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Impact Analysis of Negative Emission Technology Integration on Industrial Energy System Performance

With the continuous advancement of global carbon neutrality goals, emission reduction measures alone are insufficient to offset unavoidable emissions in certain industrial sectors. Negative emission technologies (NETs) have emerged as essential complements for achieving deep decarbonization in industrial energy systems. NETs, including bioenergy with carbon capture and storage (BECCS), biochar-based carbon sequestration, and direct air capture, enable the net removal of carbon dioxide from the atmosphere. However, integrating NETs into industrial energy systems inevitably alters energy flows, material cycles, and operational characteristics, making it necessary to assess their impact on overall system performance from an engineering perspective.

Industrial energy systems consist of multiple subsystems, such as energy conversion units, thermal supply networks, power generation systems, and process energy consumers, which are highly coupled and operate under complex conditions. The integration of NETs introduces additional energy-consuming units, heat transfer processes, and material circulation pathways, potentially affecting system efficiency, load-following capability, and operational stability. For instance, carbon capture units may increase auxiliary energy consumption, while the variability of biomass-based energy systems can influence supply reliability. Therefore, beyond evaluating emission reduction potential, a comprehensive assessment of performance impacts is required.

This study develops a system-level model incorporating energy balance, carbon flow analysis, and operational constraints to evaluate the performance of industrial energy systems with integrated NETs. Key performance indicators, including system efficiency, energy consumption distribution, and operational flexibility, are quantitatively assessed under different integration configurations. By comparing the operational behavior of typical industrial energy systems with various NET deployment scenarios, the mechanisms through which NETs influence system performance and their engineering applicability are identified. The results provide valuable insights for the rational integration and optimization of negative emission technologies in industrial energy systems.

This research establishes a quantitative link between emission reduction objectives and operational performance, offering engineering guidance for maintaining efficient and reliable industrial energy systems while progressing toward low-carbon and negative-carbon targets.