backbone of Indonesia's national energy supply. In 2024, the installed capacity of coal-fired power plants reached approximately

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54.7 GW, placing Indonesia among the world's largest users of coal for electricity generation (Yonatan, 2025). Moreover, the Government's Electricity Supply Business Plan (RUPTL) 2025–2034 still includes plans to add around 6.3 GW of new coal-fired power plant capacity to ensure a reliable national energy supply (Yonatan, 2025). This condition indicates that coal continues to play a significant role in maintaining national energy security, despite its substantial environmental impacts.

Carbon dioxide (CO_2) emissions resulting from coal combustion constitute one of the major contributors to greenhouse gas emissions that accelerate global climate change. These emissions not only pose serious environmental threats but also directly affect public health, particularly for communities living near industrial areas and power generation facilities. A study by Prakoso & Windarta, (2021) demonstrates that coal-fired power plants contribute a substantial share of total carbon emissions in Indonesia's energy sector, highlighting the urgent need for concrete mitigation measures to achieve national emission reduction targets.

In response to these challenges, the Indonesian government has established a policy target to achieve net zero emissions (NZE) by 2060. This strategy encompasses increasing the share of renewable energy, improving energy efficiency, and adopting low-carbon technologies such as Carbon Capture and Storage (CCS) and Carbon Capture, Utilization, and Storage (CCUS). These technologies are considered capable of significantly reducing CO_2 emissions from coal-fired power plants without requiring the immediate cessation of their operations. Research by Triani et al., (2024) emphasizes that the combination of biomass cofiring and CCS implementation can serve as an effective transition strategy toward a sustainable low-carbon energy system.

Accordingly, CCS technology is viewed as having a strategic role in balancing emission reduction targets with national energy security. The application of CCS not only functions as a climate change mitigation measure but also allows coal-fired power plants to continue operating to meet national electricity demand. This aspect is particularly important, as national energy security must be maintained throughout the transition toward cleaner energy sources. A study by Fikri et al., (2024) indicates that integrating carbon capture technologies into power generation systems can significantly reduce emission intensity without compromising the reliability of electricity supply.

This article aims to examine the implementation and effectiveness of CCS technology in coal-fired power plants in supporting the achievement of zero-emission policies in Indonesia, to explain its contribution to national energy security during the transition toward a sustainable low-carbon energy system, and to analyze the factors that both hinder and facilitate the

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adoption of CCS technology in Indonesia. Through this discussion, the article is expected to provide a comprehensive overview of how CCS can serve as a bridge between national energy needs and commitments to carbon emission reduction.

METHOD

This study employs a literature review method with a descriptive qualitative approach to analyze the role of Carbon Capture and Storage (CCS) technology in coal-fired power plants in supporting zero-emission policies and national energy security. The research data were obtained from various credible sources, including peer-reviewed scientific journal articles, government reports, international case studies, academic books, and publications from global energy institutions. The analysis was conducted through three main stages. First, a synthesis of the literature was performed to identify the development, operating principles, and effectiveness of CCS technology in reducing carbon emissions in the electricity generation sector. Second, the study analyzed the contribution of CCS implementation to CO_2 emission reduction and the enhancement of energy security through its integration with the national power generation system. Third, the study identified enabling and inhibiting factors and formulated strategic recommendations for CCS implementation in Indonesia based on international best practices.

RESULTS AND DISCUSSION

Implementation and Effectiveness of CCS Technology In Coal-Fired Power Plants

Carbon Capture and Storage (CCS) technology represents a critical innovation in efforts to reduce carbon emissions from coal-fired power plants. This technology is designed to capture carbon dioxide (CO_2) generated during the combustion process, transport it, and store it in underground geological formations to prevent its release into the atmosphere. Through three main stages—capture, transportation, and storage—CCS directly contributes to mitigating the environmental impacts of coal-fired power plant operations while enhancing combustion efficiency by minimizing greenhouse gas emissions.

According to Ramadhan et al., (2024), Indonesia possesses carbon storage potential exceeding 400 gigatons, distributed across various geological formations such as sandstone layers and deep saline aquifers. This substantial capacity indicates that, from a technical perspective, the implementation of CCS in Indonesian coal-fired power plants is highly feasible, particularly given the continued dominance of coal-based power generation in the national energy mix. Several pilot projects, including the Gundih CCS Pilot Project, have demonstrated technological readiness and signaled the potential for future commercial-scale deployment.

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From a technological standpoint, multiple CCS approaches have been developed to accommodate coal combustion systems. Wu et al., (2024) identify three primary carbon capture methods: post-combustion, pre-combustion, and oxy-fuel combustion. Among these, post-combustion capture is considered the most efficient and practical option for existing coal-fired power plants, as it requires minimal modification to current combustion systems. Amine-based scrubbing technology is the most widely applied method under this approach, with the capability to capture up to 90% of CO_2 emissions. Nevertheless, further efficiency improvements remain possible through the development of advanced absorbent materials such as Metal–Organic Frameworks (MOFs) and amine-functionalized zeolites, which have demonstrated potential to significantly reduce energy consumption and operational costs.

The effectiveness of CCS implementation in coal-fired power plants has also been validated through international case studies. Research conducted by Rogieri Pelissari et al., (2023) at the Jorge Lacerda thermal complex in Brazil found that CCS deployment reduced carbon emissions by up to 90% of total plant emissions. Moreover, the integration of heat recovery systems within CCS processes has been shown to improve overall plant energy efficiency and reduce energy losses typically associated with solvent regeneration. These findings indicate that CCS not only serves as an effective emission reduction strategy but can also be optimized to enhance the overall performance of power generation systems.

Within the Indonesian context Prakoso & Windarta, (2021) emphasize that post-combustion capture is the most suitable approach for existing coal-fired power plants. Its key advantages include ease of integration with existing infrastructure and flexibility for industrial-scale application. CO_2 capture efficiency under this method can be further improved through precise control of operating conditions such as pressure and temperature, as well as optimization of gas and solvent flow rates. In parallel, the development of Carbon Capture, Utilization, and Storage (CCUS) has introduced new prospects for enhancing technological effectiveness. Isya et al., (2020) demonstrate that integrating chemical CO_2 absorption processes with microalgae-based bioprocesses can improve system efficiency while generating value-added by-products such as biofuels and biomass, which may be reintegrated into the energy sector.

Contribution of CCS to National Energy Security

National energy security constitutes a fundamental pillar of economic stability and national security, encompassing a country's ability to ensure sufficient energy availability, reliable access, and affordability. Within the framework of the transition toward low-carbon

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energy systems, CCS technology has emerged as a significant strategy for sustaining the utilization of fossil energy resources while simultaneously reducing greenhouse gas emissions. Studies indicate that CCS functions not only as an environmental solution but also as an instrument for maintaining the availability and sustainability of national energy systems (Shen et al., 2022). Through CCS deployment, countries—particularly developing nations—can continue utilizing conventional energy reserves without requiring abrupt reductions in production or increased reliance on energy imports in the short term.

Furthermore, CCS strengthens national energy independence by optimizing the use of domestic resources. Research conducted in Indonesia suggests that the integration of CCS/CCUS technologies can support the achievement of national emission reduction targets while preserving the stability of domestic energy supply (Putri et al., 2024). This is particularly important for developing countries that remain heavily dependent on fossil fuels and face substantial challenges in rapidly expanding renewable energy capacity. By adopting CCS, reliance on imported technologies or alternative fuels can be reduced, thereby safeguarding domestic energy accessibility and availability.

From a systems perspective, CCS also serves as a transitional bridge between fossil fuel–based energy structures and emerging low-carbon energy systems. Global assessments emphasize that, in order to balance rising energy demand with increasing pressure for emission reductions, technologies such as CCS play a critical role in sustaining the three core dimensions of energy security: availability, accessibility, and acceptability (Liwang, 2023). Accordingly, CCS enables countries to maintain stable domestic energy production while enhancing social and environmental acceptance of the energy sector—an aspect that often constitutes a major barrier in the development of new and renewable energy sources.

Economic and Environmental Impacts of CCS Implementation in Indonesia

From an environmental perspective, the deployment of Carbon Capture and Storage (CCS) technology in Indonesia is widely regarded as a crucial option for reducing carbon emissions, particularly from coal-fired power plants and other high-emission industrial sectors. Numerous studies demonstrate that CCS can capture and store substantial volumes of CO_2, thereby contributing to emission reductions without requiring the immediate decommissioning of existing energy infrastructure (Prakoso & Windarta, 2021). The integration of CCS with complementary approaches such as biomass cofiring and power-to-gas technologies further enhances the decarbonization potential of the national energy system (Triani et al., 2024). However, excessive reliance on CCS carries the risk of moral hazard, as it may encourage the

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prolonged use of fossil fuels under the justification of carbon capture technology, potentially delaying the transition toward cleaner renewable energy sources.

From an economic standpoint, CCS implementation in Indonesia faces significant challenges, particularly due to the substantial capital investment required for capture, transportation, and storage stages (Shen et al., 2022). Increased production costs associated with CCS deployment may reduce industrial economic efficiency, especially within energy and manufacturing sectors that are highly sensitive to operational expenditures. In certain circumstances, cost pressures may drive labor efficiency measures that result in workforce reductions or layoffs if not accompanied by adequate social protection policies and economic incentives. Consequently, CCS development must be balanced with strategies for job creation and just transition mechanisms to prevent adverse socio-economic impacts (Yonatan, 2025).

In addition, governance and public acceptance are decisive factors influencing the success of CCS implementation. Regulatory certainty regarding carbon storage—including long-term liability and cross-border transportation issues—remains a major challenge within the national regulatory framework (Cipta et al., 2025). At the societal level, CCS projects may encounter public resistance, particularly in regions designated as CO_2 storage sites, due to concerns over environmental and safety risks. Limited transparency and insufficient public participation can undermine policy legitimacy and hinder implementation efforts (Yusgiantoro et al., 2025). Therefore, the development of CCS in Indonesia must be supported by inclusive governance structures, clear risk communication, and alignment with national energy security policies to ensure that environmental benefits are achieved without compromising social and economic stability (Liwang, 2023).

CONCLUSION

Carbon Capture and Storage (CCS) technology plays a strategic role in accelerating Indonesia's energy transition toward the Net Zero Emission (NZE) 2060 target without undermining the stability of national energy security. With an estimated carbon storage capacity exceeding 400 gigatons, this technology is capable of reducing CO_2 emissions by up to 90% while simultaneously maintaining energy availability, affordability, and public acceptability amid the continued dominance of coal utilization. Nevertheless, CCS implementation still faces several challenges, including high capital investment costs, policy and regulatory uncertainties, limited geological data availability, and the underdeveloped infrastructure and legal framework for long-term carbon storage. To address these barriers, comprehensive support is required through clear fiscal policies, strengthened research initiatives and pilot projects, the development of

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transparent monitoring, reporting, and verification (MRV) systems, as well as enhanced public trust through cross-sectoral and inter-institutional collaboration. With such an integrated approach, CCS has the potential to become a key instrument in Indonesia's decarbonization efforts while ensuring sustainable national energy security.

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