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Optimization of Carbon Capture Percentage for Technical and Economic Impact of Near-Term CCS Implementation at Coal-Fired Power Plants

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Abstract

While capture of carbon dioxide from coal-fired power plants has important potential for abating climate change, capturing nearly all of the emissions, or full capture, currently has a significant impact on plant technology, performance, and economics. Capturing only part of the emissions, or partial capture, can take advantage of technological differences that result in a reduction of capital investment and improved plant performance. By reducing technical and economic disincentives for first movers, partial capture can serve as an important near-term strategy to meet electrical demand while expediting widespread deployment of full capture.

Keywords: Carbon dioxide capture; partial capture; pulverized coal; integrated gasification combined cycle; electric power; climate change

1. Introduction

Increasing electricity demand in the United States creates the need to increase baseload generation capacity. Renewable and nuclear energy cannot be expected to provide baseload generation in the near-term, leaving coal and natural gas as the primary options. The use of natural gas is accompanied by concerns about high prices, price volatility, and depletion of domestic resources. However, the higher level of carbon dioxide (CO_2) emissions from coal-fired power plants is, among other factors, making it increasingly difficult to build new coal plants. Carbon capture and sequestration (CCS) provides a means of reducing carbon dioxide emissions at coal-fired power plants, but until recently research has focused on capturing 85-90% of emissions (full capture), which is likely too expensive and untested for near-term large-scale deployment. This research investigates technological differences and economic implications along the entire range of capture levels for coal plants. It is believed that capturing a smaller portion of carbon dioxide emissions, or partial capture, holds promise for reducing "first-mover"

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disincentives and expediting widespread deployment of full capture systems. In particular, 45-65% capture reduces carbon dioxide emissions levels to parity with emissions from natural gas power plants. This would allow near-term electrical generating needs to be met by coal with a climate impact similar to natural gas, and thus has strong implications for policy.

2. Coal rush, coal paralysis

In the first years of the 21st century, the United States experienced a dramatic resurgence of plans and proposals for coal-fired power plants – a "coal rush." By mid-2008, over 200 new coal plants had been proposed. However, the past few years have seen a growing "coal paralysis" that is hampering realization of the coal rush. Between January 2007 and Mid-August 2008 plans and proposals for 70 new coal plants had been shelved. Strong trends have emerged in the challenges surrounding new coal plants, revealing prevalent new issues arising primarily from escalating costs and concerns about climate change.

There are a variety of factors contributing to coal paralysis. Federal legislation addressing climate change is likely to be signed within the lifetime of new plants, but the economic viability of a new coal plant will hinge upon the details that are not yet known. Rising prices have caused the projected total capital cost of projects to as much as double, leading many power producers to abandon projects that are now simply too expensive. Financial lenders for power projects are beginning to institute policies in their lending practices that reflect these economic risks. Utilities must also be able to charge high enough rates for their electricity to recoup their costs, which both regulators and a competitive market can preclude. There is growing pressure to reduce world-wide carbon emissions by hindering new coal-based power projects that do not include carbon capture and sequestration, despite the fact that CCS technology is not yet ready to address emissions at scale. Projects are increasingly being challenged legally through formal lawsuits, regulators' requirements, and social opposition from individuals and organizations for reasons including climate change concerns. States are also taking initiatives that deter new coal plants such as making commitments to reduce carbon emissions or implementing emissions performance standards for power generators, and utilities are voluntarily abandoning coal projects in favor of less carbon-intensive projects.

3. Options for near-term generation needs

As evidenced by the cancellation of so many new projects, these issues have converged to create a coal paralysis that is begging the question of how to practically meet the United States' growing electrical demand. Reserve capacities for electrical generators are diminishing, and when electrical demand exceeds generating capacity, blackouts occur, often with serious consequences. New baseload generating capacity is necessary to avoid such situations, yet not all sources are viable. The intermittency of renewable energy such as wind and solar make it unsuitable for baseload generation, and nuclear plants have a variety of technical, economic, and social issues that make it unlikely that they can be built soon enough to address near-term generating deficiencies.

The emerging gap between the current generating capacity and near-term electrical demand must be filled then by either coal or natural gas. Despite recent increases in the price of coal, coal remains cheaper and has greater price stability than natural gas. Coal is plentiful in the United States, but domestic production of natural gas has not kept up with increased demand, leading to an increase in natural gas imports. Thus, coal is preferable economically and for the objectives of national energy security and independence. The primary argument for natural gas is that its environmental impact is smaller, especially in that its unabated carbon dioxide emissions are roughly 50% of the emissions from coal.

If the emissions from coal can be reduced to match those from natural gas, which can be achieved through carbon capture and sequestration, the advantages of coal can be realized with the same climate impact as its near-term alternative. Thus, a strong environmental, economic, and energy independence argument emerges for coal with natural gas level emissions. In recognition of these advantages of coal and the need to add generating capacity, there is momentum for a policy of natural gas parity, as exemplified by the California and Washington emissions performance standards and the recent EU vote for an emissions performance standard. Embracing a policy such as natural gas parity would ease some of the difficulties that are creating coal paralysis and allow growing electrical demand to be met.

Furthermore, it is likely that a price on carbon dioxide emissions will be implemented through a federal cap-and-trade emissions reduction program. While building natural gas power plants instead of coal power plants is assumed to be the default response to a high carbon price, it may have unintended consequences such as significantly higher natural gas prices and thus higher electricity prices. Which type of plant and what level of capture is economically preferable is dependent both on the carbon price and the fuel price differential between coal and natural gas. If the fuel price differential is large enough, it may be preferable to build a coal plant with capture even in the absence of a price on carbon dioxide emissions.

4. Technological and economic realities of partial capture

Given the potential policy implications, it is necessary to evaluate the technological and economic realities of partial capture. While the levels of capture that achieve natural gas parity, 45-65% capture, are of particular policy relevance, the entire range of capture possibilities should be assessed. Partial capture can be achieved through the use of CCS at both pulverized coal (PC) and integrated gasification combined cycle (IGCC) power plants. There are important differences to recognize in implementation of partial capture versus full capture.

4.1. Partial capture for pulverized coal plants

Partial capture at a pulverized coal plant is best accomplished by bypassing a portion of the flue gas around the carbon capture equipment straight to the stack [1]. The remaining flue gas enters the carbon dioxide absorber, which is operated just as it would be for full capture (capturing approximately 90% of the carbon dioxide flow through the column). The ratio of bypass to flow to the carbon dioxide absorber determines the capture level achieved. The primary impacts of CCS at a power plant are increased capital cost and reduced electrical output. Compared to full capture, certain technological aspects of partial capture allow these impacts to be mitigated. These factors are displayed in Table 1 and discussed below.

Table 1. Benefits of Partial Capture versus Full Capture for Pulverized Coal Plants

Technological Distinctions	Associated Performance and Economic Benefits
Reduced number, size of equipment	Reduced capital cost
Reduced and optimized steam extraction	Improved plant output and efficiency
Reduced auxiliary load	Improved plant output
Potential for temporary bypass	Greater dispatch to the grid during peak electricity demand
Reduced consumables and water use	Lower operational cost, may facilitate permitting
Selective flue gas cleanup	Avoided unnecessary costs

The capital cost associated with partial capture will be less than that for full capture. For a commercial-scale plant, full capture is often accomplished using two trains of carbon dioxide absorbers and strippers, and sometimes two compressors. Up to a certain capture level a single train can be used for partial capture, although where this "switch point" occurs will depend on the details of the plant such as its capacity and the carbon dioxide solvent being used. This represents significant savings in equipment capital costs for the absorber/stripper/compressor system and its associated components such as pumps and heat exchangers. Both above and below the switch point, reduced capture levels will allow smaller equipment to be used than in full capture, also saving capital cost.

Another cost-saving option for partial capture regards the reduction of sulfur dioxide (SO_2) levels in the flue gas to very low levels as is necessary for most types of solvents. For carbon capture the sulfur dioxide levels must be reduced beyond environmental specifications for flue gas. Instead of installing an extremely efficient flue gas desulfurizer (FGD) to reduce the concentration to ultra-low levels for the entire stream, a sulfur dioxide polisher can be added to the carbon dioxide absorber column to treat only the necessary portion of flue gas, saving capital cost.

Carbon capture systems require the use of a significant amount of steam for regeneration of the solvent in the carbon dioxide stripper, which has impacts on plant output and efficiency. Because of the required temperature and pressure of the steam, it is most often obtained by extracting steam from the crossover pipe between the intermediate pressure (IP) and low pressure (LP) sections of the steam turbine or from extraction ports in the LP section itself. In some cases up to 79% of the total steam flow must be extracted [2]. The decreased flow of steam through the turbine reduces its electrical output. Turbines are designed to operate most efficiently at a specified flowrate, so steam extraction also reduces turbine efficiency. Practical aspects of turbine operation constrain the location of potential extraction points for the steam, and reducing the amount of steam extraction could ease these constraints, resulting in better optimization of steam extraction. Reducing the level of capture reduces the amount of steam extracted for regeneration, thereby preserving greater turbine output, reducing the impact on turbine efficiency, and potentially leading to better steam extraction optimization.

Carbon capture systems require a significant amount of electricity to run compressors, flue gas blowers, and pumps. These auxiliary loads reduce the amount of electricity available to dispatch to the grid, reducing the plant's overall efficiency. Partial capture, through the use of fewer or smaller pieces of equipment and lower flowrates, can decrease this impact. There is also a significant opportunity cost associated with using power for auxiliary loads instead of dispatch to the electrical grid; this cost is highest during times of peak electrical demand. Partial capture can optionally be exploited to increase the operational flexibility of the plant. In partial capture the system to bypass the carbon capture equipment is built in, so the economics of the plant can be improved by reducing the flow through the capture equipment during peak demand. Furthermore, operational issues are likely to arise for the first wave of carbon capture systems deployed, so having a bypass system will facilitate servicing the carbon capture equipment with limited impact on the remainder of the plant.

There are also resources to be saved by implementing partial capture. For a pulverized coal plant, full capture can increase a plant's water demand by up to 116% [3]. Lower capture levels will reduce the demand for raw water, which can ease permitting, as well as reducing the cost associated with circulating water and water treatment systems. Operational costs associated with purchasing solvents for flue gas desulfurization and carbon capture can also be reduced in partial capture.

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4.2. Partial capture for IGCC plants

In an integrated gasification combined cycle plant, the syngas exiting the gasifier is composed primarily of carbon monoxide (CO) and hydrogen (H_2). For full capture, the carbon monoxide is "shifted" (with steam and a catalyst) to carbon dioxide in a series of water-gas-shift (WGS) reactors. To achieve high levels of capture, at least two stages of shift are necessary to convert the majority of the carbon monoxide. In a non-capture plant, the downstream acid gas removal unit (AGR) is used to remove hydrogen sulfide (H_2S) from the syngas. For capture, expanding the AGR to two stages and selecting an appropriate solvent allows for removal of carbon dioxide in addition to hydrogen sulfide. The solvent is flash-regenerated, releasing streams of CO_2 that are then compressed. The remaining gas, mostly hydrogen, is burned in the syngas turbine.

A few options exist for partial capture for an IGCC. The level of capture is controlled by adjusting the extent of CO to CO_2 conversion, as the AGR will capture a relative portion of the CO_2 in the stream. Some conversion happens naturally in the gasifier itself, so there is some portion of carbon dioxide in the syngas exiting the gasifier which can be removed in the AGR. This process, referred to as "skimming," can result in capture levels up to 25%. Installing a single-stage shift and removing the resulting carbon dioxide can achieve 50-80% capture [4]. Levels of capture beyond 80% require a two-stage shift. The level of capture achievable with different numbers of shifts is highly dependant on the type of gasifier, its operating parameters, plant specifics, and type of solvent used. While the number of shift reactors can be changed to achieve distinct capture levels, adjustments in the amount of catalyst or steam used in each shift may be utilized to shift a specific amount of CO to CO_2, allowing intermediate capture levels to be achieved. Bypassing a portion of the syngas around the shift reactors may also be used to control the capture level, although some issues with this option are yet to be resolved. The technological differences between partial and full capture and their associated benefits are summarized in Table 2 and discussed below.

Table 2. Benefits of Partial Capture versus Full Capture for Integrated Gasification Combined Cycle Plants

Technological Distinctions	Associated Performance and Economic Benefits
Reduced number, size of equipment	Reduced capital cost
Reduced auxiliary load	Improved plant output
Reduced consumables and water use	
Reduced steam consumption	Improved electrical output or heat integration
Reduced or avoided turbine derating	Improved plant output and efficiency

There are important capital cost implications associated with these ways to achieve partial capture. Lower capture levels will have lower associated capital costs because fewer pieces of equipment, such as the shift reactors, will be required. The amount of investment in the AGR will also depend on the level of capture, as at lower levels expansion into two fully-integrated stages may be unnecessary. Some equipment, such as the flash tanks for solvent regeneration, carbon dioxide compressors, and peripheral components such as pumps and blowers, can be smaller, or single instead of double trains could be used, saving capital cost. Similar to the pulverized coal case, partial capture also saves auxiliary loads associated with capture, reduces water demand, and potentially saves on consumables such as solvent and catalyst.

Full capture has a significant impact on the syngas turbine. The shift of CO to CO_2 results in up to a 15% decrease in heating value of the syngas [5]. Because the syngas is now primarily hydrogen, the firing temperature is increased. This makes it necessary to derate the turbine to preserve the life of the turbine and reduce NO_x formation. This is usually accomplished by diluting the gas with compressed nitrogen, which also serves to increase mass flowrate through the turbine, thus obtaining better output than without dilution. However, turbine output is still up to 10% lower than with unshifted syngas [6]. Partial capture can reduce or preclude this derating up to a certain capture level, and some of the CO heating value can be maintained. Furthermore, partial capture will reduce the amount of steam needed in the shift, which can be used for generation in the steam turbine or for heat integration.

5. Development of partial capture models

To investigate the quantitative impact of these realities, we are currently developing models to approximate relevant technical and economic aspects of partial capture for greenfield PC plants (subcritical and supercritical) and IGCC plants with different gasifier vendors. These models are based on the "end point" data of no capture and full capture from the National Energy Technology Laboratory's "Cost and Performance Baseline for Fossil Energy Plants" [3]. The same plant specifications and assumptions are used except that plant capacity, not net output, is held constant across capture levels. It is recognized that new issues about some assumptions have emerged, especially regarding the purity of carbon dioxide from the high-pressure flash in the IGCC system, but the assumptions have been maintained due to a lack of a clear resolution and a desire for consistency. Based on this data, spreadsheet models are developed to approximate corresponding data for the full range of capture from 0% to 90% for greenfield PC and IGCC plants. In 5% increments, the models calculate information such as flowrates, stream compositions, equipment sizes, heat rates, and carbon dioxide emission rates. These are used to estimate auxiliary power requirements, capital costs, and operating and maintenance costs; these in turn generate data for cost of electricity (COE), price of carbon dioxide in \$/ton CO_2 avoided and \$/ton CO_2 captured, and various other economic metrics.

Built into the models are technological switch points at which there is a discrete change in the process with respect to capture level, although this is a work in progress and these concepts are still being identified and integrated. These include the topics discussed above, such as the opportunities to use single trains of equipment or avoid derating the IGCC turbine up to a certain capture level, as well as economies of scale associated with equipment sizes. These switch points could have important economic implications, including the identification of potential optimum capture levels. Because the capture level at which these switch points occur will be plant-dependent, it is their impact, and not exact level, that is important for general consideration. The model can also be used to test the sensitivity of the economics to the capture level associated with various switch points. A variation of the model that would, where possible, use equipment sized for full capture, but operated at partial capture conditions, is being considered to investigate the opportunity to avoid carbon lock-in.

5.1. Preliminary observations from subcritical PC model

While this is still a work in progress, preliminary results from the subcritical PC plant model convey important messages. Auxiliary load, net power, and net plant efficiency are all approximately linear with respect to capture level; this concurs with a previous study that examined retrofitting a plant for distinct capture levels [1]. The cost of avoided carbon dioxide emissions (\$/ton of CO_2 avoided) decreases rapidly as capture is increased from zero, and begins to level out at about 25%. After that point, the cost of avoided emissions comes down gradually, but is relatively flat, especially beyond 60% capture.

6. Discussion

For quite some time, the paradigm in the CCS world, both research and legislative, has been one of either no capture or full capture (85-90% of emissions captured). While this is the long-term goal, the technical realities discussed above lead to important implications for partial capture as a near-term strategy.

6.1. Lower technology hurdles and risks

Implementing full capture at a coal-fired power plant involves some significant changes to the basic power plant equipment and operation. These changes sometimes involve non-standard operation or equipment designs, such as for the steam turbine in a PC capture plant or the syngas combustion turbine for an IGCC capture plant. However, these technology "step-outs" of non-standard operations or designs have not been fully tested and implemented, and thus they represent substantial technological hurdles. Reducing the desired capture level can reduce the severity of necessary changes to plant designs, or in some cases non-standard designs can be avoided altogether. This results in less financial risk for the project.

6.2. Reduced investment

The capital cost of a coal-fired power plant with full capture CCS is significantly greater than the cost of the same plant without capture. Capture can represent at least a 60% increase in costs for a pulverized coal plant, and at least 30% for an IGCC [7]. This significantly greater investment is difficult for power producers to accommodate, especially given the recent dramatic increases in capital costs. Partial capture for both PC and IGCC represents a smaller total capital investment because smaller or fewer pieces of equipment are necessary and the parasitic energy loss is reduced. At the same time, we estimate that a comparable unit cost (\$/ton avoided) for capture can be obtained.

6.3. Improved economic viability for first movers

Power plants in an electric grid are instructed when to turn on and off (and thus generate electricity and accrue revenue) according to dispatch curves. Dispatch curves represent the electrical plants in a grid and the cost to dispatch each plant's capacity. A plant's dispatch cost is comprised of its variable operating cost and fuel cost, which is highly dependent on plant efficiency. Sunk costs such as capital and fixed costs are not accounted for [8]. Thus, a plant's ability to dispatch (represented by its location on the dispatch curve) is dependent primarily on factors related to its efficiency, and not the utility's investment. It is coal's relatively low operating and fuel costs that make it economic for them to be baseload plants that dispatch a majority of the time, with plants that have higher variable and fuel costs, such as natural gas, operating as peaker plants when electrical demand is high.

Because the use of CCS at a power plant decreases efficiency, the plant's dispatch cost rises and its location on the dispatch curve shifts such that it will be relatively less economic for that plant to turn on. When many plants on the dispatch curve utilize CCS, the entire dispatch curve shifts and plants' relative positions are not as dramatically affected. However, when only a few plants in a region implement CCS, their dispatch costs may be so affected that they do not dispatch electricity as often. The implementation of full capture in a region of non-capture plants could result in stranding of the entire investment, dependent on the mix of existing plants and their characteristics. This reality is a strong disincentive to be a first mover in implementing CCS. Partial capture can allow first-mover plants to abate their carbon emissions with a smaller efficiency penalty; it can allow them to maintain baseload status and economic viability. Thus, partial capture represents a means to facilitate initial implementation of CCS by preserving economic viability of power plants with carbon capture.

6.4. Expedite large-scale deployment of full capture

There is also a technological development argument for partial capture as a near-term strategy for CCS deployment. Large-scale pilot tests are needed to obtain technical and operating knowledge and to demonstrate plant availability and reliability to the investment community. This is true for both the capture and the storage aspects of CCS. Partial capture CCS then can serve an important role as a transition strategy. By easing the economic difficulties of carbon capture, partial capture can be expected to be implemented sooner and more rapidly. Great amounts of technical and operating information can be gathered by deploying numerous partial capture CCS systems. It is likely that more knowledge, for a given amount of emissions reduction, can be gained through multiple partial capture systems than fewer full capture systems because of the greater variety of contexts and plant designs. Knowledge generation will reduce the risk of implementing full capture and costs can be expected to decrease as more plants are built. These will greatly facilitate large-scale deployment of full capture systems. Importantly, deployment of partial capture systems will provide a source of carbon dioxide to study subsurface issues, thereby reducing the uncertainty associated with storage as well. Thus, partial capture serves as an important strategy to expedite the transition to an electrical system with wide-spread use of CCS technology, while meeting growing electrical demand and, if a strategy of natural gas parity is pursued, achieving the same level of emissions as its alternative.

6.5. The coal versus natural gas decision

Given that the near-term fuel options for baseload electricity generation are coal and natural gas, coal brings advantages of a plentiful domestic supply and relatively lower prices. The primary disadvantage of coal, its high carbon emissions compared to natural gas, can be mitigated through the use of CCS. CCS at a coal-fired power plant can achieve a level of CO_2 emissions similar to those from natural gas, with a smaller investment and likely with a cost per ton comparable to that for full capture. If the price differential between coal and natural gas feedstocks is great enough, coal with CCS could become the economically preferred option. Thus, partial capture serves as an important hedge against high natural gas prices and can assuage concerns about increasing reliance on foreign supplies of natural gas.

7. Conclusions

While the long-term goal is wide-spread deployment of "full capture" CCS projects, a variety of technical and economic issues make consideration of lower capture rates, or partial capture, a more feasible first step in implementing CCS. These include:

- Lower technology risks by requiring less extensive technology "step-outs" initially, and allowing the technology "step-outs" to be phased in as we move toward full capture.
- Lower total investment costs while still maintaining a similar unit cost of mitigation (in $/ton of avoided carbon dioxide emissions).
- More economically viable plants with respect to dispatch of electricity to the grid.
- Quicker introduction of CCS into the marketplace, allowing required learning to take place quicker and leading to higher market penetration rates. This will expedite the large-scale deployment of full capture CCS.
- Allowing coal-fired power plants to be built, but with a significantly smaller carbon footprint.
- Continuation of diversified fuel options for electricity generation. The economic and energy security advantages of coal can be realized, while avoiding overreliance on natural gas, which is associated with price volatility and is increasingly from nondomestic sources.

8. Future Work

The models to estimate the quantitative technological and economic impact will be completed and refined for subcritical and supercritical pulverized coal plants and an IGCC plant with various gasifier technologies. These will be used to analyze relative performance and economic criteria, including sensitivities to the capture level associated with discrete technological changes. Sensitivities to factors such as the fuel price differential between coal and natural gas will be explored, as well as the potential for carbon lock-in that could result from partial capture hindering an upgrade to full capture. Compiled results will hold strong implications for the selection of carbon capture levels both for an individual plant and national policy, while also identifying the factors on which economic results depend.

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