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Assessment of solid sorbents as a competitive post-combustion CO₂ capture technology

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Abstract

Solid sorbents are believed to be a promising early-stage technology for achieving more cost-effective capture of carbon dioxide (CO₂) from large point sources, especially coal-fired power plants. To better assess the potential advantages of solid sorbents for post-combustion CO₂ capture, this paper presents preliminary results of an analysis of two representative sorbents in an integrated model for estimating plant-level performance and costs for a new, supercritical pulverized coal (PC) power plant. A probabilistic comparison is then made between two solid sorbents and a commercial amine-based liquid solvent system. Our results show that for a 90% CO₂ removal efficiency, the solid sorbent provides an expected net plant efficiency of 32% (higher heating value basis) for a metal-organic framework solid and 29% efficiency for a solid amine-based sorbent, versus 28% net efficiency with a liquid amine-based system using the same reference plant assumptions. Cost estimates for solid sorbent systems, however, remain highly uncertain at this time, mainly because of large uncertainties in capital cost estimates.

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC)'s fourth assessment report states that as a result of anthropogenic CO₂ emission, global atmospheric concentration increased from a pre-industrial value of ~280 ppmv to ~380 ppmv in 2005 [1], and has continued to rise to the current level of ~390 ppmv [2]. Regardless of what global temperature increase is deemed acceptable, reversing the trend towards higher emissions is essential in order to stabilize atmospheric greenhouse gas concentrations.

Lowering CO₂ emissions from large point sources, such as coal-fired power plants, petroleum refineries, and cement plants, is identified as a major option to address the problem of climate change. The electricity sector in particular is likely to be a main focus of potential legislation and/or regulation that would limit CO₂ emissions due to its large contributing role in CO₂ emissions. [1] There are several options available to decrease CO₂ emissions, one of which is carbon dioxide capture and storage (CCS).

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The National Energy Technology Laboratory (NETL) and other scientific experts—such as the Environmental Protection Agency (EPA), the Electrical Power Research Institute (EPRI), and the Intergovernmental Panel on Climate Change (IPCC)—believe that CCS represents the sole practical option to achieve considerable CO₂ emission reductions from fossil-fuelled power plants. [3]

2. Objectives of this study

A major concern with currently available CCS systems is the high energy penalty associated with separating CO₂ from the absorbing solution. The resulting increase in the cost of electricity is drastic and a priority focus area of research. As a result, additional research and development efforts are focused on developing alternative CO₂ capture strategies. Solid sorbents are believed to be among the most promising early-stage technologies for achieving that objective. [3]

Most research regarding solid sorbent-based CO₂ capture (SSCCS) has focused on the CO₂ adsorption/desorption properties of various classes of solid sorbent materials and several fine reviews of this work are available.[4,5] In addition, several ongoing and recently completed work efforts examine the influence of sorbent properties on vessel design. Several organizations have been particularly active in exploring this area, including ADA-ES and the U.S. Department of Energy. [6-8] However, relatively few publications, have put forth equipment design recommendations with respect to sorbent materials and fewer still address the implications of material performance for equipment and energy production costs.

This work seeks to address this information gap by comparing multiple solid sorbents in an integrated techno-economic model which can help the research community understand the relation between performance and cost of solid sorbents. Research questions which are addressed in this paper include:

- What are the most important parameters directing performance of solid sorbent systems?
- How does the performance of a solid sorbent-based CO₂ capture system compare to liquid solvent systems?
- Is solid sorbent-based carbon capture a potentially less costly alternative to liquid- based capture?
- Where can research and development funding best be spent to reduce the cost of Carbon Capture and Storage?

3. Process Performance Model

3.1. Base plant assumptions

All major components of a pulverized coal power plant, including coal handling, steam cycle and pollution control technologies were modeled using the well documented publically available Integrated Environmental Control Model (IECM) software [9] with the exclusion of the SSCCS process. The characteristics of the case study power plant used in this study are derived from the 2010 DOE/NETL Bituminous Baseline Report (Case 12) [10]. This plant is a pulverized coal, supercritical Rankine cycle plant burning Appalachian medium sulfur coal and located in the Midwestern USA. A process flow diagram used for this case study is shown in Figure 1.

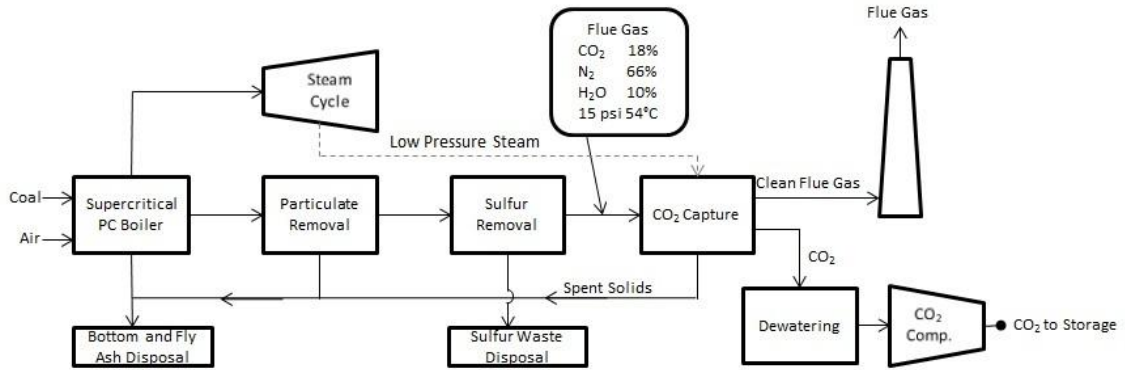


Figure 1. Operating assumptions for this case study. Bituminous Illinois #6 Medium Sulfur coal enters the supercritical boiler. The flue gas which is generated is treated to the extent that it will meet U.S. New Source Performance Standards.

3.2. Solid sorbent modeling

Numerous factors describe the quality or utility of CO₂ adsorbents. In general, fast adsorption and desorption kinetics, large adsorption capacity, full regeneration capability and stability, and a wide yet adjustable range of operating conditions define an ideal, hypothetical adsorbent.[4] In reality, no single ideal adsorbent is likely to be invented. Rather, each adsorbent's strengths and weaknesses must be considered in the context of a practical adsorption process for effective CO₂ separation. The implication of these sorbent limitations is represented in our performance model by showcasing two representative sorbents and comparing the relative strengths and weaknesses of their performance in a simulated SSCCS capture process.

Solid sorbents for CO₂ capture function either by physisorption, as in the case of metal-organic frameworks (MOFs), activated carbon and zeolites, or by chemical reaction with CO₂ usually with amine functional groups. This study compares two of the most promising and well-studied sorbents in a post-combustion setting: functionalized amines and metal-organic frameworks (MOFS). These sorbents are compared with regard to several important parameters including: (a) CO₂ capacity; (b) operating adsorption and desorption temperature window; (c) regeneration ability; and (d) rate of sorbent replacement as needed due to physical attrition and degradation. The performance parameters values for each solid sorbent are shown in Table 1.

Table 1. Parameterized characteristics of solid sorbents used in the SSCCS performance model

Performance Parameter	Units	Amine-based	MOF
Solid sorbent capacity	mol CO ₂ / kg sorbent	1.8 [11]	2.0 [14]
Material density	tonnes/m ³	1.3	0.8 [15]
Solid heat capacity	kJ / tonne-°C	1750 [12]	900 [16]
Heat of reaction	kJ / mol CO ₂	64 [13]	39 [14]
Adsorption Regenerator Temp. Dif.	K	50	30 [14]

4. Process Cost model

The results from the performance model are integrated within a cost model, which calculates the total capital cost and operating costs of the plant as well as the overall levelized cost of electricity. Models for the direct costs of all the process sections except the CO₂ capture process are obtained from the Integrated Environmental Control Model (IECM).

The major components of the SSCCS system are adapted from the solid sorbent system described by ADA Environmental Solutions in their 2011 final report to DOE/NETL.[17] The equipment costs and power use are scaled from a combination of the equipment listed ADA's itemized equipment costs assembled by Stantec, Inc., the IECM, and NETL's 2010 Baseline Report [18]. These costs are scaled from their original source using the chemical engineering scaling law. [19] Because of the absence of publically available cost information regarding solid sorbent systems, the adsorber and regenerator costs are scaled based on the surface area of the system. A diagram of the major solid sorbent equipment for this study is presented in Figure 2, and each process block is discussed in the following section and specific equipment costs for the nominal SSCCS systems will soon be available in a technical report from Carnegie Mellon University. This report will also include details of the performance and cost modeling methodology. A detailed explanation of the costing process can be found regarding the EPRI Technical Assessment Guide [20].

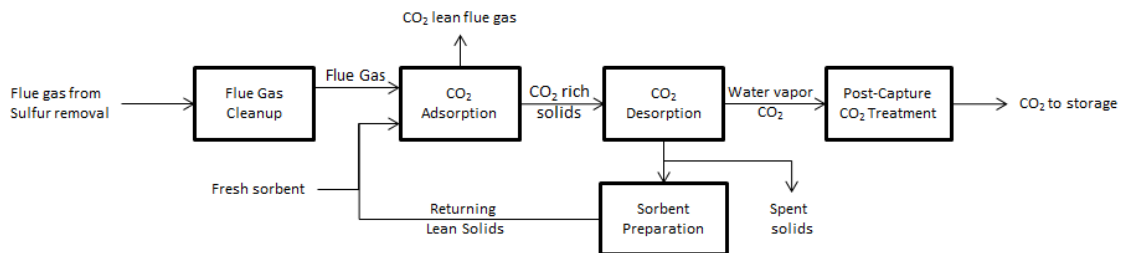


Figure 2. The solid sorbent carbon capture process uses solid sorbents in a regenerative system to separate CO₂ from other flue gas constituents. Each process area represents multiple equipment assemblies as described in each process area section.

4.1. Flue gas cleanup (flue gas cooler and SO₂ polisher, flue gas blower)

Most CO₂ capture systems necessitate the removal of sulfur dioxide and cooling of the flue gas before the adsorption process occurs. The sulfur dioxide (SO₂) is removed in order to prevent the formation of undesirable and often irreversible compounds between the adsorbing compound and SO₂. The gas is cooled in order to ensure that adsorption conditions are maintained within a given temperature range (usually 40°C to 70°C for post-combustion). A typical SO₂ polisher will serve both purposes, decreasing the sulfur content in the flue gas from ~25ppm to 1-10 ppm using a comparatively low temperature caustic slurry solution. The treated flue gas is then pulled through an induced draft fan in order to overcome the pressure drop between the gas inlet and gas outlet of the adsorber unit.

4.2. CO₂ adsorption (adsorber, cyclones, bughouses, transport to regenerator)

Multiple designs are feasibly available for the adsorber vessel. These can take the form of a batch or continuous reactor-type process, employing fixed or bubbling beds, and potentially integrating both CO₂ adsorption and desorption steps in a single unit [7]. While many of these designs show promise, the current state of the art has yet to identify a definitively superior option. For this case study, a moving bed reactor design was chosen for its more compact and therefore less cost prohibitive design. [8]

4.3. CO₂ desorption (sorbent regenerator, CO₂ booster fan)

The regenerator is modeled as a moving bed vessel in which the chemical bond or physical trapping mechanism is overcome and CO₂ is released as a concentrated gas mixed with steam and possibly other trace contaminants. The gas stream is pulled from the regenerator under a mild vacuum using a CO₂ booster fan, and routed to the dehydration and compression block.

4.4. Sorbent preparation (sorbent cooler, sorbent staging, transport, storage silo)

After exiting the regenerator, the heated solid stream enters a rotary contact cooler to rapidly reduce the temperature and prepare the sorbent for return to the adsorber. The sorbent is then conveyed back to a temporary storage area or hopper in preparation for another adsorption/regeneration cycle. A small fraction of the sorbent is replaced with fresh sorbent in order to maintain the adsorption capacity. This spent sorbent is, for the purpose of this study, considered a waste product which is mixed with bottom ash from the boiler and disposed accordingly. However, full scale implementation will likely involve a treatment process in which the degraded sorbent is regenerated and reused in order to reduce materials cost.

4.5. Post-capture treatment (dewatering, compression, transport, and storage)

The captured CO₂ is dehumidified, compressed to a supercritical phase, and transported for geologic storage. This model assumes flat rate per tonne of stored CO₂ and a flat capital and O&M costs for transport. The capital costs and energy use for the dewatering and compression process are the same as that of the IECM. Likewise, the transport and storage model emulates the method and cost from the IECM, although these costs are treated as a flat rate per unit mass of CO₂.

5. Case Study Results

This section demonstrates the application of the techno-economic assessment models of the solid sorbent system described above and a comparable liquid-based capture system. These plants are compared to a PC plant without CCS, each using the same heat input as determined by the influx of coal to the power plant. Preliminary performance and cost estimates for the two solid systems are shown in Table 2 along with an advanced liquid amine system (based on Fluor's FG+ solvent) and a baseline (no CCS) which were calculated using the IECM model. Results indicate that both amine and metal-organic frameworks are potentially competitive technologies with respect to liquid systems due to the lower steam requirement during the CO₂ desorption process.

Table 2. Power plant performance estimates.

Parameter	Amine-based	MOF	Advanced Liquid Amine (FG+)	No Capture
Gross power output (MW _{gross})	566	612	539	650
Net power output (MW _{net})	451	498	438	608
Net Plant Efficiency (%)	29%	32%	28%	39
Plant derating (%)	26%	18%	18%	N/A
Revenue required (million \$/year)	322	323	317	238
Levelized cost of electricity (\$/MWh _{net})	109	99	110	60

Results indicate that both amine and metal-organic frameworks are potentially competitive technologies with respect to liquid systems. The benefit of solid sorbent systems is the lower steam requirement during the CO₂ desorption process as indicated by the higher gross output. Combined with a comparable annual revenue requirement, the levelized cost of energy is lower for the metal-organic framework system and comparable for the amine system.

6. Sensitivity and Uncertainty Analysis

While the nominal systems discussed above indicate a potential competitive advantage to SSCCS over a liquid system, many parameters influencing the performance and cost of a solid sorbent system are the unknown for a large system setting. Through uncertainty and sensitivity analysis, several important factors that affect the performance and cost of electricity generation using solid sorbent-based CO₂ capture process are considered, including sorbent type, water retention, technical factors and cost assumptions. As a result, the uncertainty regarding full scale implementation of this technology is relatively high compared to commercially available liquid systems. A better understanding of these parameters is obtained via a sensitivity and uncertainty analysis shown below.

6.1. Variation of sorbent-specific parameters

The characteristics of solid sorbents that impact the performance and cost of the overall plant include parameters that are unique to the solid particles. Several of these variables are parameterized according to the distributions shown in Table 3 in order to better understand the importance of these solid sorbent properties on the SSCCS process and overall power plant.

Table 3. Uncertainty distribution of solid sorbent-specific characteristics used in the performance model

Parameter	Amine-based		MOF	
	Static value	Distribution	Static value	Distribution
Solid sorbent capacity	1.8	Triangular (1.7, 1.8, 1.9)	2.0	Triangular (1.9, 2.0, 2.1)
Material density	1.3	Triangular (1.25, 1.3, 1.35)	0.8	Triangular (0.7, 0.8, 0.9)
Solid heat capacity	1750	Triangular (1700, 1750, 1800)	900	Triangular (850, 900, 950)
Heat of reaction	64	Normal (64, 3.2)	39	Normal (39, 2.0)
Regen.-Adsorption Temp. Dif.	50	Triangular(45, 50, 55)	30	Triangular (25, 30, 35)

6.2. Variation of select performance and cost parameters

In the current model, the as-installed direct cost is a function of both the equipment surface area as determined by the volume of solids and a per-unit-area cost. However, the degree to which this technology will benefit from economies of scale is perhaps the most uncertain of these parameters; especially for the adsorber and regenerator vessels. To address this uncertainty, several of these parameters were adjusted in order to better understand the variability regarding this equipment. These parameters and related distributions are shown in Table 4.

Table 4. Uncertainty distribution of selected solid sorbent performance and cost parameters.

Parameter	Base case value	Distribution
Adsorber and regenerator scaling cost (million \$/m ²)	0.01	Uniform (0.005, 0.015)
Adsorber vessel retention time (minutes)	10	Uniform (8, 12)
Adsorber pressure drop (psia)	2.031	Uniform (1.031, 3.031)
Regenerator vessel retention time (minutes)	20	Uniform (15, 25)
Regenerator pressure drop (psia)	2.031	Uniform (1.031, 3.031)
Regenerator Efficiency (%)	0.7	Triangular (70%, 50%, 90%)
New solid sorbent fraction (ppm)	7	Uniform (5, 9)

The levelized cost of electricity is shown in Figure 3 and compared to a range of estimates for both solid and liquid technologies. For comparison, Table 4 lists several previous estimates of the LCOE as

estimated from industry, trade organizations, government entities, and academia. These results highlight the large uncertainty surrounding the cost of implementing CCS on a commercial scale, but also stress the importance of continuing research in the field of CCS to more accurately determine the cost of implementing CCS on a commercial scale.

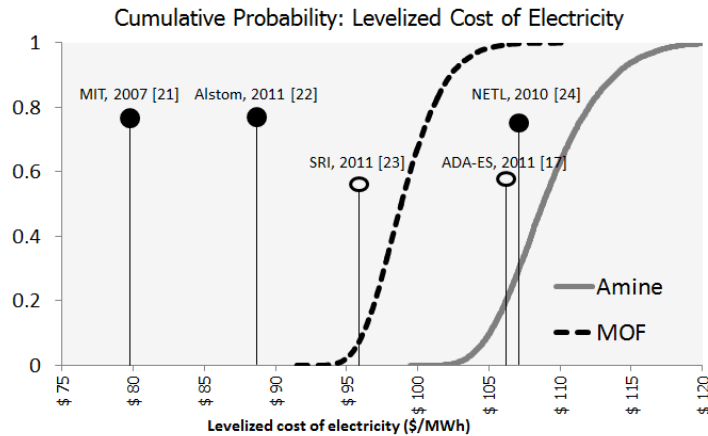


Figure 3. The levelized cost of electricity for plants with solid sorbent and liquid amine systems. Cumulative probability functions for two solid sorbent systems (labelled Amine and MOF) are shown as derived from this work as well as cost estimates from other research organizations for solid and liquid CCS systems.

7. Discussion and Conclusion

The performance and cost results presented in this paper indicate that solid sorbents are a potentially competitive alternative to liquid systems. While liquid systems are a more well understood technology for carbon capture, the lower heat requirement for regeneration of solid sorbent capture materials allows for greater production of electricity and thus a lower cost per unit of net generation capacity.

The major drawback of solid sorbents is the current lack of information regarding optimal reactor size and overall system implementation. Previous applications of this technology in the chemical and petroleum industries have treated much smaller volumes of gas and thus require smaller quantities of solids. Little to no empirical data is available on how well the necessary equipment (particularly the adsorber and regenerator vessels) will scale, rendering the required capital costs highly uncertain. Research efforts, most notably the Carbon Capture Simulation Initiative (CCSI) are currently working to better understand these limitations through computational modeling. However, without empirical data to validate these results, the true cost of implementing this technology remains uncertain.

The authors are aware of only a single project currently under development which seeks to assess the true performance of solid sorbents, namely, a joint venture between DOE/NETL, ADA-ES, and Southern Company which will install a 1MW pilot scale system at Southern Company's Wilsonville, Alabama test station. However, results from this study will not be available until the project's completion in 2014. Meanwhile, liquid systems continue to provide the only commercially viable, readily available technology for CCS from large point sources.

8. Acknowledgements

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alone are responsible for the content of this paper.

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