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U.S. DEPARTMENT OF
ENERGY

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Carbon Dioxide Capture Technologies

Chapter 4: Technology Assessments

Overview of advanced CO_2 capture technologies

Today's fossil fueled power systems include: 1) pulverized coal (PC) combustion, where coal is used to power a supercritical steam power cycle; 2) Integrated Gasification Combined Cycle (IGCC), where coal is gasified to produce synthesis gas (syngas), which is then combusted and expanded in a gas turbine with a bottoming steam cycle; and 3) natural gas systems, where natural gas is combusted and expanded in a gas turbine in a simple cycle or with an added bottoming steam cycle for a combined cycle.

Two approaches to carbon capture are post-combustion and pre-combustion capture. Each method has unique challenges as they handle separation from streams of different CO_2 concentration and different pressures. (Oxycombustion, which involves separation of other gases is addressed in the Technology Assessment 4.A Advanced Plant Technologies.) The post-combustion CO_2 capture processes occur after the combustion of coal with air, which produces a typical output stream of 10-15% CO_2 concentration at atmospheric pressure.

Pre-combustion capture refers to removing CO_2 from fossil fuels before combustion and is applicable to advanced generators, such as an IGCC plant. In an IGCC the fuel is partially oxidized to drive gasification

Evolution of CO_2 Capture Membrane from Concept to $1MW_e$ pilot scale

The DOE initiated its investment in carbon capture membranes with the first competitively awarded cost-shared R&D contract with Membrane Technology Research, Inc. (MTR), in 2006. R&D resulted in a promising material called the Polaris Membrane, which moved to bench scale testing at 10 kWe, capturing 250 lb/day of CO_2, and then to 50 kWe, capturing 1 ton per day of CO_2 from the Arizona Public Service coal-fired Cholla power plant. That success led to a 1 MW_e, 20 ton CO_2 per day, small pilot slipstream test which started operation in January, 2015, at the National Carbon Capture Center (NCCC) in Alabama (Figure 4.E.1). It is expected that a successful demonstration at this scale could lead to a full scale demonstration and subsequent commercialization.

Figure 4.E.1 The 1 Mw_e, 20 ton per day MTR Membrane Module at the NCCC

Credit: National Energy Technology Laboratory

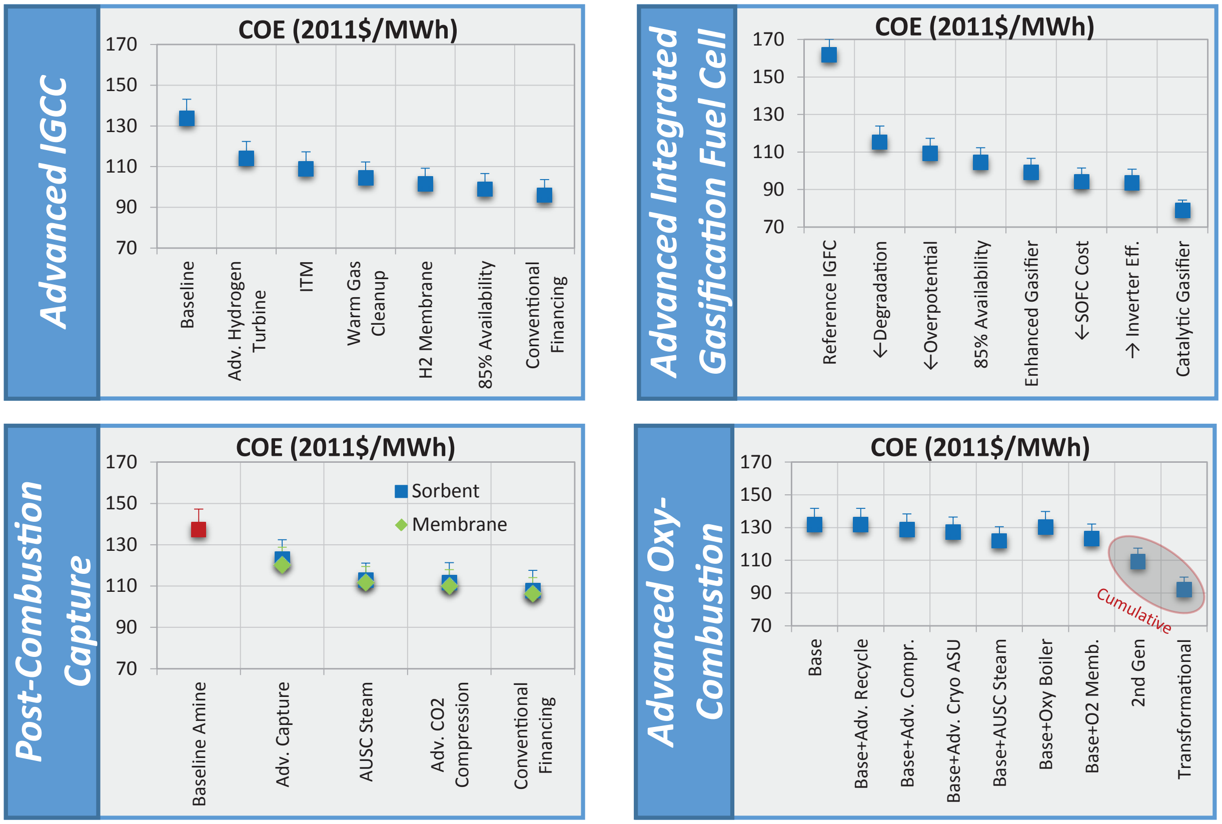
reactions. Rather than burning, most of the coal is chemically broken apart by the heat and pressure in the gasifier, setting into motion chemical reactions that produce syngas. The syngas then goes through a water-gas shift reaction, converting CO and H_2O to a H_2 and CO_2 gas mixture. This syngas has CO_2 concentration of 15-50% at high pressures, which can be more easily separated than for post-combustion streams at lower concentrations and pressures. After the CO_2 removal, the H_2 is used as a fuel in a combustion turbine or, alternatively, to power solid oxide fuel cells (SOFCs). Pre-combustion capture has the advantage of a relatively small incremental cost to capture CO_2 from an IGCC, which offers a highly efficient, flexible operation, advanced power generation system.

While "1st generation" technologies are currently being demonstrated in large-scale projects, next generation plants will be needed to achieve costs low enough for widespread deployment. Small pilot-scale tests (e.g., 1 MW_e) of second generation capture technologies such as advanced solvents, sorbents, and membranes are currently being conducted. Promising technologies are planned to be tested at large pilot-scale (10+ MW_e) to have them ready for demonstration by 2020. Successful development of these technologies would significantly reduce the capital and operating costs toward achievement of these goals. A number of similar international research activities featured at the 12th Greenhouse Gas Technologies Conference (GHGT-12) held October, 2014, in Austin, Texas, are ongoing to demonstrate similar technologies to those being developed in the United States. Additionally, transformational technologies, which have the potential for further cost reductions, are being tested at laboratory- and bench-scale and are expected to be ready for demonstration by 2025.

Analyses have evaluated the potential impacts of the cumulative effects of multiple advanced components integrated into a plant, demonstrating that multiple combustion and gasification pathways are important for significantly improving the efficiency and decreasing the cost of electricity (COE) of coal plants with CCS.[1] Figure 4.E.2 shows several such integrated evaluations of COE improvements, achieved along a variety of technology development pathways being pursued in CCS research and development. In this analysis, advanced technologies have each been assessed individually and cumulatively in the appropriate combustion and gasification pathways to assess the impact on key metrics such as net plant efficiency and COE. Technologies evaluated are at varying technology readiness levels; thus, both the cost and performance data available to perform the evaluation and the anticipated date for commercial readiness varies significantly. For each of the parallel pathways, successful RD&D of multiple advanced technologies is required. Key conclusions include:

- Technologies providing improvement in power cycle efficiency are essential for each pathway by reducing fuel costs through higher efficiencies and by spreading the significant capital costs of coal CCS plants over greater net power; examples include Absorption Heat Pump (AHP), Absorption Heat Transformer (AHT), solid oxide fuel cells (SOFC), and advanced ultrasupercritical (AUSC) steam plants.
- Reduction of auxiliary loads and cost improvements of supporting systems, such as oxygen production and gas cleanup, are critical to advanced oxy-combustion and IGCC.
- Reductions in the energy penalty and cost associated with CO_2 capture technology play a significant role in the post-combustion capture pathway and are applicable to both greenfield and retrofit applications.

Figure 4.E.2 Integrated technology improvements and parallel pathways are required to drive down the cost of CCS on fossil plants. These figures show nth-of-a-kind (NOAK) cost and performance. Technologies evaluated are at varying technology readiness levels (TRLs); thus, both the cost and performance data available to perform the evaluation and the anticipated date for commercial readiness vary significantly.[2]



Foremost Technical Issues for Carbon Capture

Key challenges for solvents and sorbents are reducing the energy required for releasing the captured CO_2 to regenerate the solvent, increasing reaction speed, and reducing material cost. Improving durability and tolerance to contaminants, and CO_2 selectivity are critical for membranes. There are needs for advanced materials that can provide high CO_2 loading capacity, improved reaction kinetics, and resistance to degradation. In addition, improvements in system configuration and operation and integration of capture technologies with plant design are critical to future economical implementation of CCS.

Advanced Solvents

Solvent-based research is focused on developing low-cost, non-corrosive solvents that have a high CO_2 loading capacity, improved reaction kinetics, low energy investment, and resistance to degradation, as well as improvements in system configuration and operation such as enhanced heat recovery and mass transfer rates. These issues are detailed in Tables 4.E.1 and 4.E.2.

Table 4.E.1 Challenges and Desired Outcomes for Advanced Solvents

Advanced Solvents

Major R&D Challenges

- Optimizing the balance of fast kinetics, equilibrium, and heat of reaction to reduce capital costs and energy requirements through heat integration and reduced reactor vessel size
- Reducing water content of solvents to eliminate sensible heat required during regeneration, which will contribute to cost reduction
- Developing solvents with reduced oxidative and thermal degradation rates compared to monoethanolamine, the current commercially available amine-based carbon-capture solvent.

Desired Outcomes:

- Scale advanced solvent technologies to 10MWe+ by 2020 to help meet the integrated 2nd generation target leading to commercial CCS technologies that reduce LCOE by at least 20%

Table 4.E.2 Technical Assessment and Opportunities for Advanced Solvents

Technical Assessment and Opportunities for Advanced Solvents

What we have learned	Current Research	Future Research Pathways
■ System integration suited for power generation is responsible for significant thermodynamic improvements. Hitachi[3,4,5] solvent has shown a 25-30 % reduction in regeneration energy compared to monoethanolamine (MEA). Solvents have been found to reduce reboiler duty by 20%-28% compared to MEA.[6,7,8] ■ Improvements to reduce solvent water fraction by GE and RTI have increased working capacity and reduced regeneration steam load.[9,10,11] ■ Some high performance solvents are extremely viscous; work on binding organic liquids has shown viscosity of non-aqueous solvents should be less than 100 cP to allow solvents to have optimal thermodynamic performance, thereby lowering both CAPEX and OPEX.[12,13] ■ High viscosity solvents reduce practical implementation challenges but may require immobilization to realize benefits.	■ Currently testing five advanced solvent systems at the 1MWe scale and nine bench scale projects at the $<0.1\text{MW}_e$ scale.[14] ■ Work by the University of Kentucky incorporating a dewatering membrane in their process that decreases the amount of water going to the regenerator and results in a reduced sensible heat demand. ■ South Korea is currently testing the advanced KoSol4 solvent at the 10 MW_e Boryeoung pilot facility. ■ Norway has been testing the Alstom Chilled Ammonia and other advanced solvents at the Test Centre Mongstad. ■ The Boundary Dam facility in Saskatchewan, Canada, is currently testing the Cansolv solvent to determine the cost of capturing 90% of CO_2 from a 150MW_e power plant. ■ Early work by LLNL is attempting to immobilize viscous solvents thereby negating the viscosity challenge ■ The University of Kentucky[15] is integrating a Hitachi solvent to reduce oxidation and thermal degradation rates by 89%.	■ Developing advanced solvents with low water content, fast kinetics, and near-zero sensible heat for regeneration will reduce both capital and energy costs. ■ Advanced Manufacturing (AM) to drive down capital costs while sustaining thermodynamic advancements. ■ Accommodating high viscosity solvents with favorable (less than 100 cP) thermodynamic properties. ■ Hybridizing system with other approaches to complement preferred separation driving forces that will reduce the energy required for solvent regeneration

Advanced Sorbents

Solid sorbent-based research is focused on developing sorbents with low-cost raw materials, thermal and chemical stability, low attrition rates, low heat capacity, high CO_2 adsorption capacity, high CO_2 selectivity, and improved system configurations such as enhanced pressure swing adsorption (PSA) and temperature swing adsorption (TSA) processes, as well as hybrid systems. These issues are detailed in Tables 4.E.3 and 4.E.4, and successful development would reduce capital and energy costs and improve reliability.

Table 4.E.3 Challenges and Desired Outcomes for Advanced Sorbents

Advanced Sorbents
Major R&D Challenges ■ Reduce sorbent attrition to reduce operation costs ■ Increase surface area to increase loading while maintaining structural integrity of the sorbents. ■ Reduce heat demand needed to reverse the chemical reaction ■ Optimize heat management systems to maintain working capacity and utilize process heat ■ Improve solids handling
Desired Outcomes: ■ Scale Sorbent technologies to $10MW_e$ + by 2020 to help meet the integrated 2nd generation target leading to commercial CCS technologies that reduce LCOE by at least 20%

Table 4.E.4 Technical Assessment and Opportunities for Advanced Sorbents

Technical Assessment and Opportunities for Advanced Sorbents		
What we have learned	Current Research	Future Research Pathways
■ Attrition rates <0.01% per cycle can dramatically improve process economics, depending on sorbent cost. ■ Water and sulfur can be major concerns for most sorbent materials and processes if not designed to accommodate them. ■ Heat recovery is a unique challenge which can be overcome by certain sorbent and process integration. ■ Moisture management is required to avoid agglomeration of materials.	■ Research is identifying limits on attrition rates to be < 0.01 percent / cycle, though ideally much less.[16,17] ■ Research adding hydrophobic surface moieties have prevented moisture from adversely impacting sorbent performance ■ Univ. of North Dakota[18] has tested an advanced solid to solid heat exchanger to improve energy performance and reduce capital costs. ■ Research of a $1MW_e$ sorbent pilot system is providing validation of heat recovery process operations in a full system.[19,20] ■ South Korean advanced KEP-CO2P2 solid sorbents are being tested at the $10MW_e$ Hadong pilot facility.[21]	■ Attrition resistant sorbents need to be improved to extend the life of materials and reduce operating costs ■ Rapid dehydration process such as thermal swing adsorption (TSA) and pressure swing adsorption (PSA) systems have opportunity to improve efficiency and reduce capital cost.[22] ■ Application of H_2O resistant metal-organic frameworks (MOF) with steep isotherms to make robust membranes.[23] ■ Solid/Solid heat exchanger development[24] will improve heat integration and reduce energy demands from the power cycle. ■ Hybridizing system with other approaches to complement preferred separation driving forces to reduce energy requirements for regeneration. ■ Advanced manufacturing to drive down capital costs while sustaining thermodynamic advancements.

Advanced Membranes

Membrane-based research is focused on the development of low-cost, durable membranes that have improved permeability and selectivity, thermal and physical stability, tolerance to contaminants in combustion flue gas, and improved system configurations such as solvent/membrane hybrid systems, and sub-ambient operation integrated with CO_2 liquefaction. These issues are detailed in Tables 4.E.5 and 4.E.6. Successful development would provide a flexible and durable capture option that is independent of the steam cycle and could significantly reduce the capital and operating costs.

Table 4.E.5 Challenges and Desired Outcomes for Advanced Membranes

Advanced Membranes

Major R&D Challenges

- Increase the selectivity and permeance to achieve high recovery rate and purity through intelligent design of materials
- Optimize module designs to reduce pressure drop and increase surface area
- Integration of multiple stages to improve performance
- Integration with the power plant to increase combustion flue gas CO_2 concentration

Desired Outcomes:

- Scale Membrane technologies to 10 MW_e+ by 2020 to meet the 2nd generation target leading to commercial CCS technologies that reduce LCOE by at least 20%

Table 4.E.6 Technical Assessment and Opportunities for Advanced Membranes

Technical Assessment and Opportunities for Advanced Membranes

What we have learned	Current Research	Future Research Pathways
■ Pre-concentrating CO_2 to increase driving force is a viable process improvement. ■ Membrane costs must decrease. ■ Optimal CO_2 recovery for membrane system may be less than 90%. ■ Integration of membranes with other processes such as solvent, cryogenic, and sorbents can significantly improve performance. ■ Improvements of 4X higher CO_2/N_2 selectivity have been achieved by operating their membrane at sub-ambient temperatures.[25,26]	■ Addition of a second stage sweep membrane has been shown to pre-concentrate CO_2 from 13% to approximately 20%.[27] Such a membrane is being demonstrated at the beginning of their solvent processes to pre-concentrate.[28,29] ■ A move from spiral wound to plate-and-frame modules is showing decreased pressure drop from 3 PSI to < 1 PSI, thereby reducing energy consumption.[30] ■ Experiments are identifying optimum separation rate for bulk separation of CO_2 via membrane, which may be approximately 60% separation.[31] ■ Scaled up demonstration of high selectivity membranes is required, for this technology to be valid in an integrated system.	■ Advanced manufacturing techniques show potential to drive down capital costs while sustaining thermodynamic advancements. ■ Facilitated transport mechanisms to increase selectivity at high permeability, driving down electricity demand. ■ Hybridizing system with other approaches to complement preferred separation driving forces that can reduce capital costs and steam demands from the power cycle.

Advanced Process Equipment and System Integration

System integration and process intensification realized through the development of advanced process equipment will aid in driving down both energy and capital costs of the new and existing carbon capture systems. Carbon capture systems demand a significant amount of energy, either in the form of steam and or electricity, to drive the differential pressures and temperatures needed to facilitate CO_2 separation. This puts a significant demand on the existing power island or auxiliary support equipment. The development of novel heat exchangers, hybrid capture systems, absorbers, and using advanced manufacturing to modularize these systems is critical to the cost and performance of future systems.

These issues are detailed in Tables 4.E.7 and 4.E.8.

Table 4.E.7 Challenges and Desired Outcomes for Advanced Process Equipment and System Integration

Advanced Process Equipment and System Integration
Major R&D Challenges ■ Develop advanced absorbers which are solvent agnostic and reduce capital costs versus conventional systems ■ Develop heat integration systems to reduce steam demand from the boiler system ■ Utilize advanced manufacturing to optimize packing and heat exchanger designs to increase surface areas which will result in smaller systems and reduce capital costs
Desired Outcomes: ■ Scale advanced process designs to 10MW$_e$ by 2020 to support 2nd generation targets leading to commercial CCS technologies that reduce LCOE by at least 20%

Table 4.E.8 Technical Assessment and Opportunities for Advanced Process Equipment and System Integration

Technical Assessment and Opportunities for Advanced Process Equipment and System Integration		
What we have learned	Current Research	Future Research Pathways
■ Capital costs are as important as thermodynamic costs – capital costs need to be addressed. ■ Hybridizing capture processes and/or combining them with balance of plant equipment already required show promise to reduce both capital and operating costs.	■ Advanced contactor that could be applied to a number of different solvents shows a 90% reduction in volume over a packed tower system, significantly reducing capital costs.[32,33] ■ Hybridized conventional amine system with a membrane contactor results in an increase in specific surface area and a 75% decrease of membrane area compared to conventional gas separation membranes alone, allowing for smaller vessel sizes thereby reducing CAPEX.[34,35] ■ High efficiency system for flue gas heat recovery at 25MW$_e$ currently under testing.[36] ■ Advanced manufacturing work on intelligent packing includes testing an advanced stripper design at the 0.1 MW$_e$ scale. ■ Reduction of steam demand through modeling advanced heat integration schemes.	■ Develop computational models of integrated systems to accelerate system design and optimization ■ Advanced manufacturing to drive down capital costs of advanced process equipment while sustaining thermodynamic advancements. ■ Optimize system configuration and operation through new equipment geometries.

Transformational Technologies

Novel research currently explores electrochemical-based approaches and direct CO_2 phase change using passive nozzle designs, and is primarily focused on developing transformational systems that have the potential to realize step change improvements in cost and performance beyond those seen using the more conventional solvents, sorbents and membranes. These issues are detailed in Tables 4.E.9 and 4.E.10 and could lead to commercial systems in 2025 that reduce the LCOE by at least 30%.

Table 4.E.9 Challenges and Desired Outcomes for Transformational Technologies

Transformational Technologies
Major R&D Challenges - Utilize specialized separation mechanisms such as desublimation, cryogenics, phase change solvents, electrochemical separations, and others to reduce capital costs. - Use advanced computing to design advanced materials for gas separations and develop advanced manufacturing technologies that enable their high-fidelity nano-scale production. These materials offer higher working capacities and lower heats of regeneration which reduce operating costs. - Accelerate the rate of novel capture systems development by integrating materials, synthesis, testing, and manufacturing into an integrated development process
Desired Outcomes: - Scale advanced process designs to $10MW_e$ by 2025 to support an integrated system which could lead to commercial systems in 2030 that reduce the LCOE by at least 30%

Table 4.E.10 Technical Assessment and Opportunities for Transformational Technologies

Transformational Technologies		
What we have learned	Current Research	Future Research Pathways
- Transformational carbon capture technologies should be designed specifically for separation of CO_2 from flue gases from advanced power generation platforms such as chemical looping, advanced gasification, oxy combustion, and industrial sources. - Integrating advanced computational tools for discovery of materials, rapid synthesis, and functionalization is possible as shown with mixed matrix materials such as MOFs and polymer membranes.	- Cryogenic projects will reduce the overall footprint of the capture system, significantly reducing footprint and capital costs.[37] - Phase change project with GE is being developed with expectations to eliminate unit operations from the capture system.[38] - Developing novel materials for gas separation with national labs and in collaboration with the Energy Frontier Research Centers. - Electrochemical processes which integrate fuel cell technology or other separations processes.[39]	- Combining transformational capture technology with balance of plant equipment already required for advanced power generation could reduce capital and energy costs. - Accelerate efforts in the discovery of carbon capture substances and systems through competitively awarded, cost-shared R&D partnerships with industry that focus parallel efforts on computational discovery, syntheses, testing, manufacturing, and functionalization of advanced concepts. These advanced materials can reduce both capital and operating costs.

Additional Information

In addition to the material provided above, extensive information has been developed on carbon capture technology development, cost and performance analysis, major projects, and a host of other issues. Table 4.E.11 provides links to some of the key information available on these and other topics related to carbon capture technology.

Table 4.E.11 Links for Additional Information

Document Title	Link To Reference	Description
DOE Carbon Capture Homepage	http://energy.gov/fe/science-innovation/carbon-capture-and-storage-research/carbon-capture-rd	Webpage
NETL Carbon Capture Homepage	http://www.netl.doe.gov/research/coal/carbon-capture	Webpage
Carbon Capture Program Plan	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	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
2014 Annual Review Meeting	http://www.netl.doe.gov/events/conference-proceedings/2014/2014-netl-co2-capture-technology-meeting	Proceedings from the 2014 DOE carbon capture project review meeting
2014 Transformational Workshop	http://www.netl.doe.gov/research/coal/carbon-capture/workshop-2014	Proceedings from the 2014 DOE sponsored workshop on transformational carbon capture technology opportunities
Boundary Dam Project	http://www.cansolv.com/rtecontent/document/Saskpower.article.in.Carbon.Capture.July.pdf	Factsheet for Boundary Dam CO_2 Capture Demonstration Project
GHGT12 Proceedings	http://www.sciencedirect.com/science/journal/18766102/63	Proceedings from 2014 IEAGHG GHGT-12 Conference

Endnotes

[1] Gerdes et al. , Energy Procedia 63 (2014) 7541 – 7557

[2] Ibid

[3] Liu et al. 2014, Study of a Novel Solvent System for CO_2 Capture from Post-Combustion Flue Gas, Energy Procedia 63, 2014, Pages 1927–1932 http://www.netl.doe.gov/research/coal/carbon-capture/post-combustion/solvent-university-kentucky

[4] NETL Project Webpage for University of Kentucky - http://www.netl.doe.gov/research/coal/carbon-capture/post-combustion/solvent-university-kentucky

[5] Energy Procedia; Volume 63, 2014, Pages 1927–1932;, Study of a Novel Solvent System for CO_2 Capture from Post-Combustion Flue Gas; http://www.sciencedirect.com/science/article/pii/S1876610214020177

[6] NETL Project Webpage for University of Kentucky -http://www.netl.doe.gov/research/coal/carbon-capture/post-combustion/de-fe0013303

[7] NETL Project Page for Linde Capture Project - http://www.netl.doe.gov/research/coal/carbon-capture/post-combustion/solvent-linde

[8] Energy Procedia, Volume 63, 2014, Pages 1456–1469; Pilot-scale Demonstration of an Advanced Aqueous Amine-based Post-combustion Capture Technology for CO_2 Capture from Power Plant Flue Gases; http://www.sciencedirect.com/science/article/pii/S1876610214019705

[9] NETL Project Page for GE Amino Silicone Solvent Capture Project - http://www.netl.doe.gov/research/coal/carbon-capture/post-combustion/de-fe0013755

[10] NETL Project Page for Research Triangle Institute Non-Aqueous Solvent Capture Project - http://www.netl.doe.gov/research/coal/carbon-capture/post-combustion/de-fe0013865

[11] Energy Procedia, Volume 63, 2014, Pages 580–594; Non-Aqueous Solvent (NAS) CO_2 Capture Process http://www.sciencedirect.com/science/article/pii/S1876610214018785

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[14] NETL Project Webpage for University of Kentucky -http://www.netl.doe.gov/research/coal/carbon-capture/post-combustion/de-fe0013303

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[16] NETL Project Page for ADA-ES Advanced Sorbent Pilot Project - http://www.netl.doe.gov/research/coal/carbon-capture/post-combustion/de-fe0012914

[17] Energy Procedia, Volume 63, 2014, Pages 1536–1545, ADA's Solid Sorbent CO_2 Capture process: Developing Solid Sorbent Technology to Provide the Necessary Flexible CO_2 Capture Solutions for a Wide Range of Applications; http://www.sciencedirect.com/science/article/pii/S187661021401978X

[18] NETL Project Page for University of North Dakota advanced sorbent capture project - http://www.netl.doe.gov/research/coal/carbon-capture/post-combustion/sorbent-univerisity-north-dakota

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[38] NETL Project Page for GE Global Research novel phase-changing absorbent - http://www.netl.doe.gov/research/coal/carbon-capture/post-combustion/de-fe0013687

[39] NETL Project Page for Fuel Cell Energy novel research into integration of CO_2 capture and energy generation -http://www.netl.doe.gov/research/coal/carbon-capture/post-combustion/membrane-fuelcell-energy

Acronyms

AM	Advanced manufacturing
AHP	Absorption heat pump
AHT	Absorption heat transformer
AUSC	Advanced ultrasupercritical
CCS	Carbon capture and storage
CO_2	Carbon dioxide
COE	Cost of electricity
cP	Centipoise
H_2	Hydrogen
H_2O	Water
IGCC	Integrated gasification combined cycle
MEA	Monoethanolamine
MW_e	Megawatt electrical
NGCC	Natural gas combined cycle
NOAK	Nth of a kind
NOC	Normal operating conditions
PC	Pulverized coal
RDD&D	Research, development, demonstration, and deployment
ROIP	Residual oil in place
ROZ	Residual oil zone
sCO_2	Supercritical CO_2w
SOFC	Solid oxide fuel cell
SOTA	State of the art
USC	Ultra-supercritical