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A new carbon capture proxy model for optimizing the design and time-varying operation of a coal-natural gas power station

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ABSTRACT

We optimize the design and time-varying operation of a CO_2-capture-enabled power station burning coal and natural gas, subject to a CO_2 emission intensity constraint. The facility consists of a coal-fired power plant and an amine CO_2 capture system, which is powered by a combined-heat-and-power auxiliary gas-fired subsystem. The detailed design of the CO_2 capture system, the detailed heat integration of the facility, and time-varying operations schedule across all hours of the year are determined in a single optimization problem. This problem is formulated as a bi-objective mixed integer nonlinear program: objectives include minimizing total capital requirement (TCR) and maximizing net present value (NPV). Because the Aspen Plus model used for the CO_2 capture system is too computationally intensive to use directly in optimization runs, we develop a statistical proxy model of the capture system that reproduces Aspen Plus results but is several hundred times faster. The integrated proxy model includes statistical submodels for the CO_2 absorption and solvent regeneration blocks, as well as simple physical models of other system components. Incorporating the detailed CO_2 capture system in the optimization provides important design information such as the optimal number of CO_2 capture trains required. Two scenarios are considered, based on historical data for Texas and India. Results show that the choice of objective function can have a strong effect on planned operating profile (constant or variable operations). Similarly, hourly electricity price variability strongly affects design and plant scheduling. In the West Texas scenario, which has high price variability, the maximum NPV objective favors variable operations, with a CO_2 capture system utilization factor of 65.9% (out of a maximum of 85%), while the minimum TCR objective favors constant operations. In contrast, because of low electricity price variability in the India scenario, there is little value in time-shifting the demand for capture heat, so constant operations are favored in this case for both objectives.

1. Introduction

With high renewable penetration, thermal power generation assets are likely to operate variably to meet consumer demand. For example, on April 8, 2015, in California, non-renewable power generation (including nuclear, imports, and thermal generation) experienced intra-daily variation in output from 16 GW to 23 GW (California Independent System Operator, 2015). This resulted from variability in generation from renewable resources: While total system output was 25 GW at both 1 p.m. and 11 p.m. on that day, renewables provided 9 GW of electric power generation at 1 p.m., and only 2 GW at 11 p.m.

Even in scenarios with very high rates of renewable penetration, substantial thermal generation capacity (though not from traditional baseload assets) likely will be required to maintain system stability (Hart and Jacobson, 2011; Elliston et al., 2012). Interestingly, with high renewable penetration, the overall electricity system may exhibit diminishing marginal returns of CO_2 emission abatement from adding renewables (Hart and Jacobson, 2012). While Hart and Jacobson (2012) suggest that seasonal-scale energy storage may be a way to achieve full electric decarbonization with nearly 100% renewable penetration, a plausible complement would be to use thermal power generation with CO_2 capture and storage (CCS) to provide low-carbon grid stabilization in high renewable penetration scenarios. Therefore, there may be a need to develop CCS-enabled thermal power stations that operate variably in time. Such facilities will work in coordination with renewables to achieve deep reductions in CO_2 emissions from electric power generation.

In this work we consider the design and variable operation of a CCS-enabled power station that burns coal and natural gas and is

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subject to a CO_2 emission intensity limit of 499 kg CO_2/MWh (consistent with requirements for new power plants proposed by the US Environmental Protection Agency, and which are in force in California). This facility represents an 'auxiliary' CCS configuration (Bashadi and Herzog, 2011) in which energy demand for CO_2 capture from the coal-fired power station is supplied by an auxiliary combined-heat-and-power natural-gas-fired system.

The detailed CO_2 capture system is modeled using Aspen Plus, though this leads to function evaluations that are very expensive relative to other model computations (Aspen Plus requires ~300 s per run, while all other function evaluations require less than one second per run). Therefore, to enable computational optimization of this facility, we develop an efficient integrated proxy model of the CO_2 capture system that reproduces the behavior of detailed Aspen Plus process simulations. The integrated proxy model runs in less than one second, thereby enabling computational optimization of the detailed design of the CO_2 capture system. This extends our earlier work, which optimized the design of heat integration (and in particular the heat recovery steam generator) in the facility, but treated the CO_2 capture system at a high level of abstraction (Kang et al., 2014).

As in our earlier work, we incorporate flexible operations in the form of discrete operating modes, which allow CO_2 capture to be turned on and off in response to time-varying electricity prices (partial capture is also allowed). We optimize the facility for two objectives, minimum total capital requirement (TCR) and maximum net present value (NPV), and identify the optimal tradeoffs between these two objectives. This bi-objective approach provides a richer characterization of designs than can be achieved by considering only a single objective. The methodology described here enables us to to resolve design tradeoffs across the entire system (including both the power plant and the CO_2 capture process), while simultaneously considering the effects of time-varying operations that are consistent with realistic future energy markets. To our knowledge, no previous studies have incorporated all of these interacting effects. Taken in total, this work accomplishes the simultaneous optimization of both the detailed design of all major components, as well as key time-varying operational controls, for a CCS-enabled power station.

1.1. Design and variable operation of CCS-enabled power stations

A growing body of literature has explored variable operation of CCS-enabled thermal power stations. Many of these studies have considered coal-fired power stations with solvent-based post-combustion CO_2 capture systems and have applied formal optimization techniques to maximize performance. Various groups have considered the valuation and viability of flexibility in power stations with CO_2 capture, including design of CO_2 capture systems (Brasington and Herzog, 2012; Bui et al., 2014; Ziaii et al., 2009a,b), and system integration (Arce et al., 2012; Chalmers et al., 2009, 2011; Cohen et al., 2010; Kang et al., 2011; Mac Dowell and Shah, 2013, 2015). Other work has considered retrofitting existing plants with CCS (Harkin et al., 2012, 2012; Kang et al., 2014; Khalilpour, 2014). CO_2 capture in conjunction with variable operation has also been shown to have important implications for power grids (Chen et al., 2010; Cohen et al., 2012). These earlier studies often are focused on one part of the system (typically either power plant steam cycle components or the CO_2 capture process), or consider only constant operations (Hasan et al., 2012; Khalilpour and Abbas, 2011; Romeo et al., 2009).

In a study methodologically similar to our earlier work (Kang et al., 2011), Zaman and Lee (2015) applied formal optimization procedures to determine the optimal hour-to-hour operation (including solvent storage and partial capture of flue gas CO_2) of a CO_2-capture-enabled power plant with time-varying electricity prices, for a set of fixed facility designs. Consistent with our earlier work, Zaman and Lee (2015) found that flexible CO_2 capture could result in substantially improved operating economics in a CO_2-capture-enabled facility compared to a facility with constant CO_2 capture rate.

One observation arising from operation-focused studies such as Kang et al. (2011) and Zaman and Lee (2015) is that operational flexibility typically entails increased capital investment. Thus, operational flexibility is not always economically preferable to constant operations. To determine whether operational flexibility is desirable, it is necessary to include both facility design and flexible operations within a single optimization formulation.

Some recent work has considered CO_2 capture from coal plants using a coupled treatment of operations and design. Mac Dowell and Shah (2013) demonstrated a method to optimize design and operations of CO_2 capture at a coal plant. For a specific facility under particular economic conditions, they found that the optimal CO_2 capture fraction was high (95%). Khalilpour (2014) applied a mixed integer linear optimization formulation for CO_2 capture retrofit decisions for a coal plant operating under a gradually tightening CO_2 emission regulation. Mac Dowell and Shah (2015) applied a multiperiod optimization approach to treat the operation of a coal-fired power plant with parasitic post-combustion CO_2 capture, for several power generation profiles. Improvements in operating profit of up to 16% in one scenario were achieved by controlling lean solvent loading to vary the rate of solvent regeneration in time. As is evident from the above studies, significant progress has been made in optimization of CO_2 capture systems through consideration of both design and operations. However, the above-cited studies focused primarily on the CO_2 capture system, and did not consider in detail either the integration of the CO_2 capture system with the power plant, or the design of a heat-integrated auxiliary energy system to power the capture process.

In this vein, in our earlier work we considered optimal heat integration in a CCS-enabled facility with flexible operations (Kang et al., 2014). This work indicated that it can be economically preferable to spend more on capital to enable flexible operations. That work, however, represented the CO_2 capture system with a single parameter for capacity, so it was not able to provide full designs for the CO_2 capture system itself. Taken together, this previous literature indicates a need for integrative studies that consider variable operations alongside all aspects of CCS-enabled power station design, including detailed design of both the CO_2 capture system and aspects of the power plant.

1.2. Overview of optimization and proxy methods

A central challenge in engineering design optimization is that modeling complex systems can be computationally costly. As such, direct use of full-physics engineering models for all function evaluations required during optimization is often impractical. Several alternative approaches have been applied for optimizing systems with computationally costly model evaluations. These approaches can be divided broadly into three categories: (1) development of procedures that efficiently provide gradients for use in optimization; (2) use of simplified (i.e., reduced physics) models; and (3) use of statistical proxy models. We now present an overview of these three approaches to provide context and motivation for our method. Our work primarily employs statistical proxy models, though we also apply some physics-based simplifications.

Combined forward modeling and gradient construction is commonly employed for the optimization of engineered systems. This approach has been applied successfully to the design of air separation units for oxycombustion and in PDE-constrained optimal control problems (Choi, 2012; Dowling and Biegler, 2015). The key