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Supporting the optimal design and operation of CO_2 capture in industrial facilities with time-resolved models

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Abstract

Carbon capture and storage (CCS) is an important technology for industrial decarbonization [1]. Extensive research has been conducted to assess and design CCS technologies, typically using process simulations integrated into techno-economic frameworks [2-4]. While this approach effectively captures the thermodynamic (and economic) performance of the process, it generally does not allow to evaluate the interplay between three key elements: (1) the real-world temporal dynamics and off-design operations, (2) the design characteristics of capture units, and (3) the economic performance of the system. Therefore, such evaluations can easily overlook key technology features that only become apparent when investigating their yearly operation. To address this gap, we propose a mixed-integer linear programming (MILP) framework that integrates these three aspects. Our framework relies on multiple on/off-design process simulations that are appropriately linearized to maintain the fidelity to the process simulation. Given that the relevant temporal dynamics and off-design conditions vary by industry, we focus on two sectors: waste-to-energy (WtE) and cement, which will most likely require CCS to achieve deep CO_2 mitigation [5,6].

In WtE facilities, municipal solid waste (MSW) is incinerated, generating significant amounts of heat that can be used for district heating and electricity production. The primary function of a WtE plant is waste incineration, but it must also meet district heating demands, which varies seasonally. Integrating CCS into WtE systems introduces additional energy requirements in the form of heat and electricity, which in turn reduces the energy available for heating and power generation [7]. Furthermore, since the energy demand of CCS is influenced by the CO_2 concentration in the flue gas, and since this concentration fluctuates in time due to variations in waste composition, the energy consumption of the CCS unit is inherently dynamic. Consequently, the sizing and operation of CCS systems in WtE facilities involve a trade-off between CO_2 capture and energy sales. Our MILP framework incorporates a linearized model of a post-combustion calcium looping (CaL) system applied to a WtE facility, where energy requirements depend on CO_2 concentration and the volume of flue gas treated based on on/off-design process simulations. This model is integrated with real-world hourly profiles of CO_2 concentration, MSW processing rates, heating demand, and electricity prices, allowing us to assess how these factors influence the optimal sizing and operation of CaL systems compared to static techno-economic analyses.

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In the cement industry, plants are typically operated continuously due to their high capital costs and the inherent plant features [8]. However, real-world operations may require temporary shutdowns lasting several days or weeks in response to fluctuations in cement demand. This intermittency can impact technology selection, system design, and operational strategies. Additionally, increasing reliance on intermittent renewable energy sources results in electricity prices that vary on daily and seasonal scales, potentially affecting the optimal operation of CCS units. Lastly, cement operators may decide to switch fuel – such as transitioning from e.g. coal to waste or biomass - after the implementation of the capture plant. This would lead to operating the CCS plant in off-design condition, altering the energy consumption and CO_2 capture rates. In this context, we develop linear models for two capture technologies for cement plants: an oxyfuel combustion of the pre-calciner and a hybrid oxyfuel with post-combustion capture, where a monoethanolamine (MEA) unit is used to treat the kiln gases coupled to the pre-calciner oxyfuel. These models, which have fuel-dependent energy consumptions and capture rates, are integrated into the MILP framework with hourly profiles of electricity prices and cement production from a real plant. Here, the optimization problem helps identifying the cost optimal technology, its size and operations.

Overall, by integrating temporal dynamics (hourly resolution for an yearly horizon) and off-design conditions into the design and operation of CCS systems in WtE and cement industries, our MILP framework allows for an advanced assessment of CCS deployment. This approach enables more informed decision-making for industrial decarbonization strategies, addressing the limitations of traditional static analyses.

Keywords: waste-to-energy; cement; optimization

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