# Trade-offs in Cost and Emission Reductions between Flexible and Normal Carbon Capture and Sequestration under Carbon Dioxide Emission Constraints

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## 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.

**Keywords:** carbon capture and sequestration, flexible carbon capture and sequestration, carbon dioxide emission reductions, reserve costs

## 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 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

Figure 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.

Table 1: Terms used to describe normal and flexible CCS operations.

| Term | Description |
|---|---|
| Normal CCS operational mode | Net electricity output to the grid and $CO_2$ capture operations, including solvent regeneration, that occur at a normal or flexible CCS generator during steady-state operations. |
| Continuous solvent | Rich and lean solvent that is continuously regenerated at a normal or flexible CCS generator in order to capture $CO_2$ during normal operations. |
| Stored solvent | Rich or lean solvent stored in storage tanks at a flexible CCS generator. |
| Charging stored lean solvent operational mode | Passing stored $CO_2$-rich solvent through the regenerator at a flexible CCS generator, and storing the regenerated $CO_2$-lean solvent that can be used to absorb $CO_2$ at some later time. Depending on the regenerator size, stored solvent passed through the regenerator may displace continuously regenerated solvent. |
| Discharging stored lean solvent operational mode | Passing stored $CO_2$-lean solvent to the absorber in order to absorb $CO_2$ at a flexible CCS generator, then storing the resulting $CO_2$-rich solvent in order to defer regeneration to some later time. Stored lean solvent passed to the absorber displaces some or all continuously regenerated solvent during “partial” or “full” discharging, respectively. |

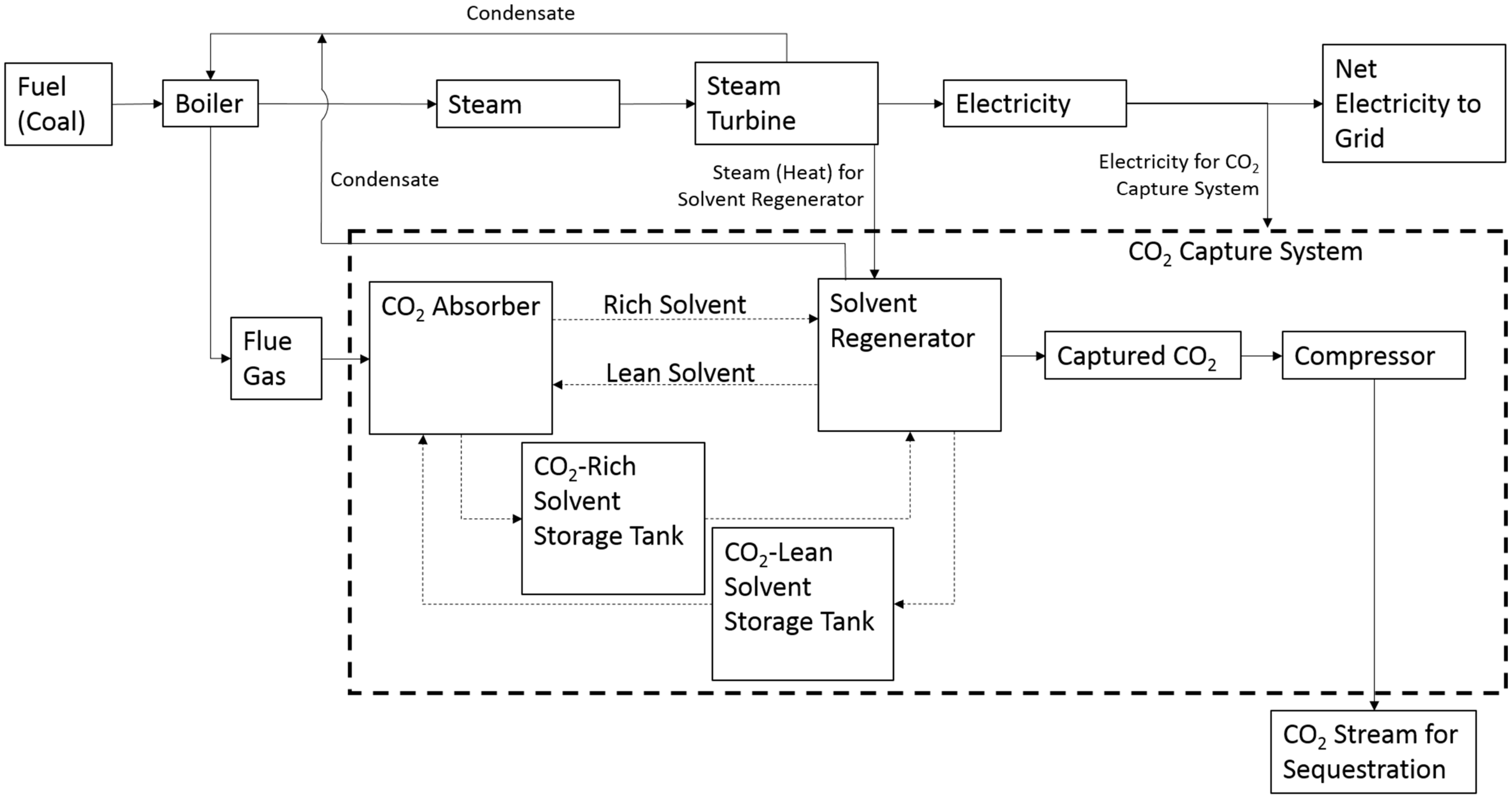

Figure 1: Schematic of a flexible CCS generator with solvent storage. The dashed box indicates the $CO_2$ capture system. Dashed lines indicate the operational choice of using stored solvent in place of continuously-regenerated solvent.

## 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 hour 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 hours. (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 (Patiño-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 assumption (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 given time period are divided among the proxy units based on the operational mode of the flexible CCS generator (Figure 2). For instance, when discharging stored solvent, the discharge stored solvent proxy unit accounts for some or all net electricity output, costs, and emissions from the flexible CCS generator in that period. Finally, UCED models typically use generator-specific net heat rates that are constant, i.e. they assume the ratio between fuel input and net electricity output does not change. However, this ratio varies significantly at a flexible CCS unit due to variability in $CO_2$ capture operations. Consequently, we use gross instead of net heat rates for most flexible CCS proxy units. This requires separately accounting for energy used to capture $CO_2$, which we do using specific proxy units.

We disaggregate a flexible CCS generator into five types of proxy units. Figure 2 indicates which proxy units are on or off given the operational mode of the flexible CCS generator at any time. Two types of proxy units account for net electricity output and reserve provision: the base and discharge stored lean solvent units. The base proxy unit represents normal CCS operations in conjunction with the continuous solvent proxy unit, which accounts for the parasitic load of the CCS system during normal operations. The discharge stored lean solvent unit accounts for increased net electricity output and efficiency relative to normal CCS operations when discharging stored lean solvent. Like the continuous solvent proxy unit, the charge stored lean solvent proxy unit accounts for energy consumed by the CCS system to regenerate solvent. Finally, the stored solvent tank proxy unit tracks the mass balance of stored rich and lean solvent over time. The continuous solvent, charge stored lean solvent, and stored solvent tank proxy units do not generate electricity or provide reserves.

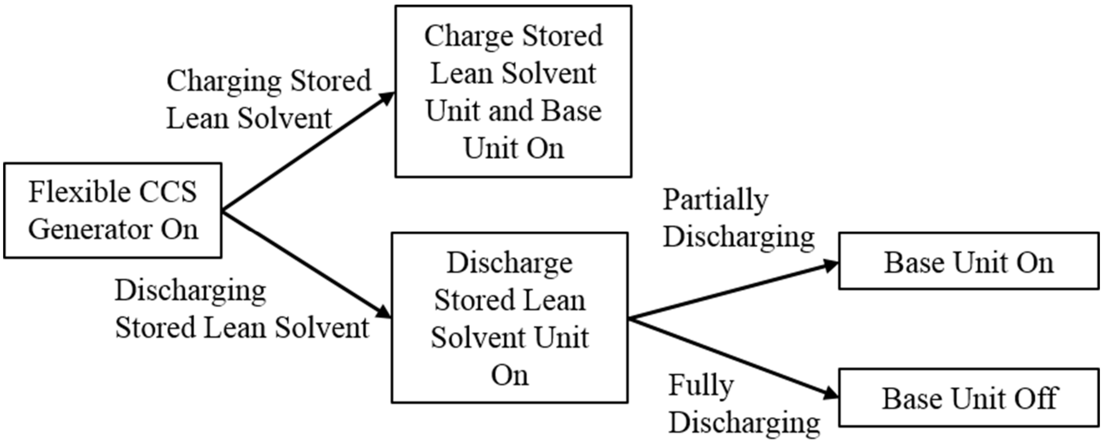

Figure 2: Tree showing which proxy units are on or off given the operations of a flexible CCS generator at any given time. When the base proxy unit is on, the continuous solvent proxy unit is also on.

Continuous and stored solvent flows are represented in units of energy. For instance, the amount of energy used to capture $CO_2$ and regenerate continuous lean solvent represent the continuous solvent flows in the model. Additionally, since proxy units in the model displace net electricity output from one another, the maximum capacity of the discharge proxy unit equals that of the flexible CCS generator while discharging stored lean solvent. To accomplish this, we determine the ratio of net electricity output while discharging stored lean solvent per unit of energy used to charge stored lean solvent using data from the Integrated Environmental Control Model (IECM) Version 8.0.2, a power plant modeling tool (Carnegie Mellon University, 2015), as detailed in the SI (Section SI.3). This ratio, which ranges from three to four depending on coal and plant type, roughly equals the ratio of net electricity output per unit of energy consumed by the CCS system's parasitic load during normal CCS operations plus the fraction of the CCS system's parasitic load transferred to net electricity output while discharging stored solvent (see assumption (3) above). The first component of the ratio allows the discharge proxy unit to displace net electricity output by the base proxy unit, and the second component of the ratio captures the incremental net electricity output of the flexible CCS generator while discharging stored solvent. Consequently, multiplying this ratio by the amount of stored lean solvent yields the net electricity output achievable by the discharge proxy unit when discharging that stored lean solvent.

To parameterize our proxy units, we obtain generator-specific estimates of seven flexible CCS operational parameters by deriving linear regressions with data from the IECM. We use the same approach to estimate two normal CCS operational parameters. Each parameter is regressed against heat rate for bituminous and sub-bituminous coal separately, which allows us to obtain fitted parameter values for each coal-fired generator retrofit with normal or flexible CCS based on the generator's heat rate and coal type. To generate each regression, we begin with a sub-, super-, or ultra super-critical plant type, then model three plant configurations: no CCS, normal CCS, and flexible CCS. Per assumption (4) above, we maintain a constant fuel input among all three plant configurations. The SI details all operational parameters and regressions estimated through this process (Section SI.3), and provides the full mathematical formulation of our flexible CCS model (Section SI.4).

## 2.3. Power System Modeling

To understand flexible CCS operations in the context of a competitive wholesale electricity market, we embed our flexible CCS model in a UCED model. The UCED model dispatches generators under "moderate" and "strong" $CO_2$ emission limits that would reduce $CO_2$ emissions by 32% and 50% from 2005 levels by 2030, respectively. The "moderate" emission limit mirrors the U.S. Clean Power Plan (U.S. Environmental Protection Agency, 2015b). Like Craig et al. (2017), we use the upper Midwest portion of the Midcontinent Independent System Operator (MISO) as our study system because of its large wind resources and expected coal-fired plant retirements in the near-term (U.S. Environmental Protection Agency, 2015a; U.S. National Renewable Energy Laboratory, 2015). Specifically, our study system includes North Dakota, South Dakota, Minnesota, Iowa, Wisconsin, Michigan, Missouri, Illinois, and Indiana.

Our UCED model minimizes total system electricity, reserve, start-up, and non-served energy costs subject to various system- and unit-level constraints. The UCED runs at hourly time intervals for a 24-hour optimization window, like the day-ahead MISO market (Kessler, 2014), plus a 24-hour look-ahead period. Including the 24-hour look-ahead period allows us to optimize dispatch decisions over a longer timeframe, which is particularly important for accurately modeling day-to-day storage of solvent. Hourly spinning reserve requirements equal 3% of maximum daily load plus 5% of hourly wind generation (Lew, 2010; Oates and Jaramillo, 2013). In order to fully capture the benefits of any increased reserve provision from flexible CCS generators, we include reserve costs in the objective function of our UCED using a reserve cost coefficient. Based on the ratio of energy to spinning reserve offer prices in MISO in 2015 (Midcontinent Independent System Operator, 2015a, 2015b), we set this reserve cost coefficient to 26% of each generator's operating cost. The UCED model is constructed in PLEXOS Version 7.2 (Energy Exemplar, 2015) and solved using CPLEX Version 12.6.1 (IBM, 2014). Additional information on the UCED, including its full formulation, is available in Craig et al. (2017).

Since the goal of this paper is to evaluate a future power plant fleet under carbon constraints, we insert normal or flexible CCS with a 90% $CO_2$ capture rate into a "base" 2030 generator fleet, and then run that fleet in our UCED model. Craig et al. (2017) detail how we construct the base generator fleet, and the SI (Section SI.5) details the composition and fuel prices of the base fleet. To test the sensitivity of our results under the moderate emission limit to natural gas price, we consider a higher natural gas price scenario by increasing the generator fleet's capacity-weighted natural gas price from \$5.4 per MMBtu to \$6.5 per MMBtu. Finally, to examine how CCS operations change with increasing capacity, we retrofit normal and flexible CCS on 2 and 4 GW of coal-fired generators, yielding 1.5 and 3 GW of de-rated CCS capacity. We retrofit CCS in order of decreasing efficiency on young (less than 40 years old), large (net capacities greater than 300 MW), and efficient (net thermal efficiency greater than 30%) coal-fired generators with $SO_2$ scrubbers and Selective Catalytic Reduction (SCR). Generators with these attributes typically provide the most economic CCS retrofit opportunities (Zhai et al., 2015).

For each generator fleet, we model compliance separately under a "moderate" and "strong" $CO_2$ emission reduction target. In each case, we assume that states in our study region will comply jointly under a single regional mass-based limit. To ensure each generator fleet complies with a given emissions reduction target, we use a simple economic dispatch model to determine a unique $CO_2$ price that applies to fossil steam, integrated gasification combined cycle, and natural gas combined cycle units greater than 25 MW in capacity (Craig et al., 2017). The resulting shadow $CO_2$ prices, which are available in the SI (Section SI.6), are included in the electricity generation and reserve provision costs of affected generators in the full UCED, and lead to re-dispatching from high- to low-$CO_2$-emitting generators. These shadow $CO_2$ prices serve as a mechanism to ensure compliance with the policies using a UCED model (Oates and Jaramillo, 2015). The shadow prices themselves are not the focus of this work and their meaning should not be overstated. Furthermore, shadow prices do not imply an actual financial transaction so we exclude shadow carbon costs from our cost calculations.

### 2.4. Capital Costs of Solvent Storage

To determine whether system-wide benefits of flexible versus normal CCS justify the additional capital costs of flexible CCS, we aggregate solvent storage capital cost estimates from a variety of sources (Oates et al., 2014; Patiño-Echeverri and Hoppock, 2012; Van der Wijk et al., 2014; Versteeg et al., 2013). We annualize capital costs using a capital recovery factor (CRF):

$$CRF = \frac{i * (1 + i)^n}{(1 + i)^n - 1}$$

assuming a discount rate ($i$) of 7% (The White House Office of Management and Budget, 1992) and that solvent storage lifetimes ($n$) are comparable to CCS retrofit lifetimes, or 30 years (Zhai et al., 2015). Ultimately, we estimate minimum, best guess, and maximum annualized solvent storage capital costs per hour of peak power output to equal $0.5, $1.5, and $4.5 per net kW per year.

## 3. RESULTS

We provide results for normal and solvent-storage-equipped flexible CCS generators while varying three key parameters: installed CCS capacity (1.5 and 3 GW), solvent storage tank size (1 and 2 hours), and $CO_2$ emission limit (moderate and strong). Table 2 summarizes our results, which are further discussed in the rest of the paper. In each subsection below, we first compare results with flexible versus normal CCS, then present the effect of shifting from the smaller to larger solvent storage tank. In order to demonstrate the capabilities of our flexible CCS model to capture venting operations, we assess operations of flexible CCS equipped with solvent storage and venting under both $CO_2$ emission limits in the SI (Section SI.7).

Table 2: Summary of major differences in CCS operations and system costs and emissions between normal and flexible CCS scenarios under the moderate and strong $CO_2$ emission limits. Note that each cell provides the difference in the relevant result with flexible CCS relative to normal CCS. To contextualize these results, shadow $CO_2$ prices range from \$4-7 per ton under the moderate $CO_2$ emission limit and \$33-36 per ton under the strong $CO_2$ emission limit with 1.5-3 GW of retrofit CCS, respectively.

| **Result with Flexible CCS Relative to Normal CCS** | **Moderate $CO_2$ Emission Limit** | **Strong $CO_2$ Emission Limit** | **Change from Moderate to Strong $CO_2$ Emission Limit** |
|---|---|---|---|
| Total net electricity output by CCS generators | Smaller by 1% to greater than 4%. | Smaller by 1%. | Normal and flexible CCS net electricity output increase by 30% to 40% due to stronger $CO_2$ emission constraint. |
| Net electricity output while discharging stored solvent | Accounts for roughly 2% to 5% of total net electricity output by flexible CCS generators. | Accounts for roughly 0.1% to 0.5% of total net electricity output by flexible CCS generators. | As net electricity output while discharging stored lean solvent increases, total net electricity output by flexible CCS generators decreases. At higher $CO_2$ emission reduction targets, the system cost necessary to replace reduced net electricity output at flexible CCS generators increases. |
| Total reserve provision by CCS generators | Greater by 10 to 40 times. | Greater by 500 to 700 times. | The amount of reserves provided by flexible CCS does not significantly change, but reserves provided by normal CCS decline. |
| System costs | Smaller by \$20-50 million due to roughly equal reductions in electricity and reserve costs. | Smaller by \$12-40 million due mostly to reduced reserve costs. | System costs decrease less under the moderate than strong limit due to lower electricity cost reductions under the latter that are only partially offset by greater reserve cost reductions. |
| System $CO_2$ emissions | Larger by 0.3-0.6 million tons due to greater reserve provision by flexible relative to normal CCS generators, which increases net electricity output by high-$CO_2$-emitting generators. | Smaller by 0.1-0.2 million tons due to greater reserve provision by flexible relative to normal CCS generators, which increases net electricity output by low-$CO_2$-emitting generators. | Under both $CO_2$ emission reduction targets, the change in emissions occurs as non-CCS generators shift from providing reserves to generating electricity. Under the moderate limit this shift occurs at high-$CO_2$-emitting generators, but under the strong limit it occurs at low-$CO_2$-emitting generators. |

## 3.1. Flexible CCS Operations

### 3.1.1. Flexible Versus Normal CCS

For flexible CCS generators equipped only with solvent storage under the moderate and strong emission limits, solvent storage is used almost exclusively for reserve provision across installed capacities of flexible CCS, as shown in Figure 3. Reserves enabled by solvent storage exceed reserves provided by normal CCS generators by roughly 10-40 times under the moderate emission limit and by 530-740 times under the strong emission limit across both solvent storage tank sizes. As a result, flexible CCS generators provide a significant share of system reserves under the moderate (14-37%) and strong (17-35%) emission limits, whereas normal CCS generators provide roughly 0.3-3.7% (moderate limit) and less than 0.1% (strong limit) of system reserves.

Figure 3 also shows that total net electricity output by flexible CCS generators is slightly less than the output by normal CCS generators in most scenarios under the moderate and strong emission limits. Specifically, total net electricity output by flexible relative to normal CCS generators differs by -1-4% under the moderate limit and by -1% under the strong limit. Net electricity output by flexible CCS generators exceeds the output by normal CCS generators only with 3 GW of CCS under the moderate limit, when normal CCS shifts towards providing reserves at the expense of net electricity output. Both normal and flexible CCS generators meet roughly 1.5-3% and 2-4% of system electricity demand under the moderate and strong emission limits, respectively, while accounting for 1-2% of the generator fleet by capacity. Due mainly to the stronger $CO_2$ emission constraint under the strong emission limit, total net electricity output by normal and flexible CCS generators increases from the moderate to strong limit by roughly 32-45%. Like total net electricity output by normal and flexible CCS generators, the capacity factor of each CCS-equipped generator increases from the moderate to strong limit, as described in Section SI.8.

Net electricity output while discharging stored lean solvent decreases from the moderate emission limit, when it accounts for roughly 2-5% of total CCS generation, to the strong emission limit, when it accounts for roughly 0.1-0.5% of total CCS generation. The physical intuition for this decrease is as follows. As discharging and subsequent charging decrease, total net electricity output by flexible CCS generators increases for two reasons. First, due to a limited regenerator size, a flexible CCS generator must reduce its net electricity output while charging.

Second, since discharging does not fully eliminate the CCS system's parasitic load, the round-trip efficiency of charging and discharging is less than one. As $CO_2$ emission reduction targets increase, electricity generation shifts from cheap, high-$CO_2$-emitting generators to more expensive, lower-$CO_2$-emitting generators, increasing the system cost to replace lower net electricity output from flexible CCS generators that charge and discharge stored solvent for electricity generation. Thus, in order to minimize system operational costs, flexible CCS generators maximize total net electricity output and therefore use stored solvent less for electricity generation at higher emission reduction targets.

Unlike net electricity output, provision of reserves does not significantly increase from the moderate to strong emission limit for normal or flexible CCS. In the case of normal CCS, providing reserves requires spare generation capacity, so provided reserves decrease as net electricity output increases from the moderate to strong limit. Flexible CCS, though, provides significant and similar amounts of reserves under the moderate and strong limits for two reasons. First, nearly all flexible CCS reserves are provided with spare generating capacity achievable by discharging stored lean solvent, which is incremental to flexible CCS's generating capacity during normal operations. Furthermore, stored-solvent-enabled reserves have a lower marginal cost than electricity generation during normal operations, since the former reflect a reduced heat rate while discharging stored lean solvent.

#### 3.1.2. Effect of Solvent Storage Tank Size

Under the moderate emission limit, net electricity output by flexible CCS generators while discharging stored lean solvent increases by 70-100% when the configuration moves from the smaller to larger solvent storage tank. However, since net electricity output while discharging stored solvent makes up less than 5% of total flexible CCS net electricity output for either storage tank size (Figure 3a), overall flexible CCS net electricity output differs by less than 2% between the smaller and larger tank size. Reserve provision by flexible CCS generators also differs little (<3%) between tank sizes. As shown in Figure 3b, under the strong emission limit, similar but smaller trends take place: electricity generation while discharging stored lean solvent increases by 10-25% from the smaller to larger solvent storage tank, but overall flexible CCS electricity generation and reserve provision differ by less than 1% between tank sizes. Thus, while solvent storage tank size strongly affects the use of stored solvent for electricity generation, it does not significantly affect overall flexible CCS operations.

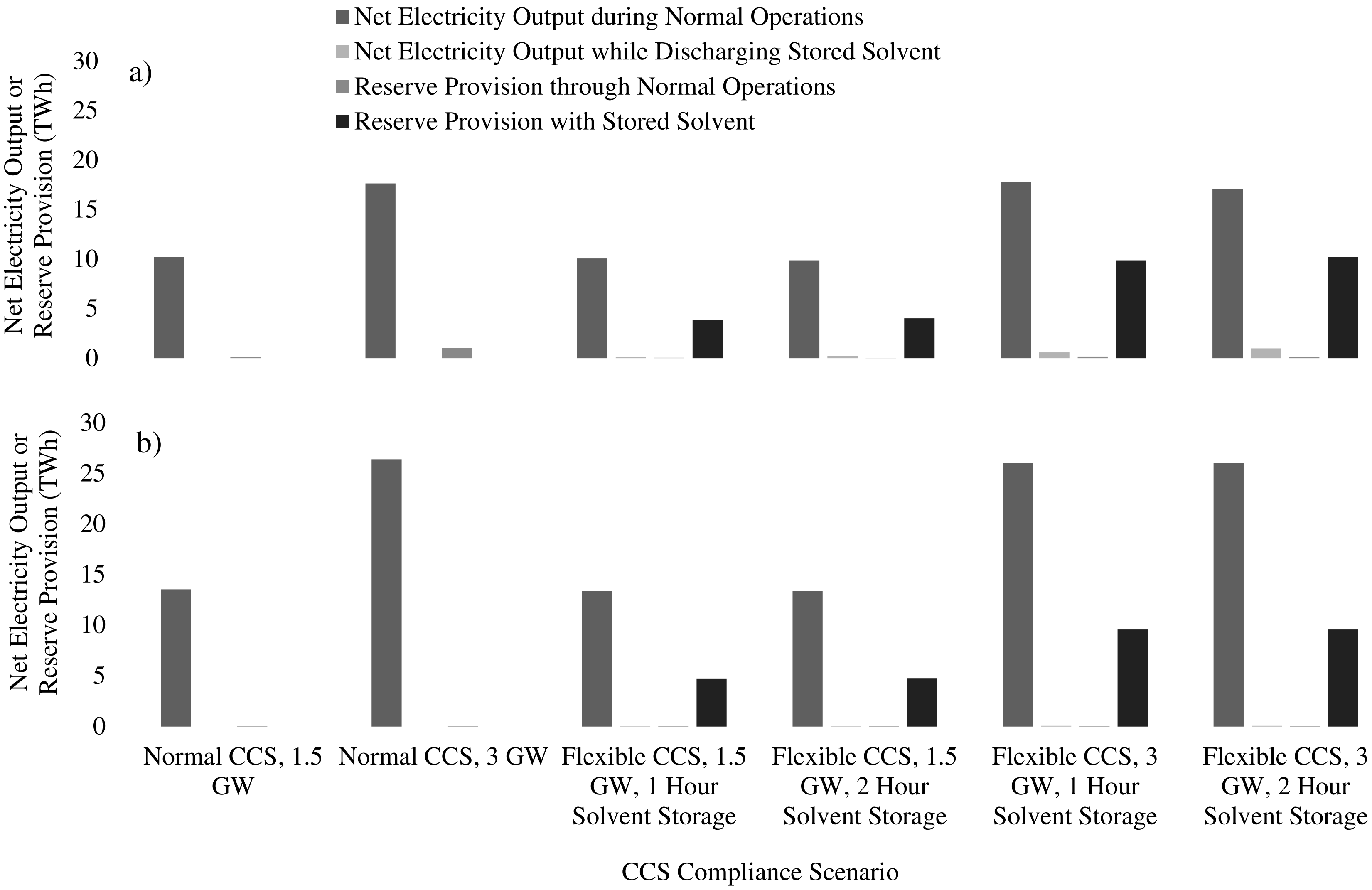

Figure 3: Annual net electricity output and reserve provision by operational mode for 1.5 and 3 GW of normal and flexible CCS generators under the (a) moderate and (b) strong emission limits. Flexible CCS generators have 1 or 2 hour solvent storage tank sizes.

### 3.1.3. Daily Profile of Stored Solvent Use

Figure 4 depicts the timing of charging and discharging stored solvent summed for all days in 2030 for all flexible CCS generators in the 1.5 GW scenario under the moderate emission limit. Charging tends to occur in the early morning, whereas discharging tends to occur at peak price and demand periods in the late afternoon. Thus, when stored solvent is discharged to enable greater net electricity output, it acts like an energy storage device by shifting energy from the early morning to late afternoon. Similar operational patterns occur under the strong limit.

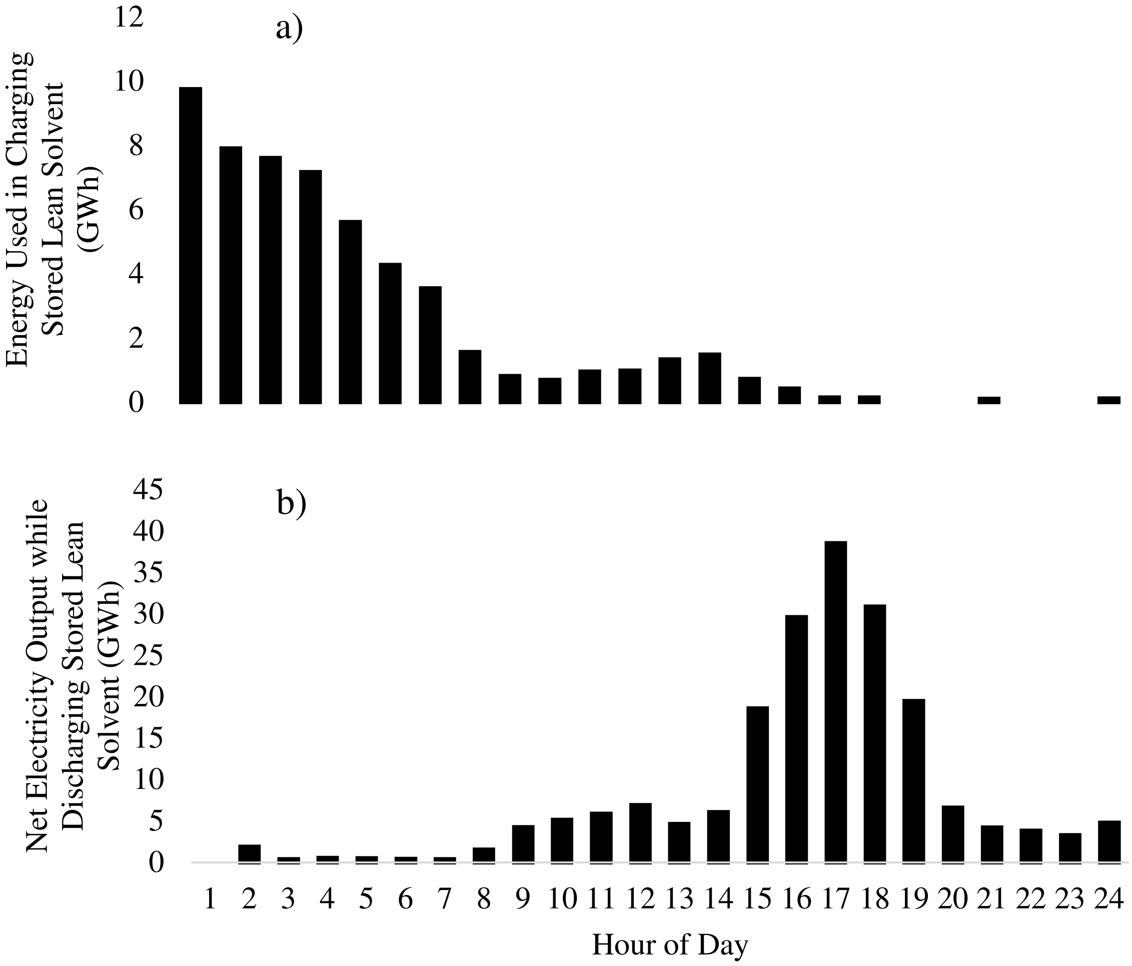

Figure 4: Sum of energy used to charge stored lean solvent (a) and net electricity output while discharging stored lean solvent (b) for each hour of the day in 2030 by all flexible CCS generators combined in the 1.5 GW scenario under the moderate emission limit.

## 3.2. System Costs and Emissions with Normal and Flexible CCS

With 1.5 and 3 GW of flexible CCS capacity equipped with a 1 hour solvent storage tank, annualized solvent storage capital costs range from \$1 to \$7 million and \$1.5 to \$13.5 million, respectively, with best guess estimates of \$2.3 and \$4.5 million, respectively. We assume that using a 2-hour solvent storage tank doubles those capital costs, but discuss how economies of scale could affect our results below.

### 3.2.1. Normal Versus Flexible CCS

#### 3.2.1.1. Moderate $CO_2$ Emission Limit

All CCS-equipped fleets comply with the moderate emission limit. However, system $CO_2$ emissions with flexible CCS exceed those with normal CCS by 0.31 to 0.56 million tons. From normal to flexible CCS, CCS-equipped generators emit more $CO_2$ due to changes in net electricity output among CCS-equipped generators (Section SI.8), but most (66-90%) of the increase in system $CO_2$ emissions occurs at non-CCS-equipped generators, which generate electricity with additional capacity that is freed-up by the availability of flexible CCS as a reserve asset. Because installed CCS capacity accounts for a small (2%) part of the total generating fleet capacity, these differences in system $CO_2$ emissions represent a small (<1%) fraction of total system $CO_2$ emissions. However, in the context of meeting $CO_2$ emission constraints, these differences in emissions matter, as they are similar to annual expected $CO_2$ emissions from a 75 MW natural gas combined cycle unit.

Total annual system costs, which equal operational plus annualized solvent storage capital costs, decrease from normal to flexible CCS retrofits by roughly \$20-47 million assuming best guess solvent storage capital costs, as shown in Figure 5a. Given the small installed CCS capacity relative to the total fleet installed capacity, total annual system cost reductions from normal to flexible CCS account for less than 1% of total annual system costs. Operational cost reductions from normal to flexible CCS exceed solvent storage capital costs, reducing total system costs. Specifically, operational costs, which include electricity generation, reserve, and start-up costs, decline by \$24-53 million from normal to flexible CCS. Electricity generation and reserve cost reductions contribute roughly equally to operational cost reductions. Greater reserve provision by flexible than normal CCS generators drive reserve cost reductions, whereas two factors drive electricity generation cost reductions: (1) greater net electricity output enabled by discharged stored lean solvent during peak demand hours, which displaces generation by high marginal cost units; and (2) greater reserve provision by flexible CCS generators, which frees capacity for electricity generation at non-CCS units that provided those reserves in the normal CCS scenarios. Note that we do not consider the shadow $CO_2$ prices to be a true economic cost, so we do not include emission costs in system operational costs presented here. As previously described in the Methods, these shadow $CO_2$ prices just serve as a mechanism to constrain the optimization model to meet the emission targets.

#### 3.2.1.2. Strong $CO_2$ Emission Limit

Unlike under the moderate limit, all CCS fleets (normal and flexible) slightly exceed the strong emission limit by 1-2%, indicating that more re-dispatch or greater installed capacity of CCS would be necessary to comply with the strong limit in our model. Furthermore, unlike the moderate limit results, annual system $CO_2$ emissions decrease from normal to flexible CCS by 0.09-0.18 million tons under the strong limit. Due to the low installed CCS capacity, this decrease accounts for less than 1% of system $CO_2$ emissions, but indicates a shift in the value of flexible versus normal CCS under stronger emission constraints. Some (8-50%) of those system $CO_2$ emission reductions occur at CCS-equipped generators as net electricity output shifts among CCS-equipped generators from normal to flexible CCS, as described in Section SI.8. However, most (50-92%) of those system $CO_2$ emission reductions come from non-flexible-CCS generators. Due to greater reserve provision by flexible than normal CCS generators, non-CCS generators shift from reserve provision to net electricity output. Greater net electricity output from some non-CCS generators, in turn, reduces electricity output at other non-CCS generators. Since a modest shadow $CO_2$ price is necessary to comply with the moderate limit, cheap high-$CO_2$-emitting sources that shift from reserve provision to net electricity output displace net electricity output from more costly lower-$CO_2$-emitting sources, increasing overall system $CO_2$ emissions under the moderate limit. Conversely, a high shadow $CO_2$ price is necessary to comply with the strong limit, increasing the cost of previously-cheap high-$CO_2$-emitting sources. Consequently, these now-expensive high-$CO_2$ emitting sources are displaced by now-cheaper low-$CO_2$-emitting sources that shift from reserve provision to net electricity output, reducing overall system $CO_2$ emissions under the strong limit.

Assuming best guess solvent storage capital costs, Figure 5b shows that total annual system costs decrease from normal to flexible CCS by $12-39 million under the strong limit, as under the moderate limit. Due to the small installed CCS capacity, this cost reduction represents less than 1% of total annual system costs. Electricity generation cost reductions from normal to flexible CCS are lower under the strong limit ($3-11 million) than under the moderate limit ($14-24 million) due to less net electricity output while discharging stored lean solvent under the strong limit. Conversely, reserve cost reductions from normal to flexible CCS are slightly greater under the strong limit ($13-32 million) than under the moderate limit ($11-27 million) because flexible CCS displaces reserves from more expensive units. Consequently, reserve cost reductions exceed electricity cost reductions by a factor of 3-5 under the strong limit.

### 3.2.2. Effect of Solvent Storage Tank Size

Shifting from the smaller to larger solvent storage tank has a secondary but non-negligible effect on system costs and $CO_2$ emissions relative to shifting from normal to flexible CCS. With respect to system $CO_2$ emissions, under the moderate limit, shifting from the smaller to larger solvent storage tank increases system $CO_2$ emissions by 0.12-0.25 million tons. Under the strong limit, shifting from the smaller to larger solvent storage tank reduces system $CO_2$ emissions by 0.02-0.04 million tons.

With respect to system costs under the moderate emission limit, operational costs decrease from the smaller to larger tank by $1-2 million. However, accounting for stored solvent capital costs and assuming capital costs double when shifting from the smaller to larger tank, total system costs increase from the smaller to larger tank by $1-3 million. In order for total system costs to decrease from the smaller to larger tank, then economies of scale would need to reduce capital costs per unit of storage from the smaller to larger tank. Specifically, capital costs per unit of storage would need to decrease by roughly 33% from the smaller to larger tank in order for total system costs to decrease from the smaller to larger tank. Under the strong emission limit, operational and total system costs both increase from the smaller to larger tank by $1 and $3-6 million, respectively. Because operational costs increase from the smaller to larger tank, economies of scale could not lead to total system cost reductions when shifting from the smaller to larger tank.

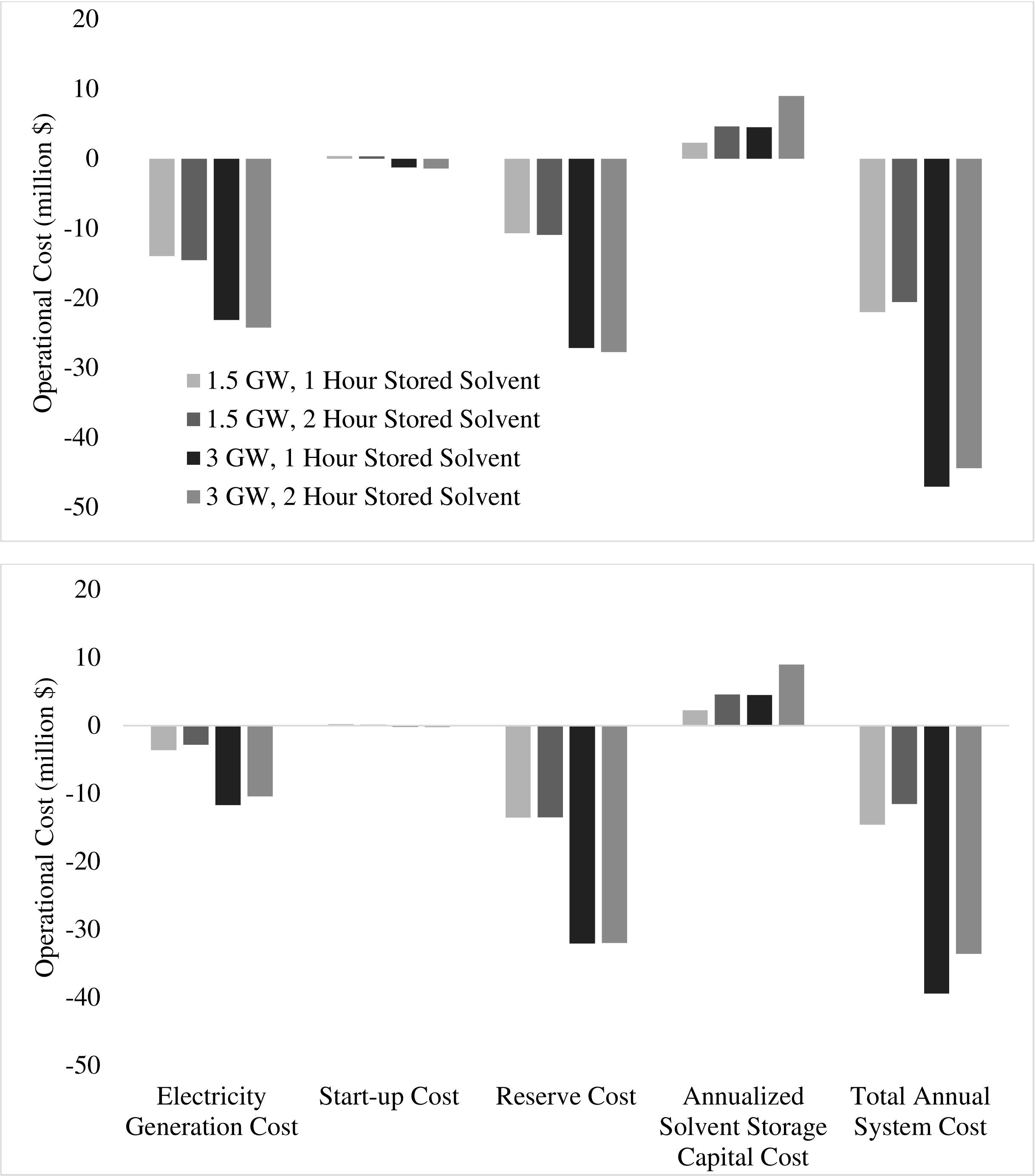

Figure 5: Change in electricity generation, start-up, and reserve costs, best guess annualized solvent storage capital costs, and the sum of all four (total annual system costs), with 1.5 or 3 GW of flexible CCS instead of normal CCS under the (a) moderate and (b) strong emission limits. Flexible CCS generators are equipped with a 1 or 2 hour solvent storage tank size.

## 3.3. Net System Value of Flexible Versus Normal CCS

### 3.3.1. Normal Versus Flexible CCS

Figure 6 plots the change in total annual system costs, accounting for a range of annualized solvent storage capital costs, against the change in annual system $CO_2$ emissions from normal to flexible CCS of equal installed capacities. Under the moderate $CO_2$ emission limit (Figure 6a), total system costs from normal to flexible CCS decrease by $7-51 million depending on stored solvent capital costs, but system $CO_2$ emissions increase by 0.31-0.56 million tons. Thus, normal versus flexible CCS poses a trade-off under moderate emission limits between cost and $CO_2$ emission reductions. Under the strong $CO_2$ emission limit (Figure 6b), total system costs largely decrease from normal to flexible CCS. At high stored solvent capital costs, total costs increase by up to $2 million from normal to flexible CCS with 1.5 GW CCS installed and with the larger solvent storage tank size. Otherwise, total system costs decrease by $7-43 million across stored solvent capital costs from normal to flexible CCS. Additionally, whereas emissions increase from normal to flexible CCS under the moderate limit, emissions decrease from normal to flexible CCS under the strong limit by 0.09-0.18 million tons. Thus, the value of flexible CCS relative to normal CCS changes with increasing emission reduction targets: whereas flexible CCS reduces system costs less under the strong limit than moderate limit, flexible CCS shifts from increasing to reducing system $CO_2$ emissions from the moderate to strong limit.

### 3.3.2. Effect of Solvent Storage Tank Size

As with shifting from normal to flexible CCS, the value of shifting from the smaller to larger solvent storage tank changes with $CO_2$ emission limit. From the smaller to larger tank under the moderate limit, annual system $CO_2$ emissions increase by 0.12-0.25 million tons and total annual system costs increase by up to $16 million at all but the lowest stored solvent capital costs, as shown in Figure 6a. Thus, under the moderate limit, the smaller tank size yields better system results than the larger tank size. Under the stronger limit, though, system costs increase by $1.3-19 million and system $CO_2$ emissions decrease by 0.02-0.04 million tons from the smaller to larger tank across stored solvent capital costs. Consequently, under the stronger limit, a tradeoff exists between system costs and $CO_2$ emissions between solvent storage tank sizes. Additionally, the value of the larger solvent storage tank shifts from increasing to decreasing system $CO_2$ emissions at stronger emission limits.

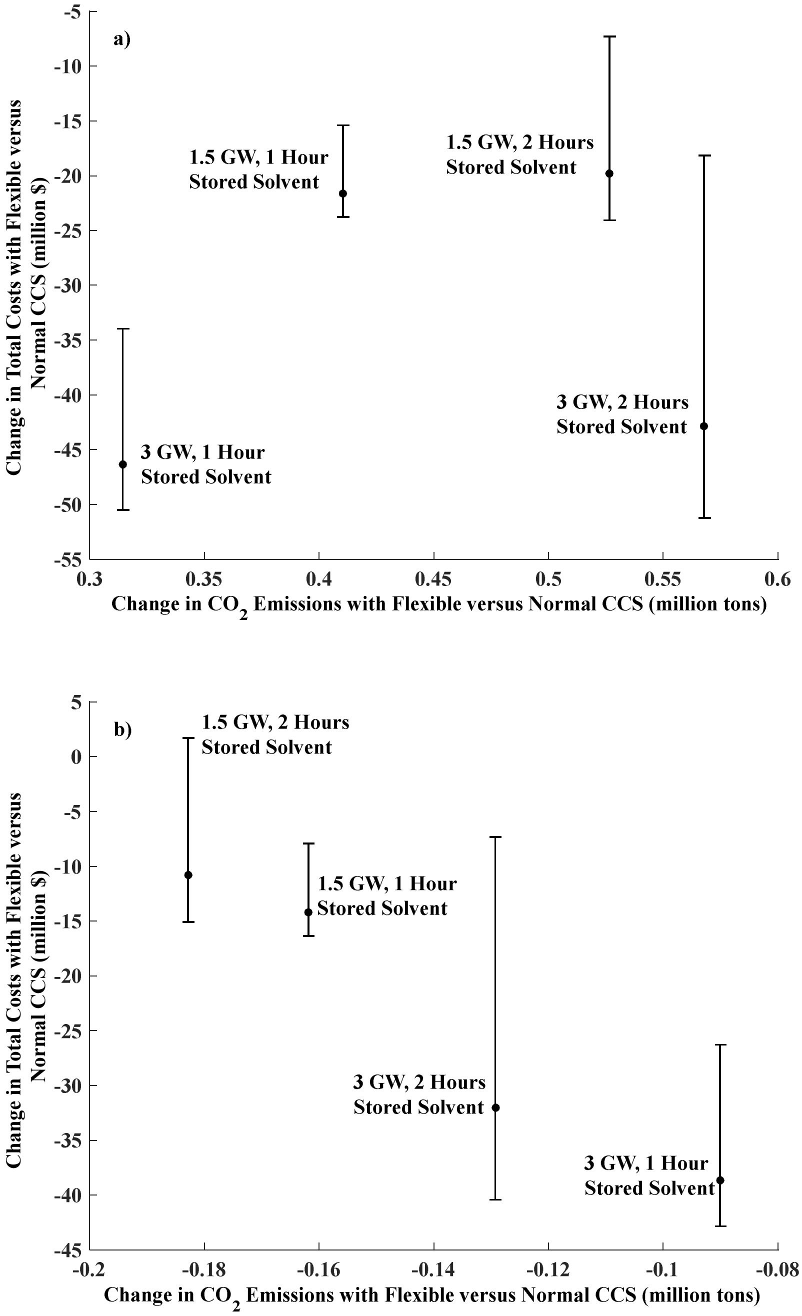

Figure 6: Annual change in total operational plus capital costs versus annual change in system $CO_2$ emissions with an equal installed capacity of flexible CCS relative to normal CCS for solvent storage tank sizes under the (a) moderate and (b) strong emission limits. Negative values indicate reductions with flexible CCS relative to normal CCS. Error bars indicate uncertainty in solvent storage capital costs. Flexible CCS generators are equipped with 1 or 2 hour solvent storage tank sizes.

### 3.4. Sensitivity to High Natural Gas Prices

By increasing the operational costs of natural gas-fired generators, higher natural gas prices generally improve the economics of normal and flexible CCS retrofits, particularly under $CO_2$ emission constraints. Of interest here, though, is how higher natural gas prices affect the trade-offs between normal and flexible CCS. Given that we find a clear trade-off between normal and flexible CCS under the moderate emission limit (Figure *6*), we test the sensitivity of our results to higher natural gas prices under the moderate emission limit by increasing the generator fleet's capacity-weighted natural gas price from \$5.4 per MMBtu to \$6.5 per MMBtu. Since we focus here on comparing normal to flexible CCS, we only consider flexible CCS equipped with a 2 hour solvent storage tank size.

The SI (Section SI.9) provides a full analysis of the high natural gas price results. The shadow $CO_2$ prices necessary to comply with the moderate emission limit increase with natural gas price. Results in the high natural gas price scenarios largely confirm our prior results. Flexible CCS primarily uses stored solvent for reserve provision, such that reserve provision by CCS generators increases by 9-80 times from normal to flexible CCS. Greater reserve provision reduces reserve costs (\$9-25 million) and largely reduces electricity generation costs (\$13-40 million) from normal to flexible CCS. Total annual system costs decrease from normal to flexible CCS by \$5-65 million across stored solvent capital costs.

At 3 GW CCS installed and high natural gas prices, system $CO_2$ emissions increase by 1 million tons from normal to flexible CCS, more than that observed under the lower natural gas price and moderate emission limit scenarios. As natural gas prices rise, coal-fired generators become more economic relative to gas-fired generators, so reserves provided by flexible CCS allow for greater coal-fired generation, increasing system $CO_2$ emissions. At 1.5 GW CCS and high natural gas prices, though, system $CO_2$ emissions do not change from normal to flexible CCS. In this scenario, greater CCS utilization from normal to flexible CCS offsets the effect of greater natural gas prices on $CO_2$ emissions. Overall, relative to lower natural gas prices, the shift from normal to flexible CCS produces similar results under high natural gas prices: total system costs decrease due to reductions in electricity generation and reserve costs, but system $CO_2$ emissions do not decrease, posing a trade-off between cost and $CO_2$ emission reductions. Thus, higher natural gas prices do not change the trade-offs posed between normal and flexible CCS retrofits under the moderate emission limit.

## 4. DISCUSSION

To better understand the system value of flexible versus normal CCS under $CO_2$ emission reduction targets, we quantified system operational costs and $CO_2$ emissions of a generator fleet with flexible or normal CCS retrofits under a moderate and strong $CO_2$ emission limit. For flexible CCS retrofits equipped only with solvent storage (excluding the option of $CO_2$ venting), stored solvent was used primarily to provide reserves under the moderate and strong limits, as found in past studies (Cohen et al., 2013; Van der Wijk et al., 2014), resulting in significantly greater reserve provision by flexible than normal CCS generators. Unlike past studies, we further quantified system reserve costs, and found that greater reserve provision by flexible than normal CCS generators reduced reserve costs by tens of millions of dollars per year. Under the moderate limit, these system reserve cost reductions were comparable to electricity generation cost reductions that occur when shifting from normal to flexible CCS. Thus, while stored solvent is used primarily to provide reserves, cost reductions from net electricity output while discharging stored lean solvent can be a key contributor to total system cost savings with flexible CCS relative to normal CCS, especially at high natural gas prices. However, under the strong limit, reserve cost reductions significantly exceeded electricity generation cost reductions when shifting from normal to flexible CCS due to decreased net electricity output with stored solvent.

Effects of solvent storage tank size on system emissions and costs, while secondary to those of using flexible versus normal CCS, differed depending on the emissions reduction target. When moving from the smaller to larger tank, system costs and emissions increased under the moderate limit, mirroring studies that have found electric vehicles with larger batteries result in higher costs and emissions (Michalek et al., 2011; Onat et al., 2015). Under the strong limit, though, costs increased and emissions decreased when shifting from the smaller to larger tank. Thus, a trade-off exists in choosing solvent storage tank size to meet near- versus long-term deployment targets. Given that past studies have found a stronger private case for deployment of smaller solvent storage tanks (Oates et al., 2014; Versteeg et al., 2013), public policies may be necessary to encourage larger tank size installation in order to accrue greater long-term public benefits.

While we modeled reserve procurement here, we did not model the dispatch of those reserves. Dispatch of reserves offered by a flexible CCS generator would require discharging stored lean solvent, which would later need to be regenerated to return to the initial level of stored lean solvent. Regenerating discharged stored lean solvent would incur costs and therefore reduce the overall benefit of flexible CCS relative to normal CCS. Future research should simulate to what extent reserve dispatch would decrease the relative benefits of flexible CCS compared to normal CCS. Doing so would require an electricity and reserve dispatch model that simulates frequency and contingency events. Our model also does not include frequency regulation and other rapid response reserves, which can have high and volatile prices. Modeling these reserves would likely improve the system value of flexible CCS relative to normal CCS and should also be a target of future research.

In optimizing our UCED over a 48-hour window, we assume a perfect net-load forecast. In reality, though, most power system operators, including MISO, only clear markets 24 hours in advance. Optimizing flexible CCS operations over shorter time horizons would likely decrease the system value of flexible CCS. Our research also assumed sufficient space is available for CCS retrofits plus the deployment of solvent storage facilities at existing coal-fired generators, such that CCS retrofits can occur at the most economic generators. Future research should examine to what extent flexible CCS retrofits are precluded by space limitations, and how the relative merits of flexible to normal CCS may change for retrofits on less economic generators. Finally, the relative value of flexible CCS compared to normal CCS may vary across power systems, e.g. with differing renewables penetration and fast-ramping resources. High wind penetration, for instance, would likely increase the value of reserves provided by flexible CCS. Our model could be used to examine how high renewable penetration and other factors may affect the relative merits of shifting from normal to flexible CCS.

## 5. CONCLUSION

We found that retrofitting flexible instead of normal CCS reduced total system-wide costs but slightly increased system-wide $CO_2$ emissions under a moderate $CO_2$ emission limit in MISO, posing a tradeoff to policymakers. Under a strong $CO_2$ emission limit, flexible CCS reduced total system-wide costs in nearly all scenarios and decreased system-wide $CO_2$ emissions in all scenarios. Consequently, while policies designed to meet near-term emission reduction targets may incentivize normal over flexible CCS deployment, such policies could lock in sub-optimal investments for meeting long-term policy objectives. Policymakers should therefore carefully weigh near- and long-term policy objectives when designing policies that specifically incentivize CCS.

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