NATIONAL ENERGY TECHNOLOGY LABORATORY

Fossil Energy RD&D: Reducing the Cost of CCUS for Coal Power Plants

Revision 1, January 31, 2012

DOE/NETL-2012/1550

U.S. DEPARTMENT OF ENERGY

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Final Report
Revision 1 January 31, 2012

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Fossil Energy RD&D:
Reducing the Cost of Carbon Capture for Coal-Fueled Power Plants

The U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) provides a worldwide leadership role in the development of advanced coal-based energy conversion technologies, with a focus on electric power generation. As part of DOE's Office of Fossil Energy, NETL implements research, development and demonstration (RD&D) programs that are moving aggressively to address the challenge of reducing greenhouse gas emissions as a climate change mitigation strategy. In partnership with both the Nation's research universities and the private sector, RD&D efforts are focused on maximizing system efficiency and performance, while minimizing the costs of new Carbon Capture, Utilization and Storage (CCUS) technologies. Improving the efficiency of power generation systems reduces emissions of carbon dioxide (CO_2) as well as other criteria pollutants while using less water and extending the life of our domestic energy resource base. NETL's RD&D Programs strive to improve technologies for current and future coal-based power plants and industrial facilities so that they can cost effectively meet emerging environmental and regulatory requirements in an economically secure and environmentally sound manner.

Coal RD&D

The NETL Coal RD&D portfolio supports two different coal conversion pathways for a wide variety of coal ranks: ***coal combustion***, which is used in Pulverized Coal (PC) power plants, and ***coal gasification***, which is used in Integrated Gasification Combined Cycle (IGCC) and Integrated Gasification Fuel Cell (IGFC) power plants.

Advanced Combustion Systems

Today's advanced combustion systems require improvements in both cost and efficiency in order to overcome the economic penalties associated with CCUS at new and repowered coal-fueled power plants. For combustion systems, NETL is pursuing two potential strategies for controlling greenhouse gas emissions: post-combustion CO_2 capture and oxy-combustion boiler technology. For post-combustion CO_2 capture, NETL and its RD&D partners are developing advanced technologies based on solvents, membranes and solid sorbents. For oxy-combustion systems, NETL and its RD&D partners are developing advanced technologies for oxy-boilers, chemical looping systems and air separation. Furthermore, research on advanced boiler and turbine materials, back-end CO_2 purification technologies and the compression of CO_2 will benefit both post-combustion CO_2 capture and oxy-combustion systems.

Advanced Gasification Systems

Advanced gasification systems convert coal or other carbon-containing feedstocks into synthesis gas, a mixture composed primarily of carbon monoxide and hydrogen used as fuel for power generation or in chemical production. NETL programs are developing advanced gasification technologies to meet the most stringent environmental regulations and to facilitate the efficient pre-combustion capture of CO_2 for subsequent utilization and storage. Gasification plants are complex systems that rely on a large number of interconnected processes and technologies.

Advances in the current state-of-the-art, as well as development of novel approaches, are required to make these systems affordable and reliable for commercial deployment. NETL's focus is on the development of coal feed systems, pre-combustion CO_2 capture, high temperature contaminant removal, revolutionary oxygen supply technology, fuel cells, and the combustion of hydrogen fuels in advanced hydrogen turbines.

Table 1 lists the advanced technologies and performance improvements being developed under NETL's Coal RD&D Program for integration into various combustion-based and gasification-based power generation systems as early as the 2020 timeframe.

Projected Performance and Cost Improvements

Table 2 quantifies the improvements that are expected to result from the Coal RD&D Program for coal-fueled power plants that incorporate CCUS. Table 3 lists improvements expected for plants that do not feature CCUS.

For coal-fueled power plants with CCUS, the cost of generating electricity will be reduced by 23 to 37 percent and their efficiency will be increased by 25 to 43 percent. The cost of avoiding CO_2 emissions from coal-fueled plants with CCUS will be reduced by 54 to 82 percent. The cost of capturing CO_2 will be reduced by 43 to 86 percent.

For coal-fueled power plants without CCUS, the cost of generating electricity will be reduced by 7 to 27 percent and their efficiency will be increased by 8 to 30 percent. Even without CCUS, a 30% increase in efficiency will reduce carbon dioxide emissions by over 20 percent.

The goal of DOE's RD&D program is to develop advanced combustion systems with carbon capture that can generate electricity at a cost that is no more than 35% higher than the COE from today's pulverized coal plants that do not capture carbon. If the technologies listed in Table 1 are successfully developed, both the advanced combustion and advanced gasification systems will meet this COE target (see Table 2).

Utilization of Captured Carbon Dioxide

Carbon dioxide is traded in commercial markets for utilization in enhanced oil recovery (EOR) from depleted oil reservoirs. Currently, approximately 85% of the CO_2 supplied for EOR comes from finite sources of naturally occurring CO_2 which may prove insufficient to meet growing demand for EOR. Accordingly, the potential exists to compliment naturally sourced CO_2 with anthropogenic sources captured from coal-fueled power plants. In such a scenario, the revenues that power plant operators receive for CO_2 could be used to fully or partially offset the cost they incurred to capture and compress the CO_2 for injection into a pipeline.

As shown in Table 2, the cost of capturing and compressing CO_2 from a supercritical PC plant using today's technology is estimated to be $42 per metric ton (tonne) of CO_2. By using advanced technologies, this cost is projected to drop to between $7/tonne and $24/tonne.

In the commercial markets, the price of CO_2 for EOR is typically correlated to the price of crude oil. During the period 2008 to 2011, the market price of CO_2 (expressed in dollars per tonne) at the Denver City, Texas "hub" varied between 27% and 63% of the West Texas Intermediate crude oil price (expressed in dollars per barrel)[1]. Applying this rule of thumb would result in CO_2 prices between $27 and $63 per tonne when the price of crude oil is $100/bbl. Although a power plant operator might receive much less than this at the plant gate, and although CO_2 prices may be lower in other regional CO_2 EOR markets, this historical data suggests that advanced coal-based power plants may be able to fully recoup their projected $7 to $24/tonne cost of capturing and compressing CO_2 by selling it for EOR.

[1] During the period 2008 to 2011, the market price of CO_2 (expressed in $/MCF) for enhanced oil recovery, quoted at the Denver City, TX "hub", varied between 1.4% and 3.3% of the West Texas Intermediate crude oil price (expressed in $/bbl). Restating this correlation, the market price of CO_2 (expressed in $ per metric ton) would be 27 to 63% of the crude oil price ($/bbl). This conversion is based on one metric tonne of CO_2 occupying 19.0 MCF at standard conditions of 60 F and 14.7 psia. Source: Wehner, Scott. Chaparral Energy. “U.S. CO_2 and CO_2 EOR Developments.” Presented at the CO_2 Carbon Management Workshop. December 6, 2011.

Table 1: Advanced technologies by plant type

Type of Power Plant	Technologies
Coal Combustion Pathway	
Advanced Ultra-Supercritical (AUSC) PC with CCUS[2]	o AUSC Steam Conditions o Advanced CO_2 Separation o Advanced CO_2 Compression
Advanced Oxy-fuel PC with CCUS[3]	o Compact Oxy-fuel Boiler o AUSC Steam Conditions o Advanced Oxygen Separation o CO_2/SO_2 Co-sequestration o Advanced CO_2 Compression
AUSC PC[4]	o AUSC Steam Conditions
Coal Gasification Pathway	
Advanced IGCC[5]	o Dry Feed Coal Pump o Advanced Oxygen Separation o Warm Gas Cleanup o Advanced Syngas Turbine o Improved Availability
Advanced IGCC with CCUS[6]	o Advanced Oxygen Separation o Warm Gas Cleanup o Advanced H_2-CO_2 Separation o Advanced H_2 Turbine o Improved Availability
IGFC[7] [8]	o Advanced Gasifier o Improved Stack Performance o Reduced Stack Costs o Increased Inverter Efficiency o Improved Availability
IGFC with CCUS[9][10]	o Advanced Gasifier o Improved Stack Performance o Reduced Stack Costs o Increased Inverter Efficiency o Improved Availability

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[2] DOE/NETL, "Current and Future Technologies for Power Generation with Post-Combustion Carbon Capture", 2011 DRAFT
[3] DOE/NETL, "Advancing Oxy-combustion Technology for Bituminous Coal Power Plants: An R&D Guide," 2011 DRAFT
[4] DOE/NETL, "Current and Future Technologies for Power Generation with Post-Combustion Carbon Capture," 2011 DRAFT
[5] DOE/NETL, "Current and Future Technologies for Gasification-Based Power Generation, Volume 1" Revision 1, 2011 DRAFT
[6] DOE/NETL, "Current and Future Technologies for Gasification-Based Power Generation, Volume 2: A Pathway Study Focused on Carbon Capture Advanced Power Systems R&D Using Bituminous Coal," Revision 2, 2012 DRAFT
[7] DOE/NETL, "Analysis of Integrated Gasification Fuel Cell Plant Configurations," Revision 1, 2011 DRAFT
[8] Additional advancements to incorporate catalytic gasification and pressurized solid oxide fuel cells on a more extended timeline have the potential to improve the efficiency to above 60% and reduce the cost of electricity even further. The more advanced system represents DOE's vision of a "transformational" coal-fueled power plant.
[9] DOE/NETL, "Analysis of Integrated Gasification Fuel Cell Plant Configurations," February 2011, (http://www.netl.doe.gov/energy-analyses/pubs/IGFC_FR_20110225.pdf)
[10] Additional advancements to incorporate catalytic gasification and pressurized solid oxide fuel cells on a more extended timeline have the potential to improve the efficiency to nearly 60% and reduce the cost of electricity and cost of avoided CO_2 even further. The more advanced system represents DOE's vision of a "transformational" coal-fueled power plant.

Table 2: Coal-fueled power systems with CCUS[11] (June 2007 Dollars)

Type of Power Plant	Cost of Electricity[12]			Total Overnight Capital[13]		Cost of Avoided CO_2[14]		Cost of Captured CO_2[14]		Efficiency		CO_2 Emissions
	$/MWh-net		Reduction from Today's Cost	$ per kW-net	Reduction from Today's Cost	$/tonne	Reduction from Today's Cost	$/tonne	Reduction from Today's Cost	%HHV	Increase from Today's Eff.	lb per MWh-net
	COE	LCOE										
Coal Combustion Pathway												
Today's Supercritical PC with CCUS[15]	107	135		3,570		69		42		28.4		244
AUSC PC with CCUS[16]	82	104	23%	2,891	19%	32	54%	24	43%	36.5	28%	188
Advanced Oxy-fuel PC with CCUS[17]	76	96	29%	2,747	23%	21	70%	16	62%	39.7	40%	18
Coal Gasification Pathway												
Today's IGCC with CCUS[18]	106	134		3,334		66		49		32.6		206
Advanced IGCC with CCUS[19]	67	85	37%	2,225	33%	12	82%	7	86%	40.9	25%	173
IGFC with CCUS[20,21]	70	89	34%	2,497	25%	14	79%	11	78%	46.5	43%	5

[11] Cost and performance estimates are for nth-of-a-kind plants. COE and cost of avoided CO_2 included estimated costs for CO_2 transport, storage and monitoring for sequestration in a favorable saline aquifer formation. Cost of captured CO_2 does not include these costs and is representative of the plant gate sales price for CO_2 that would result in a break-even COE with a supercritical PC plant without carbon capture.

[12] Cost of Electricity (COE) and Levelized COE (LCOE) are computed using a current-dollar analysis that assumes capital is expended over a five-year period beginning in 2007 with plant startup in 2012. LCOE is levelized over an assumed plant life of 30 years.

[13] Total Overnight Capital (TOC) comprises the bare erected cost plus the cost of engineering, procurement and construction services, process and project contingencies and owner's costs. TOC does not include interest during construction or escalation during construction, although these costs are reflected in the cost of electricity.

[14] Costs compared to today's state of the art supercritical pulverized coal power plant

[15] DOE/NETL, "Cost and Performance Baseline for Fossil Energy Plants, Volume 1," Revision 2, November 2010, (http://www.netl.doe.gov/energy-analyses/pubs/BitBase_FinRep_Rev2.pdf)

[16] DOE/NETL, "Current and Future Technologies for Power Generation with Post-Combustion Carbon Capture", 2011 DRAFT

[17] DOE/NETL, "Advancing Oxy-combustion Technology for Bituminous Coal Power Plants: An R&D Guide," 2011 DRAFT

[18] DOE/NETL, "Cost and Performance Baseline for Fossil Energy Plants, Volume 1," Revision 2, November 2010, (http://www.netl.doe.gov/energy-analyses/pubs/BitBase_FinRep_Rev2.pdf)

[19] DOE/NETL, "Current and Future Technologies for Gasification-Based Power Generation, Volume 2: A Pathway Study Focused on Carbon Capture Advanced Power Systems R&D Using Bituminous Coal," Revision 2, 2012 DRAFT

[20] DOE/NETL, "Analysis of Integrated Gasification Fuel Cell Plant Configurations," February 2011, (http://www.netl.doe.gov/energy-analyses/pubs/IGFC_FR_20110225.pdf)

[21] Additional advancements to incorporate catalytic gasification and pressurized solid oxide fuel cells on a more extended timeline have the potential to improve the efficiency to nearly 60% and reduce the cost of electricity and cost of CO_2 mitigation even further. The more advanced system represents DOE's vision of a "transformational" coal-fueled power plant.

Table 3: Coal-fueled power systems without CCUS[22]
(June 2007 Dollars)

Type of Power Plant	Cost of Electricity[23]			Total Overnight Capital[24]		Efficiency		CO_2 Emissions
	$/MWh-net		Reduction from Today's Cost	$ per kW-net	Reduction from Today's Cost	%HHV	Increase from Today's Eff.	lb per MWh-net
	COE	LCOE						
Coal Combustion Pathway								
Today's Supercritical PC[25]	59	75		2,024		39.3		1,769
AUSC PC[26]	55	70	7%	1,902	6%	42.5	8%	1,635
Coal Gasification Pathway								
Today's IGCC[25]	76	97		2,447		39.0		1,725
Advanced IGCC[27]	56	71	27%	1,901	22%	46.1	18%	1,458
IGFC[28] [29]	57	73	25%	2,099	14%	50.8	30%	1,335

[22] Cost and performance estimates are for nth-of-a-kind plants.
[23] Cost of Electricity (COE) and Levelized COE (LCOE) are computed using a current-dollar analysis that assumes capital is expended over a five-year period beginning in 2007 with plant startup in 2012. LCOE is levelized over an assumed plant life of 30 years.
[24] Total Overnight Capital (TOC) comprises the bare erected cost plus the cost of engineering, procurement and construction services, process and project contingencies and owner's costs. TOC does not include interest during construction or escalation during construction, although these costs are reflected in the cost of electricity.
[25] DOE/NETL, "Cost and Performance Baseline for Fossil Energy Plants, Volume 1," Revision 2, November 2010, (http://www.netl.doe.gov/energy-analyses/pubs/BitBase_FinRep_Rev2.pdf)
[26] DOE/NETL, "Current and Future Technologies for Power Generation with Post-Combustion Carbon Capture," 2011 DRAFT
[27] DOE/NETL, "Current and Future Technologies for Gasification-Based Power Generation, Volume 1" Revision 1, 2011 DRAFT
[28] DOE/NETL, "Analysis of Integrated Gasification Fuel Cell Plant Configurations," Revision 1, 2011 DRAFT
[29] Additional advancements to incorporate catalytic gasification and pressurized solid oxide fuel cells on a more extended timeline have the potential to improve the efficiency to above 60% and reduce the cost of electricity even further. The more advanced system represents DOE's vision of a "transformational" coal-fueled power plant.