International Journal of Greenhouse Gas Control 66 (2017) 25–34

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Trade-offs in cost and emission reductions between flexible and normal carbon capture and sequestration under carbon dioxide emission constraints

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ARTICLE INFO

Keywords:
Carbon capture and sequestration
Flexible carbon capture and sequestration
Carbon dioxide emission reductions
Reserve costs

ABSTRACT

Relative to “normal” amine-based post-combustion capture carbon and sequestration (CCS), flexible CCS adds a flue gas bypass and/or solvent storage system. Here, we focus on flexible CCS equipped with a solvent storage system. A primary advantage of flexible over normal CCS is increased reserve provision. However, no studies have quantified system-level cost savings from those reserves, which could drive the public benefits and rationale for policy support of flexible over normal CCS. Here, we quantify total power system costs, including generation, reserve, and capital costs, as well as carbon dioxide (CO_2) emissions of generator fleets with flexible versus normal CCS. We do so under a moderate and strong CO_2 emission limit. Relative to normal CCS, solvent storage-equipped flexible CCS reduces system-wide operational plus annualized CCS capital costs but increases system-wide CO_2 emissions under the moderate limit, whereas it reduces system-wide costs and emissions under the strong limit. Under both limits, we find that reductions in reserve costs constitute 40–80% of the reductions in total operational costs with flexible CCS rather than normal CCS. Thus, flexible versus normal CCS deployment decisions pose cost and emissions tradeoffs to policymakers under a moderate emission limit as well as tradeoffs between near- and long-term policy objectives.

1. Introduction

Climate change could significantly affect human and natural systems (IPCC, 2014). To avert those effects, carbon dioxide (CO_2) emissions from the electric power sector must decrease significantly (Fri et al., 2010). Many studies indicate that achieving such large reductions will require widespread deployment of carbon capture and sequestration (Loftus et al., 2015), yet high capital costs have largely hindered deployment of the technology (Rubin et al., 2015). In addition, operational costs in amine-based post-combustion carbon capture and sequestration (hereafter “CCS”) increase due to the large parasitic loads of the CO_2 capture process that reduce the net power capacity and efficiency of CCS-equipped generators, and thus increase fuel costs.

To address the cost barrier to CCS deployment, several papers have considered the merits of “flexible” CCS (Chalmers and Gibbins, 2007; Haines and Davison, 2009; Oates et al., 2014; Van der Wijk et al., 2014). Flexible CCS differs from “normal” CCS in that it includes two additional features that allow the power plant to temporarily eliminate most of the large parasitic loads of the CO_2 capture process: it can vent flue gas, which temporarily increases the generator’s CO_2 emissions rate; or it can use stored solvent from a reservoir, which does not change the generator’s CO_2 emissions rate (Cohen et al., 2012; Oates et al., 2014). By mostly eliminating the large parasitic loads of the CO_2 capture process, these two features allow a flexible CCS generator to temporarily increase its net capacity, net efficiency, and ramping capability relative to a normal CCS generator (Oates et al., 2014; Van der Wijk et al., 2014).

Past analyses of flexible CCS examined the private or system benefits of flexible CCS relative to normal CCS. To quantify private benefits, most papers used profit-maximizing optimization models with exogenous electricity prices to determine the profitability of generating electricity at flexible versus normal CCS generators across a range of CO_2 prices (Cohen et al., 2012; Oates et al., 2014; Patiño-Echeverri and Hoppock, 2012; Versteeg et al., 2013). These papers found that adding amine solvent storage and/or venting to a normal CCS generator tended to increase the profitability of a CCS plant at low carbon prices, but not at high carbon prices when construction of a CCS generator would be justified. Thus, these papers indicate that little private case exists for installing flexible rather than normal CCS based on profits from electricity generation.

Other research used cost-minimizing dispatch models to determine how flexible CCS generators would operate in the context of a competitive wholesale electricity market. In general, these papers found that flexible CCS provides some system-wide benefits relative to normal CCS

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http://dx.doi.org/10.1016/j.ijggc.2017.09.003
Received 27 September 2016; Received in revised form 20 March 2017; Accepted 4 September 2017
1750-5836/

primarily through increased provision of system reserves. Van der Wijk et al. (2014) found that solvent storage-equipped flexible CCS generators provided four to ten times more up reserves than normal CCS generators in the Dutch power system in 2020 and 2030 under high wind penetration. Cohen et al. (2013) similarly documented a 10% to 30% increase in reserve provision by flexible CCS generators relative to normal CCS generators in a 2020 high-wind system, although adding solvent storage to venting-enabled flexible CCS units yielded little additional benefit. Although these system-level analyses (Cohen et al., 2013; Van der Wijk et al., 2014) found the primary benefit of flexible CCS to be through increased reserve provision, they did not capture the potential cost reductions from increased flexible CCS reserves. Quantifying these cost reductions is crucial to determining the net system value of flexible CCS, which in turn has important implications for public policy as well as for the prospects of near-term CCS deployment given ongoing cost constraints on CCS deployment. Craig et al. (2017) aimed to fill this gap in the literature. Using a cost-minimizing dispatch model that included reserve costs, the authors compared the cost-effectiveness of flexible CCS to that of other CO_2 mitigation strategies in meeting a moderate or aggressive CO_2 emission reduction target. They found that flexible CCS retrofits could achieve more cost-effective emission reductions than normal CCS retrofits and re-dispatching from coal- to gas-fired generators in some cases, but achieve less cost-effective emission reductions than additional wind capacity in all cases. That work, however, did not include a detailed comparison of normal versus flexible CCS. Additionally, the authors did not consider the effect of solvent storage tank size, a key flexible CCS parameter, on the relative merits of flexible CCS. This paper aims to better understand the trade-offs between normal and flexible CCS.

In this paper, we quantify the difference in total system CO_2 emissions and costs of flexible versus normal CCS retrofits accounting for reserve procurement costs as well as electricity generation, start-up, and CCS retrofit capital costs. Using system costs and CO_2 emissions, we compare the net system value of flexible to normal CCS retrofits under two CO_2 emission constraints: a "moderate" emission limit that aims to reduce CO_2 emissions from the U.S. electric power sector by 32% from 2005 levels by 2030; and a "strong" emission limit that increases the reduction target to 50%. Given our focus on the system value of flexible CCS under CO_2 emission constraints, we focus on flexible CCS equipped with solvent storage in this paper, although our flexible CCS model also accommodates venting. We evaluate the sensitivity of our results to solvent storage tank size and natural gas price.

2. Methods

2.1. Overview of flexible CCS operations

Fig. 1 provides a high-level overview of the operations of a flexible CCS generator equipped with solvent storage. A solvent-storage-equipped flexible CCS generator has three operational modes as described in Table 1. During "normal CCS operations," a flexible CCS generator operates like a normal CCS generator. Specifically, it delivers electricity to the grid while simultaneously capturing CO_2 with "continuous lean solvent," which is continuously regenerated from rich solvent, i.e. solvent bound to CO_2. For a given fuel input quantity, continuously regenerating solvent imposes a significant net heat rate and net capacity penalty of roughly 30–45% and 25–30%, respectively, on the generator. A flexible CCS generator can also engage in "charging stored lean solvent" operations by delivering electricity to the grid while simultaneously capturing CO_2 and regenerating some controllable mix of continuous lean and "stored" lean solvent. Stored lean solvent is regenerated from stored rich solvent. Per assumptions detailed below, regenerating stored solvent imposes the same net heat rate penalty and a slightly higher net capacity penalty on the generator as regenerating continuous solvent. A flexible CCS generator can also engage in "discharging stored lean solvent" operations, during which the generator delivers electricity to the grid while capturing CO_2 with some controllable mix of continuous and stored lean solvent. The generator stores resulting rich solvent from the stored lean solvent stream for regeneration at some later time during "charging" operations. In deferring regeneration of the stored solvent, the generator reduces the CCS system's net heat rate and net capacity penalties by up to 90% depending on the amount of stored solvent discharged, thereby allowing the generator to operate more efficiently and at a higher net capacity for a brief period of time. This flexibility can lead to greater profitability, e.g. by increasing net electricity output during peak price periods, or to increase system efficiency, e.g. by reducing curtailment of renewables. The maximum duration of the "charge" and "discharge" operational modes depends on the solvent storage tank size.

2.2. Flexible CCS generator model

For our previous work (Craig et al., 2017), we developed a model of a flexible CCS generator equipped with solvent storage and/or venting. However, given our focus on solvent-storage-equipped flexible CCS, this section describes our model for a flexible CCS generator equipped only with solvent storage. The Supplemental information (SI) (Section SI.1) provides a description of the venting components of our model. In modeling a solvent-storage-equipped flexible CCS generator, we make four design assumptions. (1) Versteeg et al. (2013) found 1 h of storage capacity to be optimal for amine-based CCS, while other work has shown some flexibility benefits with similar tank sizes (Cohen et al., 2013; Van der Wijk et al., 2014). For this analysis, we thus assume that the solvent storage tanks can store sufficient lean solvent to enable maximum net electricity output while discharging stored lean solvent for either 1 or 2 h. (2) We assume that the regenerator solvent throughput capacity of a flexible CCS generator equals that of a regenerator at a normal CCS generator of equal net power output capacity during normal operations (Cohen et al., 2013; Oates et al., 2014; Van der Wijk et al., 2014; Versteeg et al., 2013). (3) We assume that discharging stored solvent can reduce the CCS system's parasitic load by up to 90%, which corresponds to eliminating the parasitic load of the solvent regenerator and CO_2 compressor (Echeverri and Hoppock, 2012). (4) We assume that the coal-fired generator's steam turbine and fuel input capacity are not modified when the generator is retrofit with CCS. Consequently, the steam turbine can provide the unit's maximum net power capacity achievable while discharging stored lean solvent or venting. The SI (Section SI.2) includes further justification for each design assumption.

Several operational features result from these assumptions. Per assumption (2), charging stored lean solvent necessarily reduces regeneration of continuous solvent. Consequently, in order to maintain a constant CO_2 capture rate (i.e., to capture 90% of CO_2 emissions) while charging, both fuel input and net electricity output to the grid must decrease. Additionally, per assumptions (3) and (4), discharging stored solvent enables greater net electricity output at greater efficiency than during normal CCS operations. Since discharging stored solvent increases net electricity generation by increasing the steam turbine load rather than fuel input, discharging stored solvent also allows for faster ramping than normal CCS operations.

In order to incorporate all of these operational features in a unit commitment and economic dispatch (UCED) model of a power system, we develop a model of flexible CCS operations that simulates the dynamic nature of the net heat rate, net capacity, and emissions and ramp rates of a flexible CCS generator. This model disaggregates a single flexible CCS generator into proxy units and links their operations with a series of constraints. Each proxy unit accounts for net electricity output, reserve provision, costs, and emissions of the flexible CCS generator in a particular operational mode, e.g. while discharging stored lean solvent. As such, we parametrize each proxy unit according to the operational mode it represents. Furthermore, proxy units substitute for one another such that net electricity output, reserve provision, and emissions for a