Quadrennial Technology Review 2015

Chapter 4: Advancing Clean Electric Power Technologies

Technology Assessments

U.S. DEPARTMENT OF ENERGY

Carbon Dioxide Capture for Natural Gas and Industrial Applications

Chapter 4: Technology Assessments

Overview of Carbon Capture Technologies for Natural Gas Cycles and Industrial Applications

A majority of carbon capture and storage (CCS)[1] research and development activities in the United States have historically focused on new-build coal-fired power plants, but there is opportunity in broadening this focus. All ongoing CO_2 storage and many CO_2 capture-related activities are applicable to natural gas-fueled power plants as well as fossil fuel consumption in large industrial facilities. While there are a number of CCS projects worldwide that capture CO_2 from natural gas processing, as shown in Table 4.D.1, cost-effectively capturing CO_2 from natural gas-fueled power plants is far more technically challenging. The U.S. has been carrying out work through bilateral agreements with its international partners in countries such as the United Kingdom and Norway,[2, 3] to leverage efforts on carbon capture from natural gas power systems and implement advances into domestic coal-focused RDD&D activities.

Coal based RDD&D has laid the foundations and advanced the field of carbon capture for all fossil fuel applications. The technology transfer to natural gas for both new plants and retrofits is relatively straightforward, but there are specific challenges, as the lower concentrations of CO_2 (3-5%) decreases efficiency of capture, and greater oxygen concentrations can degrade solvents or sorbents. Extension of coal-based research, as well as pilot-scale and large-scale demonstration, are critical activities supporting the application of existing CCS technologies to natural gas processes. With the current abundance of natural gas from both conventional and unconventional sources, and increasingly stringent emission standards, natural gas plants are replacing many aging coal plants in the United States. Other parts of the world, in collaboration with industry, are developing and demonstrating first and second generation carbon capture technologies for full scale natural gas fired units. The U.S. has not had a federal program focused on natural gas, but there is an opportunity to leverage the ongoing international efforts.[4, 5]

Table 4.D.1 International CCS Projects (Green = operational, Pink = execution)[6]

Project name	Country	Industry
Air Products Steam Methane Reformer EOR Project	United States	Hydrogen production
Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project	Canada	Power generation
Century Plant	United States	Natural gas processing
Coffeyville Gasification Plant	United States	Fertiliser production
Enid Fertilizer CO_2-EOR Project	United States	Fertiliser production
Great Plains Synfuel Plant and Weyburn-Midale Project	Canada/United States	Synthetic natural gas
In Salah CO_2 Storage	Algeria	Natural gas processing
Lost Cabin Gas Plant	United States	Natural gas processing
Petrobras Lula Oil Field CCS Project	Brazil	Natural gas processing
Quest	Canada	Hydrogen prodction
Shute Creek Gas Processing Facility	United States	Natural gas processing
Sleipner CO_2 Storage Project	Norway	Natural gas processing
Snøhvit CO_2 Storage Project	Norway	Natural gas processing
Uthmaniyah CO_2 EOR Demonstration Project	Saudi Arabia	Natural gas processing
Val Verde Natural Gas Plants	United States	Natural gas processing
Alberta Carbon Trunk Line ("ACTL") with Agrium CO_2 Stream	Canada	Fertiliser production
Alberta Carbon Trunk Lind ("ACTL") with North West Sturgion Refinery CO_2 Stream	Canada	Oil refining
Gorgon Carbon Dioxide Injection Project	Australia	Natural gas processing
Illinois Industrial Carbon Capture and Storage Project	United States	Chemical production
Kemper County Energy Facility (formerly Kempler County IGCC Project)	United States	Power generation
Abu Dhabi CCS Project (formerly Emirates Steel Industries (ESI) CCS Project)	United Arab Emirates	Iron and steel production
Petra Nova Carbon Capture Project (formerly NRG Energy Parish Coal CCS Project)	United States	Power generation

Carbon capture technology adapted for application to industrial processes has potential for a significant CO_2 reduction. In the cement industry, for example, the majority (60%) of the industry's CO_2 emissions do not originate from energy use but from the manufacture of cement from limestone. In simple terms, clinker, a major constituent of cement, is manufactured by breaking down limestone into calcium oxide and CO_2. The calcium oxide is subsequently used and the CO_2 is vented into the atmosphere.

In the U.S., as much as 21% of CO_2 from fossil fuel combustion in 2013 was from the industrial sector.[7] The IEA projects that CCS in industrial applications can reduce CO_2 emissions by up to 4.0 Gt annually by 2050, accounting for about 9% of the global reductions needed if energy-related CO_2 emissions were to be cut in half by 2050. However, achieving this would require 20% to 40% of all industrial and fuel transformation plants to be equipped with CCS by 2050.[8] Some industrial plants, such as ammonia and natural gas processing, produce high purity CO_2 streams that will enable lower capture cost and may already deploy technologies for the capture and separation of CO_2 as an inherent part of the process. Other industrial CO_2 emissions sources such as cement, iron, steel, alloys, and refinery hydrogen production are attractive targets for advanced CO_2 capture technologies, and also open up greater opportunities for other technologies to contribute to overall CO_2 mitigation. For example, research to reduce the cost of oxygen used in gasification and pulverized coal (PC) oxy-combustion could also benefit potential use of oxygen in cement kilns, refinery fluidized catalytic crackers, and blast furnaces. The challenges for industrial processes are due to the smaller equipment sizes and reduced economies of scale, which can increase capture costs compared to power plant applications.

CCS technologies for retrofitting existing plants will be critical both for U.S. and global CO_2 mitigation goals. Nearly all of the current global growth in coal electric power generation is in non-Organization for Economic Co-operation and Development (OECD) countries, creating a large coal-based capacity projected to be less than 20 years old in 2030.[9] Close collaboration with developing countries such as China to demonstrate coal CCS retrofit technologies in those countries will be critical to supporting global climate goals. Post-combustion capture technologies represent the greatest potential for CCS retrofits, and the development of second generation and transformational CO_2 capture retrofit technology is needed to enable the continued use of these valuable existing assets. Existing post-combustion systems require processes such as amine-based scrubbing that can achieve CO_2 capture rates of 90% or more from flue gas. However, these are capital intensive and require significant thermal energy to drive the solvent regeneration process.[10]

CCS for Natural Gas Cycles

The foremost technical challenges in adapting CCS technologies to natural gas cycles are to develop and demonstrate modifications to the current capture technologies to handle differences in oxygen content, impurities, partial pressure of CO_2, and integration of sources that have limited excess steam available for the capture process. The flue gas from natural gas sources has differing concentrations than coal-based systems. Challenges include lower concentrations of CO_2 (3-5%) limiting capture, greater oxygen concentrations leading to degradation of solvents, and system compatibility due to cyclic operations. These issues are detailed in Tables 4.D.2 and 4.D.3. A number of international activities focused on carbon capture from natural gas power systems have been on-going primarily in Europe and Canada. Table 4.D.7 at the end of this Technology Assessment provides links for further reference on a few of highlighted larger demonstration activities, several DOE sponsored workshops which explored transformational technology options and pathways, and a review of the breadth of current R&D summarized in the recent proceedings from the 12th International Conference on Greenhouse Gas Technologies.

Table 4.D.2 Challenges and Desired Outcomes for Carbon Capture and Storage for Natural Gas Cycles

CCS for Natural Gas Cycles: develop and test modifications to the current capture technologies to address the inherent physical and operational challenges associated with natural gas cycles.

Major R&D Challenges

- faster oxidation of standard amine based solvents due to increased O2 content (10% for NGCC vs 4% for coal)
- lower capture efficiency due to reduced CO_2 content (4% for NG vs 14% for coal based system) of the flue gas
- intermittent operation of natural gas power systems require flexibility of capture systems to follow dispatch requirements

Desired Outcomes

- demonstrating second generation carbon capture or advanced energy system technology
- transitioning advanced capture systems for use in NGCC plants

Table 4.D.3 Technical Assessment and Opportunities for Carbon Capture and Storage for Natural Gas Cycles

CCS for Natural Gas Cycles: develop and test modifications to the current capture technologies to adapt to the lower partial pressure of CO_2 inherent in natural gas cycles.

State of the Art	Current R&D	Opportunities and Future Pathways
Most capture technology developed to date is directly applicable to NGCC. Hybrid capture systems use multiple integrated technologies, such as membranes that increase the concentration of CO_2 thereby increasing partial pressure which improves performance of the next stage of separation.	Certain solvent and sorbent projects in the DOE portfolio have used external funding to test their technologies under natural gas conditions at the laboratory scale and have demonstrated feasibility of adapting these technologies for NGCC. International activities: ■ Gassnova and Test Centre Mongstad in Norway have tested three advanced solvents (ammonia and amine based) to capture CO_2 from both NGCC and refinery catalytic cracker flue gases. ■ Shell moved into engineering design for a CCS project on the Peterhead natural gas plant site which represents a 1st generation carbon capture project for an NGCC power plant.[11]	■ Develop at least 2-3 advanced capture technologies to be applied to NGCC plants. ■ Generate NGCC-specific designs to accommodate lower flue gas concentration (~4%). ■ Evaluate advanced energy systems for natural gas energy generation, which may have inherent advantages over post combustion capture. ■ Pursue R&D efforts in passive membrane systems to increase the CO_2 content in the combustion air resulting in higher concentrations of CO_2 in the flue gas.

On November 25, 2015, the UK government announced that the £1 billion ring-fenced capital budget for the UK CCS Competition is no longer available. As a result of the announcement, the Peterhead Project will not move forward at this time.

CCS for Industrial Sources

Industrial applications of CCS offer future potential for CO_2 mitigation. EIA data shows slightly more than one-quarter of the total U.S. CO_2 emissions in projections of the 2015 Annual Energy Outlook were attributable to industrial sources such as cement plants, chemical plants, refineries, paper mills, and manufacturing facilities.[12] With a focus on CO_2 emission reduction on the global scale, between 2015 and 2050 the IEA Energy Technology Perspectives 2015 2°C Scenario (2DS) includes 44% of total CCS CO_2 mitigation from application to the industrial and energy transformation sectors (37.4 gigatonnes out of 84.3 of the total CO_2 captured). The remaining 56% of CO_2 mitigation occurs in the power sector.[13] The expanded use of natural gas in industrial facilities and efforts to increase LNG exports will increase the need for technology solutions to capture CO_2 from future industrial facilities. Commercial facilities outside the power sector produce CO_2 in a variety of ways, including combustion of fossil fuels, pre-combustion processing, chemical reactions integral to the formation of a final product (process emissions), or a combination of these sources.[14] Some of these are described in Table 4.D.4. Industrial processes have a range of emission characteristics. High concentration emissions streams present initial opportunities, while dilute streams pose challenges similar to those of natural gas systems. Table 4.D.5 provides a summary of additional challenges due to the smaller equipment sizes and reduced economies of scale, which can increase capture costs compared to power plant applications, and Table 4.D.6 describes the current state-of-the-art, R&D that is underway, and opportunities going forward.

Table 4.D.4 Industrial Sources of CO_2 [15]

Food and drink. CO_2 is used primarily for the carbonation of drinks, although the brewing industry generates substantial volumes of CO_2 from the fermentation processes that convert sugars to alcohol.
Pulp and paper. CO_2 is generated from fossil fuel and/or biomass combustion for high temperature chemical pulping, mechanical pulping, onsite electricity production and drying.
Refining. Refining includes petroleum for transport fuels, which generates CO_2 from the production of heat, hydrogen, and power.
Chemicals. Chemicals includes the manufacture of ammonia, methanol, and olefins, which rely on fossil fuel feedstocks. The process emissions are a significant source of CO_2.
Cement. CO_2 is generated from the calcination of lime (process emissions), which also relies on fossil fuels.
Iron and steel. CO_2 is generated due to the dominance of coal as a reducing agent and a fuel, as well as the process emissions that cannot be avoided.
Non-ferrous metals. Non-ferrous metal includes the manufacture of aluminium, which not only generates the majority of its CO_2 from the production of electricity imported to power the electrolysis process (combustion emissions), but also from the reduction of alumina with carbon (process emissions).

Table 4.D.5 Challenges and Desired Outcomes of Carbon Capture and Storage for Industrial Sources

CCS for Industrial Sources: develop and test modifications to current and advanced capture technologies that can reduce high capture cost associated with industrial applications such as dilute CO_2 streams, smaller equipment size and contaminants.
Major R&D Challenges Adapting and developing technologies for carbon (CO_2) capture from industrial sources such as cement kilns, refineries, steel and iron production, and certain ammonia processes (Table 4.D.4)
Desired Outcomes Desired Outcomes Commercially advanced capture systems that have acceptable impact on manufacturing costs

Table 4.D.6 Technical Assessment and Opportunities for Carbon Capture and Storage for Industrial Sources

CCS for Industrial Sources: develop and test modifications to current and advanced capture technologies that can reduce high capture cost associated with industrial applications such as dilute CO_2 streams, smaller equipment size, and contaminants.

State of the Art	Current R&D	Opportunities and Future Pathways
Technologies (membranes, solvents, sorbents, and cryogenic) developed for coal and natural gas based systems can be adapted for most dilute industrial sources. Some sources, such as natural gas (NG) processing, biomass refineries, and some ammonia and oil refinery processes, naturally have high concentrations of CO_2 in their waste stream, which only requires dehydration and compression.	Dehydration and compression of CO_2 from the ADM ethanol facility at Decatur, Illinois has demonstrated the feasibility and economics of CCS on an ethanol facility. The Air Products carbon capture project at the Valero refinery has demonstrated the vacuum swing absorption process on a hydrogen production unit. Systems studies by the IEA GHG have shown the feasibility of adopting CCS technologies to other industrial sources.[16] CCS from natural gas processing has been on-going domestically and internationally for decades, such at the Sleipner, In Salah, and Gorgon projects. Major demonstrations associated with Skyonic Utilization project have demonstrated feasibility of capture and utilization of CO_2 from a cement plant.	Identify carbon capture technologies that could be adapted for industrial sectors. Demonstrate carbon capture technologies integrated with industrial settings (i.e., steam methane reformers and catalytic crackers from refineries) Address impacts of contaminants from industrial sources. Utilize CO_2 from small industrial sources.

Table 4.D.7 Links for Additional Information

Document Title	Author, Link	Description, Page Numbers, Etc
DOE Carbon Capture Homepage	DOE, http://energy.gov/fe/science-innovation/carbon-capture-and-storage-research/carbon-capture-rd	Webpage
NETL Carbon Capture Homepage	NETL, http://www.netl.doe.gov/research/coal/carbon-capture	Webpage
Carbon Capture Program Plan	NETL, http://www.netl.doe.gov/File%20Library/Research/Coal/carbon%20capture/Program-Plan-Carbon-Capture-2013.pdf	Program plan describing timelines and major R&D pathways
Carbon Capture Handbook	NETL, http://www.netl.doe.gov/research/coal/carbon-capture/capture-handbook	Describes each of the technologies that DOE support in detail including funding, current status, challenges, and opportunities
2015 Annual Review Meeting	NETL, http://www.netl.doe.gov/events/conference-proceedings/2015/2015-co2-capture-technology-meeting	2015 DOE carbon capture project review meeting
2014 Transformational Workshop, Sept 23, 2014	NETL, http://www.netl.doe.gov/research/coal/carbon-capture/workshop-2014	2014 DOE sponsored workshop on transformational carbon capture technology opportunities
USEA Workshop on CCS, April 22, 2014	USEA, http://www.usea.org/event/workshop-technology-pathways-forward-carbon-capture-storage-natural-gas-power-systems	2014 Workshop on Technology Pathways Forward for Carbon Capture and Storage on Natural Gas Power Systems
IEAGHG Roadmap for Industrial Sources	Van Alphen, GCCSI, 2011, http://www.ieaghg.org/docs/General_Docs/Summer_School/2011/Presentations/24_2011INDUSTRIALSOURCES-VANALPHEN.pdf	Website presentation
Whiterose CCS Project homepage	Capture Power Limited, http://www.whiteroseccs.co.uk/	Project website
Peterhead CCS Project homepage	Shell United Kingdom, http://www.shell.co.uk/energy-and-innovation/the-energy-future/peterhead-ccs-project.html	Project website
Mongstad Test Centre homepage	Technology Centre Mongstad, http://www.tcmda.com/en/	Project website
12th International Conference on Greenhouse Gas Control Technologies, GHGT-12	Energy Procedia, Volume 63, Pages 1-8134 (2014), http://www.sciencedirect.com/science/journal/18766102/63	Proceedings from 2014 IEA GHGT-12 Conference

Endnotes

1 All referrals to carbon capture and storage include consideration of the utilization of the carbon dioxide where appropriate and possible.

2 US DOE Press Release, July 23, 2014: http://energy.gov/fe/articles/us-norway-conference-focuses-advancing-carbon-capture-and-storage

3 US DOE Press Release, November 4, 2015: http://energy.gov/fe/articles/secretary-moniz-announces-new-co2-storage-network-multinational-carbon-sequestration

4 GCCSI, Large Scale Projects (accessed July, 2015), http://www.globalccsinstitute.com/projects/large-scale-ccs-projects

5 Global CCS Institute 2015, The Global Status of CCS: 2015, Summary Report, Melbourne, Australia., http://hub.globalccsinstitute.com/sites/default/files/publications/196843/global-status-ccs-2015-summary.pdf

6 GCCSI Global CCS Project Database, July 2015, http://www.globalcccsinstitute.com/projects/large-scale-ccs-project#overview

7 EPA, report no. 430-R-15-004, Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013, April 2015 http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html

8 IEA, Technology Roadmap: Carbon Capture and Storage in Industrial Applications, 2011, http://www.iea.org/publications/freepublications/publication/ccs_industry.pdf

9 EIA, International Energy Outlook 2013, Table H4 http://www.eia.gov/forecasts/archive/ieo13/pdf/0484(2013).pdf

10 NETL, Carbon Capture R&D Program for Existing Coal-Fired Power Plants, 2009, DOE/NETL- 2009/1356, http://www.netl.doe.gov/File%20Library/Research/Coal/carbon%20capture/Program-Plan-Carbon-Capture-2013.pdf

11 Shell, Peterhead CCS Project, http://www.shell.co.uk/energy-and-innovation/the-energy-future/peterhead-ccs-project.html

12 EIA, Annual Energy Outlook 2015, page A-35, http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf

13 IEA, Energy Technology Perspectives—2015. Paris, France: International Energy Agency, 2015. http://www.iea.org/etp/etp2015/

14 GCCSI, CCS Applications Factsheet, http://hub.globalccsinstitute.com/sites/default/files/publications/191078/fact-sheet-ccs-applications.pdf

15 GCCSI CCS Applications Factsheet, http://hub.globalccsinstitute.com/sites/default/files/publications/191078/fact-sheet-ccs-applications.pdf

16 Energy Procedia, Vol. 63, pp 1-8134, 2014, 12th international Conference on Greenhouse Gas Control Technologies, GHGT-12, http://www.sciencedirect.com/science/journal/18766102/63

Acronyms

CBTL	Coal-biomass to liquids
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CLC	Chemical looping combustion
CO_2	Carbon dioxide
COE	Cost of electricity
cP	Centipoise
EOR	Enhanced oil recovery
H_2	Hydrogen
H_2O	Water
IGCC	Integrated gasification combined cycle
IGFC	Integrated gasification fuel cell
MEA	Monoethanolamine
NGCC	Natural gas combined cycle
NOAK	Nth of a kind
NOC	Normal operating conditions
OECD	Organization for Economic Co-operation and Development
PC	Pulverized coal
RD3	RDD&D
RDD&D	Research, development, demonstration, and deployment
ROIP	Residual oil in place
ROZ	Residual oil zone
sCO_2	Supercritical CO_2
SOFC	Solid oxide fuel cell
SOTA	State of the art
USC	Ultra-supercritical