



**NATIONAL ENERGY TECHNOLOGY LABORATORY**



# **Research and Development Goals for CO<sub>2</sub> Capture Technology**

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## EXECUTIVE SUMMARY

Numerous propositions exist for the reduction of atmospheric carbon dioxide (CO<sub>2</sub>). One of the higher profile suggestions is to replace the fossil power generation base with low-carbon power generation technologies. Fossil-based electric power plants are major contributors to CO<sub>2</sub> emissions in the United States (U.S.), so it is prudent to focus on these plants in a primary strategy for atmospheric CO<sub>2</sub> reduction. A major part of the ideal solution may indeed be immediate and cost-effective conversion of high carbon power sources to low carbon sources. However, as the global knowledge base in this area continues to increase, it is becoming more evident that adequate capacity of low-carbon power generation does not exist as a timely, and as of yet significant, replacement of fossil-based power while maintaining national and global productivity. For the above reasons, it is becoming clear that:

- 1. The Fossil Power Industry Must Remain Part of the Near-Term Climate Change Solution***
- 2. CO<sub>2</sub> Emissions from Fossil Power Plants Must be Curbed***

Opportunities for significant disposition of the CO<sub>2</sub> emissions from these plants are limited to geologic sequestration and enhanced oil recovery, as these are among the most promising storage opportunities for CO<sub>2</sub> emissions in terms of feasibility and capacity.

It is possible with today's technologies to capture and sequester at least 90% of the CO<sub>2</sub> emissions from fossil power plants. However, systems analyses have shown that current technologies for CO<sub>2</sub> recovery and compression from flue gas impose severe economic and thermodynamic penalties that increase the cost of electricity (COE) by 75% or more. Therefore, the Department of Energy's (DOE) National Energy Technology Laboratory (NETL) established research and development (R&D) goals for CO<sub>2</sub> capture (CC) technology applicable to both new and existing coal-fired power plants. These research goals are designed to produce competitive and effective CO<sub>2</sub> capture technologies that:

- I.*** Are capable of reducing CO<sub>2</sub> emissions by 90%
- II.*** Reduce the overall economic penalty imparted by current carbon capture (CC) technology by 55%. This is equivalent to no more than a 35% increase in COE of an identical plant without CC.

This report will detail these goals and show that achieving them is an aggressive, but feasible pursuit.

In a separate study designed to validate the national benefits of these proposed R&D targets, NETL has found that achieving these goals results in substantial savings in energy expenditures. Because it is uncertain yet what form a regulatory CO<sub>2</sub> policy may take, this analysis examined the effect of implementing both a carbon tax on emissions and a cap and trade policy, designated by CTX and CES, respectively, in Figure 1 below. It should be noted the the CES policy chosen here is just one of may possible options for cap and trade policies.

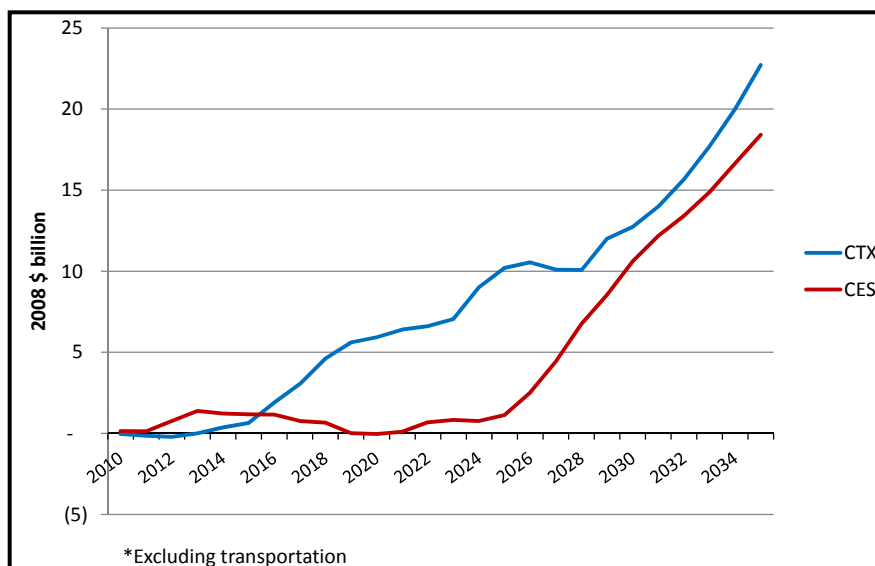


Figure 1: Potential Savings in Energy Expenditures if EPEC Goals are Met (1)

Figure 1 represents the potential savings in U.S. energy expenditures (excluding the transportation sector) if the performance of state of the art (SOTA) carbon capture technologies improves to meet the NETL Existing Plants, Emissions and Capture (EPEC) program CC goals. Savings range from \$18-23 billion dollars (net present value – 7% discount rate) between years 2010 and 2035 over a scenario without CC development, depending on whether a carbon tax or a cap and trade policy is implemented (1). Results of this study also suggest that 85% of the existing coal-based fleet would remain economically and environmentally viable power generators if CO<sub>2</sub> is the only contaminant targeted for reduction. Leveraging the existing infrastructure so successfully is a large part of the reason for the significant savings over employing alternative power generation technologies.

This same study estimates that CO<sub>2</sub> emissions from U.S. coal-fired power plants will decline from nearly 2 billion metric tonnes in 2010 to 300 million metric tonnes in 2035 if the Existing Plants Emissions and Capture (EPEC) program Research, Development & Demonstration (RD&D) goals for CC are met and advanced capture technology is employed in a practical manner under a carbon tax policy. Even though 85% of today’s coal capacity would remain in place in 2035, due in large-part to the retrofitting of existing plants with CC technologies, CO<sub>2</sub> emissions from these plants would be 85% less than the CO<sub>2</sub> emissions generated by the fleet of coal-fired power plants today.

In addition to mitigating the economic and environmental burden of reducing energy-related CO<sub>2</sub> emissions in the U.S., achieving the EPEC program goals would also have a positive impact on employment, with the cumulative net impact being approximately 800,000 jobs added and/or retained in the economy (2).

The above goals are feasible, but aggressive, and may be achievable through a focused R&D program directed toward:

- 1) Improving the efficiency of CC technology to minimize any de-rating of pulverized coal (PC) power plants fitted with this technology
- 2) Lowering the direct capital costs of in-plant CC technology
- 3) Lowering the direct operating costs of in-plant CC technology

This report provides strategies for addressing these objectives and achieving the EPEC program cost and performance goals. Further assessment will be required to quantify potential cost and performance benefits and to identify new R&D opportunities.

COMMON ACRONYMS/ABBREVIATIONS

Acronym/Abbreviation	Definition
CC	Carbon/CO <sub>2</sub> Capture
CCUS	Carbon/CO <sub>2</sub> Capture, Utilization & Storage
CO <sub>2</sub>	Carbon Dioxide
COE	Cost of Electricity
DOE	U.S. Department of Energy
EPEC	Existing Plants Emissions and Capture
GHG	Greenhouse Gas
LCOE	Levelized Cost of Electricity
NETL	National Energy Technology Laboratory
PC	Pulverized Coal
R&D	Research and Development
RD&D	Research, Development and Demonstration
SOTA	State of the Art
TSM	Transport, Storage, and Monitoring
U.S.	United States

## I. Introduction

Electric power plants are major contributors to carbon dioxide (CO<sub>2</sub>) emissions in the United States (U.S). If significant reductions in greenhouse gas (GHG) emissions are mandated in the future, the CO<sub>2</sub> emitted by these plants will need to be reduced. One approach for achieving major reductions is through carbon capture, utilization, and storage (CCUS). However, system analyses have shown that use of current scrubbing technologies for CO<sub>2</sub> recovery and compression for flue gas applications impose a severe economic penalty on the cost of electricity (COE) generation. This report establishes the rationale for research and development (R&D) goals for CO<sub>2</sub> capture (CC) that aspire to reduce the economic penalty from the current level of ~75% increase in levelized cost of electricity (LCOE) for an equivalent greenfield pulverized coal (PC) plant without carbon capture (CC) to 35%. While this metric is based on a greenfield plant, the improvements in CC technology required to achieve this goal are applicable to both new and existing coal-fired power plant technologies. These goals are intended for use in guiding the U.S. Department of Energy-sponsored (DOE) CC R&D under the National Energy Technology Laboratory's (NETL) Existing Plants Emissions and Capture (EPEC) Program and for assessing the progress of any such R&D efforts.

There are approximately 1,100 boiler furnaces operating at the 460 coal-fired power plants generating electricity within the U.S. PC plants are widely distributed across the country and vary considerably by age, footprint, coal type, and environmental controls. These factors will impact the cost and performance of CC technologies deployed across the existing PC fleet. Some PC plants will be better equipped than others to take advantage of new technologies, and some plants may be re-powered, rebuilt, or retired. However, so that power demand can be adequately satisfied as carbon constraints are implemented, it is prudent to aggressively develop and deploy technologies that will allow many of these plants to remain in operation until longer term solutions for reducing GHG emissions can be developed, tested, and implemented. This is especially true for newer plants that are not near the end of their useful life.<sup>a</sup>

The EPEC CC R&D goals include two basic components: 1.) a performance criterion related to the quantity of CC, and 2.) an economic criterion related to the total cost incurred due to capture. For establishing a quantitative performance goal, Percent CO<sub>2</sub> Captured is used, defined as:

$$\%CO_2 \text{ Captured} = \left( \frac{\text{Carbon}_{\text{Sequestered}}}{\text{Carbon}_{\text{Coal}}} \right) \times 100 \quad (1)$$

<sup>a</sup>Newer existing power plants have a high base COE relative to older plants, for which the initial capital investment may be nearly paid off. For example, in a recent NETL study [3], the COE for the existing Conesville Unit #5 was determined to range from 2-2.5¢/kWh, compared to 6-7¢/kWh for a new subcritical or supercritical power plant. The higher cost of the new plant primarily reflects the amortization of the initial capital investment, and this investment will be lost if the plant is shuttered. Therefore, mothballing a newer plant results in an inefficient use of financial capital. The inefficient use of capital should be avoided when considering carbon mitigation strategies, since it will result in either a higher overall cost of mitigation or a reduction in the total amount of carbon mitigated.

The economic metric for the EPEC carbon capture goal is percent change in COE due to the addition of CC<sup>b</sup>, defined as:

$$\%Change\ in\ COE = \left( \frac{COE_{CCS} - COE_{NoCCS}}{COE_{NoCCS}} \right) \times 100 \quad (2)$$

These criteria are consistent with previously established DOE goals for other CC Program R&D areas, and possess desirable characteristics:

- They can be related back to system parameters that are commonly reported by the power industry and are relatively easy to estimate.
- They are insensitive to the size of the power plant. While they have a specific basis related to power plant output, they are expressed in terms of percentages.
- They are dimensionless and can be easily understood by both technologists and the general public alike.

There are several other metrics in addition to percent change in COE that could be and are used when evaluating the economics of CC technologies. These are Incremental COE, Cost per Ton of CO<sub>2</sub> Captured, and Cost per Ton of CO<sub>2</sub> Avoided, among others. These are described in APPENDIX A – Economic Metrics for CC of this report, and may be more applicable in other non-R&D related assessments.

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<sup>b</sup>When comparing the impact of installing CO<sub>2</sub> capture technology on existing power plants, it is important to remember that the base COE for most existing plants will be much lower than that for a new PC power plant. Even if the incremental cost of CC on an absolute basis were the same between a new and existing power plant, the percent change in COE would not be equal. To eliminate the wide variability of COE for existing plants that implement CC, the basis for calculation and comparison of the EPEC goal is a generic, consistent, and well-defined greenfield plant.

## II. Details of EPEC R&D Program Goals

NETL's EPEC program oversees and guides the development of CC and compression technologies. With these two broad categories in mind, the EPEC-sponsored R&D goals for CC technologies are to:

- I.** Capture 90% of fossil-fuel generated CO<sub>2</sub> and compress to 2,200 psig
- II.** Reduce the current economic penalty imparted by state of the art (SOTA) CC technologies by 55%. This is equivalent to no more than a 35% increase in COE of an identical plant without CC.

The selection of a minimum 90% CC goal is based on knowledge that current SOTA acid-gas scrubbing technologies are capable of removing approximately 90% of the CO<sub>2</sub> contained in a typical flue gas stream<sup>c</sup>; more advanced technologies should, at a minimum, aspire to match this capture potential. Because SOTA technology can achieve 90% capture, goals for advanced technology should aspire to meet or exceed this value. However, although NETL has established a 90% capture goal, when economics are extremely favorable, it may be desirable to assess the impact of less than 90% CO<sub>2</sub> removal. This relaxation may be especially useful if technologies limited to less than 90% capture are guaranteed to deploy at costs significantly lower than those capable of 90%+ capture. While the intent of the EPEC program is to economically capture very significant amounts of CO<sub>2</sub>, it is not to eliminate economically promising capture technologies that may have theoretical or practical limitations on the amount of CO<sub>2</sub> that can be captured. These situations should be assessed separately on a case-by-case basis.

For determining the potential for deployment of capture technologies, electricity cost is perhaps the most important metric. If the costs of low-carbon power generation need to rise to prohibitive levels, it is unlikely carbon capture on PC plants would be selected as a primary atmospheric CO<sub>2</sub> mitigation strategy. NETL selected an electricity cost goal of reducing the incremental COE that arises from incorporating CC on an equivalent new PC plant without capture and compression by a minimum of 55%. This is equivalent to no more than a 35% increase in COE over an equivalent new subcritical baseline PC power plant without CC. NETL studies indicate that amine-based scrubbing, which is widely considered the current SOTA CC technology for PC power plants, results in a COE increase of approximately 75%.

COE is not only dependent on CC installation and operating cost, but also on thermodynamic performance. With this understanding, the EPEC goal also indirectly requires an aggressive, yet practical, performance improvement of advanced CC technologies compared to the current SOTA. To provide perspective on the feasibility of achieving these cost goals, a thermodynamic analysis of post-combustion CC from the flue gas of a PC power plant was performed. This analysis indicates the theoretical minimum energy requirements for 90% separation and compression would result in a heat rate penalty of approximately 8%. Assuming best case, but unrealistic, assumptions that the purchase and operation of the capture equipment has zero cost, the theoretical

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<sup>c</sup>This level of removal using existing technology is achieved on a smaller scale in urea and food-grade CO<sub>2</sub> production.

minimum COE increase is therefore approximately 9%, which results in an 88% reduction of the SOTA COE increase. Aspiring to achieve theoretical minimum energy requirements or zero cost for equipment is impractical. Recognizing that SOTA capture technologies result in thermodynamic costs of CO<sub>2</sub> separation and compression approximately three times higher than the theoretical minimum, NETL has selected a minimum 55% decrease in COE penalty as an aggressive, yet more practical, cost goal.

This decrease in COE must be measured with respect to that of a well-defined base plant without capture that has been chosen a priori to be the platform for all proposed CC installations. This establishes a consistent and unbiased baseline for comparison of CC technology using a generic and conceptual plant design that does not directly appeal to the interests of any specific utility or developer. NETL completed an analysis published in a report, titled, “Cost and Performance Baseline for Fossil Energy Plants,” (3) that established SOTA (circa. 2005-06) power generation technologies both with and without carbon capture. This report included a baseline design, operation, and economics for a subcritical PC power plant, which is herein considered to be the baseline for comparison of CC technologies evaluated by the EPEC Program. Complete details of this plant are represented as “Case 9” in the reference (3). It is important to emphasize that any greenfield SOTA PC installations will most likely be of supercritical design, however there is one important justification for choosing a subcritical plant as a reference for these R&D goals: Studies suggest that for significant levels of economic carbon capture to be implemented, the existing PC fleet must be retrofitted to a much greater degree than the installation of greenfield plants with CC(1). Since the majority of the existing fleet is subcritical, using this platform as a reference allows relatively direct comparison to the most anticipated application for CC.

There is also justification for choosing the greenfield subcritical PC plant represented in (3) as a base plant and not a specific existing subcritical PC plant. Incorporating capture technologies into a greenfield plant implies ideal integration, eliminating the effect of potential case-by-case retrofit difficulties that may unintentionally skew the characterization of capture performance or economics. This allows a pure isolation of capture system requirements, while representing performance that is uninfluenced by indirect factors. Establishing a general, unbiased greenfield baseline in this manner allows NETL to evaluate the direct effect of CC technologies without outside, or unique, influence. Recognizing that capture performance will indeed be affected by certain individual plant differences, a general R&D goal like that sought here should overlook niche-type applications that might result from a specific CC installation on a unique plant. A general R&D goal should also target a generalized fleet-wide solution to reduce CO<sub>2</sub> emissions and not attempt to address case-by-case eccentricities.

In addition, it was decided to conceptually apply any proposed CC technology to a plant that would result in the same net power output as the baseline power plant without CC. Typically, when CC technology is implemented, a significant auxiliary load is required to operate it. This means that the existing electric grid will lose power generation capacity. It is very difficult to quantify the effect of losing this power because there are so many options to replace it. Deciding how to replenish any lost power due to CC



implementation is extremely complex and subject to utility practice (and fortunately is not required to adequately compare one CC technology to another); it was therefore considered to be outside the scope of EPEC goal development. As previously stated, the primary purpose of this report is to explain and justify the EPEC goals for CC R&D and to compare the technical and economic performance of different CC technologies against these goals. For the purposes of evaluating CC technologies against the EPEC goals, all CC technologies will be compared as installed on a plant with a net 550 MW capacity relative to a baseline plant without capture that also has a net 550 MW capacity. Essentially, this evaluation process demands that all CC technologies make up power in the same way – by increasing plant size. While it is a theoretical construct, this process allows evaluation of CC technologies to avoid consideration of the many potential decisions to make up the power lost from the grid.

### A. R&D Goal Assessment

Figure 2 assesses long-term, EPEC-sponsored R&D by plotting direct costs versus indirect costs for CC when applied to new and existing power plants. The total cost for implementing CC on a PC plant is the sum of these two cost terms.

*Direct costs* are defined as the basic capital and operating costs associated with the capture, and compression 90% of the CO<sub>2</sub> produced (to 2,200 psig) by a 550MW plant without CC.

*Indirect costs* are defined as those costs that can be associated with modifications that reduce the power generation efficiency of the existing processes at the plant.

As mentioned previously, COE is also a function of thermodynamic performance; as thermodynamic capture and compression efficiency decreases, decreasing net power generation, the cost (and CO<sub>2</sub> generation) per remaining MWh of power generated increases. These costs include all effects of reduced power generation efficiency. For example, any power or steam required to operate the CC system results in an added parasitic load to the existing plant and lowers the plant power output, thus reduces plant revenue. The reduction in revenue increases the price of power required for the utility to maintain its return on investment, which drives up the consumer cost of electricity. In addition, this electric power loss must be made-up through other modifications to the existing plant in order to maintain a net power output of 550MW. This includes the need for proportionally larger capture equipment sizes that would otherwise be smaller if CO<sub>2</sub> generation per MWh was not increased due to an efficiency penalty<sup>d</sup>. These indirect

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<sup>d</sup> Note in Figure 2 how the minimum theoretical indirect cost increment rises as direct cost increment increases. Minimum indirect costs are calculated by applying the 8% efficiency penalty to the minimum direct costs (in \$/MWh) required to capture CO<sub>2</sub> from a plant with no efficiency penalty (i.e. a 9% increase in these “raw” CC costs). For CC technologies that begin with a higher raw cost, the fixed percent increase due to efficiency penalty results in a larger absolute indirect cost, at all levels of efficiency penalty. Again, this “residual” cost increase does not occur without a performance penalty and so is categorized as an indirect cost attributed to thermodynamic performance reduction.

costs due to reduction in plant efficiency, as will be shown later, are responsible for quite a large portion of the total electricity cost increase.

Marked on Figure 2 is point A, which represents incremental costs for installing a SOTA, amine-based capture system on a greenfield PC plant. The x and y coordinates of point A are computed from the reference costs for a SOTA plant with and without CC (3).

The solid red line in Figure 2 represents the costs which correspond to achieving the EPEC COE goal. Any capture system with direct and indirect costs that fall to the left of this line will surpass the goal. Currently, all proposed CC technologies fall above and to the right of the red line. The dashed red line is an approximation of the cost due to the minimum theoretical parasitic load for CC (also referred to here as “minimum work”). In theory, no process can be made efficient enough to fall to the left of this line<sup>e</sup>. The determination of this line is based on the expected direct costs of the capture system and a conceptual exergy analysis of an ideal separation of CO<sub>2</sub> from flue gas and compression to 2,200 psig (this analysis is detailed in APPENDIX B – Thermodynamic Analysis of CC).

It is important to note that the EPEC goal line in Figure 2 is based on an exergy analysis that assumes the balance of the plant remains constant. While the theoretical minimum work for CO<sub>2</sub> separation and compression is constant for a fixed set of conditions, alternative power cycles more suited for CO<sub>2</sub> compression may be able to utilize energy more efficiently than a typical PC power cycle such that power required by CC is offset by additional power generation not possible in a PC system without CC. By utilizing energy that the base PC plant without capture cannot, it is possible that the PC plant with CC would increase net power generation and thus revenue, driving down the required electricity cost. For example, if upon implementation of an advanced CC technology the plant was able to effectively utilize the large amount of low quality heat contained in flue gas vented from a conventional PC plant, this technology platform would have a distinct advantage by utilizing the otherwise unavailable energy in the balance of plant to help offset CC power requirements. In essence, a higher percentage of the makeup power is inherently provided in a more efficient manner. However, because of the uncertainty of future CC performance, the exergy analysis in this report does not consider supplemental power generation from untapped balance of plant energy sources.

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<sup>e</sup> This statement is true as long as the general power cycle configuration and balance of plant operation remains the same. To avoid speculation of the degree to which this heat recovery is possible, this analysis presumes conventional operation of a PC plant with zero ability to recovery lower level heat in the capture system.

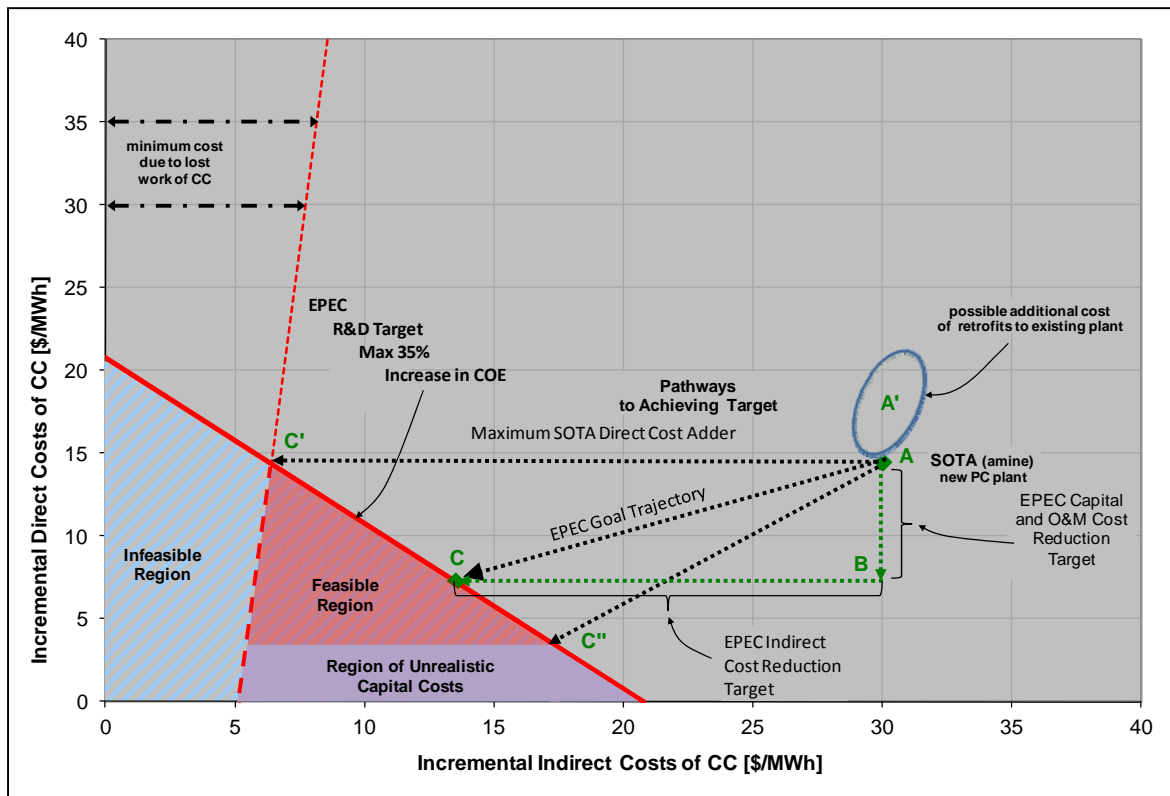


Figure 2: Trajectories for Meeting EPEC Carbon Capture Goals

To go from Point A to any feasible point on the solid red line representing EPEC goals almost certainly requires a reduction in both direct and indirect costs. Performance, and thus indirect cost, is improved by decreasing the CC parasitic power requirements (i.e., by improving the efficiency of the CC process) and represent a movement in the left direction on the graph. Likewise, a reduction in equipment and operating costs of the capture system represent movement downward on the graph. As mentioned above, these are not completely independent changes.

As shown in Figure 2 the indirect costs for the SOTA amine-based system (energy penalty) will exceed the direct costs (raw capital and operating) of CC. This implies that R&D should be focused primarily on increasing the energy efficiency of SOTA separation technologies. This is illustrated by the nature of the slope of the line from Point A to any feasible point on the EPEC goal line; in general, more reduction in indirect costs is required than in direct costs. In fact, as is further elaborated in Figure 4, complete elimination of direct costs will not meet the EPEC goal; **thermodynamic performance improvement is essential.**

However, the capital cost of the SOTA amine-based technology cannot be ignored in this R&D effort. With zero cost improvement of a SOTA capture system, the goal can only be achieved at the point of maximum theoretical efficiency of CC (red dashed line and Point C in Figure 2). Although this is coincidental, it implies that **no advanced CC system should have a direct cost increment larger than SOTA amine systems.** This is especially true in the event of a retrofit where capital costs can increase direct costs by a

factor of 1.2 to 1.5. Therefore, *improvements in both capture efficiency and capital and operating cost reductions will be required to meet the EPEC goal*. Infinite cost reduction pathways are possible for achieving the EPEC goal, so the proposed EPEC goal trajectory (A → C) is just one possibility. Tradeoffs and relationships between direct and indirect costs must be carefully examined and considered in parallel in any R&D effort, but the EPEC goal primarily requires performance improvement of SOTA capture technologies.

While the cost of retrofitting an existing plant was strategically ignored in developing the EPEC goal, major cost reductions for retrofitting will in all likelihood be needed. Further assessment will be required to quantify these costs, and novel approaches and technologies for retrofits should be a major area within the EPEC R&D Program<sup>f</sup>.

Various other CC technology platforms, such as membranes, adsorption, and cryogenic fractionation will exhibit different distributions for direct and indirect costs. If the make-up power cost is high, then the direct capital and operating costs will need to be low, and vice versa (analogous to the tradeoff that often exists between capital and operating costs in most industrial processes). In addition, some technologies may be more applicable to a retrofit of an existing PC plant. Further assessments are needed in order to quantify the benefits and drawbacks of other CC and pressurization technologies.

## **B. CC Cost Breakdowns**

In 2010, NETL completed an extensive techno-economic systems analysis of current SOTA fossil energy-based power plants that included PC power plants (3) producing the same net power generation. All base system performance and cost methodology represented here is derived from this study.

It is important, even if only conceptually, to compare the effect of CC technologies on plants of equivalent net power output so that an unbiased basis for comparison can be established for all proposed CC technologies. Doing so also eliminates the need to consider the cost of making up the lost power to the grid, which can become very complex due to the numerous possibilities available. Table 1 lists the COE breakdown for the new subcritical PC power plant without CC and the incremental COE components for the same plant designed with CC as represented by the NETL study.

The total COE of the reference power plant is 59.3 \$/MWh, and the incremental COE for the same plant with CC is 44.6 \$/MWh, resulting in a total COE of \$103.9/MWh. These

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<sup>f</sup> For a grassroots plant engineered and designed for CC, the retrofit costs would be zero. These include incidental costs associated with installing the CC on the existing plant such as wiring and rerouting piping and tie-ins, plant layout modifications, etc. Retrofitting costs are likely to be up to 50% of the CC capital or possibly more, due to modifications to the existing boiler and steam turbine, which would be necessary if the CC system consumes large quantities of steam. Make-up power must also be supplied to the grid by some unidentified source outside or within the plant fence whereas the new plant is sized appropriately to supply the power deficit caused by the operation of the CC systems.

costs are allocated to four categories: capital costs; fixed operating and maintenance costs; variable operating and maintenance costs; and fuel costs.

*Table 1: Current Cost Breakdown for CO<sub>2</sub> Capture (3)*

[\$/MWh]	Sub PC w/o CC (Baseline)	Sub PC w/CC	CC w/o Energy Penalty (EP)	Cost Increase Excluding EP	Cost Increase Due to EP Only
Capital	31.2	60.2	42.8	11.6	17.4
Fixed O&M	7.8	13.1	9.3	1.5	3.8
Variable O&M	5.1	9.2	6.5	1.4	2.7
Fuel	15.2	21.4	15.2	0.0	6.2
<b>Total FY COE</b>	<b>59.3</b>	<b>103.9</b>	<b>73.9</b>	<b>14.6</b>	<b>30.0</b>

Table 1 lists the cost breakdown of the chosen reference plant without CC and the same plant with SOTA CC in the first and second data column, respectively. The third column represents the total cost of CC if there were no thermodynamic penalty for capturing carbon.<sup>§</sup> The fourth column represents the incremental cost of CC if there were no thermodynamic penalty for capturing carbon and as such is the difference between column three and column one. The breakdowns in columns three and four are insightful because they reveal the “raw” economic costs of installing and operating CC. The fifth column represents the incremental costs due to the loss of plant efficiency resulting from the power required to run the CC equipment and implicitly includes the resultant need to capture more CO<sub>2</sub> per net MW of power generation. This column thus includes the indirect effects that reducing the power generation efficiency has on the capital and operating costs, in addition to the effects of the loss of power generation capacity.

Recall that the indirect costs due to the energy penalty are defined as any costs that result from a decrease in plant power generation efficiency, including any need to increase, among others, plant size, equipment costs, and operational costs to maintain the original 550MW of net power output. It is important to note that interpolation of “raw” capital cost increases using the calculation mentioned above will not accurately represent the non-linear cost changes due to economies of scale (which would likely, but minimally, offset some of the energy penalty costs as the required plant and equipment sizes become larger). The two endpoints presented here, however, do include the lumped effect of economies of scale since there were two independent estimates (including economies of scale) supporting the costs in columns one and two.

Isolation of the economic and thermodynamic penalties is useful because they represent two very different, but very relevant, areas of potential advancement: cost decreases and performance improvement. Such an allocation is valuable for establishing a realistic COE goal and for strategic program R&D planning to identify the most effective technologies and projects to pursue.

<sup>§</sup> Costs in column three were derived by assuming the heat rate of the plant in column two is equivalent to that in column one; the resultant cost is then only the cost required to purchase and operate the base plant with CC equipment, assuming there is no power requirement to run the capture equipment.

Meeting the EPEC CC goals likely requires reductions in all of the cost categories presented in Table 2. There are two general R&D strategies for reducing the COE: performance improvement and cost decreases of CC. In reality, these two collaborating strategies can provide an infinite number of contributions to reach the EPEC goal. Recognizing this, NETL has targeted one set of categorical reductions required to meet the EPEC goal in Table 3.

*Table 2: Targeted Cost Breakdown of Plant Meeting EPEC Goal*

[\$/MWh]	Sub PC		CC w/o Energy Penalty (EP)	Cost Increase Excluding EP	Cost Increase Due to EP Only
	Sub PC w/o CC (Baseline)	Sub PC w/CC (Targeted Goal)			
Capital	31.2	44.5	37.0	5.8	7.5
Fixed O&M	7.8	10.8	9.0	1.2	1.8
Variable O&M	5.1	6.5	5.4	0.3	1.1
Fuel	15.2	18.3	15.2	0.0	3.1
<b>Total FY COE</b>	<b>59.3</b>	<b>80.1</b>	<b>66.6</b>	<b>7.3</b>	<b>13.5</b>

*Table 3: Targeted COE Reductions to Meet the EPEC Goal*

Categorical COE Goals [\$/MWh]	% Reductions in SOTA increases
Capital	50%
Fixed O&M	20%
Variable O&M	80%
Fuel	0%
Energy Penalty	55%

With some knowledge of what can be a reasonable expectation for energy penalty, NETL chose the targets in Table 3 in order to reduce the COE adder that arises by use of SOTA capture technology by 53% (this is the exact value which is rounded to 55% in general presentation of the goal). However, the over-arching EPEC COE goal may still be met even with substantial variation in the above numbers.

Figure 3 below illustrates the comparison of the COE resulting from use of SOTA CC, theoretical best CC performance, and performance CC technology that meets the EPEC goal. Note it is expected that the energy penalty is realistically expected to comprise ~2/3<sup>rds</sup> of the total COE penalty. This is the reason, on an absolute basis, the energy penalty of CC is the most significant target for R&D.

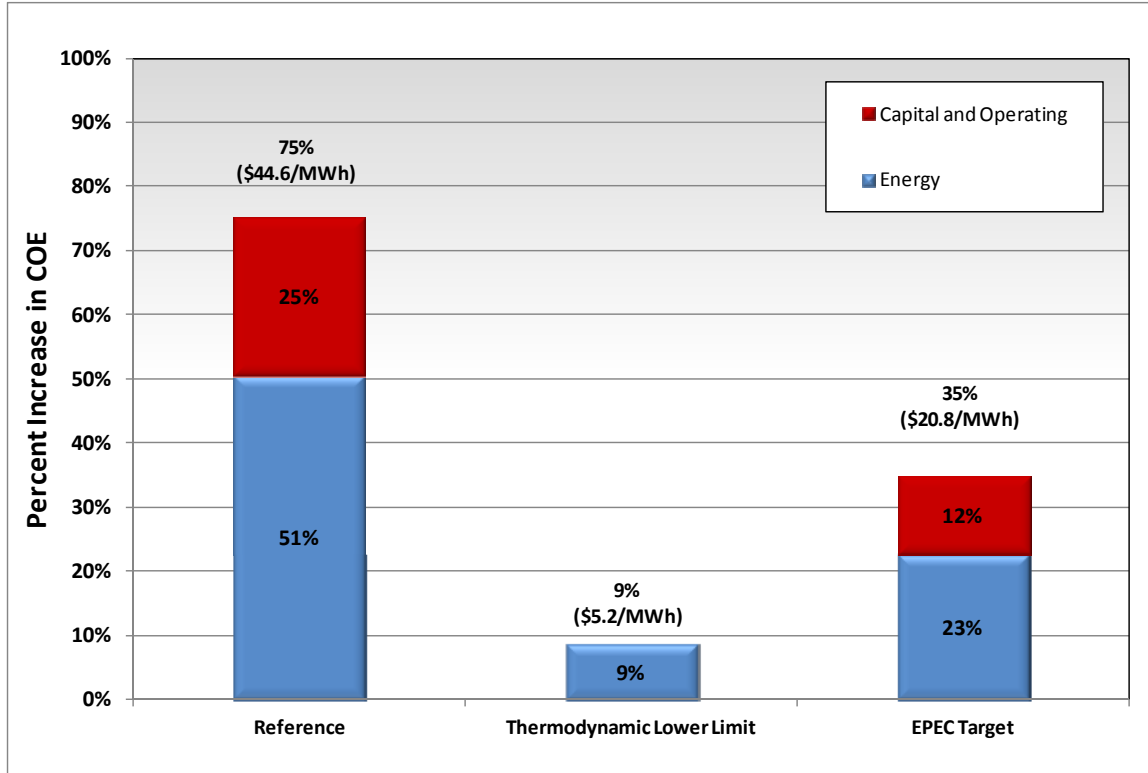


Figure 3: Composition of COE Increases Due to Carbon Capture

### C. Effect of Performance Improvements

Because the thermodynamic performance of the CC process is such an important factor in the final COE, it is useful to understand how realistic expectations of the performance may influence the choices one has in selecting a performance target. Via the thermodynamic analysis of the minimum energy required for a post-combustion based capture process (APPENDIX B – Thermodynamic Analysis of CC), it has been determined that the minimum COE increase is approximately 9%. Therefore, there is a lower bound on the goal for thermodynamic penalty. The process that exhibits the theoretical best performance can be defined as having 100% capture efficiency. Furthermore, the process that effectively captures zero carbon per unit of energy input can be defined as having zero percent capture efficiency. In general, capture efficiency is defined here as:

$$\eta_{capture} = \frac{W_{minimum}}{W_{actual}}$$

Where,

$\eta_{capture}$  = Capture Efficiency

$W_{actual}$  = Actual Separation Work Required

$W_{minimum}$  = Theoretical Minimum Separation Work

With the minimum separation work calculated as a function of flue gas composition, separation pressure, and separation temperature, it can be considered relatively constant for most PC systems. Varying  $W_{actual}$  allows representation of expected COE as a function of capture efficiency in Figure 4 below.

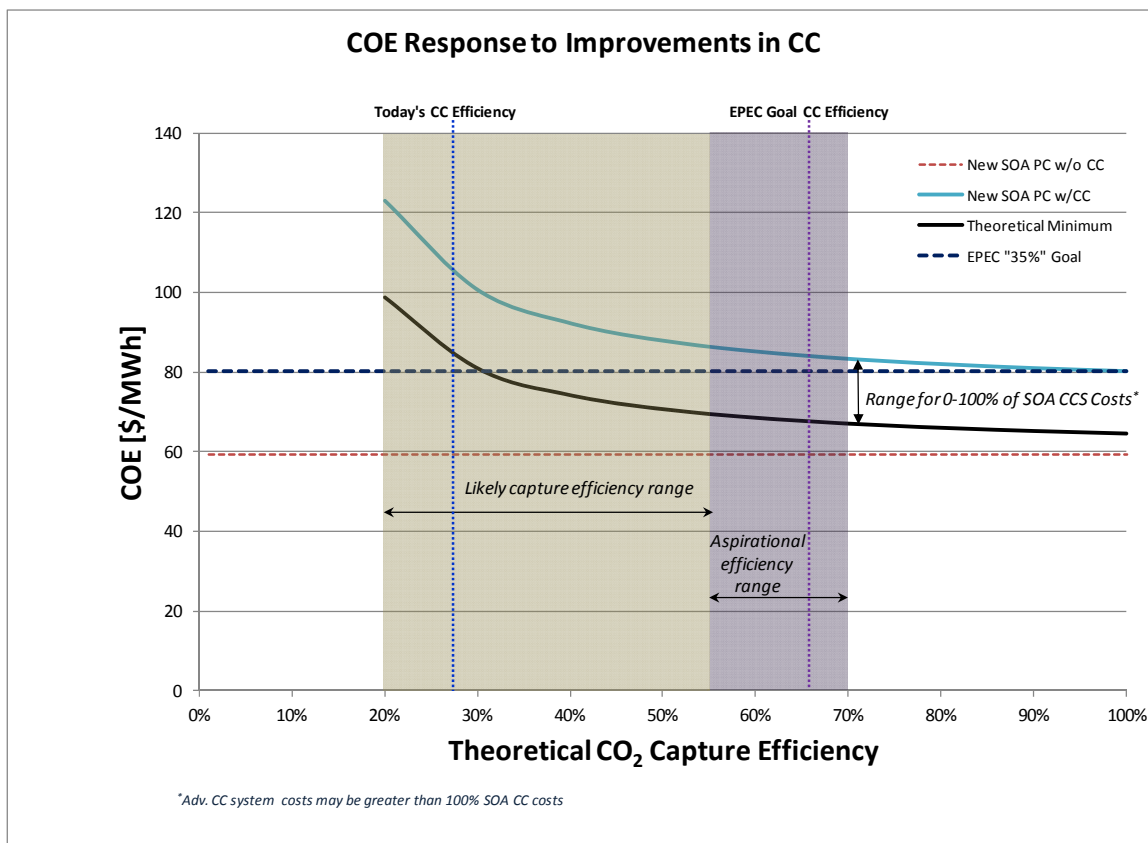


Figure 4: Response of COE to Improvements in Carbon Capture Performance

SOTA amine-based post combustion capture as reflected in (3) has a capture efficiency of approximately 27%. The EPEC-targeted reduction in cost of energy penalty is 55%, which results in a target capture efficiency of ~66%. The light blue line represents how COE would decrease if capture efficiency improved but equipment and O&M costs of SOTA capture systems remained constant<sup>h</sup>. It is clear from the chart above that reaching this high level of capture efficiency is still insufficient to meet the EPEC goal. Cost reductions are essential to meeting EPEC goals. This presents a challenge to industry as capture systems become more advanced and likely more complex. However, DOE's role in the carbon capture industry is to help fund necessary breakthrough development efforts that may be too high risk for private industry alone to create an efficient market for deployment. The NETL CC goals are consistent with this role, as such they balance electricity costs the market is anticipated to bear with the aggressive requirements for reducing climate change.

<sup>h</sup> On a \$/MWh basis. It is quite possible that absolute CC system costs will increase as they become more advanced.



### III. REALIZING EPEC PROGRAM R&D GOALS

Figure 2, discussed in Section II, illustrates a number of approaches for lowering the cost of CC for existing plants. Table 4 lists EPEC R&D Program objectives that should be considered moving forward and also provides strategies for achieving these objectives, with examples of technology-based solutions to consider.

*Table 4: Objectives for EPEC Program Sponsored R&D*

<b>OBJECTIVE 1 – Improve Energy Efficiency of CC</b>	
<b>Strategy</b>	<b>Examples</b>
Reduce Sorbent/Solvent Regeneration Energy	New or improved solvents, solid sorbents
Reduce CC Requirement	Supplement coal with alternative fuels such as natural gas, biomass, and wastes (lowers fossil carbon footprint) Use CO <sub>2</sub> for algal aquaculture to produce supplemental fuel on site
Process Intensification & System Integration	Combine unit operations to improve driving forces; Integrate processes to improve efficiency
Raise System Mechanical/Electrical Efficiencies	Employ steam turbine drives for compression; Direct CO <sub>2</sub> liquefaction
<b>OBJECTIVE 2 – Lower Specific Capital Costs of CC</b>	
Improve CC Process Technologies	Advanced absorption, adsorption, membrane, cryogenic, oxy-combustion, chemical looping, or hybrid technologies
Develop Alternative Materials of Construction	Use less and substitute lower cost materials
Process Intensification	Combine absorption/desorption in single vessel; Combine capture and compression/liquefaction
Reduce Equipment Volumes	Use oxygen-enriched combustion air to reduce flue gas volumetric flow and increase flue gas CO <sub>2</sub> concentrations (improved driving force)
<b>OBJECTIVE 3 – Lower Specific Operating Costs of CC</b>	
Improve Solvents, Solid Sorbents, Membranes, etc.	Lower materials and manufacturing costs and improve operating life
Improve CC Operability & Reliability	Develop and design for minimum maintenance, e.g., gas separation membranes
<b>OBJECTIVE 4 – Lower Specific Retrofit Costs</b>	
Process Synthesis	Develop new “re-design” concepts for retrofits
Reduce Engineering, Design, Installation Costs	Develop standard/modular CC retrofit packages
<b>OBJECTIVE 5 – Increase Onsite Steam &amp; Power Generation</b>	
Supply CC Parasitic Load with Waste Heat	Condensation of flue-gas water vapor
Add Supplemental Boiler for Steam Generation	Produce steam required by CC, possibly from alternative fuels such as natural gas, biomass, and wastes

The list in Table 4 is not complete since it is certain that future technology developments and further analysis will lead to new ideas and improved concepts.

Table 5 summarizes the general impact the various strategies outlined in Table 4 could have on the components of the direct and indirect costs of CC. Note that some approaches affect more than one component of the total cost, and in some cases result in both increases as well as decreases.

*Table 5: Cost Implications of EPEC Program R&D Strategies*

<b>OBJECTIVE 1 – Improve Energy Efficiency of CC</b>					
<b>Strategy</b>	<b>In-plant Capex</b>	<b>In-plant Opex</b>	<b>TSM</b>	<b>Retro-fit</b>	<b>Energy Penalty</b>
Reduce Sorbent/Solvent Regeneration Energy				↓	↓
Reduce CC Requirement	↓	↓	↓	↑	↓
Process Intensification and System Integration				↓	↓
Raise System Mechanical/Electrical Efficiencies				↑	↓
<b>OBJECTIVE 2 – Lower Specific Capital Costs of CC</b>					
Improve CC Process Technologies	↓				
Develop Alternative Materials of Construction	↓				
Process Intensification	↓				
Reduce Equipment Volumes	↓				
<b>OBJECTIVE 3 – Lower Specific Operating Costs of CC</b>					
New or Improved Solvents, Sorbents, Membranes		↓			
Improve CDR Operability and Reliability		↓			
<b>OBJECTIVE 4 – Lower Specific Retrofit Costs</b>					
Process Synthesis				↓	
Reduce Engineering, Design, Installation Costs				↓	
<b>OBJECTIVE 5 – Increase Onsite Steam &amp; Power Generation</b>					
Supply CDR Parasitic Load with Waste Heat				↑	↓
Add Supplemental Boiler for Steam Generation	↑↓	↑↓	↑↓	↑	↓

#### IV. CONCLUSIONS

It is clear that the fossil power industry must remain intact as climate change solutions are developed. However, this requires that CO<sub>2</sub> emissions from existing and new fossil power plants be significantly reduced in an economically viable fashion.

The R&D funded by NETL's EPEC Program is focused on longer-term, higher-risk CC projects. Accordingly, the CC R&D goals developed by NETL are feasible yet aggressive. The following long-term R&D goals have been established for capture and compression technologies to be deployed on existing PC power plants in the future:

- I. Reduce CO<sub>2</sub> emissions from fossil power plants by 90%**
- II. Reduce the overall economic penalty imparted by current CC technology (COE) by 55%. This is equivalent to no more than a 35% increase in COE of an identical plant without CC.**

These goals are feasible and may be achieved through a focused, aggressive R&D program directed toward:

1. Improving the efficiency of CC technology to minimize de-rating of existing PC power plants
2. Lowering the direct capital and operating costs of in-plant CC technology
3. Increasing the potential to utilize heat currently wasted in conventional PC plant operation

In addition, lowering the costs associated with retrofitting existing PC plants with CC will be needed to ensure that CC R&D can be implemented at a level necessary to significantly impact climate change. While this document focuses heavily on the discussion of greenfield plants, this is merely the basis for comparison of capture technologies. It is essential that the existing fleet of power plants be utilized to the maximum extent possible so that the nation can leverage the capital already invested in the current infrastructure. Building new, low-carbon power generation facilities is likely to be more expensive than retrofitting the existing fleet with CC(1). The goals presented in this document fully promote the advancement of CC technologies that can be implemented on both new and existing fossil based power plants.

The goals herein will be used to evaluate the progress of DOE-sponsored CC R&D under the EPEC Program. The strategies presented will be applied as guidance for existing and future DOE R&D projects related to PC power generation fitted with CC technology.

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## APPENDIX A – Economic Metrics for CC

There are several “metrics” that can be defined for measuring the economic performance of CO<sub>2</sub> capture (CC) technologies that are applicable to both new and existing power plants. Four possible options are:

Incremental cost of electricity (COE) – additional electricity generation costs due to adding CC, transport, and storage. Scalar is cost per electricity production unit (\$/kWh, ¢/kWh, mills/kWh, \$/MWh, etc.).

$$\text{Incremental COE} = COE_{\text{Capture}} - COE_{\text{NoCapture}} \quad (\text{A-1})$$

Percent increase in COE – percent increase in COE due to adding CC, transport, and storage above that of the non-capture equivalent power plant.

$$\% \text{Increase COE} = \left( \frac{COE_{\text{Capture}} - COE_{\text{NoCapture}}}{COE_{\text{NoCapture}}} \right) \times 100 \quad (\text{A-2})$$

Cost per ton of CO<sub>2</sub> captured (or removed) – cost specific to adding CC, transport, and storage. It does not completely account for CC energy penalty, because it does not account for CO<sub>2</sub> emitted during generation of parasitic power.

$$CO_2 \text{ Capture Cost} = \left( \frac{COE_{\text{Capture}} - COE_{\text{NoCapture}}}{CO_2 \text{ Captured}_{\text{PerNetOutput}}} \right) \quad (\text{A-3})$$

Cost per ton of CO<sub>2</sub> avoided – CO<sub>2</sub> avoided is the difference between the amount of CO<sub>2</sub> emitted by the plant without CC and the CO<sub>2</sub> emitted by the plant with CC (see Figure 5).

$$CO_2 \text{ Avoided Cost} = \left( \frac{COE_{\text{Capture}} - COE_{\text{NoCapture}}}{CO_2 \text{ Emissions}_{\text{NoCapture}} - CO_2 \text{ Emissions}_{\text{Capture}}} \right) \quad (\text{A-4})$$

The incremental COE or percentage increase in COE may be the easiest concept to grasp. However, for policymakers and regulators, CC cost in \$/ton of CO<sub>2</sub> captured or avoided are alternative metrics that may have more meaning when comparing to a potential CO<sub>2</sub> tax value.

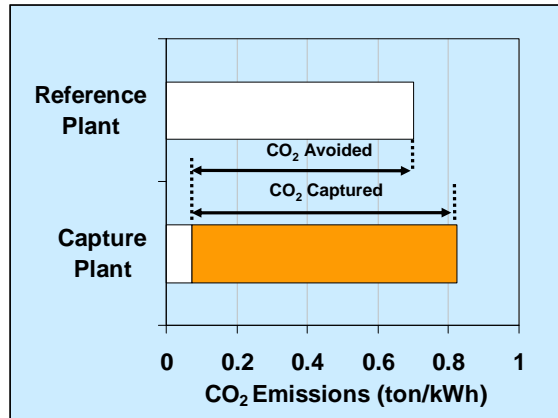


Figure 5: Difference Between “CO<sub>2</sub> Captured” and “CO<sub>2</sub> Avoided”

Table 6 and Table 7 consolidate values of various ways to express the economic portion of the EPEC CC goals.

Table 6: Various Representations of EPEC Economic Capture Goal<sup>i</sup>

Economic Metrics	Base Value	Goal Value	Metric Value
% Decrease in $\Delta$ COE for Capture [%]	44.6	20.8	53% <sup>i</sup>
Absolute Decrease in $\Delta$ COE for Capture [%]	44.6	20.8	23.8
% Increase in Baseline COE [%]	59.3	80.1	35%
$\Delta$ Baseline COE [\$/MWh]	59.3	80.1	20.8
Avoided Cost [\$/ton CO <sub>2</sub> Avoided]	N/A	25.0	25.0
Captured Cost [\$/ton CO <sub>2</sub> Captured]	N/A	20.3	20.3
$\Delta$ Dispatch Cost [\$/MWh]	28.1	35.6	7.5
% Increase in Dispatch Costs [\$/MWh]	28.1	35.6	27%

Table 7: COE Category Goals

Categorical COE Goals [\$/MWh]	% Reductions in SOTA increases
Capital	50%
Fixed O&M	20%
Variable O&M	80%
Fuel	0%
Energy Penalty	55%

<sup>i</sup> The 55% COE reduction goal cited throughout the report is rounded for convenience from the 53% listed in Table 6, which originates from previous versions of the NETL CC goal oriented in a different fashion.

## APPENDIX B – Thermodynamic Analysis of CC

The minimum energy of CO<sub>2</sub> separation can be deduced according to the first and second law of thermodynamics. Consider the following steady state flow system (also assuming that the kinetic and potential energy terms are negligible):

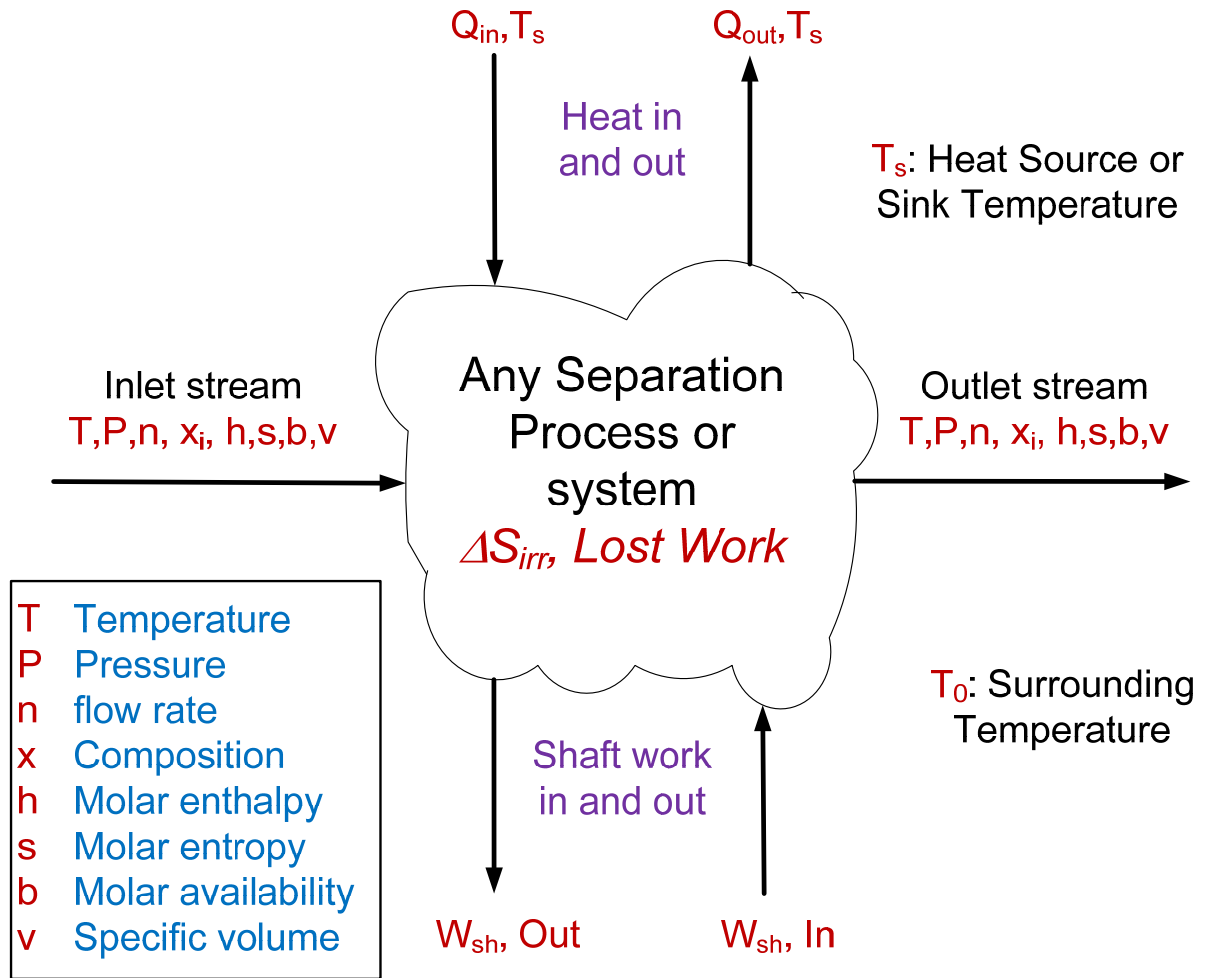


Figure 6: Schematic of a Steady State Flow System

The first law of thermodynamics requires that:

$$\begin{aligned}
 & (\text{Stream enthalpy flow} + \text{heat transfer} + \text{shaft work})_{\text{leaving system}} \\
 & - (\text{Stream enthalpy flow} + \text{heat transfer} + \text{shaft work})_{\text{entering system}} = 0
 \end{aligned}$$

Or mathematically:

$$\sum_{\text{out of system}} (nh + Q + W_{sh}) - \sum_{\text{into system}} (nh + Q + W_{sh}) = 0 \tag{B-1}$$

And the second law of thermodynamics requires that:

$$\begin{aligned} & (\text{Stream entropy flow} + \text{entropy flow by heat transfer})_{\text{leaving system}} \\ & - (\text{Stream entropy flow} + \text{entropy flow by heat transfer})_{\text{entering system}} \\ & = \text{Production of entropy by the process} \end{aligned}$$

Or it can be expressed as:

$$\sum_{\text{out of system}} \left( ns + \frac{Q}{T_s} \right) - \sum_{\text{in to system}} \left( ns + \frac{Q}{T_s} \right) = \Delta S_{irr} \quad (\text{B-2})$$

Here,  $\Delta S_{irr}$  is a measure of the energy inefficiency of the process, the greater the value of  $\Delta S_{irr}$ , the more inefficient of the process.

The availability (Exergy) balance of the system is:

$$\sum_{\text{in to system}} \left( nb + Q \left( 1 - \frac{T_0}{T_s} \right) + W_{sh} \right) - \sum_{\text{out of system}} \left( nb + Q \left( 1 - \frac{T_0}{T_s} \right) + W_{sh} \right) = LW \quad (\text{B-3})$$

Here “b” is the molar availability of the stream and is defined as:

$$b = h - T_0 s = \sum x_i \cdot h_i(T) - T_0 \left[ \sum x_i \cdot s_i(T) + R \sum x_i \cdot \ln \left( \frac{1}{x_i} \right) \right] \quad (\text{B-4})$$

And LW is the lost work of the process, which is defined:

$$LW = T_0 \Delta S_{irr} \quad (\text{B-5})$$

The minimum work required can be achieved when the inefficiency loss of the separation process LW is zero, that is, the separation process is reversible. Under such circumstances equation (B-3) can be rearranged into:

$$W_{\min} = \sum_{\text{into system}} nb - \sum_{\text{out of system}} nb \quad (\text{B-6})$$

Equation (B-3) is now applied to the flue gas CO<sub>2</sub> separation system. For simplicity, the flue gas is assumed to be an ideal gas mixture and it has only two components (N<sub>2</sub> and CO<sub>2</sub>). The mole fractions of the flue gas components are  $x_{\text{CO}_2}$  for CO<sub>2</sub> and  $1 - x_{\text{CO}_2}$  for N<sub>2</sub>, respectively. Further, the required recovery rate for CO<sub>2</sub> is  $\theta$  and the product CO<sub>2</sub> is assumed to be 100% pure. Figure 7 is the schematic diagram of the separation process.



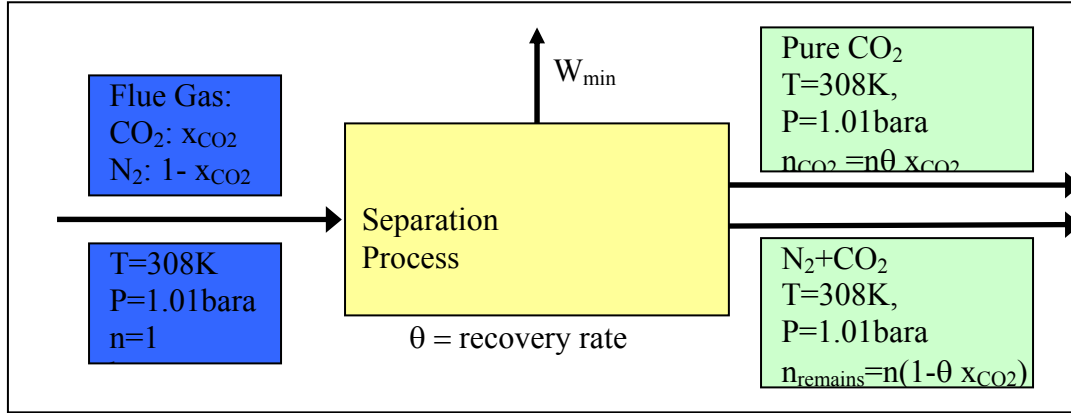


Figure 7: Schematic Diagram of CO<sub>2</sub> Separation from Flue Gas

Under the above assumptions and the conditions shown in Figure 7, each term in equation (B-6) can be calculated as follows.

The molar availability of the feed stream is:

$$b_{feed} = h - T_0 s = \sum x_i \cdot h_i(T) - T_0 \left[ \sum x_i \cdot s_i(T) + R \sum x_i \cdot \ln\left(\frac{1}{x_i}\right) \right]$$

$$b_{feed} = x_{CO_2} h_{CO_2} + (1 - x_{CO_2}) h_{N_2} - T_0 \left[ x_{CO_2} s_{CO_2} + (1 - x_{CO_2}) s_{N_2} + R \left\{ x_{CO_2} \ln \frac{1}{x_{CO_2}} + (1 - x_{CO_2}) \ln \frac{1}{(1 - x_{CO_2})} \right\} \right] \quad (B-7)$$

The molar availability of pure CO<sub>2</sub> stream is:

$$b_{CO_2} = h - T_0 s = h_{CO_2} - T_0 s_{CO_2} \quad (B-8)$$

And the molar availability of the remaining flue gas is:

$$b_{remains} = h - T_0 s = \sum x_i \cdot h_i(T) - T_0 \left[ \sum x_i \cdot s_i(T) + R \sum x_i \cdot \ln\left(\frac{1}{x_i}\right) \right]$$

$$b_{remains} = \frac{(1 - \theta) x_{CO_2}}{1 - \theta x_{CO_2}} h_{CO_2} + \frac{(1 - x_{CO_2})}{1 - \theta x_{CO_2}} h_{N_2} - T_0 \left[ \frac{(1 - \theta) x_{CO_2}}{1 - \theta x_{CO_2}} s_{CO_2} + \frac{(1 - x_{CO_2})}{1 - \theta x_{CO_2}} s_{N_2} + R \left\{ \frac{(1 - \theta) x_{CO_2}}{1 - \theta x_{CO_2}} \ln \frac{1 - \theta x_{CO_2}}{(1 - \theta) x_{CO_2}} + \frac{(1 - x_{CO_2})}{1 - \theta x_{CO_2}} \ln \frac{1 - \theta x_{CO_2}}{(1 - x_{CO_2})} \right\} \right] \quad (B-9)$$

The minimum work of the separation system in terms of per mole of feedstock is:

$$W_{min} = \sum_{\text{into system}} b - \sum_{\text{out of system}} b = b_{in} - \theta x_{CO_2} b_{CO_2} - (1 - \theta x_{CO_2}) b_{remains}$$

$$W_{min} = \text{Eq. (B-7)} - \theta x_{CO_2} * \text{Eq. (B-8)} - (1 - \theta x_{CO_2}) * \text{Eq. (B-9)} \quad (B-10)$$

Through mathematical manipulations, Equation (B-10) can be simplified to:

$$W_{\min} = -RT_0 \left( x_{CO_2} \ln\left(\frac{1}{x_{CO_2}}\right) + (1-\theta)x_{CO_2} \ln\left(\frac{1}{(1-\theta)x_{CO_2}}\right) + (1-\theta)x_{CO_2} \ln((1-\theta)x_{CO_2}) \right) \quad (B-11)$$

And the minimum work in terms of per mole of CO<sub>2</sub> captured is:

$$W_{\min} = -\frac{RT_0}{\theta} \left( \ln\left(\frac{1}{x_{CO_2}}\right) + \frac{(1-\theta)x_{CO_2}}{x_{CO_2}} \ln\left(\frac{1}{(1-\theta)x_{CO_2}}\right) + (1-\theta) \ln((1-\theta)x_{CO_2}) \right) \quad (B-12)$$

Using equation (B-12), the minimum work required to recover  $\theta$  of the CO<sub>2</sub> with 100 percent purity can be calculated. At  $\theta = 90\%$  the minimum work is -7.68 kJ/moleCO<sub>2</sub> or -175 kJ/kgCO<sub>2</sub>. The negative value indicates input of work to the process is required. Since practical CO<sub>2</sub> separations are carried out at around 40°C (308 K), 308 K is used for T<sub>0</sub>, instead of 298 K in this calculation.

The pressure of the separated CO<sub>2</sub> in the above calculation (Figure 7) is 1.01 bars. However, for pipeline transportation, CO<sub>2</sub> must be compressed to 150 atmospheric pressures (about 2,200 psia), that is the separated CO<sub>2</sub> needs to be further compressed.

The minimum compression work, W<sub>c</sub>, required to compress CO<sub>2</sub> from 1.01bar to 150bar (2,200 psia) can be easily obtained by using the equation (B-6):

$$W_{\min} = \sum_{\text{into system}} nb - \sum_{\text{out of system}} nb = [h - T_0 s]_{p=1.01\text{bar}} - [h - T_0 s]_{p=150\text{bar}} = \Delta h - T_0 \Delta s \quad (B-13)$$

**Table 8: Thermodynamic Properties of CO<sub>2</sub> at Different Pressures (4)**

<b>T</b> (C)	<b>P</b> (atm)	<b>h</b> (kJ/mol)	<b>s</b> (J/mol*K)
<b>40</b>	<b>1</b>	<b>22.828</b>	<b>122.3</b>
<b>40</b>	<b>150</b>	<b>12.543</b>	<b>54.737</b>

Using the thermodynamic data from NIST Webbook (See Table 8) we have

$$W_c^{\min} = \Delta h - T_0 \Delta s \approx -10.87(\text{kJ/molCO}_2) = -247.0(\text{kJ/kgCO}_2) \quad (B-14)$$

**Again, negative value indicates that work input is required.** Therefore, the total minimum energy required for capturing 90% of the CO<sub>2</sub> from a post-combustion flue gas and compressing it to 2,200 psia is:

$$W_{CCS}^{\min} = 175\text{kJ/kgCO}_2 + 247\text{kJ/kgCO}_2 = 422\text{kJ/kgCO}_2 = 180.3\text{BTU/lbCO}_2 \quad (B-15)$$

The separation energy consumption for the current state of the art (SOTA) amine process can be obtained from the NETL Baseline Report which is 1,506 kJ/kgCO<sub>2</sub> (3). The current efficiency of the amine process is:

$$\text{Efficiency} = 422/1506 = 28.0\% \quad (\text{B-16})$$

Obviously, the efficiency of current SOTA amine process is still low with significant room to improve. For the EPEC program goal, a 55% reduction in energy consumption was assumed. If achieved through new separation technology development, the efficiency of the separation process will be:

$$\text{Efficiency} = 422 / \{(1 - 0.55) \times 1506\} \approx 62\% \quad (\text{B-17})$$

Efficiency of 62% is high for a separation process, but is theoretically possible.