Topical Report 4: Conceptual 500 MW Design

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ABSTRACT

Under cooperative agreement DE-NE0005649 ADA-ES, Inc. is working to assess the viability and accelerate development of solid sorbents for post-combustion CO_2 capture. This program is focused on retrofitting the existing fleet of coal-fired power plants, taking into consideration the DOE's goal for commercialization by 2020. To adequately assess the viability of solids for post-combustion capture, the costs associated with a commercial system must be considered. However, since sorbent-based CO_2 capture is not yet a commercial technology, processes and equipment that are currently used for other applications were evaluated to provide insights related to operating costs, footprint, etc. of a full-scale CO_2 capture system. The conceptual design was developed specifically for a retrofit at AEP's Conesville Unit 5. ADA worked with Stantec Consulting, an engineering firm with extensive experience in the power sector, to complete a technology survey of potential equipment options and develop high level cost estimates for the operation of a sorbent-based CO_2 capture system based on the selected technology. The sorbent-based design was directly compared to an MEA-based design for the same installation.

The operating costs were determined to be significantly less for the sorbent-based capture design compared to the MEA system. As expected this can be attributed to the lower energy penalty due to the lower specific heat capacity of the sorbents versus aqueous systems. The capital costs as projected by Stantec were also lower than that of the MEA system, therefore leading to an overall levelized cost of electricity savings greater than 30%.

The high level cost analysis conducted by Stantec was based on equipment currently utilized in other industries for different applications (i.e. not CO_2 capture). For this reason the capital costs can only be considered order of magnitude estimates, but such estimates are still helpful in the areas of importance for future technology development. The estimated costs listed in order of significance are:

Capital Costs > Operating Costs >> Sorbent Replacement > Employees

The capital costs and operating costs are the most significant contributors to the LCOE increase. Although the costs for sorbent-based CO_2 capture were lower than those for aqueous MEA-based capture, the savings were not enough to achieve the DOE's goals of ≤35% increase in the LCOE; further reductions in costs will be necessary. Future technology development efforts will be directed at reducing the key cost factors identified during this study: capital costs and operating costs.

Table of Contents

EXECUTIVE SUMMARY **5**
INTRODUCTION **7**
APPROACH **8**
RESULTS AND DISCUSSION **10**
CONCLUSIONS **15**
REFERENCES **16**
LIST OF ACRONYMS AND ABBREVIATIONS **17**

List of Figures

Figure 1: Conceptual Flow Sheet.....10

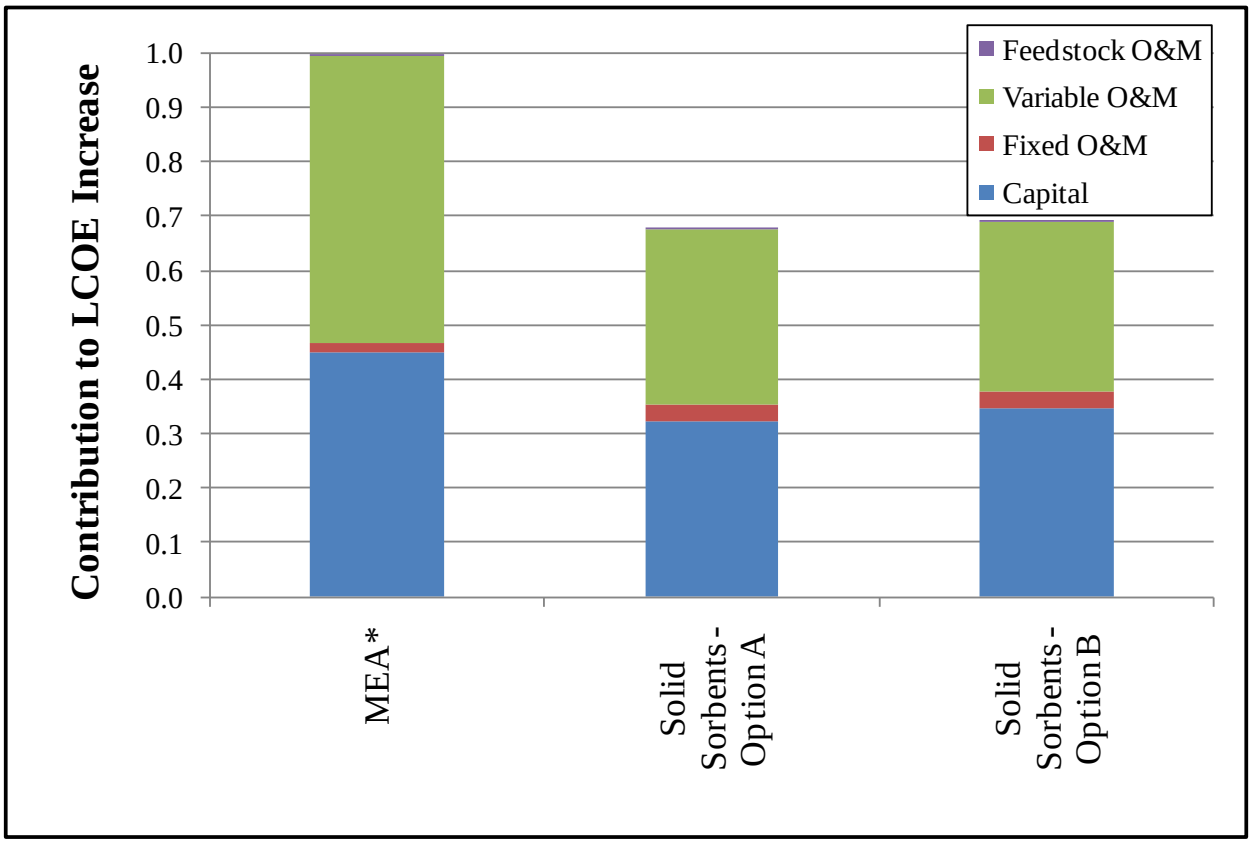
Figure 2: Comparison of Energy Penalty for MEA and Solid Sorbent-Based CO_2 Capture at AEP's Conesville Power Plant.....12

Figure 3: Contribution of LCOE Increases for CO_2 Capture Options at AEP's Conesville Power Plant (*MEA Costs from NETL, 2007 with costs scaled to 2010 dollars) 13

EXECUTIVE SUMMARY

Under cooperative agreement DE-NE0005649 ADA-ES, Inc. is working to assess the viability and accelerate development of solid sorbents for post-combustion CO_2 capture. This program is focused on retrofitting the existing fleet of coal-fired power plants, taking into consideration the DOE's goal for commercialization by 2020. To adequately assess the viability of solids for post-combustion capture, the costs associated with a commercial system must be considered. However, since this is not a commercial technology, processes and equipment that are currently used for other applications were evaluated to provide insights related to capital costs, operating costs, footprint, etc. when implemented at AEP's Conesville Unit 5. ADA worked with Stantec Consulting, an engineering firm with extensive experience in the power sector, to complete a technology survey of potential equipment options and develop high level cost estimates for the operation of a sorbent-based CO_2 capture system based on the selected technology. The sorbent-based design was directly compared to a monoethanolamine (MEA)-based design for installation at the same power plant.

The contribution to the levelized cost in electricity (LCOE) for MEA (from a 2007 DOE report) and two sorbent based options are provided in the figure below. All costs have been non-dimensionalized by the LCOE for MEA. For the solid sorbent-based Option A there was no heat exchange between the hot CO_2 lean sorbent exiting the regenerator and the cooler CO_2 laden sorbent entering the regenerator. For Option B two heat exchangers were used, with a heat transfer fluid circulated between them, to transfer sensible heat from the hot CO_2 lean sorbent exiting the regenerator to the cooler CO_2 lean sorbent entering the regenerator. Option B led to a further reduction in the energy penalty and cooling requirements versus aqueous MEA, but also resulted in additional capital costs due to the purchase of the heat exchangers. All LCOE contributions in the figure below have been non-dimensionalized using the overall estimated LCOE increase for MEA. Between the two sorbent-based processes, Option A is less costly compared to Option B because the capital costs associated with two heat exchangers is greater than the cost savings by recovering some of the sensible heat from the sorbent exiting the regenerator.



The operating costs were determined to be significantly less for the sorbent-based capture process compared to the MEA system. As expected this can be attributed to the lower energy penalty. The capital costs as projected by Stantec were also lower than that of the MEA system, therefore leading to an overall LCOE savings of over 30% for both sorbent-based options.

The high level cost analysis conducted by Stantec was based on equipment currently utilized in other industries for different applications (i.e. not CO_2 capture). For this reason the capital costs can only be considered order of magnitude estimates, but such estimates are helpful to rank importance of costs to direct future technology development. The estimated costs listed in order of significance are:

Capital Costs > Operating Costs >> Sorbent Replacement > Employees

The capital costs and operating costs are the most significant contributors to the LCOE increase. Although sorbent based CO_2 capture led to a reduction in costs versus an MEA system, the cost savings were not enough to achieve the DOE's goals of ≤35% increase in the LCOE; further reductions in costs will be necessary. Future technology development efforts will be directed at reducing the key cost factors identified during this study: capital costs and operating costs.

INTRODUCTION

There are many potential CO_2 capture technologies in the research phase of the development process. Many such technologies offer promising laboratory or bench-scale experimental results, but it is difficult to convert such results into meaningful estimates for a commercial CO_2 capture process. Solid sorbents are a potential option for CO_2 capture that could lead to a significant reduction in the energy penalty associated with regeneration. Such a reduction in the energy penalty should result in less steam extraction and, thus, a smaller impact to the amount of electricity produced. With an overall smaller impact to the power plant, the CO_2 capture technology operating costs related to steam extraction and energy penalty should be lower for solid sorbents compared to aqueous MEA.

Under cooperative agreement DE-NE0005649 ADA-ES, Inc. is working to assess the viability and accelerate development of solid sorbents for post-combustion CO_2 capture. This program is focused on retrofitting the existing fleet of coal-fired power plants, taking into consideration the DOE's goal for commercialization by 2020. To adequately assess the viability of solids for post-combustion capture, the costs associated with a commercial system must be considered. However, since this is not a commercial technology, processes and equipment that are currently used for other applications were evaluated to provide insights related to operating costs, footprint, etc. This topical report discusses the costs associated with implementation of commercial-scale sorbent-based CO_2 capture at AEP's Conesville Unit 5 (430 MW prior to CO_2 capture). This power plant was selected as the reference plant because extensive information was available regarding the power plant operations in addition to information related to the integration and application of an aqueous MEA-based CO_2 capture process at this site from a comprehensive report issued by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL).[1] Using the same cost and technical assumptions provided in the NETL report, a high level evaluation of the costs associated with post-combustion CO_2 capture was completed.

APPROACH

ADA-ES is worked closely with Stantec Consulting, an engineering firm with experience in the power sector as well as retrofit post-combustion CO_2 capture, to examine potential process and equipment options. In a previous topical report, 05649T01 "Topical Report 1, 2, and 3: Technology Survey, Screening, and Final Selection"[2], different equipment options were considered for post-combustion CO_2 capture with solids. These options were compared to each other and a final technology selection was made. The purpose of this technology selection was not to propose a final commercial-scale process and equipment for CO_2 capture with solids, but rather to identify one specific process that could be an option to develop high level cost estimates. There were two main objectives related to completing the high level cost assessment:

1) To complete a viability assessment it is important to understand the costs associated with large-scale implementation.
2) To accelerate the technology development it is important to understand the cost drivers for the technology so that future research and development efforts can be focused on these key areas.

This report highlights the major findings of the high level cost assessment conducted by Stantec. Even though the cost assessment completed by Stantec was high level in nature, it is crucial that there be a baseline for comparison. Since aqueous monoethanolamine (MEA) is the most understood, demonstrated, and documented post-combustion CO_2 capture process, it was used a basis for comparison for the sorbent-based capture process. The costs associated with CO_2 capture are highly dependent upon the power plant at which the process is being implemented. For this reason, a reference power plant was selected where the costs of both MEA and sorbent-based CO_2 capture could be compared. A report issued by NETL detailing the costs associated with implementation of MEA at AEP's Conesville power plant was used as the basis for comparison.[1] Note that the costs from the DOE report were escalated to 2010 dollars by Stantec.

The key considerations in the cost analysis included:

- Capital costs
  - CO_2 capture equipment
  - CO_2 compressors
  - Back pressure turbine
- Energy penalty costs
  - Steam derate
  - Auxiliary power (including compression)
  - Let down turbine (provides additional electricity)

Costs that were not included in the assessment include:

- Sequestration costs (including monitoring, liability, etc.)

Because the technology selection and cost analysis began concurrently with the start of sorbent-related experimental data collection by ADA, Stantec made several assumptions based on publicly available literature. Key assumptions used for the cost analysis include:

- Particles physically resemble activated carbon with respect to size and density (provided by ADA)

- Five seconds of reaction time required for adsorption (provided by ADA based on initial fixed bed tests)
- Five hundred seconds of reaction time is required for desorption (provided by ADA based on initial fixed bed tests)
- Heat capacity[3] of the sorbent is 0.3 BTU/lb·°F
- Working capacity[3] of solid sorbents is 10 wt%
- Heat of reaction is 760 Btu/lb CO_2 adsorbed
- Solid sorbent loss of 0.005% per cycle due to physical attrition[4]
- CO_2 product pipeline and storage was not included[2]
- The power plant capacity factor[2] was 85%
- Make-up power cost was 7.02 ¢/kWh (2010 dollars)[2]
- Costs extracted from the DOE report[1] were adjusted to 2010 dollars using an annual inflation rate[2] of 2.35%
- Potential revenue from selling CO_2 product was excluded[2]

According to Stantec, the level of cost accuracy most likely matches a class V estimate, as determined by the Association for the Advancement of Cost Engineering International (AACE). A Class V estimate is of suitable accuracy for screening purposes, and applies when a low level of project definition exists. All costs are estimated in 2010 U.S. dollars, including the overall costs for the MEA capture process, which have been scaled to 2010 dollars so the two technologies could be compared.

RESULTS AND DISCUSSION

For details on the technology selection process, please refer to the preceding topical report.[2] A short description is provided for reference, but is not the focus of this report. The conceptual flow sheet provided in Figure 1 shows how the selected equipment could be arranged in a power plant to capture carbon dioxide from flue gas.

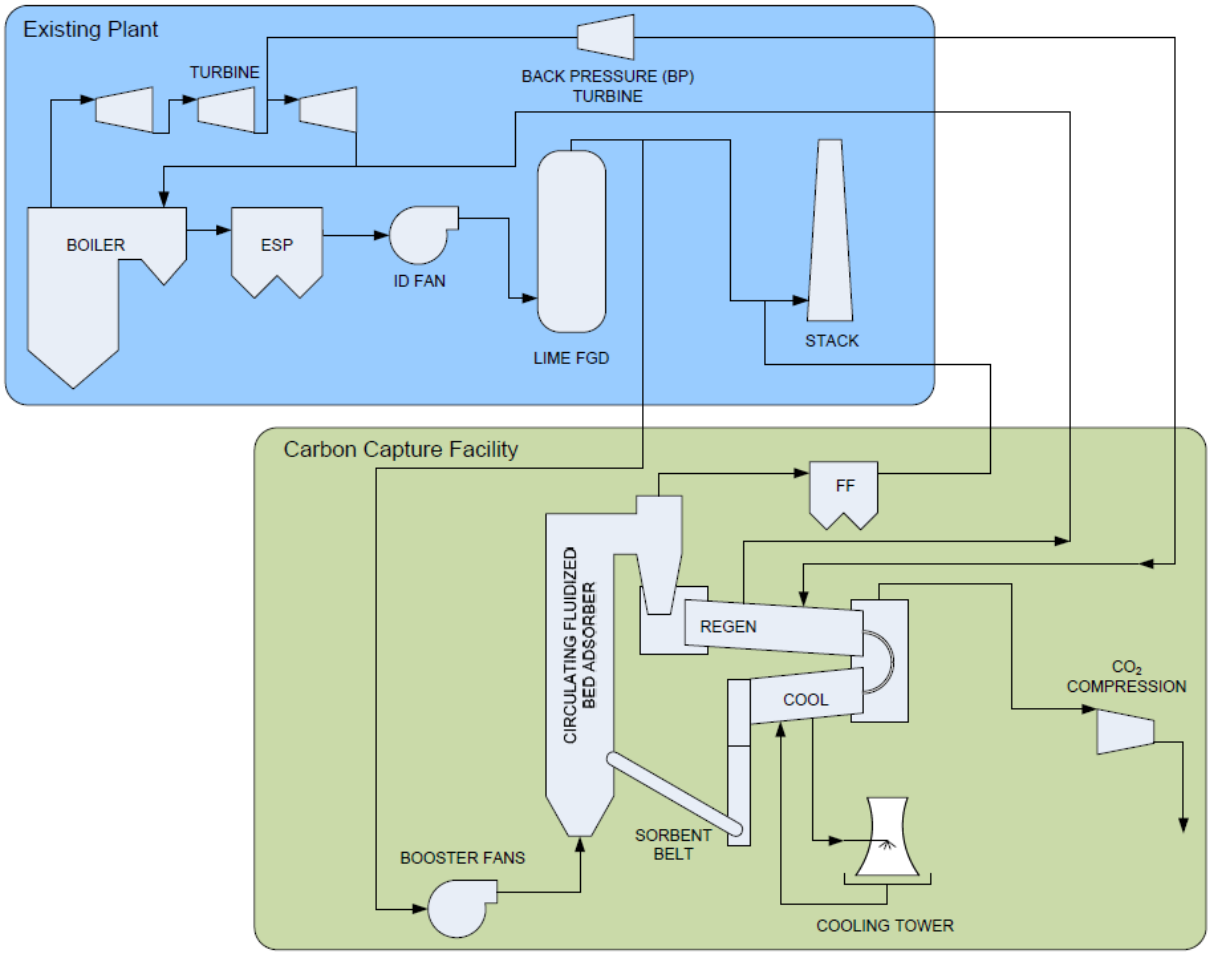


Figure 1: Conceptual Flow Sheet

In this conceptual arrangement, flue gas is sourced from the existing unit after particulate removal. It then proceeds through a heat recovery device, where the flue gas is cooled. The recovered heat is incorporated with the regeneration of the sorbent. The cooled flue gas then enters a wet FGD system for desulphurization and additional cooling. The pretreated gas then proceeds through a booster fan, then through a vertically arranged adsorber. Cooled solid sorbent is introduced to the bottom of the adsorber, and the flue gas carries it upwards in a circulating fluidized bed (i.e. transport reactor).

Carbon dioxide is adsorbed by the solid particles (either through a physical reaction, a chemical reaction, or a combination of the two), which are separated from the flue gas by a cyclone. The flue gas then proceeds back to stack, while the solids are directed towards regeneration. A rotary

kiln, jacketed to provide heat, conveys the solids slowly away from the adsorber, and then back. The CO_2 is driven off as the reaction is reversed and is withdrawn for compression. A final kiln is jacketed for cooling, which prepares the sorbent for reintroduction to the adsorber.

Stantec used the CO_2 capture process shown in Figure 1 to develop estimates for the capital costs, operating costs, footprint, and other important criteria for a commercial-scale power plant that is retrofit for CO_2 capture. Stantec provided high level costs grouped into the following categories:

- Feedstock O&M
  - Natural gas used to dry CO_2
- Variable O&M
  - Levelized make-up power
  - Sorbent replacement
  - Costs for additional chemicals for SO_2 scrubbing
  - Make-up water
  - Water disposal
- Fixed O&M
  - Employees
  - Maintenance
- Capital
  - CO_2 capture equipment
  - Back pressure turbine
  - Compressors

Two different options for a solid-based system were evaluated. For Option A there was no heat exchange mechanism provided between the hot CO_2 lean sorbent exiting the regenerator and the cooler CO_2 laden sorbent entering the regenerator. For Option B two heat exchangers were used, with a heat transfer fluid circulated between the two, to transfer sensible heat from the hot CO_2 lean sorbent exiting the regenerator to the cooler CO_2 lean sorbent entering the regenerator. Option B led to a further reduction in the energy penalty and cooling requirements versus aqueous MEA, but also resulted in additional capital costs due to the purchase of the heat exchangers.

The fundamental reason that solid sorbents are being evaluated for post-combustion CO_2 capture is to reduce the energy penalty associated with the release of the CO_2 during sorbent regeneration. Using the assumptions provided in the Approach section, Stantec evaluated the energy penalty from the MEA and sorbent-based CO_2 capture processes. The energy output for the power plant with and without CO_2 capture is provided in Figure 2. The blue bars in the figure represent the net electricity generation from the power plant. Conesville Unit 5 without CO_2 capture generates 430 MW net electricity. The purple bars represent the additional power generated using the back pressure turbine, which was used to generate steam at the appropriate temperature and pressure necessary for regeneration. The green and red bars represent the energy penalty (negative in value) due to the steam derate and auxiliary power, respectively. Because significantly less steam was required for the sorbent-based process, Option A and Option B at Conesville resulted in 343 MW and 346 MW of electricity generation, respectively, while the MEA process resulted in 303 MW net electricity generation. Since the case with

MEA-based capture required more steam than the sorbent-based process, the BP turbine for MEA generated more electricity. It is possible that at a new power plant where the steam can be extracted directly from the low pressure turbine the sorbent-based capture options would perform even more favorably compared to the MEA process.

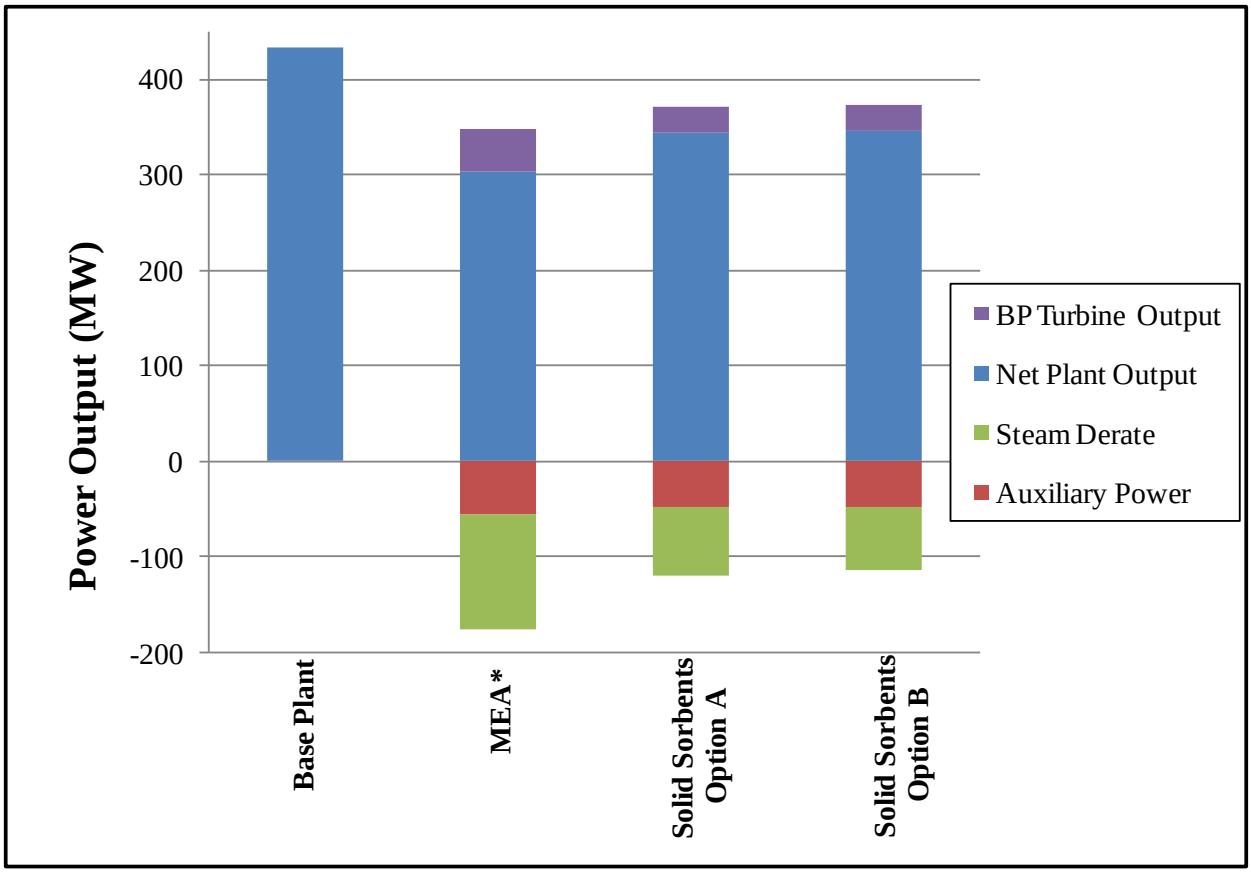


Figure 2: Comparison of Energy Penalty for MEA and Solid Sorbent-Based CO_2 Capture at AEP's Conesville Power Plant.

The contribution to the levelized cost in electricity (LCOE) for MEA[1] and the two sorbent based options are provided in Figure 3. All costs have been non-dimensionalized using the overall estimated LCOE increase for MEA (7.59 ¢/kWh). Between the two sorbent-based processes, Option A was less costly compared to Option B because the capital costs associated with two heat exchangers was greater than the cost savings by recovering some of the sensible heat from the sorbent exiting the regenerator.

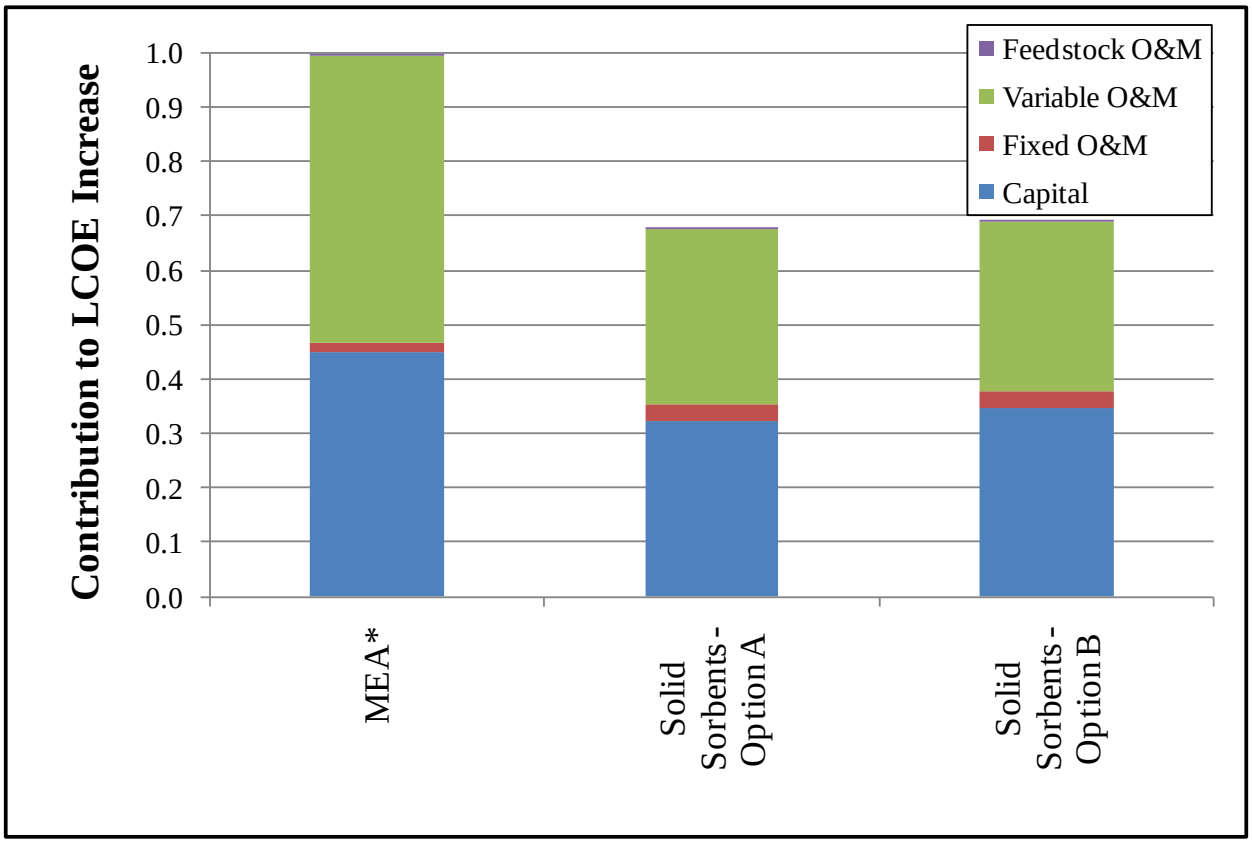


Figure 3: Contribution of LCOE Increases for CO_2 Capture Options at AEP's Conesville Power Plant (*MEA Costs from NETL, 2007 with costs scaled to 2010 dollars)

As expected the operating costs are significantly less for the sorbent-based processes compared to the MEA system, which can be attributed to the lower energy penalty. The capital costs as projected by Stantec were also lower than that of the MEA system, therefore leading to an overall LCOE savings of 32% and 31% for Option A and Option B, respectively.

The high level cost analysis conducted by Stantec was based on equipment currently utilized in other industries for different applications (i.e. not CO_2 capture). For this reasons the capital costs can only be considered order of magnitude estimates, but such estimates are still helpful in the areas of importance for future technology development. The estimated costs listed in order of significance are:

Capital Costs > Operating Costs >> Sorbent Replacement > Employees

The capital costs and operating costs are the most significant contributors to the LCOE increase. Therefore, future technology development efforts will be aimed at identifying means to reduce such costs.

CONCLUSIONS

A high level cost analysis was completed to determine the key cost drivers for a sorbent-based CO_2 capture process. The sorbent-based capture options yielded significant energy penalty and cost savings versus an aqueous amine system. In fact, for a sorbent-based CO_2 capture process without a CO_2 laden/lean sorbent heat exchanger the LCOE increase was over 30% lower than that of the MEA capture process. However, this cost savings is not currently enough to meet the DOE's target of <35% increase in LCOE. The cost drivers were also identified during this study; because the capital costs and operating costs were the most significant contributors to the LCOE, future technology development efforts will be directed at reducing these costs.

REFERENCES

1. Ramezan M., Skone T.J., Nsakala N., Liljedahl G.N., "Carbon Dioxide Capture from Existing Coal-Fired Power Plants", Final Report DOE/NETL-401/110907, December, 2007.
2. Martin, C., Sjostrom, S., Krutka, H., Richard, M., Cameron, D., "Topical Report 1, 2, and 3: Technology Survey, Screening, and Final Selection, Topical Report 05649T01, July 2010.
3. Tarka, T. J., Ciferno, J. P., Gray, M. L., Fauth, D., "CO_2 Capture Systems Using Amine Enhanced Solid Sorbents", 5th Annual Conference on Carbon Capture and Sequestration, Alexandria, VA, May 2006.

LIST OF ACRONYMS AND ABBREVIATIONS

DOE	Department of Energy
LCOE	Levelized Cost of Electricity
MEA	Monoethanolamine
NETL	National Energy Technology Laboratory
TSA	Temperature Swing Adsorption