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Optimal operation of flexible post-combustion CO₂ capture in response to volatile electricity prices

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Abstract

Flexibly operating post-combustion carbon dioxide (CO₂) capture in response to electricity prices should improve overall CO₂ capture economics. Optimization and rule-based models are used to simulate a 500 megawatt coal-fired facility that adjusts the operating point of its amine CO₂ scrubbing system to maximize profits in response to volatile electricity prices. Between CO₂ prices of 20 and 70 U.S. dollars per metric ton (USD/tCO₂), a flexible capture system that vents CO₂ while increasing power output can maintain significant CO₂ emissions reductions while improving annual operating profits by up to 10% over inflexible capture. The benefits of venting diminish at high CO₂ prices, but a solvent storage system that permits high CO₂ absorption during partial-load stripping and compression achieves a 9–29% profit advantage at 30–100 USD/tCO₂. Profit improvements with flexibility appear insensitive to CO₂ capture ramping limitations. This case study also suggests that solvent storage should only be large enough to take advantage of high electricity prices for 15–30 minutes each day.

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1. Introduction to flexible CO₂ capture

Most analyses of carbon dioxide capture and sequestration (CCS) assume the carbon dioxide (CO₂) capture system always operates at the full gas load of the power plant, but flexible operation could improve CO₂ capture economics [1, 2]. Post-combustion amine scrubbing with 90% CO₂ removal is well-suited for flexible operation due to its relative independence from the power system [3, 4]. In a coal-based retrofit, stripping CO₂ requires that 30–50% of the steam be extracted between the intermediate and low pressure (IP and LP) turbines [5, 6]. CO₂ stripping and compression result in 20–30% net electrical output reduction [7].

A flexible system, however, allows the CO₂ stripping steam to be sent to an LP turbine to produce electricity. The resulting drop in CO₂ flow exiting the stripper then reduces CO₂ compression energy requirements. A prior case study of the Electric Reliability Council of Texas (ERCOT) electric grid found that reducing CO₂ capture load at peak electricity demand can eliminate the need to replace the generation capacity lost to CO₂ capture energy requirements with minimal increase in CO₂ emissions [8]. Partial- or zero-load CO₂ capture during high electricity

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prices could also improve operating profits, though CO₂ emissions might increase [9]. Systems that respond very quickly could also allow the facility to earn payments for providing grid reliability services [3].

There are two general concepts for flexible CO₂ capture. The configuration shown in Figure 1A simultaneously and equally reduces steam and rich solvent flow to the stripper during partial- or zero-load operation [9]. Power output increases, but redirecting rich solvent to the absorber reduces the CO₂ removal rate. CO₂ emissions might increase, but incremental capital cost is negligible if the base plant is already sized to accept the additional steam, as with a retrofit. An alternative configuration (Figure 1B) enables continued high CO₂ removal when stripping and compression load is reduced by feeding the absorber from a lean solvent storage tank and depositing rich solvent into another tank. At times such as low electricity price periods, CO₂ stored in rich solvent can be stripped and compressed in larger stripping and compression equipment sized to treat both the current stream and stored solvent. CO₂ emissions remain low, but the capital costs of solvent inventory, storage tanks, and larger stripping and compression equipment are significant.

(A)

(B)

Figure 1: Flexible CO₂ capture might entail venting additional CO₂ emissions during reduced capture load (A), or solvent storage could allow continued high CO₂ removal with stripping and compression systems at partial- or zero-load (B).

Previous work studied the value of the venting-only configuration in Figure 1A using a first-order electricity dispatch model that sets electricity prices equal to the marginal cost of the most expensive plant dispatched at a given time [9, 10]. Actual electricity prices do not necessarily correspond to the marginal costs of a given facility, so the current work uses historical electricity price data to study the implications of flexible CO₂ capture in response to volatile electricity prices. An optimization model constructed within the General Algebraic Modeling System (GAMS) compares profit-maximizing operation of a single coal-fired facility with no CO₂ capture, inflexible CO₂ capture, and flexible CO₂ capture with and without a solvent storage system. A best-case scenario assuming perfect knowledge of all future electricity prices is compared to operation in response to day-ahead price forecasts, and a rule-based MATLAB model is also created to analyze operation without any price foreknowledge.

2. Methodology

This study analyzes a 500 megawatt (MW) coal-fired unit operating in response to 2008 ERCOT electricity prices posted each 15-minutes, so all monetary values are 2008 USD [11]. Large coal-fired facilities can influence electricity price, but this analysis assumes the plant is a price-taker. ERCOT electricity prices are most strongly influenced by natural gas-fired facilities, so the effect of CO₂ price on electricity prices is approximated by adding the emissions costs of an average ERCOT gas-fired facility [12, 13].

In this work, “base plant load” refers to the fraction of maximum gross power plant output, independent of CO₂ capture energy. “Absorber load” is the ratio of the current quantity of CO₂ removed to the total quantity removed with the base plant at full load. “Stripper load,” which implies CO₂ compressor load, is the ratio of the current stripping steam flow to the steam required to treat all rich solvent stream with the absorber and base plant at full-load. Thus, absorber load cannot exceed base plant load; 50% absorber and base plant load means the absorber treats all flue gas being produced. Additional CO₂ is vented only when the base plant load exceeds absorber load.

In this analysis, an inflexible CO₂ capture system must treat all flue gas exiting the boiler, so absorber, stripper, and base plant load must always be equal, though all systems may reduce load simultaneously. Inflexible scenarios imply regulatory, not process, rigidity. With venting-only flexible CO₂ capture, absorber and stripper load must be
equal but can be simultaneously reduced below the base plant load. If solvent storage is available, absorber load may exceed stripper load while excess rich solvent is sent to storage, and stripper load may exceed absorber load when stripping and compressing CO$_2$ from the stored rich solvent. Stripper load can then surpass 100% with enough stripping/compression capacity and available LP steam. This study assumes a CO$_2$ capture retrofit where 100% stripper load requires 40% of the LP steam from a turbine that has a 10% minimum load [5, 14]. Without equipment size limitations, stripper load could achieve 225%. However, stripping and compression systems are sized based on the time required to completely fill an empty rich solvent tank at 0% stripper load and 100% absorber load, assuming daily cycling of the storage system. For example, if the maximum number of hours in “full storage mode” is four, stripping and compression systems are sized for the average load in the remaining 20 hours, 120%.

2.1. Profit maximization model for perfect price foreknowledge and day-ahead forecasting

A mixed-integer linear programming (MILP) model is created in the GAMS platform to find the base plant, absorber, and stripper loads that maximize profit given one year of electricity prices. The model also includes binary variables that designate when base plant startups occur and whether the base plant is on or off in each interval. There are constraints on minimum load, maximum load, and load per time ramp limit for the base plant, absorber, and stripper. With solvent storage, a CO$_2$ flow balance governs the net quantity of CO$_2$ stored in rich solvent each interval, and the maximum quantity of stored CO$_2$ is limited by solvent capacity (difference between rich and lean loading), solvent physical properties, and storage facility size. Without CO$_2$ capture, the profit objective function includes startup costs and variable costs of fuel, CO$_2$ emissions, and other base plant variable operation and maintenance (VOM) costs. With CO$_2$ capture, there are additional costs for solvent makeup, caustic for solvent reclaiming, waste disposal of solvent degradation products, CO$_2$ transport and storage, and additional water use for the CO$_2$ capture system. This analysis assumes no operating cost penalty for flexibly operating CO$_2$ capture.

Perfect price foreknowledge is simulated by using CO$_2$ price-adjusted historical electricity prices directly. Day-ahead price forecasting is modeled by optimizing operation for pseudo-forecasted prices but calculating profits using historical prices. Pseudo-forecasted prices are generated by removing outliers from historical data and smoothing the result until prices achieve a forecast mean square error (FMSE) of 13.0 USD per megawatt-hour (MWh) and mean absolute percent error (MAPE) of 9.0%, values which are reasonably close to the 5–7 USD/MWh FMSE and 10–12% MAPE achieved with accurate day-ahead price forecasting models [15, 16]. With solvent storage, the model also requires the quantity of CO$_2$ stored in rich solvent to return to a specified value at the end of each day.

2.2. Rule-based model for no price foreknowledge

Some price prediction is necessary with solvent storage to plan when to store and regenerate rich solvent, but a venting-only flexible CO$_2$ capture system could simply operate in response to the most recent price signal. Venting-only flexible capture without price foreknowledge is analyzed using a rule-based MATLAB model that includes constraints on the CO$_2$ capture system ramp rate and the maximum load of the base plant and CO$_2$ capture system. This model does not include base plant ramp limits, base plant minimum load, or startup costs, so the GAMS model must be run with limited constraints to enable direct comparison. Assuming CO$_2$ prices are high enough for short-run marginal costs of electricity production (SRMC) to be lowest with full-load CO$_2$ capture, the model chooses to turn the base plant off if the electricity price falls below the SRMC at full-load CO$_2$ capture. If the electricity price is high enough for additional electricity sales at partial-load CO$_2$ capture to offset increased CO$_2$ emissions costs, capture load will decrease. Between these two price thresholds, the facility will move towards full-load base plant and CO$_2$ capture operation.

2.3. Default input parameters

Default input parameters are tabulated for the base power plant (Table 1), electricity market (Table 2), and CO$_2$ capture system (Table 3). Base plant heat rate in million British thermal units per MWh (MMBTU/MWh) and CO$_2$ emissions rate in metric tons (t) of CO$_2$ per MWh (tCO$_2$/MWh) are averages across all ERCOT coal-fired plants and are assumed constant across base plant and capture load [13]. Base plant minimum output, ramp limit, and startup cost are estimated from literature [17-19]. Ramp limits are assumed the same in either direction for each component, and absorber and stripper ramp limits are assumed equal. The study uses the average coal price for electricity
generators in 2008 and a default CO₂ price sufficiently high for lower SRMC at full-load CO₂ capture [20]. Coal and CO₂ prices are kept constant throughout the year. The CO₂ capture system uses a 30 wt % monoethanolamine (MEA) solvent with steam requirements, energy performance, CO₂ removal, and capacity are taken from literature [5, 9, 21]. CO₂ capture energy performance is assumed constant across absorber and stripper load [9]. The default solvent storage capacity has been suggested as a reasonable storage size, and the day-end stored CO₂ level is the average day-end CO₂ level under optimal plant operation with perfect price foreknowledge [4].

3. Results & discussion

3.1. Operating modes with flexible CO₂ capture

Figure 2 illustrates different operating modes by plotting optimal CO₂ capture load and net power output fraction (net output divided by maximum output) across two sample days, January 6 and June 12, 2008. With venting-only flexible CO₂ capture (Panel A), the base plant ramps down when electricity prices fall below 52 USD/MWh, its SRMC at full-load CO₂ capture. On Jan. 6, low prices persist long enough to justify a full shutdown and incur startup costs at 7:00. Between 12:45 and 19:30 on June 12, capture load falls to zero when electricity prices exceed the 136 USD/MWh required for revenue from selling an extra 125 MW to offset costs of venting additional CO₂. At 52–136 USD/MWh, the base plant and CO₂ capture systems tend to operate at full-load with a 375 MW net output.

Figure 2B demonstrates operation with a solvent storage system. When prices are relatively low, absorber load is 100% while stripper load is 120% in order to strip and compress CO₂ from stored rich solvent. Absorber load exceeds stripper load when electricity prices are relatively high and increased power output is desirable. The base plant still ramps down below prices of 52 USD/MWh, but increased stripping capacity reduces net minimum power output and allows the plant to avoid startup costs and remain online before 7:00 on Jan. 6. During the first portion of the June 12 high price times 12:45–19:30, both absorber and stripper load fall to 0%, meaning CO₂ is being vented despite the existence of a solvent storage system. Though full storage mode is utilized during many of the highest price times, CO₂ venting might sometimes be economically justified in order to withhold storage capacity for later or return to a specified CO₂ level at a particular time.

3.2. Comparison of annual performance with default input parameters

Table 4 contains aggregate annual results for several scenarios. Columns (1)–(3) compare all three price foreknowledge cases for the venting-only flexible CO₂ capture configuration when base plant minimum load, ramp limits, and startup costs are ignored to maintain consistency with the MATLAB model. Though annual output is nearly the same, profits are over 4% greater with perfect or no knowledge than when using day-ahead forecasting. Reactive operation is nearly as profitable as having perfect price foreknowledge because CO₂ capture can ramp quickly in response to irregular high price spikes ignored during day-ahead forecasting.
Columns (4)–(7) compare CO₂ capture configurations under the most realistic conditions: day-ahead price forecasting and all base plant constraints. At 50 USD/tCO₂, annual operating profits are quite low without CO₂ capture; adding inflexible capture improves profits by nearly 16%. Relative to inflexible capture, venting-only flexible capture improves profits by 6%, and 66,400 m³ solvent storage capacity improves profits by nearly 13%. CO₂ emissions are greater with flexible capture than with an inflexible system, but emissions still fall by over 72% from the no-capture case, with solvent storage achieving a 79% reduction. Because the base plant is utilized nearly 30% more often with CO₂ capture, more CO₂ is captured in all capture scenarios than is emitted in the no-capture case. With perfect price foreknowledge, operating profits at the facilities in columns (4)–(7) improve by 1–4%, indicating that improved price forecasts would enhance profits, but only slightly.

![Figure 2](image_url)

Figure 2: The operation of a facility with flexible CO₂ capture depends on electricity price levels and trends as well as whether a solvent storage system is available (B) or not (A). Default input parameters (Tables 1-3) are assumed.

<table>
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<th>(1)</th>
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<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
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<td>Venting only</td>
<td>Venting only</td>
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<td>Inflexible</td>
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<tr>
<td>Base plant capacity factor</td>
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<td>Avg. CO₂ emissions rate</td>
<td>tCO₂/MWh</td>
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| 3.3. Sensitivity to CO₂ price |

CO₂ price was varied from 0 to 100 USD/tCO₂ for the most realistic case that uses all base plant constraints and day-ahead price forecasting. Figure 3 shows annual CO₂ emissions at each CO₂ price for each CO₂ capture configuration to demonstrate CO₂ capture utilization and the resulting environmental impact. Corroborating previous work, prices below 20 USD/tCO₂ do not justify CO₂ capture operation, so CO₂ emissions with flexible capture equal those without CO₂ capture [9]. Solvent storage systems sit mostly idle at these low CO₂ prices. From 20 to 70 USD/tCO₂, venting CO₂ with flexible capture becomes less common until CO₂ capture is utilized nearly 100% of the time at 70 USD/tCO₂ and above. Any emissions above the inflexible case reflect CO₂ venting, so solvent storage reduces, but does not eliminate, CO₂ venting at intermediate CO₂ prices. Emissions trends with inflexible and no CO₂ capture correspond to changes in the base plant capacity factor.
Figure 4 shows annual operating profits with each capture configuration at each CO₂ price. Because electricity prices increase with CO₂ price by the emissions cost of an average ERCOT gas-fired facility, changes in operating profits with CO₂ price reflect the CO₂ emissions rate of the plant relative to 0.43 tCO₂/MWh. As CO₂ price increases, profits fall monotonically without CO₂ capture and rise monotonically with inflexible CO₂ capture. Profits with venting-only flexible capture are greater than those with inflexible and no-capture by as much as 10% during the 20 to 70 USD/tCO₂ transition period, but a facility with solvent storage maintains an economic advantage at any CO₂ price above the minimum required for CO₂ capture operation. The profit improvement with solvent storage over inflexible CO₂ capture decreases slightly with CO₂ price, but remains over 9% at 100 USD/tCO₂.

3.4. The importance of CO₂ capture ramping ability

Flexible CO₂ capture scenarios were studied for ramp rates of 0.25–8%/min., with 8%/min. being fast enough for the stripper to ramp from 0 to 120% load in one pricing interval (Figure 5). Any improvement over the profits earned with inflexible capture is nearly constant above 1%/min., and more than half the benefit is realized with 0.25%/min. Recalling the base plant ramp limit of 4%/min., these data suggest that flexible CO₂ capture can improve profits even with a very low ramp limit below that of the base plant. However, the importance of capture ramp limit might change with electricity market conditions, and ramp limits will likely be important for providing grid reliability services.

3.5. Cost/benefit analysis of solvent storage

A retrofitted venting-only flexible CO₂ capture system entails negligible incremental capital cost, but the operating profit advantage with solvent storage must be weighed against the capital cost of the solvent storage system. This tradeoff is investigated by using the annual profit improvement over inflexible capture in a cash flow analysis to determine the net present value (NPV) over a 20-year book life for solvent storage systems sized for 0.5–6 hours in full storage mode. Day-ahead price forecasting is assumed. Capital costs are depreciated on a 20-year modified accelerated cost recovery system (MACRS) half-year convention schedule, profits are taxed at 38%, and future cash flows are discounted by a 10.3% inflation-adjusted discount rate [22].

The capital cost for solvent storage is divided into the cost of additional solvent inventory, storage tanks, and larger stripping and compression equipment. Solvent inventory cost is calculated using the parameters in Table 3 and MEA at 2.52 USD/kg [5]. Storage tank capital costs are determined from a cost curve for large field-erected tanks after scaling by the appropriate Chemical Plant Indices [23, 24]. A baseline cost of stripping and compression systems for an inflexible CO₂ capture facility is scaled by the maximum stripper load raised to a conservative 85% economy of scale factor [25].

For each storage system size, Figure 6 plots additional operating profits and capital costs along with the resulting NPV. Capital cost is dominated by MEA inventory and larger stripping/compression equipment, which make up 56–59% and 31–37% of the total, depending on system size. Additional profits increase with storage system size, but rapidly increasing capital costs allow a storage system sized for just 22.5 minutes in full storage mode to achieve the greatest NPV. However, solvent inventory cost depends strongly on the design solvent capacity and MEA price, and stripping and compression equipment might already be oversized in the original plant design, so larger storage systems could be optimal at facilities with lower capital costs or different design and market specifications.
4. Conclusions

Optimization and rule-based models are created and used to study profit-maximizing operation of a facility with flexible CO₂ capture with and without solvent storage under varying degrees of electricity price foreknowledge. At intermediate CO₂ prices, a coal-fired facility with flexible CO₂ capture can improve operating profits by up to 10% relative to an inflexible system by venting CO₂ when additional electricity sales offset increased emissions costs. Within this CO₂ price regime, flexible capture systems with solvent storage may choose to vent CO₂ and reserve storage capacity for other times. The value of venting CO₂ disappears at high CO₂ prices, but a flexible CO₂ capture system with solvent storage maintains a 9–29% operating profit advantage over inflexible capture at any CO₂ price above the minimum required for CO₂ capture operation. Under the conditions studied, the operating profit improvement from flexible CO₂ capture exists for any reasonable CO₂ capture system ramp limit, and electricity price foreknowledge is only important with solvent storage to allow operators to plan when to store and regenerate rich solvent. CO₂ emissions are greater with flexible CO₂ capture than with inflexible capture, but CO₂ emissions remain far below those without CO₂ capture at CO₂ prices that justify capture operation. At CO₂ prices where venting occurs, CO₂ emissions are lower with solvent storage than with venting-only CO₂ capture because the increased operating flexibility with solvent storage allows greater overall CO₂ capture utilization.

In a retrofit application, venting-only flexible CO₂ capture incurs negligible capital cost, but any operating profit benefits of solvent storage must be weighed against the capital cost of the storage system, which is dominated by the cost of solvent inventory and larger stripping and compression equipment. In this case study, the most valuable solvent storage system is only large enough to take advantage of a few high price periods per day, but optimal storage size is expected to be sensitive to solvent and equipment capital cost parameters and accounting procedures.
5. References