Dinamika Transisi Energi dengan Implementasi Carbon Capture, Utilization, and Storage (CCUS) pada
PLTU di Indonesia
Eufrasia Andranetta Gracelynne Eka Pramudita, Prof. Ir. Bertha Maya Shopa, S.T., M.Sc., Ph.D., IPU., ASEAN Eng.
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INTISARI

Indonesia terus mengalami peningkatan emisi, terutama dari sektor energi. Pada 2023, emisi CO_2 mencapai 674,5 juta ton CO_2e atau meningkat 16 kali lipat dari setengah abad sebelumnya, dengan sektor ketenagalistrikan berbasis batu bara sebagai salah satu kontributor utama. Meskipun berbagai upaya transisi energi dan kebijakan karbon telah diterapkan, ketergantungan terhadap batu bara masih sulit dikurangi dalam jangka pendek. Dalam kondisi ini, investasi teknologi *Carbon Capture, Utilization, and Storage* (CCUS) dipandang sebagai salah satu solusi potensial untuk menekan emisi tanpa mengganggu pasokan listrik. Namun, implementasinya masih menghadapi tantangan besar, seperti tingginya biaya investasi, potensi kenaikan tarif listrik, serta kompleksitas interaksi antar pemangku kepentingan. Oleh karena itu, penelitian ini bertujuan menganalisis dinamika transisi energi dan mengevaluasi kebijakan karbon dalam mendukung implementasi CCUS dan pengembangan energi terbarukan di Indonesia.

Penelitian ini menggunakan metode *system dynamics* melalui pembangunan model konseptual dan simulasi berbasis data sekunder secara terbatas. Model disimulasikan pada skenario dasar tanpa intervensi CCUS dan pada 3 skenario intervensi, yakni: (1) penerapan CCUS karena adanya urgensi alamiah; (2) penerapan kebijakan pajak karbon pada level Rp30 ribu, Rp500 ribu, Rp1,5 juta, dan Rp2,5 juta; dan (3) penerapan kebijakan *Emission Trading System* (ETS) pada level harga karbon Rp47.824, Rp400 ribu, Rp830 ribu, dan Rp1,3 juta. Performa skenario dievaluasi berdasarkan penurunan laju emisi sebagai indikator utama, serta tiga indikator *trade-off,* yakni perubahan harga tarif listrik, penurunan profitabilitas PLTU, dan peningkatan kapasitas PV dengan tidak memasukkan kapasitas CCUS terinstal dalam penentuan skenario terbaik karena tidak secara langsung merefleksikan efektivitas penurunan emisi.

Hasil simulasi menunjukkan bahwa CCUS efektif menurunkan emisi apabila didukung dengan kebijakan karbon. Namun, penerapan keduanya juga menimbulkan *trade-off* berupa penurunan profit PLTU, kenaikan tarif listrik, dan menciptakan adanya kompetisi teknologi dengan peningkatan adopsi *photovoltaic* (PV). Berdasarkan hasil *system improvement test* dan pengurutan gap skenario, kombinasi skenario pajak karbon Rp1,5 juta dan harga karbon Rp400 ribu menjadi skenario optimal dengan mempertimbangkan keseimbangan antar aspek. Implikasinya, pemerintah perlu menerapkan kebijakan komprehensif melalui kombinasi instrumen karbon, dukungan pembiayaan CCUS, serta insentif energi terbarukan untuk menekan emisi dengan meminimalkan *trade-off* sistemik.

Kata kunci: Emisi, CCUS, PLTU, *Trade-off, System dynamics*

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ABSTRACT

Indonesia continues to experience rising emissions, particularly from the energy sector. In 2023, CO_2 emissions reached 674.5 million tons of CO_2e—a 16-fold increase from half a century ago—with the coal-fired power sector being one of the main contributors. Although various energy transition efforts and carbon policies have been implemented, reducing dependence on coal remains difficult in the short term. Under these circumstances, investment in Carbon Capture, Utilization, and Storage (CCUS) technology is viewed as a potential solution to curb emissions without disrupting electricity supply. However, its implementation still faces significant challenges, such as high investment costs, the potential for rising electricity rates, and the complexity of interactions among stakeholders. Therefore, this study aims to analyze the dynamics of the energy transition and evaluate carbon policies in support of CCUS implementation and renewable energy development in Indonesia.

This study employs system dynamics methodology through the development of a conceptual model and simulations based on limited secondary data. The model was simulated under a baseline scenario without CCUS intervention and under three intervention scenarios, namely: (1) the implementation of CCUS due to natural urgency; (2) implementation of carbon tax policies at levels of Rp30,000, Rp500,000, Rp1.5 million, and Rp2.5 million; and (3) implementation of carbon pricing policies at levels of Rp47,824, Rp400,000, Rp830,000, and Rp1.3 million. Scenario performance was evaluated based on emission rate reduction as the primary indicator, as well as three trade-off indicators: changes in electricity tariffs, reduced coal-fired power plant profitability, and increased PV capacity. Installed CCUS capacity was not included in determining the best scenario because it does not directly reflect the effectiveness of emission reductions.

The simulation results show that CCUS is effective in reducing emissions when supported by carbon policies. However, the implementation of both also creates trade-offs in the form of reduced profits for coal-fired power plants, increased electricity rates, and technological competition resulting from the growing adoption of photovoltaics (PV). Based on the results of the system improvement test and scenario gap ranking, the combination of a carbon tax of Rp1.5 million and a carbon price of Rp400,000 emerges as the optimal scenario, balancing various aspects. Implications: The government needs to implement comprehensive policies through a combination of carbon instruments, CCUS financing support, and renewable energy incentives to reduce emissions while minimizing systemic trade-offs.

Keywords: Emissions, CCUS, Coal-fired power plants, Trade-off, System dynamics