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Optimization of carbon-capture-enabled coal-gas-solar power generation

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ABSTRACT

Computational optimization is used to determine the optimal design and time-varying operations of a carbon dioxide capture retrofit to a coal-fired power plant. The retrofit consists of an amine-based temperature-swing absorption system, to which process steam is supplied from an auxiliary unit. Two candidate auxiliary heat sources are explored: natural gas and solar thermal. The NPV (net present value) of the retrofitted facility is maximized to determine which auxiliary system is preferable, under a variety of economic conditions. Optimized NPV is found to be most sensitive to the price of natural gas and the electricity price. At an 8% real discount rate, without renewable energy incentives, natural gas prices must be high (in excess of 10 USD/GJ) for a solar thermal design to be preferable, and electricity prices must reach ≈55 USD/MWh in order for solar-thermal-based designs to have a positive NPV. Incentives such as investment tax credits and solar power purchase agreements can make solar-thermal-based designs preferable to natural-gas-based designs under certain circumstances.

1. Introduction

CCS (carbon capture and storage) is expected to be a "critical component" in the portfolio of measures applied to address climate change [1]. To date, technical challenges and a lack of regulatory certainty have hindered CCS deployment. Recent studies, however, suggest that several CCS technologies may be commercialized in the next 10–20 years [2]. This work focuses on ABTSA (amine-based temperature-swing absorption) systems, which are the most mature CCS technology due to their history of use in natural gas sweetening [3].

ABTSA systems require large capital investment and a substantial amount of low-temperature steam for the desorption of CO_2 (approximately 3.6 MJ/tonne CO_2 [4]). This steam can be extracted from the power plant itself, or can be provided by an adjacent auxiliary system. Auxiliary systems have several advantages. First, reductions in the base-plant electricity output are avoided (these reductions range from 24 to 40% of plant capacity) [3,5]. In fact, depending on the design, auxiliary systems can increase overall electricity generation from the facility. Additionally, fewer alterations to the base-plant are required, which may make the retrofit process simpler. Finally, any fuel source can be used to generate the required steam, allowing for the integration of renewable energy sources.

This work explores the optimal design and time-varying operations of an auxiliary CCS facility. Two heat sources are explored – natural gas and solar thermal. The use of solar thermal systems mitigates concerns about increased energy consumption associated with CCS [6]. While net energy consumption clearly increases, fossil energy consumption remains unchanged. However, if the (optimal) economics of solar thermal auxiliary systems are less favorable than those of corresponding natural gas systems, they are less likely to be utilized. In order to identify the optimal system configuration under a range of possible economic scenarios, computational optimization is utilized to determine high-level system design and operations of the major retrofit components.

Optimizing facility operations has been shown to decrease the cost of CCS-enabled power generation. Chalmers et al. [7] demonstrated the technical feasibility of flexible operation in carbon capture systems, and Cohen et al. [8] found substantial benefits from optimizing the operations of a parasitic ABTSA system. By including both the design and operations in the optimization procedure, further economic benefits have been demonstrated. Mac Dowell and Shah [9] optimized the design and operation of a parasitic ABTSA system in order to minimize the total annualized cost, and found benefits from operating the capture system

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intermittently at higher capture rates. Khalilpour [10] utilized coupled design and operations optimization to maximize NPV (net present value) of solvent-based post combustion capture. Khalilpour additionally developed a multilevel decision-making methodology.

CCS facilities using auxiliary natural gas systems have also been studied. Bashadi and Herzog [11] explored three different natural gas system configurations and determined that in some situations, auxiliary systems could be preferable to parasitic systems. Optimization of these auxiliary natural-gas-based CO_2 capture systems has also been performed. Kang et al. [12] optimized the time-dependent system operations of an ABTSA system with a natural-gas-based auxiliary heat supply, and found an increase in operating profit of up to 20% compared to heuristic operations. This work was extended [13] to additionally include the optimization of facility design. Through application of bi-objective optimization, Kang et al. [13] determined the optimal trade-off between the capital investment requirement for a CCS retrofit and the NPV from the facility, given different natural gas and electricity price scenarios.

Solar thermal auxiliary CCS systems have also been studied. Cohen et al. [14] explored high-temperature, high-efficiency solar thermal auxiliary systems at various carbon tax rates, and concluded that without a high carbon tax, the direct use of a solar thermal system for power generation was more profitable. Li et al. [15] explored multiple locations and solar thermal design costs, and concluded that the cost of a non-concentrating vacuum tube would have to fall below 90 USD/m^2, and a concentrating parabolic trough system would have to fall below 150 USD/m^2, for the cost of electricity to be lower than it would be in a parasitic system. Mokhtar et al. [16] utilized an iterative search to explore solar thermal system designs with fixed operations, and concluded that solar collectors would have to decrease to 100 USD/m^2 under 2009 conditions for the system to have a positive NPV. To date, computational optimization has not been used to determine optimal design and operations of auxiliary solar thermal CCS systems.

While both solar thermal and natural gas auxiliary CCS systems have been considered independently, the two have not been compared within a consistent modeling framework, as is accomplished in this study. In addition, previous work [13] on the optimal design and operations of natural gas auxiliary systems utilized price—duration curves to account for variable operations, which did not enable certain time-dependent effects, such as the storage of CO_2-rich amine, to be incorporated into the modeling. Such effects are included in this work. Also, while the existing literature on solar thermal auxiliary systems has examined a variety of configurations and costs [14,15], the low efficiency/low cost systems considered here have yet to be explored. Our optimizations are performed with various fuel prices, electricity prices, discount rates, and solar incentives, with the goal of determining the optimal facility for a variety of plausible economic conditions.

This paper proceeds as follows. In Section 2, the overall problem setup is presented, and descriptions of the models and optimization parameters for each of the major facility subsystems are provided. The optimization methodology is discussed in Section 3. In Section 4, we present our procedure for clustering time-varying data to create a small number of representative days, which is necessary to render the optimization problem computationally tractable. Results for a wide range of scenarios are presented in Section 5. We conclude with a summary and suggestions for future work in Section 6. Additional details on the optimization of the heat recovery steam generator are provided in the online Supplementary Information.

2. System model

Our system is modeled as a set of interacting subsystems. Fig. 1 illustrates the mass flows between systems, and indicates the decision variables that determine the characteristics of each module. Two categories of decision variables enter the formulation: design variables ($\mathbf{x}$), which specify component sizes and configurations, and hourly operational variables ($\mathbf{u}$), which govern mass flow rates throughout the system over a set of representative days. The combination of these two types of decision variables allows for the calculation of the NPV of the entire facility, which is maximized by the optimization algorithm (described in Section 3). We first provide an overview of the general problem setup, and we then describe the natural gas, solar thermal, and CO_2 capture subsystems. Variables are defined when first used, and key variables are listed in the Nomenclature section.

In this work, we represent the auxiliary natural gas plant, auxiliary solar thermal system, and CPP (coal-fired power plant) as a series of modules that interact by exchanging energy and mass flows. The mathematical model entails a set of coupled algebraic equations describing mass and energy balances for each component. For the capture model, the quantities required are extracted from the IECM 8.0.2 modeling software [17,18], as described in Section 2.4. The models for the CPP, auxiliary natural gas plant (including heat recovery steam generator), and CO_2 capture subsystems are essentially identical to those used in Kang et al. [12,13]. Those references (including the online Supplementary Material [13]) should be consulted for full details. The solar thermal system assessed here has not, to our knowledge, been previously considered for use in a CCS retrofit.

2.1. General problem setup

We consider a 440 MW CPP that provides base-load power and is being retrofit for CCS. For simplicity, we assume that the CPP has a 100% capacity factor. The capital cost of the CPP is assumed to have been recovered, but capital investment in carbon capture systems and auxiliary heat units is included in the NPV calculation. The CPP, assumed to be located in Farmington, New Mexico, exports power to Southern California. Presently, two GW-scale power plants (the 2.04 GW Four Corners Power Plant, and the 1.9 GW San Juan Generating Station) exist at this location and have exported a sizeable fraction of their electricity to Southern California in recent history. Largely due to California law SB 1368[1], a greenhouse gas emissions regulation which limits the annual average emissions intensity to 499 kg CO_2/MWh, much of this power is no longer exported to California. In our model, we consider CPP retrofits using ABTSA, with the goal of reducing the emission intensity to meet this standard.

Two different options are considered for supplying auxiliary heat for CCS: using natural gas as fuel, and using a solar thermal array. As indicated in Fig. 1, the steam from either or both subsystems can be sent to the reboiler in the capture subsystem regeneration column, and upon return the condensate is split such that mass is conserved in each subsystem. If both auxiliary systems are active, the steam streams can be combined after each is expanded to the required (reboiler) pressure and temperature. Both auxiliary systems can produce electricity, but we assume that the electricity production is not large enough to influence the electricity price. Consistent with this assumption, we limit the total

[1] This type of regulation is not unique to California. Oregon, New York, and Washington all have similar standards in effect. Additionally, new federal regulations will place a similar limit on new CPPs.