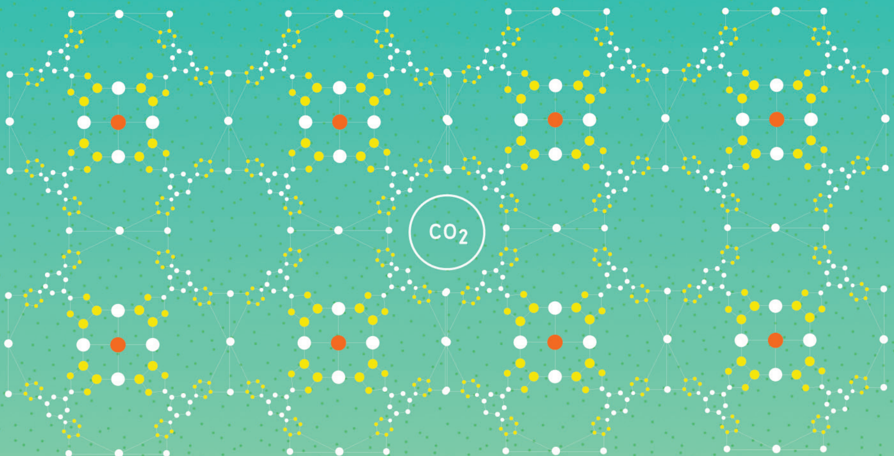
Emerging Carbon Capture Technologies Overview

A Review of New Post-Combustion Technologies and Processes that Capture Industrial Carbon Dioxide Emissions at Power Plants



PrizeCapital®

Prize Capital, LLC
1616 Camino Del Mar
Del Mar, CA 92014

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Volume 2 of syndicated research sponsored by Tri-State Generation and Transmission Association, Inc.

© 2012 Prize Capital LLC

Matt Peak
Director of Clean Technologies
Prize Capital, LLC
matt@prizecapital.net
(213) 327-8935

This document is legally privileged and only for the use of its intended recipient. It is confidential and exempt from disclosure under applicable law. This document is not intended to create a legal binding contract of any nature whatsoever and neither the sending nor the receipt hereof, nor any comment contained herein, is intended to have legal effect. If you are not the intended recipient, or the employee or agent thereof, you are hereby notified that any unauthorized use, dissemination, distribution or copying of this document is strictly prohibited. If you have received this document in error, please call 858-724-9300.

Table of Contents

Overview >>

Carbon Capture Without Sequestration? ... 12
Carbon Capture and Recycling (CCR) ... 12
The Value of End-to-End Solutions ... 14
Conventional Post-Combustion Carbon Capture ... 15
Amine Solvents ... 15
Ammonia ... 16
Challenges with Conventional Carbon Capture ... 17

Emerging Carbon Capture Technologies >>

Solvents ... 19
Enzyme Based Systems ... 19
Physical Sorbents ... 20
Precipitated Calcium Carbonate ... 20
Ionic Liquids ... 20
Gas Separation Membranes ... 20
Metal Organic Frameworks (MOFs) ... 22

Select Emerging Carbon Capture Company Overviews >>

3H Company, LLC ... 27
ADA-ES ... 28
Advanced Fuel Research, Inc. ... 29
AIL Research, Inc. ... 30
Aker Clean Carbon ... 31
Akermin ... 32
American Air Liquide, Inc. ... 33
ATK (and ACEnT Laboratories) ... 34
Babcock & Wilcox Power Generation Group ... 35
BASF ... 36
Battelle/Pacific Northwest National Laboratory ... 37
C12 Energy ... 38
Cansolv Technologies ... 39
Carbon Capture Scientific ... 40
Carbon Engineering ... 41
Carbozyme ... 42
Catacel Corporation ... 43
CFD Research Corporation ... 44
Climeworks ... 45
CO2 Solution ... 46
Codexis ... 47
Compact Membrane Systems, Inc. ... 48
Fluor Corporation ... 49
FuelCell Energy ... 50
Gas Technology Institute (GTI) ... 51
GE and the University of Pittsburgh ... 52
GE Global Research ... 53
GE Global Research ... 54
GE Global Research ... 55

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

GE Global Research 56
Global Thermostat 57
Honeywell 58
InnoSepra 59
Inventys 60
ION Engineering, LLC 61
Kilimanjaro Energy 62
Linde Engineering 63
Membrane Technology and Research, Inc. 64
Mitsubishi Heavy Industries (MHI) 65
Nalco Company 66
Nano Terra, Inc. 67
Neumann Systems Group, Inc. 68
Novozymes 69
Porifera Nano, Inc. 70
Process Group 71
Siemens 72
Sustainable Energy Solutions 73
TDA Research, Inc. 74
Trimeric Corporation 75
United Technologies Research Center 76
UOP, LLC. 77
URS Corporation 78
W.R. Grace 79

Select Emerging Carbon Capture University and Laboratory Overviews >>

Columbia University 83
Columbia University Earth Institute 84
Georgia Institute of Technology 85
Georgia Tech Research Corporation 86
Georgia Tech Research Corporation 87
GKSS-Research Centre 88
Hampton University 89
Illinois State Geological Survey 90
Institution of Mechanical Engineers 91
Lawrence Berkeley National Laboratory 92
Lawrence Livermore National Security 93
Lehigh University 94
Massachusetts Institute of Technology 95
National Energy Technology Laboratory (NETL) 96
National Institute of Carbon, Oviedo 97
Northwestern University 98
Oak Ridge National Laboratory 99
Ohio State University 100
Pennsylvania State University 101
Research Triangle Institute – Fluorinated Polymer Membranes 102
Research Triangle Institute – Non-Aqueous Solvents 103
Research Triangle Institute - Regenerable Sorbent 104

SRI International 105
Texas A&M 106
University of Akron 107
University of California, Santa Cruz 108
University of Colorado at Boulder 109
University of Illinois at Urbana-Champaign 110
University of Kentucky- Center for Applied Energy Research 111
University of New Mexico 112
University of North Dakota – EERC 113
University of North Dakota – Institute for Energy Studies 114
University of Notre Dame – Brennecke Research Group 115
University of Notre Dame - Maginn Group 116
University of Sydney 117
University of Texas at Austin 118
University of Wyoming 119
William Marshall Rice University 120

Works Cited >> 123

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Overview

To date, most reviews of carbon capture technologies are accompanied by a discussion of sequestration, which is the process of burying carbon dioxide (CO_2) deep into the ground where it will remain out of the atmosphere. This paradigm views CO_2 as a liability and a waste product, and avoids liability issues and regulatory challenges. Thus, burying it deep in geologic formations for eternity makes sense.

Our review of CO_2 technologies is different, for while we acknowledge the potential of sequestration to provide a long-term environmental service, it is by no means the only method of handling CO_2 to lead to the emergence of this service.

Specifically, a previous Prize Capital report that was released in 2011 discussed "carbon capture and recycling" (CCR), a process by which carbon is recognized as a fundamental building block in the production of numerous products, such as fuel and building materials, and thus treated as an asset.

While many of the emerging 136 CCR entities profiled in that previous report are able to handle raw flue gas from power plants and thus avert the need for a separate carbon capture function, a significant portion of these technologies do not.

So while CCR can bypass some of the technological and perceptual challenges that have delayed the emergence of sequestration, the CCR approach that proves most effective in scaled, real-world applications may itself depend on the emergence of a scalable, real-world carbon capture technology at significantly lower costs and lower energy consumption than currently possible.

To date, the primary carbon capture demonstration technologies have focused on amines and chilled ammonia. These approaches were developed decades ago for use in other industries, such as synthetic ammonia production, H_2 production, and limestone calcination, where they have served these industries well given the relatively low volumes of carbon captured and high price points. Yet now that the power industry is examining carbon capture approaches and experimenting with scaling up these existing technologies to meet their volumetric needs and price-points, the industry is realizing that these traditional technologies are falling far short.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12 | PrizeCapital.

One statistic alone –that power plants need to devote approximately 30 percent of their electric output, so called "parasitic" load, from a given plant to power an accompanied traditional carbon capture technology to isolate and bury a product – is enough to keep the carbon capture industry (as applied to power plants) at bay. One of the most well known and thorough carbon capture demonstrations in the United States (at AEP's Mountaineering Plant) shut down in 2011 after a successful two-year run because, as the company stated, there was no compelling regulatory or business reason to continue the program.[1]

In order to spur advancements, governments around the world have provided billions of dollars in funding to support the development of carbon capture breakthroughs. In the United States, the Department of Energy (DOE) has been actively funding technological development of advanced technologies for a decade, and has dramatically increased its level of financial support in recent years, largely through its National Energy Technology Laboratory (NETL) and Advanced Research Projects Agency-Energy (ARPA-E).

Through these DOE programs, breakthrough technologies have been targeted in the areas of:

- Solvents: Improved primary, secondary, and tertiary amines;
- Enzyme Based Systems: Biologically based capture systems;
- Physical Sorbents: Solids reacting at different temperatures to both absorb and release CO_2;
- Precipitated Calcium Carbonate: A soluble carbonate reacting with CO_2 to form a bicarbonate, which when heated releases CO_2 and reverts to a carbonate;
- Ionic Liquids: A broad category of salts that can dissolve gaseous CO_2 and are stable at temperatures up to several hundred degrees centigrade;
- Gas Separation Membranes: Using membranes to recover CO_2 from flue gas;
- Metal Organic Frameworks (MOFs): a new class of hybrid material built from metal ions with carefully sized cavities that can adsorb CO_2.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

This report examines these emerging technologies. We narrow our focus specifically to post-combustion carbon capture technologies, given that there is an existing power generation infrastructure to address and equip. Contrary to Prize Capital's CCR Industry Overview, this report is largely not an original nor a comprehensive piece of literature, but rather an aggregation of partial information, data, and developments in this field, with a particular eye towards the targets of recent government funding (given that the government has been by far the industry's largest funding source).

The true value of this report is in its accompaniment of the CCR Industry Overview. Reviewing the two reports side-by-side reveals the complementary nature of the technologies, the mutual nascency of both industries, and the overwhelming potential that is presented not just by these industries respectively, but in the combination of these industries to form effective end-to-end (i.e. flue gas to sellable product) solutions.

Note that we use the term "solutions" in its plural form, for our analyses in both reports indicates that multiple technologies may emerge as scalable, affordable, real-world solutions. Given that there are 136 (and counting) emerging CCR entities and 90 emerging carbon capture entities presented in this report alone, simply providing a platform to allow these various entities to experiment with each other leaves the door open for nearly 13,000 possible end-to-end solutions.

As we move forward, the key to realizing the reality and potential of end-to-end solutions is constructing the platform that allows for and encourages just such experimentations and radical breakthroughs, through the diversification of innovation, that traditional R&D approaches do not achieve. A centralized test center at a real world, functioning power plant that leverages existing government and industry support, deliberately fosters collaboration, and incorporates competitive elements may be precisely the platform needed to catalyze and fuse these two industries and create the radical breakthroughs society needs to deal with CO_2.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Carbon Capture Without Sequestration?

Most discussions about carbon capture are accompanied by a discussion of sequestration. In this report, we deliberately avoid this accompaniment. Instead, we look at carbon capture through the prism of "carbon capture and recycling" and the potential for viable end-to-end (i.e. flue gas to sellable product) solutions to emerge.

Carbon Capture and Recycling (CCR)

An industry is emerging with a new option to mitigate industrial CO_2 emissions while generating additional revenue.[2]

Dubbed "Carbon Capture and Recycling", this new industry dispels the notion that CO_2 is a liability that needs to be buried – as is the case with carbon capture and sequestration (CCS) – and instead views the gas as a resource to be capitalized upon, using it as a feedstock in the production of valuable products such as fuel, building materials, animal feed, specialty chemicals, and plastics, among other things. In the near-term, this new industry represents a paradigm change that could avert the need to resolve complex issues associated with CCS (given that several CCR entities are able to handle raw flue gas) and instead prompt renewed action on CO_2 mitigation. Such action is essential as a carbon-constrained world emerges.[3]

CCR approaches fall into three categories:[4]

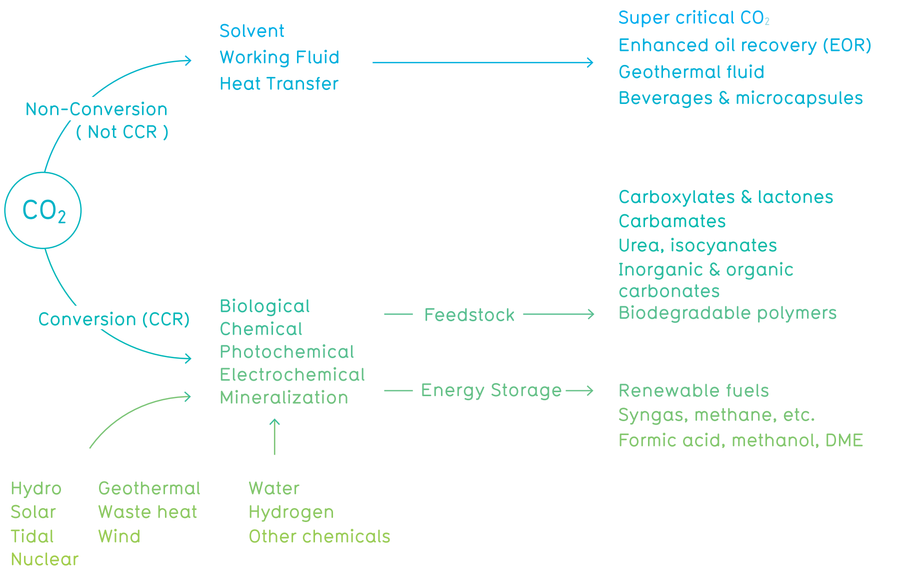
- Biological: a biological organism rapidly absorbs CO_2 to produce a product (e.g. algae oil refined to fuel)
- Chemical and catalytic: a catalyst prompts donor electrons to break or augment the carbon-oxygen bond in CO_2 molecules, then combines the carbon with other elements to produce a product (e.g. concentrated solar reforms CO_2 into CO, which then combines with hydrogen to produce synthetic diesel fuel)
- Mineralization: Through the use of feldspars and carbonization, CO_2 is locked into solid structures that can then be incorporated into products (e.g. CO_2 is reduced via anorthite to produce aluminum oxide, which is then sold to the advanced ceramic and chemical processing industries)

By absorbing, rearranging, and combining CO_2 to produce new products, well-established markets of sizeable proportion (i.e. the market for gasoline alone is approximately $700 billion

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

per year) are fed, and new revenue streams are established for their producers,[5] some of which are presented in Figure 1:

Figure 1
Different Pathways for Utilizing CO_2



Source: DNV

The CCR industry is nascent, but already is comprised of at least 136 total entities (37 biological, 63 chemical/catalytic, 23 mineralization, 1 blended approach, and 12 uncategorized entities). These entities vary in size from unfunded concept to >$50 million. They have received government and private funding totaling approximately $1 billion. Some are offering full spectrum solutions from capture to reuse, others focus on reuse and need viable capture solutions to promote their value proposition.[6]

These entities and others are working to overcome the challenges associated with commercializing and deploying CCR technologies. These challenges include: being able to recycle carbon year round, in various climactic conditions; thermodynamic and thermochemical logistics and efficiencies; scalability; proximity to necessary resources; and many others. With the emerging array of technologies and producers, as well as the current slate of technological challenges, this industry would benefit from models that promote diversity of innovation as well as financial diversity, rather than placing “bets” on single technologies and producers.[7]

Prize Capital’s CCR Industry Overview took an initial look at this emerging industry and the innovators within it, given that little aggregated, public data is currently available. It examined the rationale for CCR, current CCR approaches, the forces emerging to shape such approaches, and focused the majority of its content on providing snapshots of the innovators leading the creation of this new industry, including their respective stages of development as they march towards commercialization.[8]

The Value of End-to-End Solutions

This previous examination of the CCR industry revealed that the CCR approach that proves most effective in scaled, real-world applications may itself depend on the emergence of a scalable, real-world carbon capture technology, for a significant portion of the identified CCR technologies are not able to handle raw flue gas.

The package that is of most value to point source carbon emitters, such as those that comprise the power industry, is one that is end-to-end. In other words, as case studies indicate, point source operators have no compelling regulatory or business reason to simply capture carbon dioxide for the sake of capturing it. They also have no need for equipment that produces marvelous products from gas streams (i.e. CO_2) but is not compatible with their plant's particular gas stream (i.e. flue gas).

Yet if a solution that can plug in to existing point-source infrastructure and, in one approach, convert something that is currently discharged into something that creates value, a package of tremendous importance is presented to point-source emitters. Such is the value of end-to-end solutions.

Arriving at an end-to-end solution will require cross-pollination between the CCR and carbon capture industries and a significant level of experimentation to determine which combination of CCR and carbon capture technologies perform best.

One format that could encourage just such cross-pollination and experimentation is a centralized test center at a real world, functioning power plant. Many of the future needs of the electric industry are being developed primarily in laboratory settings, which could be significantly advanced through research and testing at an operating coal-fired electric plant.

Unfortunately, laboratory conditions don't mimic the real world, where large-scale energy providers are charted with the responsibility to provide consistent, affordable electricity to their customers. Innovators find it difficult to test their technologies in the real world because of utilities' "stack risk" – the legal, permitting, operational, and cost burdens encountered by a utility seeking to test one single technology.

A centralized test center can mitigate this risk by providing a working environment for research and testing in not just one but numerous areas that will be critical to the future viability and affordability of the electric sector.

Such a center can complement the existing government-supported National Carbon Capture Center (NCCC), which is a proven technology accelerator in the area of mostly conventional carbon capture. It can particularly complement the Post-Combustion Carbon Capture Center (PC4) located within the NCCC. The PC4 provides access to coal combustion flue gas streams for testing of post-combustion carbon capture regimes but requires substantial capital investment and does not pursue CO_2 utilization approaches.

A new test center can build upon the successful approaches of the NCCC and the PC4 to accelerate development of unconventional carbon capture technologies that breakthrough the current capital and parasitic load burdens and pair with CO_2 utilization technologies to create value out of what is currently a waste product.

It could also be of value to integrate competitive inducement prize(s) with the new center. Such prizes could provide cash (and other) awards to carbon capture and their recycling partners to further incentivize the pairing and experimentation of carbon capture with recycling technologies and facilitate breakthroughs in end-to-end applications. The art and science of inducement prize competitions is well understood.[9]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital.

Conventional Post-Combustion Carbon Capture

Given that, on a mass basis, CO_2 is the 19th largest commodity chemical in the United States, CO_2 is routinely separated and captured as a by-product from industrial processes, which include synthetic ammonia production, H_2 production, and limestone calcination.[10]

Conventional post-combustion carbon capture process implemented at power plants have simply scaled up these smaller scaled processes. The dominant methods of carbon capture include the use of bases: amine solvents and chilled ammonia.

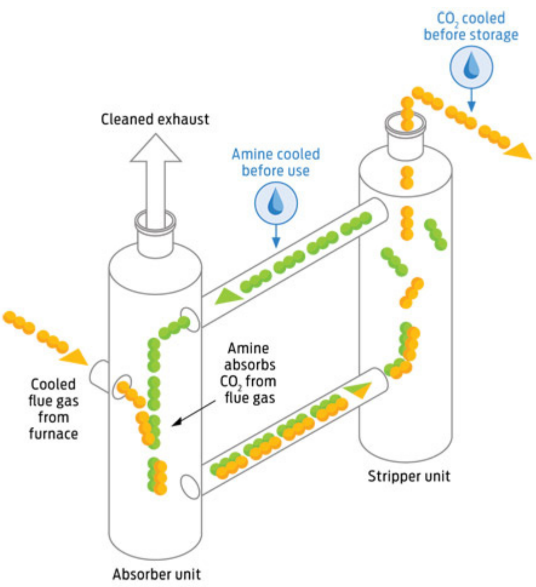
Amine Solvents

Gas absorption processes using chemical solvents, such as amines, to separate CO_2 from other gases have been in use since the 1930s in the natural gas industry. These processes are also used to produce food and chemical grade CO_2 from gas streams containing 3 to 25 percent CO_2.[11]

In this process, CO_2 is recovered from combustion exhaust by using amine absorbers and cryogenic coolers.[12] Amines react with CO_2 to form water-soluble compounds.[13] Because of this compound formation, amines are able to capture CO_2 from streams with a low CO_2 partial pressure, but capacity is equilibrium limited.[14] Thus, amine-based systems are able to recover CO_2 from the flue gas of conventional pulverized coal (PC) fired power plants.[15]

The process is illustrated in Figure 2:

Figure 2
A Typical Amine-Based Carbon Capture Process



Source: The Institute of Electrical and Electronics Engineers

Ammonia

The easiest way of looking at the basic properties of amines is to think of an amine as a modified ammonia molecule. In an amine, a hydrocarbon group has replaced one or more of the hydrogen atoms in ammonia.[16]

Replacing the hydrogen atoms still leaves the lone pair on the nitrogen unchanged – and it is the lone pair on the nitrogen that gives ammonia its basic properties. Amines will therefore behave much the same as ammonia in all cases where the lone pair is involved.[17]

Accordingly, AEP implemented an Alstom patented chilled post-combustion ammonia system at its 1300-megawatt coal-based Mountaineer Plant in New Haven, West Virginia,[18] as pictured in Image 1, where a 20-megawatt validation project ran between September 2009 and May 2011.

At the facility, the plant's slipstream was chilled and combined with a solution of ammonium carbonate, which absorbs the CO_2 to create ammonium bicarbonate.[19] The ammonium bicarbonate solution was then pressurized and heated in a separate process to produce a high-purity stream of CO_2, which was in turn sequestered.[20]

This was the first fully integrated CCS project at an existing coal-burning power plant.[21]

Image 1
AEP's Mountaineer Chilled Ammonia Carbon Capture Plant Built by Alstom

Source: Alstom

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Challenges with Conventional Carbon Capture

Existing capture technologies are not cost-effective when considered in the context of sequestering CO_2 from power plants.[22]

Unlike previous industrial applications, most power plants and other large point sources use air-fired combustors, a process that exhausts CO_2 diluted with nitrogen. Flue gas from coal-fired power plants contains 10-12 percent CO_2 by volume.[23] For effective carbon recycling, the CO_2 in these exhaust gases must be separated and concentrated and the solvent must be regenerated, as previously described.

These processes currently consume a tremendous amount of energy. A common estimate is that the energy required per MWh would rise 36% for a typical post-combustion plant retrofit.[24]

Accordingly, the cost of CO_2 capture using current technology is on the order of $150 per ton of carbon.[25] Analysis indicates that adding existing technologies for CO_2 capture to an electricity generation process could increase the cost of electricity by 2.5 cents to 4 cents/kWh depending on the type of process.[26]

Furthermore, the conventional carbon capture technologies are water intensive. Cooling the amines for CO_2 absorption, which generates heat, leads to an additional load on the cooling tower, causing more water to be lost.[27] Compressing the CO_2 to the supercritical conditions needed for storage requires cooling, too.[28] Thus, conventional technologies increase water requirements at a given plant by 33%.[29] If the energy lost in the carbon capture process is accounted for by adding additional capacity, then water consumption would increase by 80 percent.[30]

Finally, there is a general lack of experience with current carbon capture systems at the appropriate scale at power plants. Currently operating CO_2 capture systems in coal-based power plant applications (i.e. amine and chilled ammonia solvent systems) process about 75,000 to 300,000 tons of CO_2 per year. By comparison, a single 550-megawatt (MW) net output coal-fired power plant capturing 90 percent of the emitted CO_2 will need to separate approximately 5 million tons of CO_2 per year.[31]

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Emerging Carbon Capture Technologies »

A variety of technologies are emerging that introduce new approaches to carbon capture geared specifically towards large point-source CO_2-emitting sources, rather than simply scale-ups of older applications in different industries. These technologies – which include new solvents, enzyme based systems, physical sorbents, precipitated calcium carbonate, ionic liquids, gas separation membranes, and metal organic frameworks – have the potential to break through the energy, water, and cost barriers that afflict traditional carbon capture technologies.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Solvents

Amines are available in three forms (primary, secondary, and tertiary), each with its advantages and disadvantages as a CO_2 solvent. In addition to options for the amine, additives can be used to modify system performance. Also, design modifications are possible to decrease capital costs and improve energy integration.[32]

Improvements to amine-based systems for post-combustion CO_2 capture are being pursued by a number of process developers. R&D pathways to improved amine-based systems include modified tower packing to reduce pressure drop and increase contacting, increased heat integration to reduce energy requirements, additives to reduce corrosion and allow higher amine concentrations, and improved regeneration procedures.[33]

Aqueous ammonia is a related emerging option. Ammonia-based wet scrubbing is similar in operation to amine systems. Ammonia and its derivatives react with CO_2 via various mechanisms, one of which is the reaction of ammonium carbonate (AC), CO_2, and water to form ammonium bicarbonate (ABC). This reaction has a significantly lower heat of reaction than amine-based systems, resulting in energy savings, provided the absorption/desorption cycle can be limited to this mechanism.[34]

Ammonia-based absorption has a number of other advantages over amine-based systems, such as the potential for high CO_2 capacity, lack of degradation during absorption/regeneration, tolerance to oxygen in the flue gas, low cost, and potential for regeneration at high pressure.[35]

Enzyme Based Systems

Biologically based capture systems are another potential avenue for improvement in CO_2 capture technology. These systems are based upon naturally occurring reactions of CO_2 in living organisms. One of these possibilities is the use of enzymes. One process, utilizing carbonic anhydrase (CA) in a hollow fiber contained liquid membrane, has demonstrated in the laboratory a significant technical improvement over the MEA temperature swing absorption process.[36]

The rate of CO_2 dissolution in water is limited by the rate of aqueous CO_2 hydration, and the CO_2-carrying capacity is limited by buffering capacity. Adding the enzyme CA to the solution speeds up the rate of carbonic acid formation; CA has the ability to catalyze the hydration of 600,000 molecules of carbon dioxide per molecule of CA per second compared to a theoretical maximum rate of 1,400,000. This fast turnover rate minimizes the amount of enzyme required.[37]

Coupled with a low make-up rate, due to a potential CA life of 6 months based on laboratory testing, a biomimetic membrane approach has the potential for a step change improvement in performance and cost for large scale CO_2 capture in the power sector. The idea behind this process is to use immobilized enzyme at the gas/liquid interface to increase the mass transfer and separation of CO_2 from flue gas.[38]

Technical challenges exist before this technology can be pilot tested in the field. These limitations include membrane boundary layers, pore wetting, surface fouling, loss of enzyme activity, long-term operation, and scale-up, which are being addressed in a current project.[39]

Physical Sorbents

A number of solids can be used to react with CO_2 to form stable compounds at one set of operating conditions and then, at another set of conditions, be regenerated to liberate the absorbed CO_2 and reform the original compound. However, solids are inherently more difficult to work with than liquids, and no solid sorbent system for large scale recovery of CO_2 from flue gas has yet been commercialized, although molecular sieve systems are used to remove impurities from a number of streams, such as in the production of pure H_2.[40]

Precipitated Calcium Carbonate

Carbonate systems are based on the ability of a soluble carbonate to react with CO_2 to form a bicarbonate, which when heated releases CO_2 and reverts to a carbonate.[41]

A major advantage of carbonates over amine-based systems is the significantly lower energy required for regeneration. Analysis has indicated that the energy requirement is approximately 5% lower with a higher loading capacity of 40% versus about 30% for MEA. System integration studies indicate that improvements in structured packing can provide an additional 5% energy savings, and multi-pressure stripping can reduce energy use 5–15%.[42]

Ionic Liquids

Ionic liquids (ILs) are a broad category of salts, typically containing an organic cation and either an inorganic or organic anion shows the computed electron density for a CO_2 molecule interacting with the ionic liquid [hmim][Tf2N].[43]

ILs can dissolve gaseous CO_2 and are stable at temperatures up to several hundred degrees centigrade. Their good temperature stability offers the possibility of recovering CO_2 from flue gas without having to cool it first. Also, since ILs are physical solvents, little heat is required for regeneration.[44]

Some ionic liquids are commercially available, but the ones most suited for CO_2 separation have only been synthesized in small quantities in academic laboratories. As such, current unit costs are high, but should be significantly lower when produced on a commercial scale for the volumes that would be needed by the power generation sector.[45]

The viscosity of many ILs is relatively high compared to conventional solvents. Viscosities for a variety of ILs are reported to range from 66 to 1110 cP at 20 to 25 8C, and high viscosity may be an issue in practical applications.[46]

Based on the finding that the anion is critical in determining CO_2 solubility, several ionic liquids have been developed that have exhibited CO_2 solubilities 40 times greater than traditionally achieved. Capacity still needs to be significantly improved, however, to meet cost targets. Task specific ILs (TSIL) that contain amine functionality are being investigated to provide the next step change improvement in CO_2 solubility.[47]

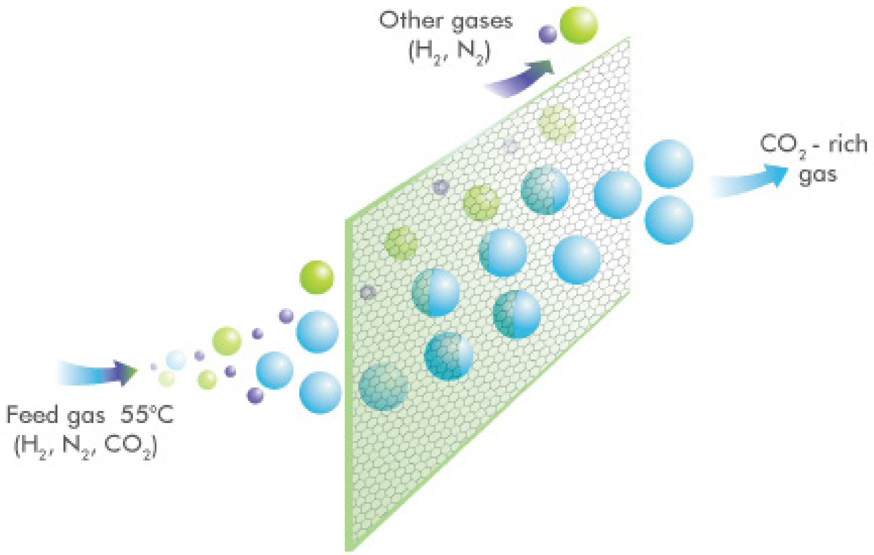
Gas Separation Membranes

There are a variety of options for using membranes to recover CO_2 from flue gas. In one concept, flue gas would be passed through a bundle of membrane tubes, while an amine solution flowed through the shell side of the bundle. CO_2 would pass through the membrane and be absorbed in the amine, while impurities would be blocked from the amine, thus decreasing the loss of amine as a result of stable salt formation. Also, it should be possible to achieve a higher loading

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

differential between rich amine and lean amine. After leaving the membrane bundle, the amine would be regenerated before being recycled. R&D pathways to an improved system include increased membrane selectivity and permeability and decreased cost.[48] Another concept under development is the use of an inorganic membrane (see Figure 3). Such membranes can selectively separate CO_2 from CH_4; others can contain amine functional groups for the separation of CO_2 from flue gas. Such a membrane can have better CO_2 selectivity than a pure siliceous membrane, if the illusive balance between permeance and selectivity can be achieved.[49]

Figure 3
Gas Separation Membrane Flatsheet Module



Source: CO2CRC

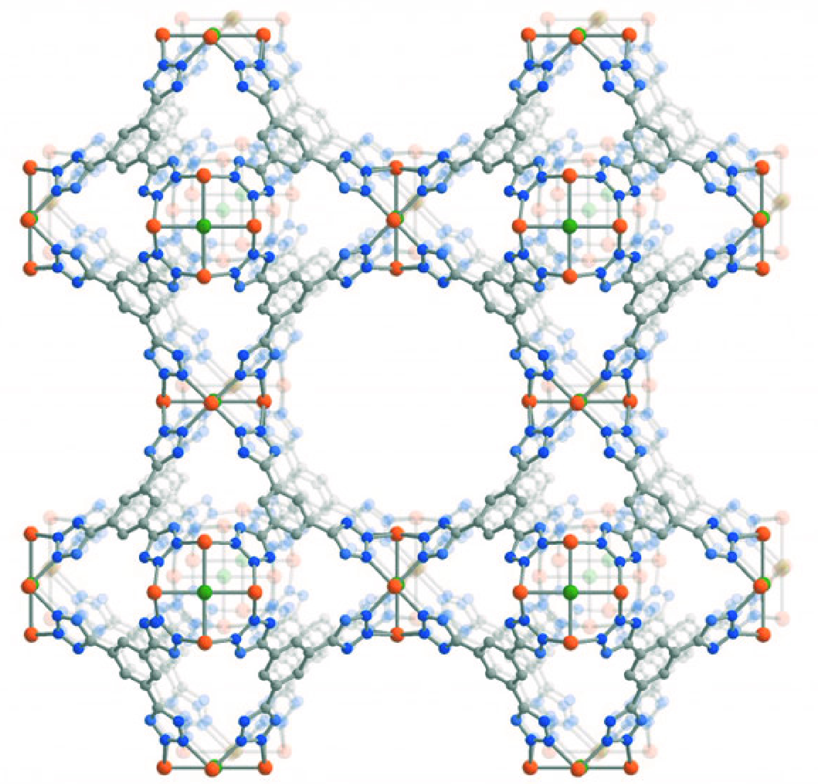
Membrane gas separation processes have been widely used for hydrogen recovery in ammonia synthesis, removal of CO_2 from natural gas, and nitrogen separation from air. Each of the membranes used in these capacities could be applied to carbon capture. Commonly used membrane types for CO_2 and H_2 separation include polymeric membranes, inorganic microporous membranes, and palladium membranes.[50] Polymeric membranes, including cellulose acetate, polysulfone, and polyimide are the most commonly used for separation of CO_2 from nitrogen, but have relatively low selectivity to other separation methods.[51] Inorganic membranes, able to withstand high temperatures, are capable of operating inside combustion or gasification chambers.[52] Membrane reactors based on inorganic membranes with palladium catalyst can reform hydrocarbon fuels to mixture of H_2 and CO_2 and at the same time separating the high-value H_2.[53] Combining membranes with chemical solvents has also been proposed.[54] Despite an extra energy requirement, this arrangement may eliminate problems associated with direct contact between the liquid solvent and gas mixture.[55]

Most membranes have inherent difficulty achieving high degrees of gas separation due to varying rates of gas transport. Stream recycling or multiple stages of membranes may be necessary to achieve CO_2 streams amenable to geologic storage, increasing energy consumption.[56] However, the potential for high surface area could reduce the chemical potential difference required to drive gas separation.[57]

Metal Organic Frameworks (MOFs)

Metal organic frameworks (MOFs) are a new class of hybrid material built from metal ions with well-defined coordination geometry and organic bridging ligands (see Image 2). They are extended structures with carefully sized cavities that can adsorb CO_2. High storage capacity is possible, and the heat required for recovery of the adsorbed CO_2 is low. Over 600 chemically and structurally diverse MOFs have been developed over the past several years. MOF-177 has shown one of the highest surface areas and adsorption capacity for CO_2 at elevated pressure.[58] Additional work is needed to determine stability over thousands of cycles and the effect of impurities at typical flue gas temperature and pressure.[59]

Image 2
Typical Illustration of a Metal Organic Framework for Carbon Capture



Source: Jeffrey Long, Lawrence Berkeley Laboratory

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

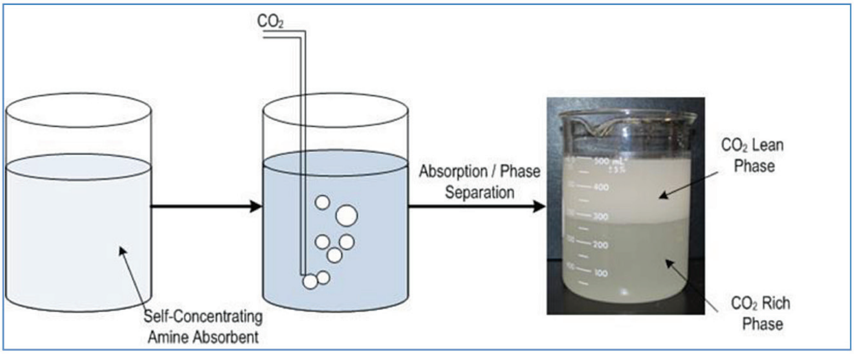
Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Select Emerging Carbon Capture Company Overviews »

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Dr. Liang Hu
Weblink: uky.edu/econdev/astecc-agtecc-campus-incubators
Phone: 757.725.1213

Level of Funding: $3,484,770
Location: Lexington, Kentucky
E. lianghu59@yahoo.com



Source: NETL

Concept of the Proposed Self-Concentrating Amine Absorbent Process.

3H Company, LLC

3H Company received $2.7M in July 2010 from the DOE and is contributing additional funds to bring the total to $3,484,770 to evaluate the feasibility of its "Self-Concentrating Absorbent CO_2 Capture Process."

The process is based on amines in a non-aqueous solvent that, upon reaction with CO_2, separate into two distinct phases: a CO_2-rich liquid phase and a dilute lean phase.

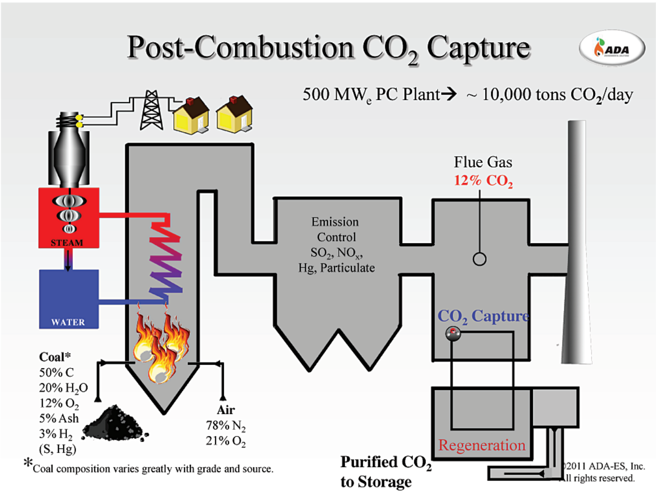
The proposed process offers several potential advantages. Preliminary experimental data show that the process has the potential of reducing the total regeneration energy by as much as 70 percent. The solvent has high working capacity, thus required solvent volume would be lower than that required in a currently available amine system. This results in lower pumping requirements, lower auxiliary power demands, and reduced equipment size. In addition, since the solvent is non-aqueous, corrosion issues would be reduced.

During the three-year project (between 4/11 and 9/13), an engineering design supported by laboratory data and economic justification will be developed to construct and operate a slipstream demonstration facility at an E-ON power plant in the United States as a next stage of commercialization development.

The company is working with the Electric Power Research Institute, LG&E and KU Energy LLC, Nexant, Inc., and the University of Kentucky. The company also partners with Bechtel Power Corporation, Western Kentucky University, and Sask Power.

Project Leader(s): Mike Durham
Weblink: adaes.com/carbon/co2/
Phone: 303.734.1727

Level of Funding: ~$22 million
Location: Littleton, CO
E. miked@adaes.com



Source: ADA-ES

ADA-ES

ADA-ES modeled its approach to CO_2 capture on 20 years of experience developing and commercializing solutions for particulate and mercury control. The company has set the goal of developing a commercially available, cost effective, post-combustion CO_2 capture technology by the year 2020. The company is currently working on several projects to develop a CO_2 capture technology based on solid regenerable sorbents.

In the company's CO_2 capture system, located immediately upstream of the stack, the flue gas is sent through a contactor where a solid sorbent separates the CO_2 from the other flue gas constituents. Then the CO_2-laden sorbent material is moved out of the flue gas into the re-generation chamber where it is regenerated through a change in temperature or pressure. During this regeneration step, the CO_2 gas is released in a nearly pure stream and collected in a separate vessel. This purified CO_2 is now ready for beneficial re-use or sequestration. The regenerated sorbent material can be used again to capture more CO_2.

The most important advantage of solid sorbents is the potential to significantly reduce the amount of energy required to capture and release the CO_2. The company's initial research using solid sorbents indicates that this process may use as much as 50% less energy than other CO_2 capture technologies.

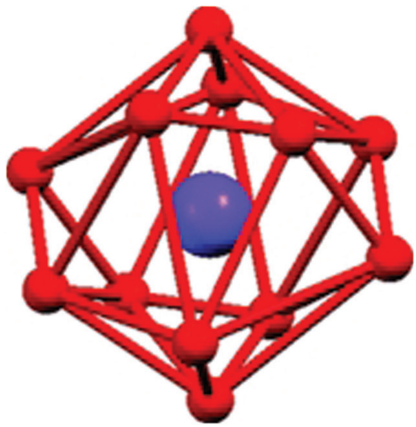
In 2008, ADA-ES was awarded a $2.0 million collaborative research and development agreement from the U.S. Department of Energy's (DOE) and the National Energy Technology Laboratory (NETL) for CO_2 capture research. In addition, we have received $1.2 million in cost share funding and technical guidance from the Electric Power Research Institute (EPRI) and several electrical utility companies that will also participate in the research.

Based on the success of the initial phase of research and development, in 2010, ADA-ES was awarded a $15 million collaborative agreement from the U.S. DOE, with another $3.75 million in cost share provided by several utility partners, to move the technology development and pilot-scale demonstration phase.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital.

Project Leader(s): James R. Markham
Weblink: afrinc.com
Phone: 860.528.9806 ext. 104

Level of Funding: $99,969
Location: East Hartford, CT
E. jim@AFRinc.com



Source: AFR and NETL

Advanced Fuel Research, Inc.

Advanced Fuel Research, Inc. was awarded in 2005 and has since completed a small business innovative research (SBIR) project that initiated development of a novel sorbent for the removal of CO_2 from combustion flue gas. The primary goal of this project was to develop a process using a supported amine for CO_2 capture that exhibits better system efficiency, lower cost, and less corrosion than current aqueous amine-based processes.[60]

The project was to demonstrate performance of carbon-supported amine sorbents under simulated flue gas conditions. Three tasks were undertaken: (1) the development of six to ten carbon-supported amine sorbents for CO_2 adsorption testing; (2) the sorbents were to undergo CO_2 adsorption and desorption tests to determine the effect of temperature on adsorption capacity and make recommendations for sorbent-regeneration conditions; and (3) an assessment was to be conducted to evaluate the concept in terms of comparison with alternative technologies, materials requirements, economics, and life-limiting factors.[61]

PrizeCapital
Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Andrew Lowenstein
Weblink: ailr.com
Phone: 609.452.2950

Level of Funding: $99,937
Location: Princeton, NJ
E. ail@ailr.com

AIL Research, Inc.

AIL Research, Inc. (AIL) is in the second phase of a small business initiative research (SBIR) project that is assessing the economic and technical feasibility of a CO_2 stripper that uses an internally heated contactor. The project will determine whether the construction of the internally heated contactor is compatible with the operating conditions of a monoethanolamine stripper and an advanced scrubber (e.g., one that uses a mixture of potassium carbonate and piperazine) and it will also determine the maintenance procedures required to fall within acceptable operation and maintenance practices at power plants.[62]

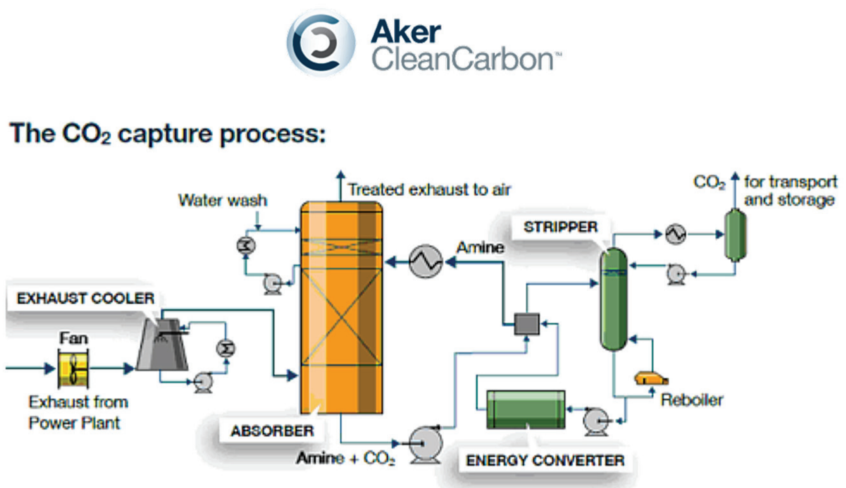
AIL will also work to scale-up the CO_2 stripper concept that utilizes an internally heated contactor. This work includes the development of both the surface treatment and physical structure for the contact surface of the internally heated stripper. Researchers will also identify a solvent that will produce the most economically viable CO_2 scrubber system by testing several thermally regenerated CO_2 absorbents under controlled laboratory conditions, while gaining a better understanding of the operating parameters that control scrubber performance.

In addition, this project will evaluate the impact that the proposed CO_2 capture system will have on the performance and economics of coal-fired power plants.[63]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Liv Monica Bargem Stubholt
Weblink: akercleancarbon.com
Phone: + 47 22 12 24 05

Level of Funding: Unknown
Location: Oslo, Norway
E. lms@akercleancarbon.com



Source: Aker Clean Carbon

Aker Clean Carbon

Aker Clean Carbon has developed its own technology for carbon capture. The basis of the process is the chemical reaction between a liquid absorbent, normally an amine, and CO_2.[64]

In the capture plant, the exhaust containing CO_2 is routed via inlet coolers to a large absorption tower. The gas enters at the bottom of the absorber and gets in contacts with the (liquid) amine, which flows downwards. The amine will absorb most of the CO_2 by a chemical reaction. The remaining flue gas is treated in the water wash unit, to ensure removal of all amines before disposal to air from the top of the absorber.[65]

The amine containing CO_2 is pumped via heat exchangers to the stripper part where CO_2 is "stripped" off (or boiled off) by heat from the re-boiler. After the stripping process the amine is pumped back to the absorber via an energy converter, and the cycle is repeated.[66]

Aker Clean Carbon is a private company owned 50 per cent by Aker ASA and 50 percent by Aker Solutions.

Project Leader(s): Barry Blackwell
Weblink: akermin.com
Phone: 314.824.1952

Level of Funding: $14.6 Million
Location: St. Louis, MO
E. blackwellb@akermin.com

Source: Akermin

Akermin

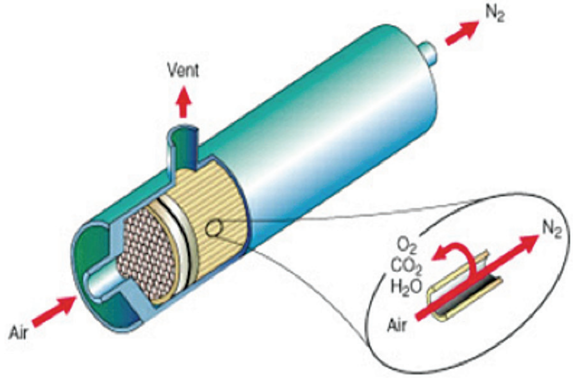
Akermin's technology uses an enzyme, Carbonic Anhydrase, to accelerate absorption of carbon dioxide. Carbonic Anhydrase is a naturally occurring enzyme that catalyzes the hydration of CO_2 to carbonate. The Akermin technology immobilizes and stabilizes an engineered version of this enzyme in a polymer structure and enables them to operate under the extreme pH levels, higher temperatures and shear forces that exist in the harsh environments of industrial processes. This enables the enzyme to operate for the extended periods necessary to make the process economically attractive for carbon capture and separation.

Akermin technology enhances the rate of CO_2 absorption using a naturally occurring enzyme that does not affect the energy consumption for CO_2 desorption. It can be applied to cost effectively reduce the size of the CO_2 absorber column for any process that applies carbonate solution chemistry to capture CO_2 in an energy efficient and environmentally-friendly manner. And by reducing the required capital and energy requirements, initial estimates supported by third-party analysis suggest that this technology can capture CO_2 at a cost up to 50% lower than commercially available technologies.

In August 2010, Akermin was awarded $4.6 million in grants and contracts. $3.2 million of that figure comes from a U.S. Department of Energy (DOE) grant to develop a bench scale reactor for demonstration of Akermin's carbon capture process.[67]

Project Leader(s): Sudhir Kulkarni
Weblink: us.airliquide.com
Phone: 302.286.5474

Level of Funding: $1,582,837
Location: Houston, TX
E. sudhir.kulkarni@airliquide.com



Source: Air Liquide and NETL

American Air Liquide, Inc.

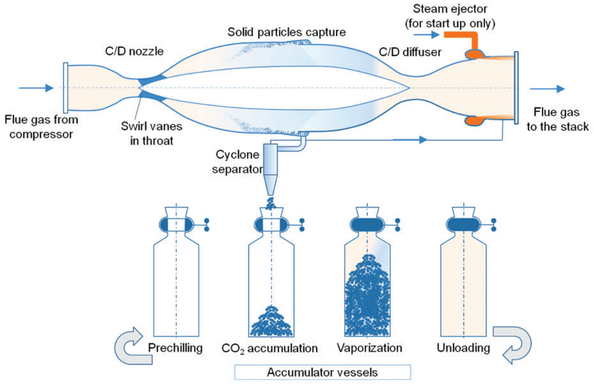
Between October 2010 and September 2012, American Air Liquide, Inc. will develop a system for CO_2 capture based on sub-ambient temperature operation of a hollow fiber membrane.

The membrane will be coupled with cryogenic processing technology in a closed-loop test system that will verify the effect of possible contaminants, such as SOx, NOx and water, on membrane performance. Experimental results will be used to refine the integrated process simulation and to design a slipstream facility.

Other objectives of the project are to demonstrate high selectivity and permeance performance with a commercial scale membrane module in a bench-scale test skid, verify mechanical integrity of commercial scale membrane module structural components at sub-ambient temperatures, and demonstrate the long-term operability of the sub-ambient temperature membrane skid. Cryogenic operating temperatures will be achieved through the controlled expansion of the gas across the test system valves.[68]

Project Leader(s): Vladimir Balepin
Weblink: atk.com
Phone: 406.494.7177

Level of Funding: $1 Million
Location: Ronkonkoma, NY
E. Vladimir.Balepin@atk.com



Source: ATK and ARPA-E

ATK (and ACEnT Laboratories)

Aerospace/defense contractor ATK and small business ACEnT Labs are developing Inertial CO_2 Extraction System (ICES) based on rocket nozzle and wind tunnel applications.[69]

This technology offers the potential for the lower COE increase and simplified integration with the existing power plants. ICES process comprises the steps of: swrling/expansion/ cooling in convergent/divergent nozzle, CO_2 desublimation/ precipitation, solid CO_2 particles capture and accumulation, CO_2 self-pressurization through sublimation back to the gaseous phase.[70]

ATK and ACEnT Laboratories received a $1 million ARPA-E award in April, 2010.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Kevin McCauley
Weblink: babcock.com/about/business_units/power_generation_group/
Phone: 330.860.1850

Level of Funding: $3,544,600

Location: Barberton, Ohio
E. kjmccauley@babcock.com

thebabcock&wilcoxcompany

Babcock & Wilcox Power Generation Group

The Power Generation Group will identify chemical additives that will improve overall performance of B&W's amine-based CO_2 capture technology. Recent testing at B&W indicates that blends of the solvent with additives capture CO_2 more effectively when combined versus the pure solvent. Technology objectives include improving the CO_2 capture system operability and reliability, minimizing environmental impacts, reducing corrosion potential in the system, and maximizing solvent durability.[71]

Babcock & Wilcox Power Generation Group was awarded $2,835,680 in August 2011 by the Department of Energy, as part of a larger $41 million investment in carbon capture technologies, to support this effort.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Andreas Northemann
Weblink: basf.com
Phone: +49 621 60-95138

Level of Funding: Unknown
Location: Cologne, France
E. andreas.northemann@basf.com

BASF

Since 2009 RWE, Linde and BASF have been testing a new technology for separating CO_2 from flue gas. The results of the practical test are were announced in September 2010: compared to processes commonly run today, the new chemical solvents can reduce energy input by about 20 percent and have clearly superior oxygen stability, which reduces solvent consumption significantly.[72]

Now the partners are working on solutions for demonstration and large-scale power plants. RWE Power will spend about nine million euros in total while the German Federal Ministry of Economics and Technology contributed about four million euros to the cost of the pilot plant.[73]

In February 2011, BASF announced its "High Pressure Acid Gas Capture Technology" (HiPACT) technology, which was co-developed with Japanese corporations JGC and INPEX. Yet current applications are focused on natural gas.[74]

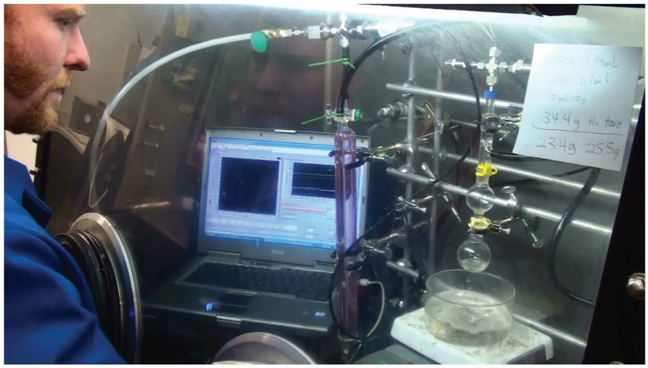
The testing with RWE and Linde has taken place at in a pilot plant at RWE's Niederaussem power station near Cologne. The pilot plant is part of the Coal Innovation Center of RWE Power. BASF is testing the newly developed solvents while Linde was responsible for pilot plant engineering and construction. [75]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): David Heldebrant
Weblink: battelle.org
Phone: 509.372.6359

Level of Funding: $2,499,693
Location: Richland, WA
E. david.heldebrant@pnnl.gov

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*



Source: PNNL

Battelle/Pacific Northwest National Laboratory

The bench-scale project investigates new organic-based solvents designed specifically for capturing post-combustion CO_2 emissions from coal-fired power plants.[76] The technology is dubbed Polarity Swing Assisted Regeneration (PSAR).

The low solvent regeneration temperatures of the proposed technology facilitates energy integration that has the potential to reduce overall CO_2 capture energy penalty by more than 50 percent compared to commercial systems.[77]

The PSAR process uses organic liquids to capture and separate out the carbon dioxide from flue gas at a much lower temperature than the process currently used in coal-fired power plants. That process, called thermal swing regeneration, requires significant power to heat, boil and cool harsh chemical sorbents in a series of steps to remove the CO_2 from the flue gas.[78]

Continuous absorption-desorption tests will be performed on the optimal solvents over a one-year period.[79]

Babcock & Wilcox Power Generation Group was awarded $1,999,693 in August 2011 by the Department of Energy, as part of a larger $41 million investment in carbon capture technologies, to support this effort.

Battelle scientists will work with the Fluor Corporation and Queens University to evaluate the advanced carbon capture system.[80]

Project Leader(s): Justin Dawe
Weblink: c12energy.com
Phone: 617.895.7276

Level of Funding: $4.5 Million
Location: Berkeley, CA

E. justin.dawe@c12energy.com

C12 Energy

Very little is known about the company's technology or what it does — except that its chief scientist just registered a patent for electrochemical weathering, a process that allows the ocean to effectively absorb carbon dioxide.[81]

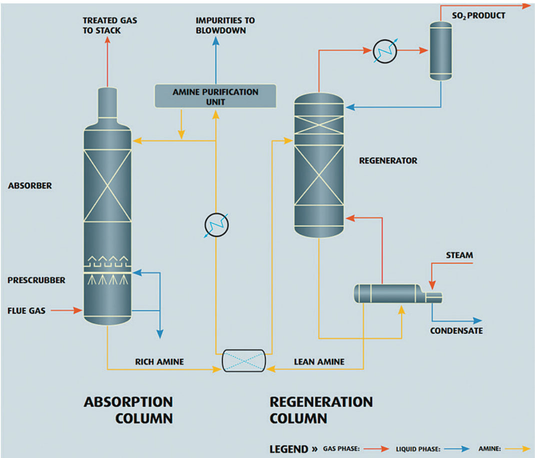
In a previous paper, C12's co-founder stated that "by electrochemically removing hydrochloric acid from the ocean and then neutralizing the acid by reaction with silicate (volcanic) rocks, the researchers say they can accelerate natural chemical weathering, permanently transferring CO_2 from the atmosphere to the ocean,"[82] which has led many to assume that this is the focus of C12's work.

C12 Energy, Inc. was founded in 2008 and is based in Berkeley, California.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006–12
PrizeCapital

Project Leader(s): Marcel Ayotte
Weblink: cansolv.com
Phone: 514.382.4411

Level of Funding: Unknown
Location: Montreal, Québec, Canada
E. ayottem@cansolv.com



Source: Cansolv

Cansolv Technologies

Cansolv Technologies, Inc. proposes to reduce costs by incorporating CO_2 capture in a single column with processes for capturing pollutants, such as SO2, NOx, and Hg.[108]

The company's new DC1031 tertiary amine solvent has demonstrated fast mass transfer and good chemical stability with high capacity—a net of 0.5 mol of CO_2 /mole of amine per cycle compared to 0.25 mol/mol for monoethanolamine (MEA) (Hakka, 2007).[109]

The CANSOLV CO_2 Capture System enables CO_2 to be absorbed from the feed gas by counter-current contact with the regenerable absorbent in the absorption tower. Since CANSOLV Absorbent DC reacts reversibly with CO_2, multi-stage counter-current contacting is used to achieve maximum loading of the CO_2 into the regenerable absorbent. The solvent is fed to the top of the absorption tower and as it flows down the tower it selectively reacts with CO_2. At the bottom of the absorption tower, the CO_2-laden or "rich" amine is pumped to a regeneration tower where it is heated to reverse the absorption reaction. As CANSOLV Absorbent DC moves down the regeneration tower, it is gradually stripped of CO_2. At the bottom, the CO_2-depleted absorbent is referred to as "lean" amine. Sensible heat from the lean amine is then used to heat incoming rich amine to maximize heat recovery.[110]

Project Leader(s): Scott Chen
Weblink: carboncapturescientific.com
Phone: 412.805.0468

Level of Funding: $3,750,925
Location: Pittsburgh, PA
E. scottchen@carboncapturescientific.com

Carbon Capture Scientific, LLC

Carbon Capture Scientific

Carbon Capture Scientific received DOE funding to pursue a project that will perform bench-scale development and testing of a novel solvent-based CO_2 scrubbing technology, known as Gas Pressurized Stripping (GPS).[83]

The GPS technology has the potential to significantly reduce the energy penalty associated with solvent regeneration by operating at higher pressures, which in turn reduces the compression requirements for placement of CO_2 in pipelines.[84]

The GPS technology seamlessly integrates CO_2 separation and compression into one step. This approach could potentially eliminate CO_2 compression entirely, hence reducing the total parasitic power load of a CO_2 capture process to about 0.14kWh/kg CO_2. This parasitic power load is a 60% reduction compared to baseline case of 0.38kWh/kg CO_2 and meets the DOE's target set for the total parasitic power reduction.[85]

Successful results could reduce the total parasitic power load of a CO_2 capture process by 60 percent compared to the DOE baseline case.[86]

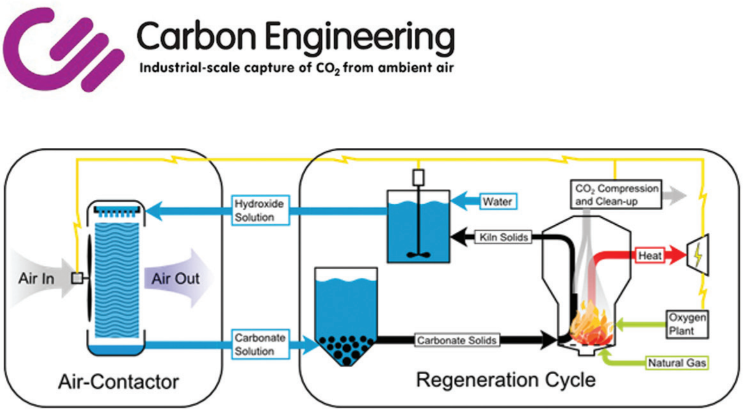
Carbon Capture Scientific was awarded $2,999,756 in August 2011 by the Department of Energy, as part of a larger $41 million investment in carbon capture technologies, to support this effort.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): David Keith
Weblink: carbonengineering.com
Phone: 403.210.8857

Level of Funding: $6 million
Location: Cambridge, MA

E. david_keith@harvard.edu



Source: Carbon Engineering

Carbon Engineering

Carbon Engineering's (CE's) air capture method is known as "wet scrubbing" because it uses a water-based solution to absorb CO_2 out of air passed through a contactor device.[87]

CE's patented technology integrates two processes: an air contactor, and a regeneration cycle, for continuous capture of atmospheric carbon dioxide and production of pure CO_2.[88]

These two processes work together to enable continuous capture of CO_2 from atmospheric air, with energy (and small amounts of make-up chemicals) as an input, and pure CO_2 as an output. The stream of pure CO_2 can be sold and used in industrial applications and/or permanently sequestered (geologically stored) deep underground.[89]

Our capture system brings atmospheric air containing CO_2 into contact with a chemical solution that naturally absorbs CO_2, in a device called a contactor. This solution, now containing the captured CO_2, is sent to a regeneration cycle that simultaneously extracts the CO_2 as a high-pressure pipeline-quality product while regenerating the original chemical solution, for re-use in the contactor.[90]

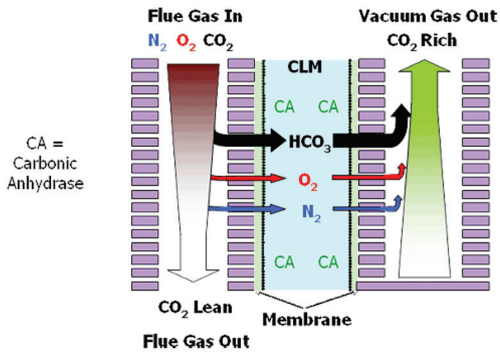
CE's air capture facility requires an input of high-temperature heat to drive the chemical reactions and produce all the electricity required to carry out the process. Our design is flexible enough that natural gas combustion, solar thermal generation, or even nuclear power could supply this energy input. CE's air capture facility takes in air and outputs air with reduced amounts of CO_2, along with a pipeline-quality stream of pure CO_2 that can be sold for industrial applications or permanently sequestered (geologically stored) deep underground.[91]

Since 2010, one of CE's principal efforts has been the design, engineering, and fabrication of its "Outdoor Contactor" (OC) prototype. The OC has been designed to test critical aspects of our full-scale air contactor design, and to gain us the operational experience in running our device outdoors in the harsh spectrum of weather we will see over several seasons here in Alberta.

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Michael C. Trachtenberg
Weblink: carbozyme.us
Phone: 732.724.0657
Level of Funding: $7,181,243
Location: Monmouth Junction, NJ
E. mct@cz-na.com

Carbozyme, Inc.



Source: Carbozyme

Carbozyme

Carbozyme Inc. is conducting the second of two projects (NT43084 active, NT42824 completed) for the Department of Energy with the goal of developing a cost efficient, low energy, CO_2 capture system applicable to coal-fired power plant flue gas exhaust streams, while achieving an energy consumption target of less than 15 percent.[92]

Carbozyme, Inc. has developed an enzyme-catalyzed, contained liquid membrane (CLM) permeator that selectively extracts CO_2 from mixed gas streams. Initial efforts will demonstrate the ability of the CLM permeator to efficiently extract CO_2 from a variety of flue gas streams, including coal and natural gas. The permeator performance will be considered successful if it achieves the U.S. Department of Energy (DOE) targets of at least 90 percent separation and 95 percent purity in the captured flue gas stream with a cost of energy of less than 20 percent by 2012. The project objective is to achieve a parasitic load of less than 15 percent. The project will demonstrate progressive cost, performance, and feature improvements that will support acceptance of the CLM permeator system for both retrofit and greenfield power plants.[93]

The performance of Carbozyme's EBCLM technology depends upon more fully matching coal-based power plant operating conditions and economic constraints. This relies on appropriate use of the information on the chemical, physical, and process-engineering characteristics of the EBCLM design.[94]

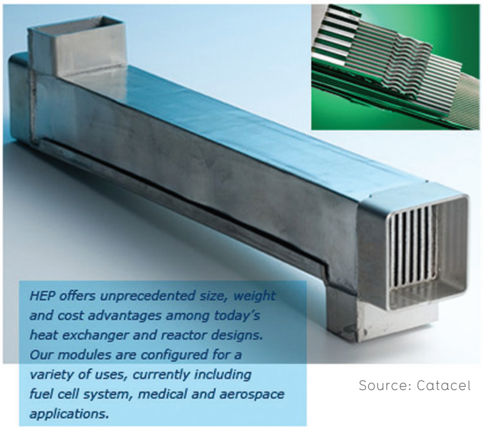
The successful EBCLM permeator will have high CO_2 permeance and high selectivity while maintaining low energy requirements for regeneration. Carbozyme will scale the permeators and test them under controlled actual conditions to focus on the ability to manage the flue gas streams from different ranks of coal.[95]

Carbozyme process has demonstrated at laboratory-scale the potential for 90% CO_2 capture followed by regeneration at ambient conditions. The Carbozyme process has been shown to have a very low heat of absorption that reduces the energy penalty typically associated with absorption processes.[96]

The DOE provided a grant of $5,743,981 to support this work between May 2006 and May 2007.

Project Leader(s): William Whittenberger
Weblink: catacel.com
Phone: 330.527.0731

Level of Funding: Unknown
Location: Garrettsville, OH
E. waw@catacel.com



Source: Catacel

Catacel Corporation

Catacel Corp. was awarded an ARPA-E grant to display novel DOE sorbent materials in power plant exhaust for effective post-combustion CO_2 capture.

The company's sorbent materials are coated on thin metal foils, which are packaged in a heat-exchange relationship in exhaust stream. Heat exchange prevents material degradation and enables easy CO_2 extraction from the sorbent.

The technology permits low parasitic pressure drop and easy change-out of spent sorbent material. It claims to be a low-risk technology similar to that used to display catalytic materials in gas turbine exhausts. Its goals for reducing CO_2 from coal-fired power plants are: - 90% capture - 1.7 billion tons/year impact - 31% cost of electricity increase.

Catacel was promoted as an "Encouraged Applicant" by ARPA-E.

Project Leader(s): Alex Vasenkov
Weblink: cfdrc.com
Phone: 256.726.4886

Level of Funding: Unknown
Location: Huntsville, AL
E. avv@cfdrc.com

CFD Research Corporation

The company is working on carbon dioxide capture and resonance desorption based on carbon nanofibers.

The company was highlighted by the DOE's ARPA-E, where the agency focused on the program to develop, demonstrate, and validate innovative technology with the following components: (1) carbon nanofiber (CNF) material with adsorption capacity 10x of CNTs and (2) energy-efficient CO_2 regeneration with 10x saving in energy over current regeneration methods.

The proposed CNFs consisting of stacked cones of graphene sheets will preserve many unique properties of CNTs such as natural ability for CO_2 physisorption, high thermal and chemical stability and will be 1,000x cheaper than CNTs ($10 per pound).

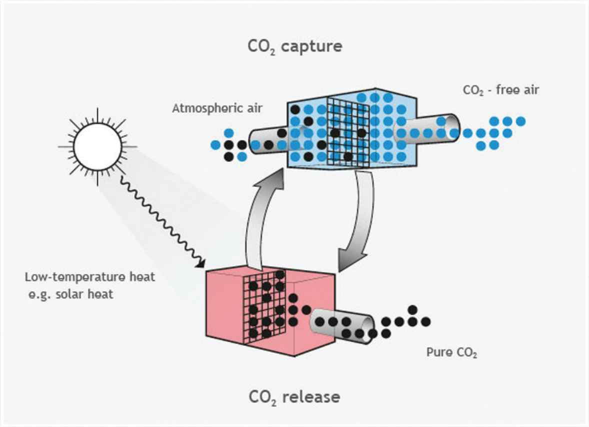
This program is meant to form the basis of a scalable, fieldable system with the following attributes: Power plant parasitic power loss ≤ 4.4%; CO_2 regeneration temperature close to room temperature due to resonance desorption nature of proposed technology; Potentially cheap carbon nanofiber sorbent material.

Currently, the carbon nanofiber price is $85 per pound and is projected to drop to $10 per pound in the few next years. Stable performance of carbon nanofiber material over 1,000 adsorption/desorption cycles with attrition below 5%.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Jan Andre Wurzbacher
Weblink: climeworks.com
Phone: + 41 (0)78 793 18 41

Level of Funding: Unknown
Location: Zurich, Switzerland
E. jan.wurzbacher@climeworks.com



Source: Climeworks

Climeworks

Climeworks is an ETH Spin-off company that is working to commercialize a patent-pending, highly efficient technology for CO_2 capture from ambient air that has been developed at ETH Zurich.[97]

The CO_2 capture technology of Climeworks is based on a cyclic adsorption-desorption process that occurs on a novel filter material ("sorbent"). During adsorption, atmospheric CO_2 is chemically bound to the sorbent's surface. Once the sorbent is saturated with CO_2, the CO_2 is driven off the sorbent through heating the sorbent to around 60-100°C, thereby delivering high-purity gaseous CO_2. The CO_2-free sorbent can be re-used for many adsorption-desorption cycles.[98]

Over 90% of the system's energy demand can be supplied by low-grade heat; the remaining energy is required in the form of electricity for pumping and control purposes.[99]

The patent-pending technology has been developed in collaboration with the Professorship of Renewable Energy Carriers at ETH Zurich. The optimization of the sorbent and scale-up of the sorbent synthesis process is carried out in collaboration with the Swiss Laboratories for Materials Science and Technology.

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Jonathan A. Carley
Weblink: co2solution.com
Phone: 905.320.6260

Level of Funding: ~$16 million
Location: Quebec, Canada
E. jonathan.carley@co2solution.com

Prototype CO_2 Capture Unit

Source: CO2 Solution

CO2 Solution

CO2 Solution Inc. has developed a proprietary bio-technological platform for the efficient capture of CO_2, the most important greenhouse gas (GHG, from power plants and other large stationary sources of emission.[100]

The technology platform exploits the natural power of a biocatalyst (enzyme), carbonic anhydrase (CA), which functions within humans and other mammals to manage CO_2 during respiration. CO2 Solution has successfully adapted the enzyme to function within a reactor so that it could act as an industrial lung to capture CO_2 from industrial flue (exhaust) gases. Once the CO_2 is captured, the enzyme assists in subsequent production of pure CO_2 for underground storage and/or use in oil recovery. In this way, the Company has taken advantage of a biomimetic approach to CO_2 capture based on millions of years of evolution.[101]

CO2 Solution's technology has been proven successful at prototype scale. The prototype reactor underwent first testing in an industrial environment at Alcoa Inc.'s aluminum smelting facility at Deschambault, Quebec, Canada. Subsequent to this, the Company conducted a continuous (24 / 7) trial of the prototype at the Quebec City, Canada waste incinerator. This test demonstrated that the enzyme functioned effectively and was stable in a real world environment.

In December 2009, CO2 Solution said that it's received a $2 million investment from Codexis, and that the two companies will work together under an exclusive joint development agreement on what's called enzymatic carbon capture technology. Codexis will be using its technology to toughen up the natural enzyme in CO2 Solution's method, improving its performance in the harsh conditions of an industrial flue.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): James Lalonde
Weblink: codexis.com
Phone: 650.421.8100

Level of Funding: $4,657,045
Location: Redwood City, CA
E. jim.lalonde@codexis.com

Codexis

Codexis, Inc., a California-based company, is seeking to improve the process used to capture carbon dioxide, a greenhouse gas, produced as a result of burning coal in coal-fired power plants.[102]

In an effort to develop a low cost catalyst for efficient carbon capture, Codexis is developing new forms of carbonic anhydrase to accelerate the absorption of carbon dioxide within the solvents. Despite the many attempts to engineer a robust carbonic anhydrase, no previous methods have succeeded in creating an enzyme that both withstands the harsh chemical environment found in coal-fired power plants and that is economically viable.[103]

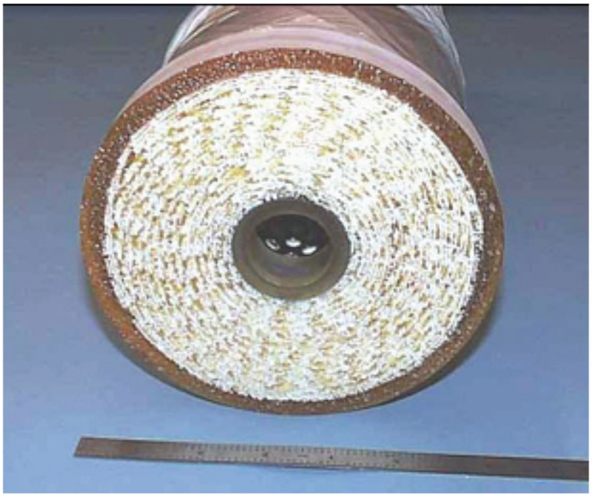
Codexis is creating new forms of carbonic anhydrase enzyme that, if successful, would enable carbon dioxide capture under the challenging conditions in coal-fired power plants and transform the best available carbon dioxide capture processes into significantly more economical processes.[104]

In April 2010, Codexis and its partner Nexant received nearly $5 million from the ARPA-E Innovative Materials & Processes for Advanced Carbon Capture Technologies (IMPACCT) program.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): John Bowser
Weblink: compactmembrane.com
Phone: 302.999.7996

Level of Funding: $100,000
Location: Wilmington, DE
E. john.bowser@compactmembrane.com



Source: NETL

Compact Membrane Systems, Inc.

Compact Membrane Systems, Inc. developed and tested a CO_2 removal system for flue gas streams from large point sources that offers improved mass transfer rates compared to conventional technologies.[105]

The project fabricated perfluorinated membranes on hydrophobic hollow fiber membrane contactors, demonstrated CO_2 removal from a simulated flue gas mixture via amine absorption using the fabricated membranes, examine chemical compatibility of the membrane with amines, and demonstrate enhanced stability of the perfluoro-coated membranes.[106]

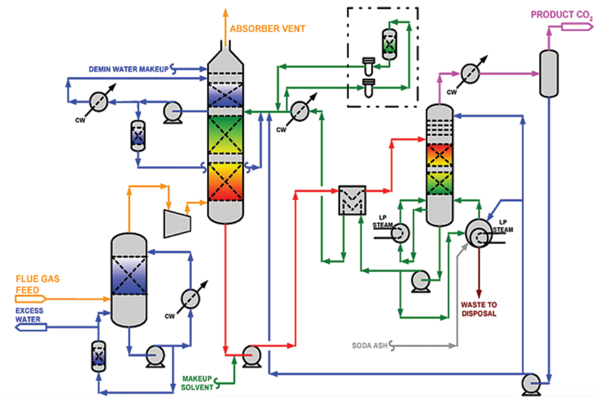
In addition, an economic analysis was performed to demonstrate that the perfluoro-coated hydrophobic hollow fiber membrane contactors are superior to existing commercial CO_2 removal technology.[107]

In 2006, Compact Membrane Systems, Inc. received $100,000 from the National Energy Technology Laboratory to support the development of this technology.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Satish Reddy
Weblink: fluor.com/econamine
Phone: 949.349.4959

Level of Funding: Unknown
Location: Aliso Viejo, CA
E. satish.reddy@fluor.com



Source: Fluor

Fluor Corporation

Econamine FG Plus is a Fluor proprietary, amine-based technology for large-scale, post-combustion CO_2 capture.[111]

The Econamine FG Plus technology is one of the first and among the most widely applied commercial solutions that has been proven in operating environments to remove carbon dioxide from high oxygen content flue gases (up to 20% by volume).[112]

The Econamine FG Plus solvent formulation is specially designed to recover CO_2 from low-pressure, oxygen-containing streams, such as boiler and reformer stack gas and gas turbine flue-gas streams.[113]

The CO_2 recovered by the Econamine FG Plus process can be tailored to meet the end user's specifications. The CO_2 can be compressed for use within a chemical plant, liquefied for transport, compressed to supercritical pressures for Enhanced Oil Recovery (EOR) applications, or further purified for use in the food and beverage industry.[114]

Fluor's Econamine FG Plus is a proprietary acid gas removal system that has demonstrated greater than 95% availability with natural gas fired power plants, specifically on a 350 ton/day CO_2 capture plant in Bellingham, MA. It is currently the state-of-the-art commercial technology baseline and is used in comparing other CO_2 capture technologies.[115]

Prize Capital is a Service Mark of Prize Capital, LLC. 2006–12

Project Leader(s): Chip Bottone
Weblink: fce.com
Phone: 203.825.6000

Level of Funding: $3,742,635
Location: Danbury, CT
E. cbottone@fce.com

Source: FuelCell Energy

FuelCell Energy

FuelCell Energy's molten carbonate fuel cell (MCFC) technology separates and concentrates carbon dioxide as a side reaction during the power generation process. Research by the company has demonstrated that this is a viable technology for efficient carbon capture from a variety of industrial flue gases. The research also showed that the fuel cell technology can help destroy the nitrogen oxides (NOx) in the flue gas.[116]

According to the company's Direct FuelCells® (DFC®) carbon capture research conducted by the company, DFC is a viable technology for the efficient separation of CO_2 from a variety of industrial facility flue gases such as cement plants and refineries.[117]

The DFC consists of ceramic-based layers filled with carbonate salts, separating CO_2 from the flue gas with a selectivity of 100 percent over the nitrogen present in the gas.[118]

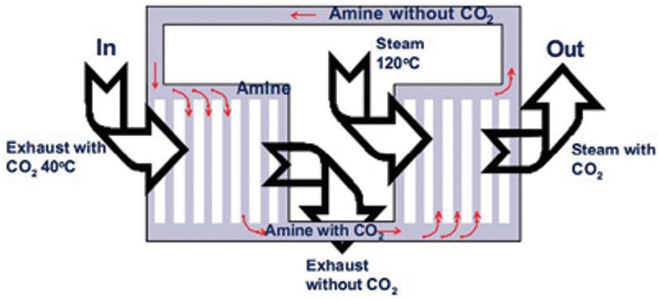
Because of fast reactions, the CO_2 concentration of less than 15 percent normally found in the PC plant flue gas is suitable for this application.[119]

The Department of Energy provided nearly $3 million to FuelCell Energy in mid 2011 to verify that the company's patented membrane-based DFC® can achieve at least 90 percent CO_2 capture from flue gas of an existing PC plant with no more than 35 percent increase in the COE.[120]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital.

Project Leader(s): Shaojun Zhou
Weblink: gastechnology.org
Phone: 847.544.3403

Level of Funding: $3,736,063
Location: Des Plaines, IL
E. shaojun.zhou@gastechnology.org



Source: GTI

Gas Technology Institute (GTI)

The Gas Technology Institute (GTI), in partnership with PoroGen Corporation and Aker Process Systems, is developing a cost-effective separation technology to capture CO_2 from coal-fired power plant flue gas based on the combination of a hollow fiber membrane contactor with absorption technologies.[121]

The hybrid process utilizes solvent absorption, which performs as the selective layer, within a hollow fiber configured membrane contactor made of the chemically and thermally resistant polymer polyether ether ketone (PEEK). With the novel hollow fiber configuration, the interfacial area is increased by an order of magnitude compared to conventional packed or tray column systems, increasing CO_2 mass transfer rates and reducing the overall size of the processing equipment.

The reduced size requirements translate to lower solvent inventories, less metal exposure to corrosive liquids, and lower space impact for siting at congested power plants, ultimately leading to reduced capital and operating costs. The membrane contactor process combines the advantageous features of both membrane and absorption technologies and enables economical utilization of advanced absorption solvents.

The company is working with PoroGen Corporation and Aker Process Systems on this project, which was provided with a $2,986,063 DOE grant in October 2010.

PrizeCapital
Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Bob Enick
Weblink: recovery.gov/Transparency/RecipientReportedData/pages/RecipientProjectSummary508.aspx?AwardIdSur=113718
Phone: 412.624.9649

Level of Funding: $3,017,511
Location: Niskayuna, NY
E. rme@pitt.edu

GE and the University of Pittsburgh

In a two-year project, GE and the University of Pittsburgh will jointly develop a novel CO_2 capture process in which a liquid absorbent, upon contact with CO_2, changes into a solid powder.

The solid can then be separated, and the CO_2 released for sequestration by heating. Upon heating, the absorbent returns to its liquid form, where it can be reused to capture more CO_2.

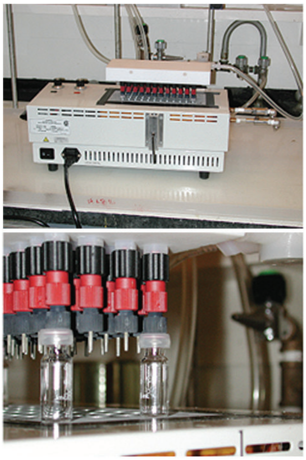
Because the absorbent solid contains a high percentage of CO_2, the energy efficiency of the process is improved over current technology, and compression and capital costs are reduced. This ultimately leads to a lower cost of CO_2 capture and a lower cost of electricity compared to plants retrofitted with existing technology.

GE Global Research, GE Energy, and the University of Pittsburgh are working together on this project.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Teresa Grocela-Rocha
Weblink: ge.geglobalresearch.com
Phone: 518.387.6220

Level of Funding: $3,091,452
Location: Niskayuna, NY
E. grocela@ge.com



Source: GE and NETL

GE Global Research

GE Global Research, in collaboration with GE Energy and the University of Pittsburgh, is working to develop a novel oligomeric solvent and process for post-combustion capture of CO_2 from coal-fired power plants. An oligomer is a short chain polymer with relatively few repeating units that can be synthesized with varying chain lengths and a wide variety of functional groups. Both the chemical and physical CO_2 absorption / desorption properties can be adjusted to achieve optimal CO_2 capture performance (high CO_2 carrying capacity, low heat of absorption, thermal and chemical stability).[122]

Researchers will utilize both computational and laboratory methods to identify and produce oligomeric solvents for post-combustion capture of CO_2. Molecular modeling will be employed to identify oligomeric solvents having potential for high CO_2 capture capacity under low energy usage conditions. Researchers will use advanced synthetic methods to synthesize and modify the solvents and determine their ability to absorb and desorb CO_2 using high throughput screening.[123]

In order to determine the overall feasibility of the proposed process, a rigorous model of the solvent absorption- desorption system will be developed and combined with an existing power plant model. The combined model will use a cost of energy (COE) analysis based on existing power plant operational models to optimize the integrated system for minimum capital and operational cost with maximum CO_2 capture.[124]

GE Global Research is working with GE Energy and the University of Pittsburgh on this technology. In 2009, the Department of Energy provided $2,473,162 to support this effort.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Benjamin Wood
Weblink: ge.geglobalresearch.com
Phone: 518.387.5988
Level of Funding: $3,747,879
Location: Niskayuna, NY
E. woodb@research.ge.com

GE Global Research

GE Global Research, along with their partners GE Energy and SiVance LLC, will continue the development and testing of a novel aminosilicone-based solvent using a continuous bench-scale system to capture CO_2 from simulated coal-fired flue gas. In a previous DOE-funded project (DE-NT0005310), the novel solvent was developed and tested in a laboratory-scale continuous CO_2 capture system. The testing and associated detailed cost modeling and analysis demonstrated that the novel solvent has superior performance for CO_2 capture as compared to a baseline monoethanolamine (MEA) process.[125]

As this solvent system effectively demonstrated cost-effective CO_2 capture from flue gas at the laboratory scale, development and testing of a bench-scale system represents a readily achievable next step on the path to commercialization.[126]

Previously measured experimental data from the laboratory-scale CO_2 capture system will be used to design the continuous bench-scale system. Basic engineering data, such as kinetics and mass transfer information, will be obtained at the bench scale to determine process scalability and likely process economics. A manufacturing plan for the aminosilicone solvent and price model will be used for optimization of the solvent system. GE Global Research will design, build, and operate the bench-scale system and gather the engineering and property data required to assess the technical and economic feasibility of the process. GE Energy will be responsible for developing a model of the bench-scale process and the cost of electricity (COE), performing the technical and economic feasibility studies, and developing the scale-up strategy. SiVance will evaluate the manufacturability of the aminosilicone capture solvent, analyze the cost to manufacture the solvent, provide material for bench-scale and property testing, and perform a technology Environmental, Health, & Safety (EH&S) risk assessment.[127]

GE Global Research is working with GE Energy and SiVance LLC on this technology. In 2011, the Department of Energy provided $2,998,303 to support this effort.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Benjamin Wood
Weblink: ge.geglobalresearch.com
Phone: 518.387.5988

Level of Funding: $3,042, 852
Location: Niskayuna, NY
E. woodb@research.ge.com

GE Global Research

The group is developing novel polymer membranes at bench scale, including modifying the properties of the polymer in a coating solution and fabricating highly engineered porous hollow fiber supports that have the potential to meet DOE's CO_2 capture goals.[128]

These membranes permit CO_2 to pass through to produce a concentrated CO_2 stream while blocking all other gases.[129]

Physical, chemical, and mechanical stability of the materials (individual and composite) toward coal flue gas components will be evaluated using exposure and performance tests. Module design, technical, and economic feasibility analyses will be conducted to evaluate the overall performance and impact of the process on the cost of electricity.[130]

GE Global Research was awarded $2,434,282 in August 2011 by the Department of Energy, as part of a larger $41 million investment in carbon capture technologies, to support this effort.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Teresa Grocela-Rocha
Weblink: ge.geglobalresearch.com
Phone: 518.387.6220

Level of Funding: $3,017,511
Location: Niskayuna, NY

E. grocela@ge.com

GE Global Research

This General Electric-led team will develop a novel, cost-efficient carbon dioxide capture process that uses a liquid absorbent that changes into a solid powder upon contact with carbon dioxide.[131]

The solid can then be isolated and the carbon dioxide can be released by heating. The absorbent then returns to its liquid form so that it can be reused. Because the absorbent solid contains a high percentage of carbon dioxide, the energy efficiency of the process is improved over current technology, and compression and capital costs are reduced.[132]

The goal is to achieve less than 10 percent parasitic power load at 90 percent carbon dioxide capture and at less than $25 per ton carbon dioxide capture cost. This approach also offers a smaller footprint than existing processes and could be retrofit onto existing plants.[133]

GE Global Research received a $ 3,017,511 ARPA-E award in April, 2010.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12 | PrizeCapital

Project Leader(s): Graciela Chichilnisky
Weblink: globalthermostat.com
Phone: 212.678.1148

Level of Funding: Unknown
Location: New York, NY
E. chichilnisky1@gmail.com

global thermostat
a carbon negative solution

Source: Prize Capital, LLC

Global Thermostat

Global Thermostat's (GT's) patent-pending technology uses low-cost left over process heat as energy for the capture of CO_2 from the atmosphere.

It can be installed at new or legacy power plants, cement smelters, refineries, etc. Since energy typically accounts for two-thirds of the total operating cost with other carbon capture technologies, Global Thermostat's solution allows for dramatic cost efficiencies in reducing carbon emissions.

Global Thermostat has found a way to use chemicals known as amines to bind with CO_2 from the air; the CO_2 is then separated from the amines in a process that uses low-temperature heat. Relying on low-temperature heat keeps costs down because it is widely available at little or no cost as a waste product from power plants or energy-intensive factories. Global Thermostat has retained Carmagen Engineering, a New Jersey firm led by former Exxon engineers, to design its carbon-capture machines, which are envisioned as tall, narrow structures through which air flows. Corning helped the company develop honeycomb-like structures called monoliths on which the carbon is trapped, and BASF is working to develop the required sorbents.[134]

Global Thermostat estimates that its process can remove 5lb of CO_2 per kWh of electricity.[135]

Global Thermostat works in partnership with Corning and BASF, who supplies the technology's proprietary absorbent. The company is also working with Summit Power, and has a partnership with Algae Systems, whereby Global Thermostat provides CO_2 to Algae Systems for algae growth.

PrizeCapital
Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Yuandong (Alex) Gu
Weblink: honeywell.com
Phone: 763.954.2071

Level of Funding: Unknown
Location: Plymouth, MN
E. alex.gu@honeywell.com

Honeywell

Honeywell's technology marries an Ultrasound Assisted Electrospray (UAE) process with the desirable properties of novel Ionic Liquids (ILs), where UAE generates a high surface area plume of the IL at very low power and the IL promises 0.4 mole of CO_2 capture in 1 mole of IL.[136]

The undetectable vapor pressure and low desorption enthalpy of CO_2 from IL enables significant infrastructure and operation cost reductions.[137]

This synergistic approach will result in a COE increase of between 26 and 43% (vs. 81% increase for MEA CCS), relative to non-CCS-equipped pulverized coal (PC) power plants.[138]

This technology was listed as an "Encouraged Applicant" and showcased by DOE's ARPA-E.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Ravi Jain
Weblink: N/A
Phone: 908.672.7395

Level of Funding: $3,244,885
Location: Bridgewater, NJ
E. ravi.jain@innosepra.com

InnoSepra

This process utilizes sorbents with much lower CO_2 capture energy requirements compared to competitive processes and has been successfully demonstrated at the lab scale to obtain greater than 99 percent CO_2 purity, and more than 90 percent CO_2 recovery.[139]

The ultimate goals of the project are to confirm the projected performance of the InnoSepra process at the bench scale; provide sufficient data for design of a commercial-scale plant; and provide a high degree of confidence in the applicability, cost effectiveness and practical feasibility of this process.[140]

Projections based on detailed engineering evaluations show that the technology can reduce the power consumption for CO_2 capture by more than 40 percent, and the capital cost for the CO_2 capture equipment by more than 60 percent at commercial scale, resulting in a more than 40 percent reduction in the CO_2 capture cost compared to alternate technologies such as amines.

InnoSepra was awarded $2,594,885 by the DOE in August 2011.

PrizeCapital
Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): André Boulet
Weblink: inventysinc.com
Phone: 604.999.4642

Level of Funding: Unknown
Location: Burnaby, BC Canada
E. Andre.boulet@inventysinc.com

Inventys

The VeloxoTherm™ intensified temperature swing adsorption (TSA) process provides significant benefits over incumbent technologies for the post-combustion capture of CO_2 from industrial flue gases.[141]

The heart of the VeloxoTherm™ process is its proprietary structured adsorbent. When flue gases contact the structured adsorbent, CO_2 becomes trapped on the material while allowing other gases such as nitrogen and water vapor to pass through it. Once the structured adsorbent becomes saturated with CO_2, the adsorbent is regenerated using low quality steam.[142]

The key to the low operating cost of the Veloxotherm™ process is energy management. The structured adsorbent has enhanced heat and mass transport properties that ensure a minimal amount of energy is required to regenerate the adsorbent. This distinctive property ensures that a minimum of energy is required for regeneration. The adsorbent structure has an extremely low pressure drop, which allows flue gases to readily flow through the VeloxoTherm™ gas separation system.[143]

The VeloxoTherm™ process is scalable and can be readily integrated into new and existing combustion and chemical processes (heaters, boilers, crackers, cement kilns, blast furnaces, and gas turbines). Any facility can continue operating during the installation, commissioning, and maintenance of a VeloxoTherm™ plant as it is downstream of all unit operations within the facility.[144]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12 | PrizeCapital.

Project Leader(s): Alfred (Buz) Brown
Weblink: ion-engineering.com
Phone: 303.578.1165
Level of Funding: $3,736,936
Location: Boulder, CO
E. brown@ion-engineering.com

ION Engineering, LLC

ION Engineering, in collaboration with its partners, will design, construct, operate, and evaluate a bench-scale CO_2 capture system using simulated flue gas at ION Engineering's laboratories.[145]

The project will demonstrate ION's innovative solvent approach for amine-based CO_2 capture, using amines as chemical solvents with ionic liquids (IL) as the physical solvent. ION's IL-amine solvent system is related to well understood aqueous amine solvent-based processes in that it utilizes proven amines as chemical solvents for CO_2 capture; however, it differs significantly with the use of an IL rather than water as the physical solvent.[146]

Because ILs do not incur the high energy penalties of an aqueous system, utilizing ILs in place of water can significantly reduce energy requirements compared to aqueous amine systems. Higher CO_2 loading capacities can also be achieved by selectively balancing the amines and ILs. The 18-month project will demonstrate the ability of the IL-amine solvent system to capture CO_2 using a 1.0 gallon per minute (gpm) bench-scale process unit, and will include simulation modeling to finalize process designs, laboratory evaluations, solvent selection, and scale-up from the existing laboratory units to the bench-scale process unit.

Design, construction, installation, integration, operation, monitoring, and decommissioning of the bench-scale unit will be performed, as well as commercial and operational assessments of the technology's ability to perform at full-scale. Project success will advance the achievement of DOE's goals of 90 percent CO_2 capture with less than a 35 percent increase in the cost of electricity (COE) with a viable retrofit solution for existing coal-fired power plants.[147]

In July 2010, ION Engineering received a grant of $2.8 million from the U.S. Department of Energy to design, build and conduct a field test for a carbon dioxide-capture unit to process flue gas from Xcel Energy's coal-fired power station in Boulder. Ion also will partner with the Electric Power Research Institute, the University of Alabama, Boulder-based Eltron Research and Development Inc., Evonik Goldschmidt and WorleyParsons Group on the project.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Nathaniel David
Weblink: kilimanjaroenergy.com
Phone: 773.380.6600

Level of Funding: $11.5 million
Location: San Francisco, CA
E. nathanieldavid@archventure.com

Kilimanjaro Energy

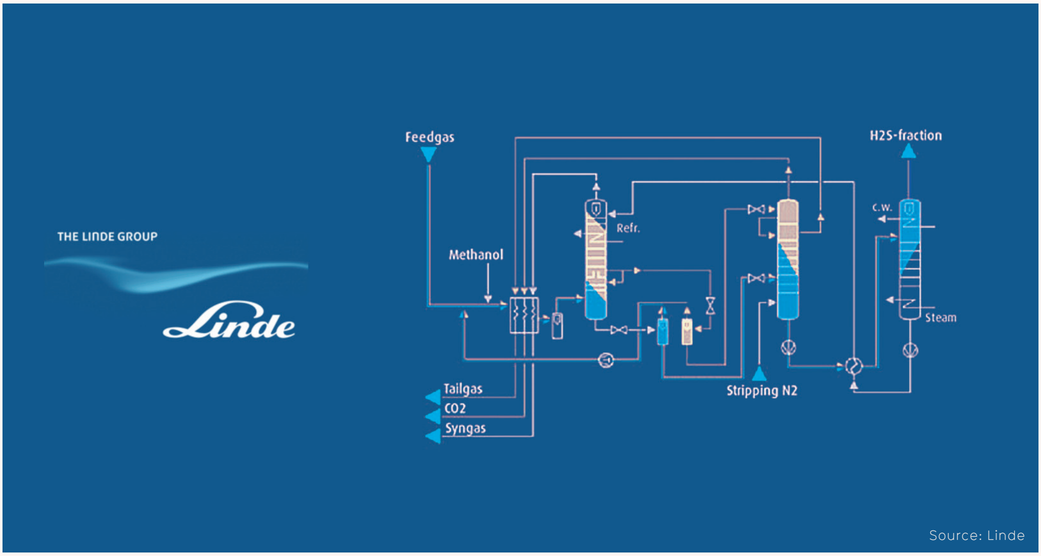
Kilimanjaro Energy is developing technologies to capture carbon dioxide from the air for beneficial commercial use in a variety of existing and new industries. Our technologies will economically capture CO_2 wherever and whenever it is needed. Atmospheric CO_2 is a vast resource whose transformation into useful products can help humanity close the carbon cycle.[148]

Dr. Klaus Lackner and Allen Wright discovered Kilimanjaro's core technology with the generous financial support of the late Gary Comer and the Comer Science & Education Foundation. As of 2010, the Company has begun commercializing its developments with the added support of ARCH Venture Partners.[149]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006–12
PrizeCapital

Project Leader(s): Andreas Opfermann
Weblink: linde-engineering.com
Phone: + 49.89.7445.3540

Level of Funding: $15 million
Location: Pullach, Germany
E. andreas.opfermann@linde.com



Source: Linde

Linde Engineering

Linde has developed a technology it calls the RECTISOL® Wash. RECTISOL® is a physical acid gas removal process using an organic solvent (typically methanol) at subzero temperatures. RECTISOL® can purify synthesis gas down to 0,1 vppm total sulphur (including COS) and CO_2 in ppm range.[150]

The main advantages of the process are the rather low utility consumption figures, the use of a cheap and easily available solvent and the flexibility in process configuration.[151]

A simplified flow scheme of the RECTISOL® process is shown above. CO_2 and sulphur compounds are removed in separate fractions, resulting in a pure CO_2 product (for example for urea production) and an H2S/COS enriched Claus gas fraction. Due to the application of RECTISOL® in connection with various upstream and downstream processes, a large design and operational experience is available also regarding handling of trace components.[152]

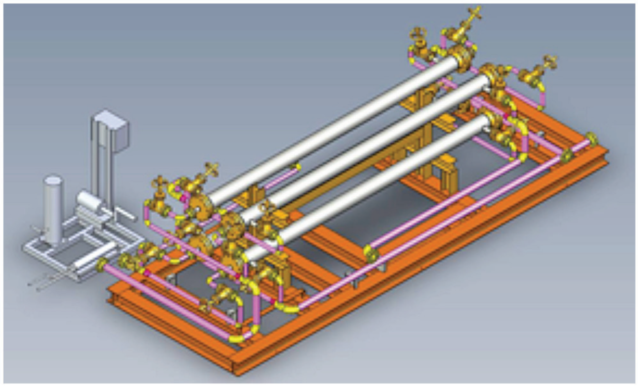
A special feature of the process is the coil-wound heat exchangers supporting energy efficiency and plant economics.[153]

In August 2011, Linde Group was awarded a $15 million from the US Department of Energy to pioneer the advancement of carbon capture technologies, with a pilot plant in Wilsonville, Alabama aiming to be up and running by early 2014.

Project Leader(s): Tim Merkel
Weblink: mtrinc.com
Phone: 650.543.3362

Level of Funding: $4,394,749
Location: Menlo Park, CA
E. tcmerkel@mtrinc.com

MTR Membrane Technology & Research



Source: MTR

Membrane Technology and Research, Inc.

The DOE provided $3,347,119 in 2008 to support this project to demonstrate a cost-effective membrane-based process to capture CO_2 from coal-fired power plant flue gas.[154]

The process will reduce power plant CO_2 emissions and mitigate the potentially damaging effects of global warming. This project will provide a demonstration of CO_2 capture from actual coal- fired flue gas with a membrane system using commercial-scale components. Results from this field test will provide key performance data to allow a thorough technical and economic evaluation of the proposed membrane process.[155]

The impact of system scale-up and the development of low-cost components on the capture process economics will be determined. The endpoint and primary technical objective of the program will be to complete a field test of MTR's CO_2 capture membrane process at a coal-fired power plant.[156]

This project is a collaborative effort between Membrane Technology and Research, Inc. (MTR), Arizona Public Service (APS), and the Electric Power Research Institute (EPRI) that will demonstrate a cost-effective membrane-based process to separate CO_2 from coal-fired power plant flue gas through laboratory and slipstream field tests at an operating coal-fired power generation plant.[157]

Testing results will provide vital performance data to allow thorough technical and economic evaluations of the proposed membrane process. Further analysis will focus on the economics behind clarifying the challenges to scaling-up the system to meet commercial demands and on developing low-cost plastic components on the capture process in order to lower operational and maintenance costs.

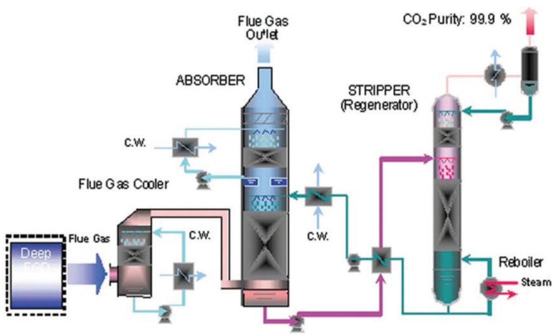
Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Steven Holton
Weblink: mhi.co.jp/en/products/detail/km-cdr_process.html
Phone: 512.219.2348

Level of Funding: Unknown
Location: Nagasaki, Japan

E. steven_holton@mhiahq.com

MITSUBISHI HEAVY INDUSTRIES, LTD.



Source: Carbon Capture Journal

Mitsubishi Heavy Industries (MHI)

Mitsubishi Heavy Industries (MHI) has developed a new absorption process, referred to as KS-1. A key factor in this development is the utilization of a new amine-type solvent for the capture of CO_2 from flue gas.[158]

MHI has successfully used KS-1 at several large-scale commercial plants for fertilizer and heavy oil production. The first testing of KS-1 on coal-generated flue gas is under way at a 10 tpd CO_2 pilot at J-POWER's Matsushima Plant in Nagasaki, Japan.[159]

MHI's KS-1 solvent is a "sterically hindered amine" which tends to form weaker bonds with CO_2, thereby decreasing the energy required for regeneration. MHI's system is called KM CDR for "Kansai Mitsubishi Carbon Dioxide Recovery" and features a conventional scrubber and stripper configuration. The flue gas enters an absorption column with two packed beds and solvent intercooling. Lean solvent is injected between the upper and lower packed beds and trickles down, mixing with the flue gas in counter-flow. A second amine stream is injected at the top of the absorber and allowed to trickle down through both the upper and lower packed beds. The loaded solvent enters the thermal stripper where low-pressure steam heats the rich amine to the point of regeneration, liberating the absorbed CO_2.[160]

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Wayne Carlson
Weblink: nalco.com
Phone: 630.305.1000

Level of Funding: $2,250,487
Location: Naperville, IL
E. Unknown

Nalco Company

With ARPA-E's financial support, Nalco Company is developing a novel process to capture carbon in the smokestacks of coal-fired power plants.[161]

Nalco Company's electrochemical platform will rapidly capture carbon dioxide and desorb it at atmospheric pressure without heating, vacuum, or consumptive chemical usage. If successful, this technology will reduce the incremental carbon capture costs by up to 50 percent and make it more affordable for coal-fired power plants to clean their smokestack emissions.[162]

The CO_2 RW-EDI (CO_2 Resin Wafer-Electrodeionization) platform is a transformational process to capture CO_2 with significant improvements to parasitic energy losses.[163]

The purpose of this project is to develop an electrochemically driven platform to capture CO_2 from coal flue gas without requiring heat or vacuum to desorb CO_2 from an amine or basic solution. The proposed process leverages an elegant design that switches the acidity in the process stream. The result is a method to rapidly capture CO_2 from flue gas and desorb it at atmospheric pressure without heating, vacuum, or consumptive chemical usage.[164]

This technological advance will minimize the impact on cost of electricity for carbon capture as it could reduce incremental capture costs by as much as 50% to keep coal-fired power production affordable. Additionally, water consumption is minimized since the process solution can be re-circulated through the process for additional capture/release cycles.[165]

The company received $2,250,487 from ARPA-E to support this work.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12 | PrizeCapital

Project Leader(s): Joseph McLellan
Weblink: nanoterra.com
Phone: 617.621.8500

Level of Funding: Unknown
Location: Brighton, MA
E. jmclellan@nanoterra.com

Nano Terra, Inc.

Nano Terra, Inc. is developing a new Nanofiber Absorbent (NFA) for use in carbon capture and sequestration (CCS).[166]

This technology will reduce energy for capture by ~50% over current state of the art (i.e. reduce the cost per ton of CO_2 avoided from $52 to $28) and will enable the US to take significant steps towards CO_2 reduction.[167]

The technology employs a novel, reusable nanofiber absorbent material with a functional coating that is similar to monoethanolamine (MEA; the current state of the art). The system differs from MEA systems in that it uses polymeric amines on a solid nanofiber support instead of molecular amines in solution.[168]

The use of NFA materials eliminates the need for boiling and condensing of water during each regeneration cycle (the major source of parasitic energy in MEA systems). The NFA materials also remove the requirement for handling highly corrosive liquids (i.e. MEA solutions).[169]

This technology was listed as an "Encouraged Applicant" and showcased by DOE's ARPA-E.

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): David Neumann
Weblink: neumannsystemsgroup.com
Phone: 719.593.7848

Level of Funding: $7,165,423
Location: Colorado Springs, CO
E. davidn@neumannsystemsgroup.com

Neumann Systems Group, Inc.

Neumann's approach breaks the shower apparatus into small modules and uses a specially designed nozzle that sprays thinner streams of a clear liquid through the emissions. Because they provided greater contact with pollutants, Rankin found the modules removed a higher level of them. There were also other benefits: The devices took up about a third of the space and appeared to need only half of the water and half the maintenance required by a conventional scrubber.

NSG's Carbon Absorber Retrofit Equipment (CARE) project will be located at the Colorado Springs Utilities' Martin Drake Power Plant Unit 7. Patented NeuStream™ absorber technology will be used in combination with an advanced solvent for capture and regeneration of CO_2 from a .5 MW flow of flue gas. The NeuStream™ absorber technology is applicable to a variety of solvents and can be added to existing pulverized coal power plants at reduced cost and in a smaller footprint when compared to conventional technologies. The modularity of the NeuStream™ technology contributes to rapid fielding of larger systems and retrofit of existing plants.

Colorado Springs Utilities is a vital partner in the CARE project. Test equipment at the plant from the previous sulfur dioxide (SO_2) pilot plant project will be adapted for the CARE CO_2 program. NSG's SO_2 control technology is now being designed and constructed for operation by 2014 on Martin Drake Units 6 and 7. The system performance will exceed the new and more stringent EPA and State Air Quality requirements. Colorado Springs Utilities' progressive actions have been the means for bringing the NSG technology to the marketplace while at the same time improving the environment and achieving low cost, reliable energy solutions for their customers.

The overall goal of the DOE research is to develop CO_2 capture and separation technologies that can achieve at least 90 percent CO_2 removal at no more than a 35 percent increase in the cost of electricity.

The U.S. Department of Energy's Office of Fossil Energy selected Neumann Systems Group, Inc. (NSG) in August 2011 for a $7,165,423 grant. The grant is aimed at reducing the energy and cost penalties of advanced carbon capture systems applied to power plants.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Sonja Salmon
Weblink: novozymes.com
Phone: 919.494.3196

Level of Funding: $2,088,643
Location: Franklinton, NC
E. SISA@novozymes.com

Novozymes

Novozymes North America, Inc. (Novozymes) has teamed with the University of Kentucky, Doosan Power Systems, Ltd., and Pacific Northwest National Laboratory (PNNL) to design, build, and test an integrated bench-scale CO_2 capture system that combines the attributes of the bio-renewable enzyme catalyst carbonic anhydrase (CA) with low-enthalpy absorption liquids and novel ultrasonically-enhanced regeneration. This unique CO_2 capture system is expected to achieve improved efficiency, economics, and sustainability in comparison with existing CO_2 capture technologies.[170]

The capture process will use a potassium carbonate solvent with low regeneration energy coupled with CA as a catalyst to promote higher rates of absorption in the carbonate solution. The application of ultrasonic energy forces dissolved CO_2 into gas bubbles, thereby increasing the over-all driving force of the solvent regeneration reaction. Addition- ally, through ultrasonics, a coupled effect of rectified diffusion is also believed to have the potential to drive dissolved CO_2 into gas bubbles at pressures greater than the equilibrium pressure for CO_2 over the solution. The combination of these synergistic technologies is projected to reduce the net parasitic load to a coal-fired power plant by as much as 51 percent com- pared to conventional monoethanolamine (MEA) scrubbing technology.[171]

The project team will build on previous laboratory tests of the novel solvent and CO_2 recovery technique to obtain additional laboratory data sufficient to design a bench-scale system and perform a final analysis of the technology. This bench-scale study will validate the potential of the system to provide a low cost of energy solution for post-combustion CO_2 capture.[172]

In November 2011, the DOE's NETL provided $1,658,619 to Novozymes to support this effort.

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Olgica Bakajin
Weblink: poriferanano.com
Phone: 510.695.2777
Level of Funding: $1,153,975
Location: Hayward, CA
E. olgica@poriferanano.com

Porifera Nano, Inc.

This $1,153,975 ARPA-E project is developing high flux/selectivity carbon nanotube (CNT) membranes for efficient separation of CO_2 from the industrial emission streams.[178]

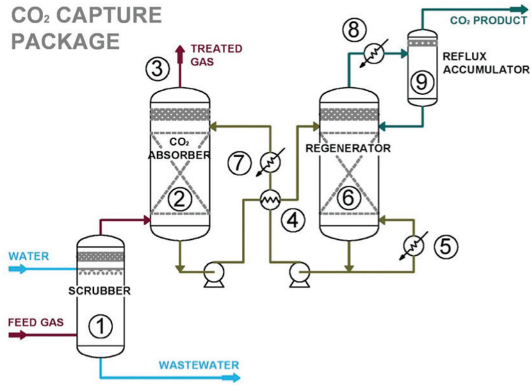
Current commercial operations manage CO_2 from the power station emissions using chemical absorption, which is inherently expensive, energy-intensive, and produces negative environmental impact of its own. Membrane-based CO_2 separations could potentially deliver better efficiency, cheaper sequestration, and low energy consumption, but the development of this technology has been hampered by the lack of membranes that can combine sufficiently high CO_2 selectivity with high flux necessary for viable industrial use.[179]

Unique structure of sub-2-nm carbon nanotube-based membrane pores results in gas permeation fluxes that are two orders of magnitude higher than any other membrane of comparable pore size. This work seeks to develop a breakthrough technology that will capitalize on these advantages. The team will develop and demonstrate a comprehensive set of chemical and physical modifications of CNT membranes that enhance their CO_2 selectivity to reach industrially-viable levels of >100 (CO_2/N_2) and permeability of 104 barrer.[180]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006–12
PrizeCapital

Project Leader(s): Craig Dugan
Weblink: processgroup.com.au
Phone: +61 3.9212.7100

Level of Funding: Unknown
Location: Victoria, Australia
E. Craig.dugan@processgroup.com.au



Source: Process Group

Process Group

Process Group's carbon capture technology can be instantly retrofitted to virtually any exhaust gas system, including coal or gas-fired boilers, gas turbines, blast furnaces, and cement kiln off-gas. The capture process enables carbon dioxide to be selectively absorbed from flue gas via counter-current contact with a regenerable solvent. The solvent is typically an amine-based aqueous solution specially designed to selectively absorb CO_2 from gas streams.[173]

In a typical CO_2 Capture package, hot flue gas passes through the scrubber tower where it is cooled with cooling water (1), before being fed to the absorber tower. The gas enters near the bottom of the absorber tower and flows upward through the internal packing (2), coming into contact with the solvent, which enters near the top of the tower, as the solvent cascades down through the tower. As the flue gas rises through the tower the carbon dioxide level is progressively reduced as it is absorbed by the solvent, meaning the treated gas vented from the absorber (3) is virtually free of CO_2.[174]

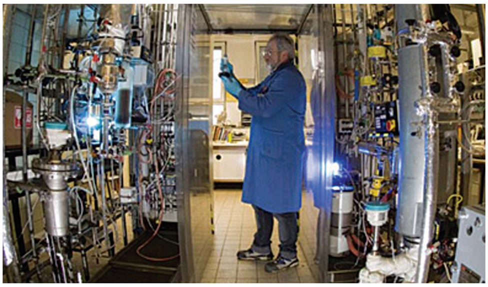
From the bottom of the absorber tower the CO_2-rich solvent is pumped through the lean-rich exchanger (4) to pre-heat the solvent before it enters the regenerator tower. In the regenerator the solvent is heated via the reboiler (5) to reverse the absorption reaction. As the solvent cascades down through the tower, CO_2 is gradually desorbed from the solvent (6). By the time the solvent reaches the bottom of the tower virtually all of the absorbed CO_2 has been released, and the CO_2-lean solvent is cooled and pumped back to the top of the absorber tower to repeat the process (7).[175]

The desorbed CO_2 exits the regenerator tower as a pure, water-saturated gas where it is cooled (8) and then passes through the reflux accumulator to remove excess water (9). The pure carbon dioxide product gas is then ready for direct use or further processing.[176]

Process Group is closely associated with The Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC). Participation in the CO2CRC, combined with our activity in the design and construction of carbon capture packages, provides us with access to the latest advances in carbon capture technologies. Process Group will continue to be in the vanguard of carbon capture and storage innovation, and help more companies and governments achieve their emissions objectives.[177]

Project Leader(s): John Winkler
Weblink: energy.siemens.com/co/en/power-generation/power-plants/carbon-capture-solutions/post-combustion-carbon-capture/
Phone: 412.563.7004

Level of Funding: $18,750,000
Location: Pittsburgh, PA
E. john.winkler@siemens.com



Source: NETL

Siemens

Siemens Energy, Inc. will design, install, and operate a pilot plant for treating a 2.5 MW equivalent slipstream at the TECO Energy Big Bend Station to demonstrate POSTCAP technology for post-combustion CO_2 gas capture.[181]

POSTCAP based technology utilizes an amino acid salt (AAS) that can operate in a conventional scrubber system similar to that for MEA, but with negligible solvent volatility, less corrosion, very low degradation and lower regeneration energy.[182]

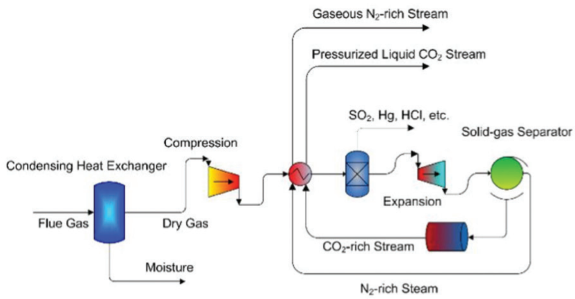
The absorption activity is believed to be similar to MEA, but the capacity of AAS is theoretically double that of MEA. Design capacity is close to this theoretical capacity, which will lead to lower solvent flow rate and inventory for AAS. The solvent is an aqueous solution of approximately 30 – 40 percent AAS and water.[183]

In 2010, the DOE's NETL provided $15 million to support this project.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Larry Baxter
Weblink: sustainablees.com
Phone: 801.850.6364

Level of Funding: $750,000
Location: Orem, UT
E. info@SustainableES.com



Source: Sustainable Energy Solutions

Sustainable Energy Solutions

Under an ARPA-E supported project, Sustainable Energy Solutions will develop and validate novel process components, and design a cryogenic carbon capture prototype system suitable for testing at coal-fired power plants.[184]

Cryogenic Carbon Capture (CCC) is designed to separate a nearly pure stream of CO_2 from power plant gases. This technology adds a process to the plant after the normal energy production and there separates the CO_2 from the other gases. In conservative estimates Cryogenic Carbon Capture technology provides a significantly more cost effective and practical solution to carbon capture in today's market.[185]

The cryogenic CO_2 capture (CCC) process (Figure 1) dries and cools flue gas from existing systems, modestly compresses it, cools it to a temperature slightly above the point where CO_2 forms a solid, expands the gas to further cool it, precipitating an amount of CO_2 as a solid that depends on the final temperature, pressurizes the CO_2, and reheats the CO_2 and the remaining flue gas by cooling the incoming gases. The final result is the CO_2 in a liquid phase and a gaseous nitrogen stream. CO_2 capture efficiency depends primarily on the pressure and temperature at the end of the expansion process. At 1 atm, the process captures 99% of the CO_2 at -211 °F (-135 °C) and 90% at -184 °F (-120 °C). Compared to competing processes, these are relatively mild conditions.[186]

Furthermore, the captured CO_2 has virtually no impurity in it. A thermodynamic feature of CO_2 in flue gases (< 15% CO_2 on a dry basis) is that the CO_2 will not form a liquid phase at any temperature or pressure. Rather, the CO_2 desublimates, forming an essentially pure solid phase rather than a liquid solution that must be distilled.[187]

The approach is estimated to provide a 50 percent energy reduction for capturing carbon dioxide, in comparison to state-of-the-art amine-based solvent processes.[188]

Project Leader(s): Jeannine E. Elliott
Weblink: tda.com
Phone: 303.261.1142
Level of Funding: $1,374,380
Location: Wheat Ridge, CO
E. jelliott@tda.com

TDA Research, Inc.

TDA will produce a low-cost solid alkalized alumina sorbent, evaluate its cyclic life, and measure its performance in a bench-scale test apparatus on simulated coal gases at TDA and then on a slipstream of a coal-derived flue gas at Western Research Institute's (WRI's) coal combustion test facility. The mass and energy balances for a commercial-scale PC-fired power plant retrofit with TDA's CO_2 capture system will be modeled and losses in plant efficiency will be calculated by Louisiana State University (LSU) using Aspen Plus®. The experimental and simulation data will be used to carry out an extensive engineering and economic analysis of the post- combustion CO_2 capture system. The analysis will be done using the DOE National Energy Technology Laboratory's (NETL) 2005 "Carbon Capture and Sequestration Systems Analysis Guidelines."[189]

The objective of this project is to demonstrate that TDA's low-cost sorbent can cost-effectively and efficiently capture CO_2 produced by existing PC-fired power plants. More specifically, this project will develop a low-cost CO_2 sorbent and evaluate its performance by fabricating a bench-scale unit, testing with simulated and real coal-derived flue gases, modeling the mass and energy balances, and calculating the loss in plant efficiency for a commercial-scale PC-fired power plant.[190]

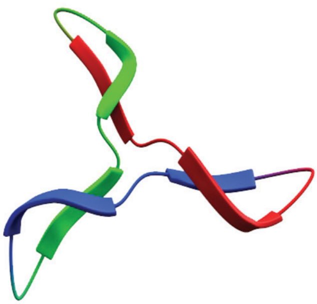
The goal for this project is to develop a low-cost, regenerable CO_2 sorbent system capable of removing and concentrating 90 percent of the CO_2 emissions from PC-fired power plant flue gas.[191]

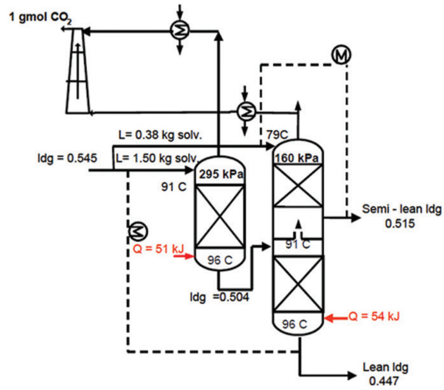
The DOE's NETL provided $1,097,839 towards this project, which began in November 2008 and ended October 2011.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Kevin S. Fisher
Weblink: trimeric.com
Phone: 512.431.6323

Level of Funding: $99,969
Location: Buda, TX
E. kevin.fisher@trimeric.com





Source: NETL

Trimeric Corporation

Under a NETL contract, Trimeric Corporation investigated the feasibility of a highly-integrated, advanced amine scrubbing system, along with a novel amine solvent, that can significantly reduce the parasitic energy requirements.[192]

In Phase I, detailed costs for full-scale units were prepared on the basis of rigorous process models, detailed heat and material balances, and equipment selection. An economic and engineering analysis were conducted and the results compared with the baseline monoethanolamine scrubbing system.[193]

The appropriate construction materials were to be evaluated and selected and Trimeric was to work with contacts within the utility industry to develop realistic and effective process integration strategies for steam system tie-ins, additional heat recovery options, and operability.[194]

A plan for integrating these amine units in a full-scale, coal-fired power plant was also to be developed.[195]

Project Leader(s): J. Michael McQuade
Weblink: utrc.utc.com
Phone: 860.610.7754

Level of Funding: $2,263,898
Location: East Hartford, CT
E. J.Michael.McQuade@utc.com

United Technologies Research Center

United Technologies Research Center (UTRC) is using ARPA-E funding to develop a new process for capturing the carbon dioxide emitted by coal-fired power plants.[196]

UTRC is focusing its research on a naturally-occurring enzyme that is used by nearly every organism on Earth to manage carbon dioxide levels. The naturally occurring form would not survive within a smokestack environment, so UTRC seeks to develop a synthetic analogue of the enzyme that could be used to study aspects of its catalytic mechanism.[197]

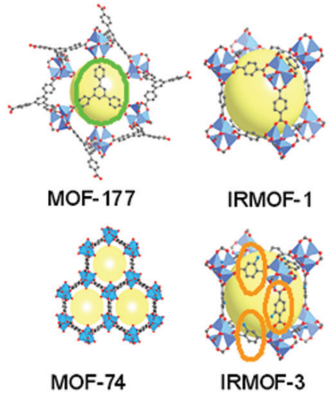
The ultimate objective of this research is to create an enzyme analogue / polymer nano-composite thin-film structure that could act as a selective membrane to separate carbon dioxide from other gases in power plant smokestacks.[198]

The proposed technology maybe easier to install and more reliable than existing technologies because it does not involve any moving parts or consumables. If successful, the proposed technology would allow coal-fired power plants to capture up to 90 percent of carbon at a significantly lower incremental cost.[199]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Richard Willis
Weblink: uop.com
Phone: 847.391.3190

Level of Funding: $3,734,798
Location: Des Plaines, IL
E. richard.willis@uop.com



Source: NETL

UOP, LLC.

UOP LLC, in collaboration with Vanderbilt University, the University of Edinburgh, the University of Michigan, and Northwestern University is working to develop a MOF-based CO_2 removal process and to design a pilot study to evaluate the performance and economics of the process in a commercial power plant.[200]

During Phase I, UOP will use its combinatorial chemistry capabilities to systematically synthesize a wide range of state-of-the-art MOFs and related materials. UOP will screen the materials for hydrothermal stability and characterize materials of particular interest. Detailed isotherm data will be collected in the low-pressure regime in order to establish a consistent, relevant baseline for subsequent development and optimization. The results of the baseline studies will be used to guide the ongoing synthesis, screening, and measurement of new MOFs.

In Phase II, up to 10 candidates will be selected for optimization, based on Phase I results. The effects of water on CO_2 adsorption will be measured in parallel with the development and validation of material scale-up and forming procedures.[201]

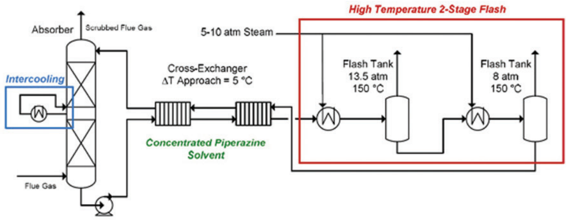
During Phase III, one or two of the best materials will be selected for final optimization and scale-up to pilot-scale quantities. The effects of contaminants on the performance of scaled-up, formed materials will be optimized and detailed kinetic and equilibrium data will be collected. These data will be incorporated into a process design and process economic analysis, leading to the design of a pilot study.[202]

UOP received two NETL grants to support this work. One was for $900,000 in 2004 and the other was for $2,256,750 in 2007.

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Katherine D. Dombrowski
Weblink: urscorp.com
Phone: 512.419.5092

Level of Funding: $3,866,711
Location: Austin, TX
E. katherine_dombrowski@urscorp.com



Source: NETL

URS Corporation

URS Group, in collaboration with the University of Texas and Trimeric Corporation, will investigate the use of concentrated piperazine (PZ) as a solvent for absorbing CO_2 from coal-fired power plant flue gas.[203]

Laboratory research, CO_2 capture process modeling, and preliminary pilot results with synthetic flue gas have shown concentrated PZ to have several advantages over other solvents. When coupled with a novel, high-temperature regeneration system that takes advantage of PZ's enhanced thermal stability, the modeled process has demonstrated significant progress toward meeting the DOE goal of capturing 90 percent of the CO_2 with less than a 35 percent increase in the cost of electricity (COE). This project will investigate the concentrated PZ process for the first time with coal-fired flue gas and at scales of 0.1 MWe and 0.5 MWe to provide data to assess the technical and economic feasibility of a potential future full-scale version of this technology.[204]

The PZ-based CO_2 absorption process will undergo a series of three field tests to gain operational experience with the solvent in coal-fired flue gas, while employing a novel, high- temperature, two-stage flash regeneration design. The tests will be conducted at Commonwealth Scientific and Industrial Research Organization's (CSIRO) Post-Combustion Capture (PCC) facility, University of Texas' Separations Research Program (SRP) plant, and DOE's National Carbon Capture Center (NCCC).[205]

The DOE's NETL contributed $3 million towards this project, for a start date of October 2010.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006–12

Project Leader(s): George Young
Weblink: grace.com
Phone: 410.531.4000

Level of Funding: $3,748,626
Location: Columbia, MD.
E. George.young@grace.com

W.R. Grace

ARPA-E funded this project with $2,998,705 to develop a cost-effective CO_2 capture process known as pressure swing adsorption (PSA), which utilizes rapid pressure changes to capture and release CO_2.[206]

Key to this project is finding a suitable match between the adsorbent and the pressure change cycle configuration. The applicants will develop a low-pressure-drop, structured adsorbent material, based on commercially available materials that are suitable for use in a rapid PSA cycle configuration.[207]

The proposed work builds upon promising results for CO_2 capture from flue gas obtained in a previous project employing a traditional PSA cycle configuration with long cycle times of 300 seconds or so.[208]

Columbia-based Grace (NYSE: GRA) will partner with Battelle Corp. of Columbus, Ohio, Catacel Corp. of Garrettsville, Ohio, and researchers at the University of South Carolina on the project.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Select Emerging Carbon Capture University and Laboratory Overviews »

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Ah-Hyung Alissa Park
Weblink: eee.columbia.edu
Phone: 212.854.8989

Level of Funding: $1,014,707
Location: New York, NY
E. ap2622@columbia.edu

Columbia University

The focus of this ARPA-E sponsored work is on enhanced weathering by the acceleration of the natural reaction between CO_2 and minerals such as magnesium silicates by using chelating agents that target brucite and silica layers to produce a stable precipitate.[209]

Enhanced weathering could provide an alternative to carbon sequestration that does not require monitoring, verification or accounting for stored carbon.[210]

ARPA-E provided $1,014,707 in April 2010 to support this work.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Klaus Lackner
Weblink: energy.columbia.edu
Phone: 212.851.0241
Level of Funding: Unknown
Location: New York, NY
E. kl2010@columbia.edu

Lenfest Center for Sustainable Energy
EARTH INSTITUTE | COLUMBIA UNIVERSITY

Columbia University Earth Institute

The Earth Institute proposes to develop and demonstrate a novel technology for capturing CO_2 from a range of dilute sources, based on an approach originally developed for capture from air, the ultimate dilute source of CO_2.[211]

The Earth Institute will use the dilute CO_2 capture resin as a CO_2 concentration booster pump and cleaning filter that avoids contamination of the conventional sorbent with sulfur and nitrogen oxides. With the booster pump, the conventional sorbent does not need to work as hard as before, enabling the use of a weaker sorbent than MEA, which is the current standard.[212]

The Earth Institute's goal is to take the process successfully designed for air capture, and modify it to apply to other dilute streams of CO_2 spanning the range from air to natural gas-fired power plants and finally to flue gas from coal-fired power plants.[213]

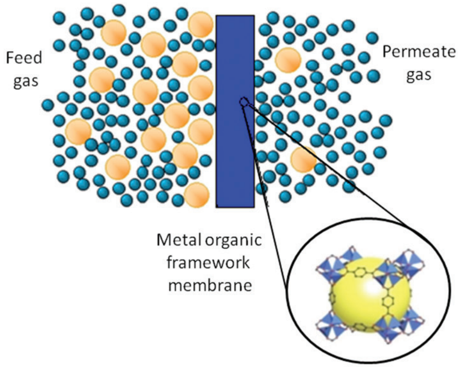
This project was highlighted as an "encourage applicant" by ARPA-E in March 2011.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12 | PrizeCapital

Project Leader(s): David Sholl
Weblink: sholl.chbe.gatech.edu
Phone: 404.894.2822

Level of Funding: $1,000,000

Location: Atlanta, GA
E. david.sholl@chbe.gatech.edu



Source: Georgia Tech

Georgia Institute of Technology

Researchers at Georgia Tech will incorporate metal organic frameworks, new compounds that show great promise in carbon capture, into hollow fiber membranes for improved carbon dioxide selectivity.[214]

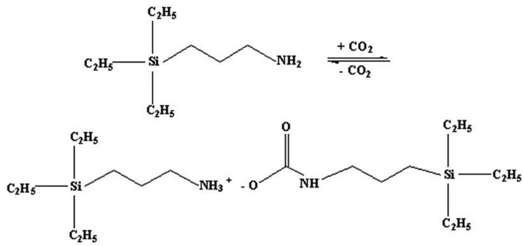
The use of hollow fiber membranes allows for high surface area, and the selective incorporation of metal organic frameworks into the polymer matrix will improve throughput and selectivity, helping to reduce capture costs.[215]

Experimental partners in this work include the National Energy Technology Laboratory (NETL), the University of Maine, Georgia Tech, and Exxon Mobil.[216]

This project received a $1 million ARPA-E grant in April 2010.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Charles A. Eckert
Weblink: eckert.chbe.gatech.edu
Phone: 404.894.7070
Level of Funding: $2,033,549
Location: Atlanta, GA
E. charles.eckert@chbe.gatech.edu



Source: NETL

Georgia Tech Research Corporation

In this project, the Georgia Tech Research Corporation is using totally novel chemistry to engender the dramatic changes needed for widespread implementation of CO_2 capture in a both environmentally benign and economical process. Current methods of CO_2 post-combustion recovery from coal-fired power plants focus on such techniques as absorption in aqueous ethanolamine scrubbers – and this is now a mature technology unlikely to achieve a quantum change in either capacity or cost.[217]

The objective of this project is to develop a novel class of solvents for post-combustion recovery of CO_2 from fossil fuel-fired power plants that will achieve a substantial increase in CO_2 carrying capacity with a concomitant plummet in cost. The project team is a combination of chemical engineers and chemists with extensive experience in working with industrial partners to formulate novel solvents and to develop processes that are both environmentally benign and economically viable. Further, the team has already developed solvents called "reversible ionic liquids," essentially "smart" molecules that change properties abruptly in response to some stimulus, and these have quickly found a plethora of applications.[218]

In this project, cutting-edge chemistry will be combined with established methods of implementation to produce a solvent that results in a less-expensive, more energy efficient CO_2 scrubbing system. The first step will be to synthesize and characterize optimum molecules for two classes of reversible ionic liquids, one based on silyl amines and one based on guanadines. Structure-property relationships will be used to optimize the structure of these ionic liquids to yield desired thermodynamic and physical properties, ranging from a favorable heat of absorption to a low viscosity. Next, CO_2 capture systems using these ionic liquids will be designed and the costs of implementing these systems will be analyzed. Finally, economical methods for commodity scale production of the novel solvents will be developed if they are selected for implementation.[219]

Further, if this novel method for CO_2 capture from coal-fired power plants is successful, it could easily be extended to CO_2 capture from any other CO_2-producing process, such as the burning 'of other fossil fuels or biofuels, or even for fermentation.[220]

Georgia Tech Research Corporation received $1,620,478 from the DOE to support this work.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006–12
PrizeCapital

Project Leader(s): Christopher Jones
Weblink: jones.chbe.gatech.edu
Phone: 404.385.1683

Level of Funding: $3,023,680
Location: Atlanta, GA
E. cjones@chbe.gatech.edu

Georgia Tech Research Corporation

By using a rapid temperature change, a novel process, referred to as rapid temperature swing adsorption (RTSA), is being investigated for CO_2 capture.[221]

The CO_2 is captured on hollow fibers loaded with silica-supported adsorbents. The outcomes of the project will be bench-scale demonstration of the concept of RTSA for CO_2 capture, coupled with preliminary design, optimization and economic analysis of a full-scale system to demonstrate the potential for this technology to meet cost and performance goals set by DOE.[222]

Georgia Tech Research Corp was awarded $2,386,633 in August 2011 by the Department of Energy, as part of a larger $41 million investment in carbon capture technologies, to support this effort.

Project Leader(s): Wilfredo Yave
Weblink: iopscience.iop.org/0957-4484/21/39/395301
Phone: +49 (0)4152 87-0

Level of Funding: Unknown
Location: Geesthacht, Germany
E. wilfredo.yave.rios@gkss.de

GKSS-Research Centre

Researchers from the Institute of Materials Research and Institute of Polymer Research, both at GKSS-Research Centre Geesthacht, have fabricated multiblock copolymers consisting of polyethylene oxide and polybutyleneterephtalate into thin-film composite membranes on laboratory and technical scales.[223]

In order to manufacture their ultra-thin defect-free coatings with extremely high CO_2 permeance and high selectivity, the researchers used a highly permeable intermediate layer (PDMS; thickness <300 nm) between the microporous support and the selective coating. The highly permeable intermediate layer worked as a gutter and protective coating which prevents the diluted polymer solution penetration into the porous structure, and at the same time renders the entire membrane surface smoother.[224]

To test the performance of their membranes, the researchers performed experiments with gas mixtures in order to evaluate the application in power plants. They found that their ultra-thin film membrane has roughly a 20 times higher CO_2 permeance than commercial membranes, combined with one of the highest CO_2/N_2-selectivities known (facilitated transport materials excluded).[225]

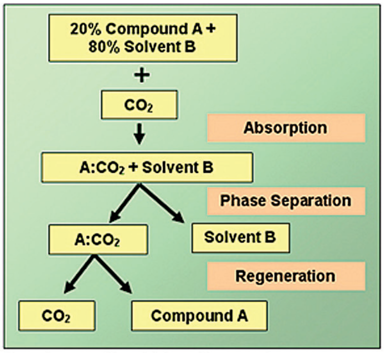
According to the team, a preliminary technical and economical analysis shows that this membrane has potential for carbon capture in coal-fired power plants. They note that the capture cost using the conventional amine absorption process is in the range of 30-50 Euro per ton recovered CO_2.[226]

By applying a membrane-based process design the separation costs can be lower than 30 Euro/t using the high permeance membrane developed at the Institute. These membranes are currently under evaluation at pilot scale in a German project for CO_2 capture in power plants (MEM-BRAIN).[227]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Liang Hu
Weblink: hamptonu.edu
Phone: 757.727.5530

Level of Funding: Unknown
Location: Hampton, VA
E. Liang.hu@hamptonu.edu



Note: Compound A and Solvent B are proprietary components.

Source: NETL

Hampton University

Hampton University researched a novel CO_2 absorption concept, phase transitional absorption that utilizes a two-part proprietary absorbent consisting of an activated agent dissolved in a solvent.

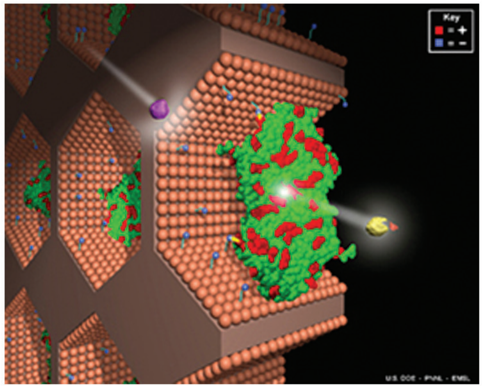
Phase separation of the activated agent from the chemical solvent occurs during CO_2 absorption and physical separation of the two phases exiting the absorber reduces the volume of process liquid requiring thermal regeneration. This unique aspect of phase transitional absorption also decreases the amount of energy (i.e., steam) required to liberate the CO_2. If the proper liquid phases are selected, the absorption rate of CO_2 may also be enhanced. Following regeneration, the activated agent and solvent are mixed and recycled back to the CO_2 absorber vessel.[228]

Researchers will investigate the effects of liquid phase ratios, temperature, agitation speed, CO_2 partial pressure, liquid holdup, and the gas-liquid interface.[229]

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Yongqi Lu
Weblink: isgs.uiuc.edu/index.shtml
Phone: 217.244.4985

Level of Funding: $1,030,450
Location: Champaign, IL
E. lu@isgs.illinois.edu



Source: NETL

Illinois State Geological Survey

The Illinois State Geological Survey is developing an integrated vacuum carbonate absorption process (IVCAP) for post-combustion CO_2 capture.[292]

This process employs potassium carbonate solution as a solvent that can be integrated with the power plant steam cycle by using low-quality steam.[293]

Researchers will confirm IVCAP process parameters through laboratory testing, identify an effective catalyst for accelerating CO_2 absorption rates, and develop an additive for reducing regeneration energy.[294]

In 2008, the DOE's NETL provided $691,191 to support this technology.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12 | PrizeCapital.

Project Leader(s): Tim Fox
Weblink: imeche.org
Phone: +44 (0)20 7222 7899

Level of Funding: Unknown
Location: London, UK
E. timf2@imeche.org

Institution of Mechanical Engineers

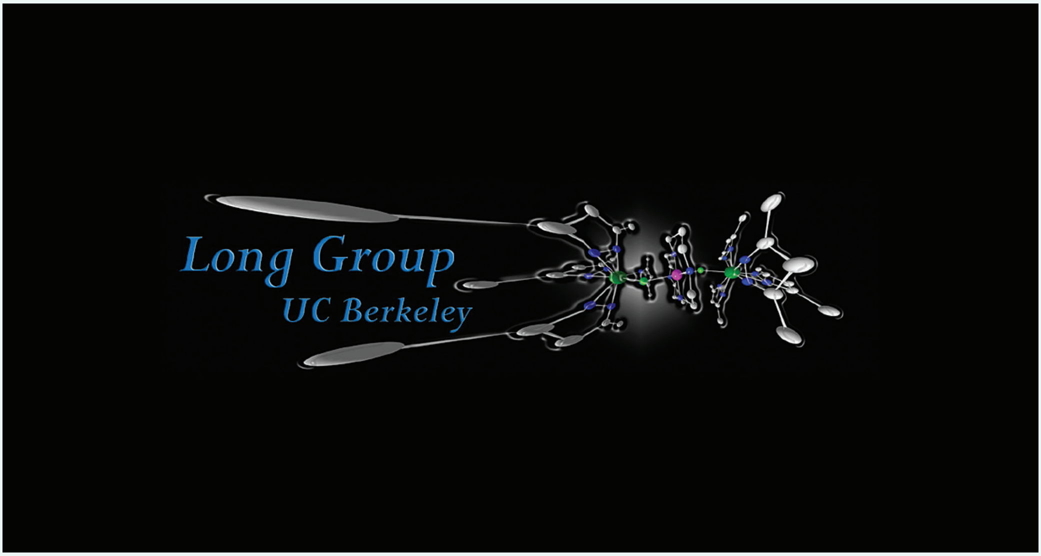
The UK-based institution is demonstrating the air capture technology on a small scale as the UK government and academics meet to discuss its potential.[230]

The device, resembling a giant fly swat, is a thousand times more effective at absorbing carbon dioxide from the air than a tree of about the same size, according to the IME, whose members are developing it.[231]

The Institution projects that the technology will be ready in 2018.[232]

Project Leader(s): Jeffrey Long
Weblink: alchemy.cchem.berkeley.edu
Phone: (510) 642-0860

Level of Funding: $3,663,696
Location: Berkeley, CA
E. jrlong@berkeley.edu



Lawrence Berkeley National Laboratory

The team led by Lawrence Berkeley National Laboratory will utilize robotic instrumentation tools and computational algorithms to accelerate the development of metal organic framework materials to capture carbon dioxide.[233]

There are many different metal organic framework structures that can be made, and the team will use nuclear magnetic resonance signals to quickly identify promising structures.[234]

This research is expected to lead to materials with improved selectivity and robustness that are worthy of large-scale testing and commercialization for carbon dioxide capture in power plants.[235]

DOE's ARPA-E provided $3,663,696 in funding in April 2010 to support this project.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Roger Aines
Weblink: llnsllc.com
Phone: 925.423.7184

Level of Funding: $3,665,000
Location: Livermore, CA
E. aines@llnl.gov

Lawrence Livermore National Security

This project combines scientific experience in creating synthetic small-molecule catalysts with industrial experience to make them operationally useful.[236]

The approach will also demonstrate the effective use of the catalysts under a range of process conditions.

DOE's ARPA-E provided $3,665,000 in April 2010 to support this project.

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Kai Landskron
Weblink: www.3.lehigh.edu/engineering
Phone: 610.758.5788
Level of Funding: $566,641
Location: Bethlehem, PA
E. kal205@lehigh.edu

Lehigh University

With ARPA-E's financial support, Lehigh University is developing an innovative approach to separate carbon dioxide from other gases in the smokestacks of coal-fired power plants.[237]

Lehigh University intends to use electric fields to reversibly and selectively enhance the affinity of certain high-surface-area, solid, absorbent materials for carbon dioxide. By flicking a switch, coal-fired power plants could control whether the materials adsorb carbon dioxide or release it for collection.[238]

Electric Field Swing Adsorption (EFSA) is a fundamentally new approach for separation of carbon dioxide from flue gases of coal-fired power plants. The key feature of this new technology is the use of electric fields to reversibly and selectively enhance the affinity of CO_2 for high surface area solid sorbent materials. This means that both adsorption and desorption can be done under ambient conditions, simply by switching the electric field on and off, avoiding the need for costly heating or pressurization cycles. The current project is focused on developing the scientific basis of the EFSA technology, and determining its practicality for carbon capture applications. The first phase of the project aims to establish proof of concept of the EFSA technique, and to tailor solid sorbent materials and to optimize the field induced adsorption change. Once a suitable system has been identified, we will initiate the second phase of the project, to develop a bench-top gas separation reactor that is capable of CO_2 separation from a simulated flue-gas mixture.[239]

ARPA-E funding will be used to develop appropriate materials and optimize the adsorption process. If successful, this technology would significantly reduce the time and energy required for carbon capture.[240]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006–12
PrizeCapital

Project Leader(s): T. Alan Hatton
Weblink: web.mit.edu/hatton-group/index.html
Phone: 617.253.4588

Level of Funding: $1,000,000
Location: Cambridge, MA
E. tahatton@mit.edu

Massachusetts Institute of Technology

The MIT-led team will develop electrochemically mediated separation processes for post-combustion carbon dioxide capture at coal-fired power plants.[241]

Anticipated benefits include greatly increased energy efficiency for carbon dioxide capture, easier retrofitting of existing coal-fired power plants, and simpler integration with new facilities.[242]

The project will involve molecular modeling and experimental optimization of carrier structure, fabrication and evaluation of prototype separation units.[243]

DOE's ARPA-E provided $1,000,000 in April 2010 to support this project.

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): McMahan Gray
Weblink: fossil.energy.gov
Phone: 412.386.4826
Level of Funding: Unknown
Location: Pittsburgh, PA
E. mcmahan.gray@netl.doe.gov

National Energy Technology Laboratory

NETL scientists have developed an amine-enriched sorbent that has been investigated with flue gas streams at temperatures similar to those found after lime/ limestone desulfurization scrubbing.[244]

The CO_2 capture sorbents are prepared by treating high surface area substrates with various amine compounds. The immobilization of amine groups on the high surface area material significantly increases the contact area between CO_2 and amine. This advantage, combined with the elimination of liquid water, has the potential to improve the energy efficiency of the process compared to MEA scrubbing.[245]

Application of this technology reduces the costs and energy associated with more conventional scrubbing processes to capture CO_2 in large-scale power generation facilities; consequently, its transfer from the laboratory to the marketplace is another important step in moving forward the commercialization and deployment of innovations that help decrease atmospheric emissions of greenhouse gases.[246]

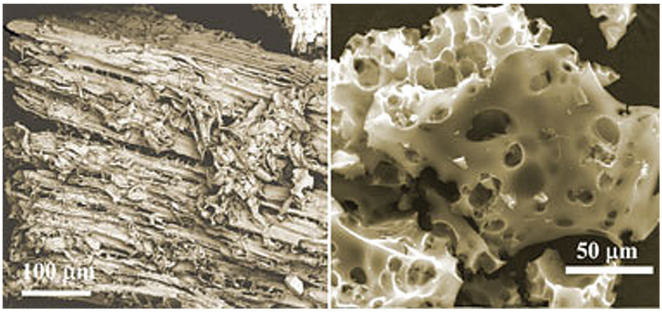
The “BIAS” Process will use low-cost, regenerable, solid CO_2 sorbents in large-scale fossil fuel-burning power plants. An amine compound, composed of nitrogen and hydrogen atoms, is treated to make it more selective and reactive towards CO_2. Combined with a porous solid support, the amine becomes a sorbent, which selectively reacts with CO_2 to extract it from the flue gas. The sorbent is then heated to release the CO_2 for storage, thereby refreshing the sorbent for reuse.[247]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006–12
PrizeCapital

Project Leader(s): Antonio Fuertes
Weblink: incar.csic.es
Phone: +34 985 11 90 90

Level of Funding: Unknown
Location: Oviedo, Spain
E. abefu@incar.csic.es

CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS CSIC



Source: Royal Society of Chemistry

National Institute of Carbon, Oviedo

Antonio Fuertes and his group at the National Institute of Carbon, Oviedo, have made a porous carbon material that performs better than other currently available ones, using a simple and inexpensive process. The major difference in this work, however, is that the raw material is sawdust.[248]

The two-step synthesis involves hydrothermal carbonisation of the sawdust, creating a hydrochar, which is then activated using potassium hydroxide. The KOH treatment creates pores in the sawdust structure by oxidation of carbon and carbon gasification from K_2CO_3 decomposition. These pores are responsible for the material's uptake capabilities, bestowing it with a capacity as high as 4.8mmol CO_2/g. In addition, Fuertes' material has good selectivity for CO_2 over N_2, fast adsorption rates and can be easily regenerated.[249]

Sustainable porous carbons have been prepared by chemical activation of hydrothermally carbonized polysaccharides (starch and cellulose) and biomass (sawdust). These materials were investigated as sorbents for CO_2 capture. The activation process was carried out under severe (KOH/precursor = 4) or mild (KOH/precursor = 2) activation conditions at different temperatures in the 600–800 °C range. Textural characterization of the porous carbons showed that the samples obtained under mild activating conditions exhibit smaller surface areas and pore sizes than those prepared by employing a greater amount of KOH. However, the mildly activated carbons exhibit a good capacity to store CO_2, which is mainly due to the presence of a large number of narrow micropores (<1 nm). A very high CO_2 uptake of 4.8 mmol·g^{-1} (212 mg CO_2·g^{-1}) was registered at room temperature (25 °C) for a carbon activated at 600 °C using KOH/precursor = 2. To the best of our knowledge, this result constitutes the largest ever recorded CO_2 uptake at room temperature for any activated carbon. Furthermore, we observed that these porous carbons have fast CO_2 adsorption rates, a good selectivity for CO_2–N_2 separation and they can be easily regenerated.[250]

Project Leader(s): Ross Forgan
Weblink: stoddart.northwestern.edu
Phone: 847.491.3793

Level of Funding: Unknown
Location: Evanston, IL
E. forgan@northwestern.edu

Northwestern University

Chemists from Northwestern University in Evanston, Illinois created a carbon capture and storage material which is made of sugars, salt and a little bit of alcohol - organic compounds that produce less emissions.[251]

Because the materials, known as metal-organic frameworks or MOFs, are made from naturally derived ingredients, they are not only non-toxic but carbon-neutral too, the researchers said.[252]

The researchers found that their all-natural metal-organic framework reacted with carbon dioxide in a process akin to carbon fixation that binds the carbon dioxide to the crystals.[253]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006–12
PrizeCapital

Project Leader(s): Sheng Dai
Weblink: ornl.gov/sci/csd/Research_areas/NC_group.htm
Phone: 865.576.7307

Level of Funding: $987,547
Location: Oak Ridge, TN
E. dais@ornl.gov

Oak Ridge National Laboratory

A team from Oak Ridge National Laboratory and Georgia Tech will integrate new designer ionic liquids that capture carbon dioxide in flue gas with hollow fiber membranes that provide a robust, high surface area support.[262]

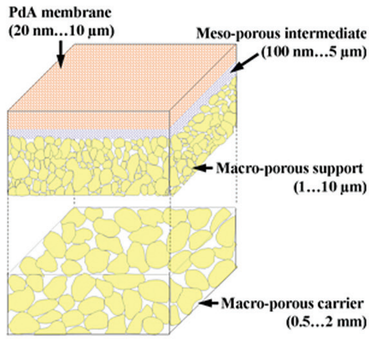
The objectives of this catch-and-release system are to cut the cost and energy associated with capturing carbon dioxide, as well as to design a platform that can be scaled up to coal-fired power plants across the country.[263]

DOE's ARPA-E provided $987,547 in April 2010 to support this effort.

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Hendrik Verweij
Weblink: matsceng.ohio-state.edu/ims
Phone: 614.247.6987

Level of Funding: $4,262,300
Location: Columbus, OH
E. verweij.1@osu.edu



Source: NETL

Ohio State University

The objective of this $3,000,000 DOE project is a cost-effective design and manufacturing process for new membrane modules that separate CO_2 from flue gas.[264]

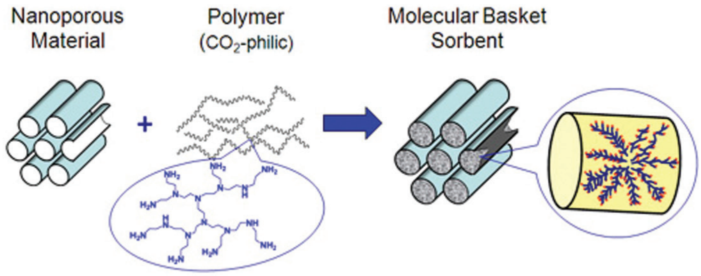
The membranes consist of a thin selective inorganic layer embedded in a polymer structure so that it can be made in a continuous manufacturing process. They will be incorporated in spiral-wound modules for bench-scale tests at actual conditions.[265]

Preliminary cost calculations show that options of using a single-stage membrane process or a two-stage process can meet or exceed the DOE cost goals.[266]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Chunshan Song
Weblink: energy.psu.edu/cfc/index.html
Phone: 412.863.4466

Level of Funding: $571,291
Location: University Park, PA
E. csong@psu.edu



Source: NETL

Pennsylvania State University

Pennsylvania State University (PSU) will develop a new generation of solid polymer-based sorbents for more efficient capture and separation of CO_2 from flue gas of coal-fired power plants. The project is based on the concept of a molecular basket sorbent (MBS), which was invented and developed at PSU. The idea of MBS development is to load CO_2-philic polymers onto high surface area nanoporous materials. This process increases the number of approachable sorption sites on/in the sorbent and enhances the sorption/desorption rate by increasing the gas-sorbent contacting interface and by improving the mass transfer in the sorption/desorption process. The expected result of this project will be a concentrated CO_2 stream that can be directed to CO_2 sequestration or CO_2 utilization.[267]

Development of the new generation of MBS involves the selection of the best performing, most cost-effective CO_2-philic polymer and nanoporous materials. Different types of nanoporous materials will be purchased as support materials. A series of polymers will be immobilized in the nanoporous materials to prepare different sorbents. The prepared sorbents will be tested and evaluated for CO_2 capture in a fixed-bed flow system. The promising MBSs will be further characterized to determine their structure; surface properties; thermal, physical, and chemical properties; and CO_2-sorption/desorption properties. Advanced molecular modeling will be used to facilitate the screening of the polymer sorbents and the design of novel polymers. Computational results will be utilized to guide project experimental approaches. A techno-economic analysis will also be performed on the new MBSs and CO_2 capture process. The analysis will focus on energy consumption and the cost of the sorbents in comparison to a conventional post-combustion CO_2 capture process.[268]

The DOE provided $456,992 to support this project between September 2009 and 2012.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Lora Toy
Weblink: rti.org/page.cfm/Carbon_Capture_and_Utilization
Phone: 919.316.3393

Level of Funding: $2,431,027
Location: Research Triangle Park, NC
E. ltoy@rti.org

Previous membrane test skid built
(Skid footprint ~ 4 ft. × 6 ft.)

Source: NETL

Research Triangle Institute – Fluorinated Polymer Membranes

Research Triangle Institute (RTI) International is researching fluorinated polymer membranes for carbon dioxide capture. RTI's research effort includes membrane materials development, module design, and process design. RTI is pursuing the development of two hollow-fiber membrane materials. First, RTI is working with Generon to develop a membrane material constructed of polycarbonate-based polymers. Lab-scale membrane modules are being studied with simulated flue-gas mixtures with and without flue gas emission contaminants. Two larger-scale polycarbonate membrane module prototypes are being tested with a slipstream of actual flue gas from the U.S. Environmental Protection Agency's (EPA) Multipollutant Combustion Research Facility (MPCRF). RTI is also working with Arkema to develop the second membrane material constructed of polyvinylidene fluoride (PVDF)-based polymers.[272]

Membranes could provide PC-fired power plants with a cost-effective method for CO_2 capture. The membrane module system is relatively easy to install within an existing PC-fired plant and does not require any major modifications to the existing equipment and infrastructure. The membrane utilizes passive separation of gases, making it energy efficient because it does not require regeneration energy, as do solvent and sorbent processes. The module's compact design and ability to link with hundreds of modules in tandem makes the hollow fiber membrane system easy to scale and retrofit. The membrane also lacks any moving parts, reducing the risk of a mechanical failure.[273]

The DOE's NETL provided $1,944,821 towards this project in 2008.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Luke Coleman
Weblink: rti.org/page.cfm?obj=27F633A1-5056-B100-311B8F-CBCBC98219
Phone: 919.541.6000

Level of Funding: $2,000,000
Location: Research Triangle Park, NC
E. lcoleman@rti.org

Research Triangle Institute – Non-Aqueous Solvents

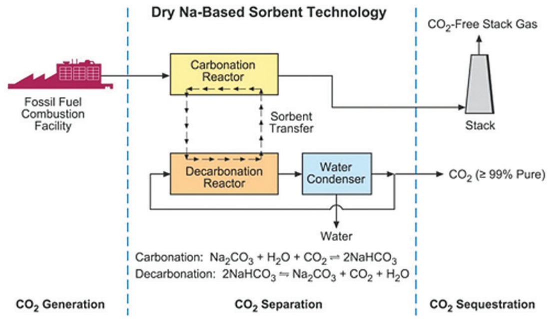
RTI International and BASF are teaming up to explore a new class of non-aqueous solvents that exploit a new reversible carbon dioxide-solvent chemistry.[274]

The lower energy penalty results from the milder regeneration temperature that allows carbon dioxide to be released using less energy. The team estimates that this approach could reduce the regeneration energy so that it is 40 percent lower than that of conventional, state-of-the-art amine based solvent processes.[275]

RTI International and BASF received a $2 million ARPA-E grant in June 2010 to support this work.

Project Leader(s): Thomas Nelson
Weblink: rti.org/page.cfm/Carbon_Capture_and_Utilization
Phone: 713.203.6737

Level of Funding: $6,553,506
Location: Research Triangle Park, NC
E. tnelson@rti.org



Source: NETL

Research Triangle Institute – Regenerable Sorbent

Research Triangle Institute (RTI) International completed two projects, NT43089 and NT40923, to investigate the use of sodium carbonate (Na_2CO_3 or soda ash) as an inexpensive, dry, and regenerable sorbent for CO_2 capture in the Dry Carbonate Process.[269]

In this process, Na_2CO_3 reacts with CO_2 and water to form sodium bicarbonate at the temperature of the flue gas exhaust; the sorbent is then regenerated at modest temperatures (~120°C) to yield a concentrated stream of CO_2 for sequestration or other use.[270]

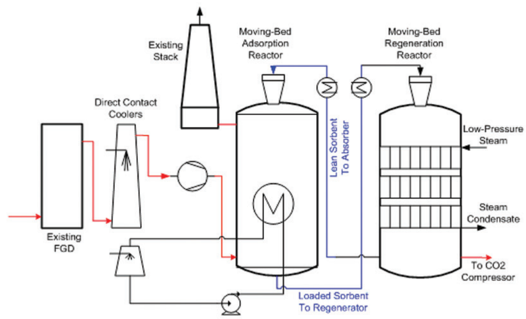
This process is ideally suited for retrofit application in the non-power and power generation sectors. Laboratory and pilot plant tests have consistently achieved over 90% CO_2 removal from simulated flue gas. RTI's process has advanced through pilot-scale testing with simulated and coal combustion flue gases. In addition, the reproducibility of their sorbent at a commercial operating facility has been confirmed. The process advantages translate into lower capital costs and power requirements than conventional MEA technology (based on a preliminary economic analysis).[271]

DOE's NETL provided $2,026,724 for the first phase of the project and $3,217,056 for the second phase.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Gopola Krishnan
Weblink: sri.com/focus_areas/energy
Phone: 650.859.2627

Level of Funding: $2,249,957
Location: Menlo Park, CA
E. gopola.krishnan@sri.com



Source: NETL

SRI International

In collaboration with Advanced Technology Materials Inc. (ATMI), SRI International (SRI) will develop an innovative, low-cost, and low energy-consuming CO_2 capture technology based on adsorption on a high capacity and low-cost carbon sorbent.[276]

SRI will identify and determine the chemical, physical, and mechanical properties of the sorbent that are relevant to the effective capture of CO from PC-fired flue gas streams. SRI will achieve this by chemically functionalizing the-2high surface area sorbent in order to increase the selectivity and loading for CO_2 capture and reduce thermal requirements for CO_2 desorption.[277]

A bench-scale, fixed-bed reactor system will be designed and constructed for performing adsorption and regeneration studies. In addition, a simulated flue gas stream containing both major gases and minor contaminants will be used to determine the CO_2 capture rates.[278]

Based on the results of the adsorber and regenerator parametric tests, a selected set of conditions will be used to perform cyclic tests with the reactors operating in adsorption and regeneration modes. Finally, a technical and economic evaluation will be conducted on the feasibility of the novel carbon sorbents for cost-effective CO_2 capture from PC-fired power plants. The information obtained from this project will be used to design a 0.25 MW or larger capacity pilot unit that will treat a slipstream from an operating PC-fired power plant in a future phase.[279]

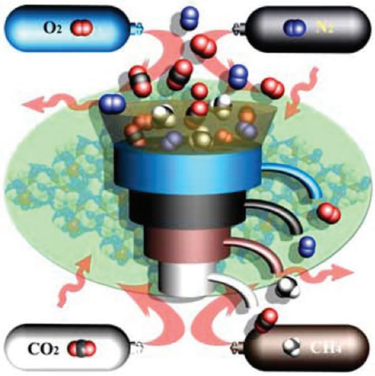
In 2008, the DOE's NETL provided $1,799,957 to support this project.

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Hongcai "Joe" Zhou
Weblink: chem.tamu.edu/rgroup/zhou
Phone: 979.845.4034

Level of Funding: $1,019,874
Location: College Station, TX

E. zhou@mail.chem.tamu.edu



Source: Texas A&M

Texas A&M

Texas A&M will develop innovative metal organic framework based molecular sieves whose adsorption and desorption properties can be finely tuned by controlling their mesh size.[280]

This will enable more energy-efficient carbon dioxide capture and will reduce the cost of carbon dioxide capture by enhancing carbon dioxide/N2 selectivity at high carbon dioxide loadings[281] and by greatly lowering the cost of regeneration.

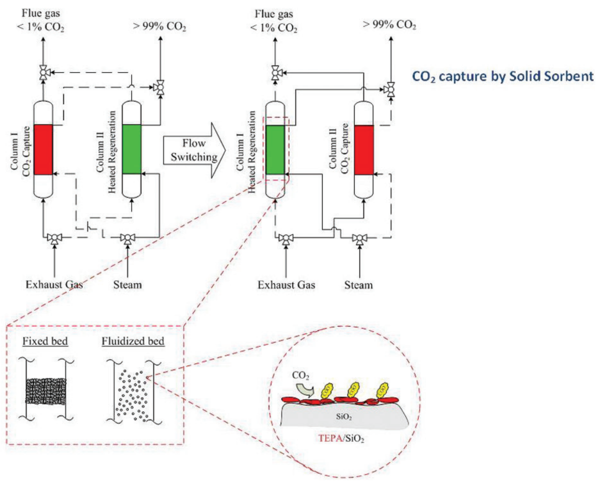
The team will demonstrate a process that it predicts can capture 90 percent of the carbon dioxide in flue gas with substantially reduced parasitic power demand.[282]

The DOE's ARPA-E provided $1,019,874 in April 2010 to support this technology.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital.

Project Leader(s): Steven Chuang
Weblink: coel.ecgf.uakron.edu/~chuang
Phone: 330.972.6993

Level of Funding: $957,833
Location: Akron, OH
E. schuang@uakron.edu



Source: University of Akron

University of Akron

The University of Akron is investigating a new sorbent for CO_2 capture that involves the novel integration of metallic monolith structures coated with amine-grafted zeolites.[283]

This sorbent would eliminate the use of corrosive liquid amine and decrease the energy required for sorbent regeneration. The metal monoliths consist of straight channels: one row of channels coated with amine-grated zeolite and one used for heat transfer media for either cooling for adsorption or heating for regeneration.[284]

In combination with the innovative applications of metal monoliths as an adsorbent structure, the low cost of raw materials for the synthesis of zeolite-grafted amine sorbents may result in a breakthrough technology for the effective capture of CO_2 from flue gas of coal-fired power plants.[285]

In 2007, the DOE's NETL provided $764,995 to support this project.

Project Leader(s): Greg Rau
Weblink: ims.ucsc.edu/facres/ocean.html
Phone: 925.423.7990

Level of Funding: Unknown
Location: Livermore CA
E. rau4@llnl.gov

Source: LLNL

University of California, Santa Cruz

Greg Rau, a senior scientist with the Institute of Marine Sciences at UC Santa Cruz and who also works in the Carbon Management Program at Lawrence Livermore National Laboratory, conducted a series of lab-scale experiments to find out if a seawater/mineral carbonate (limestone) gas scrubber would remove enough CO_2 to be effective, and whether the resulting substance -- dissolved calcium bicarbonate -- could then be stored in the ocean where it might also benefit marine life.[286]

In addition to global warming effects, when carbon dioxide is released into the atmosphere, a significant fraction is passively taken up by the ocean in a form that makes the ocean more acidic. This acidification has been shown to be harmful to marine life, especially corals and shellfish.[287]

In his experiments, Rau found that the scrubber removed up to 97 percent of CO_2 in a simulated flue gas stream, with a large fraction of the carbon ultimately converted to dissolved calcium bicarbonate.[288]

At scale, the process would hydrate the carbon dioxide in power plant flue gas with water to produce a carbonic acid solution. This solution would react with limestone, neutralizing the carbon dioxide by converting it to calcium bicarbonate -- and then would be released into the ocean. While this process occurs naturally (carbonate weathering), it is much less efficient, and is too slow paced to be effective.[289]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Richard Noble
Weblink: colorado.edu/che/faculty/noble.html
Phone: 303.492.6100

Level of Funding: $3,144,646
Location: Boulder, CO
E. nobler@colorado.edu

Chemical and Biological Engineering
University of Colorado at Boulder

University of Colorado at Boulder

University of Colorado at Boulder will develop a novel gelled ionic liquid membrane, which provides mechanical rigidity into what is normally a liquid solvent, allowing extremely thin membranes to be fabricated.[290]

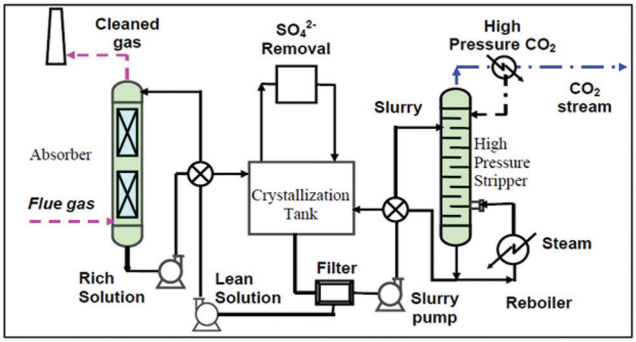
Since the membrane permeance increases as the membranes become thinner, higher fluxes of carbon dioxide can be selectively passed through the membrane, reducing the cost and size of membrane treatment for flue gas.[291]

The DOE's ARPA-E provided $3,144,646 in April 2010 to support this project.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Yongqi Lu
Weblink: illinois.edu
Phone: 217.244.4985

Level of Funding: $1,642,156
Location: Champaign, IL
E. lu@isgs.illinois.edu



Source: NETL

University of Illinois at Urbana-Champaign

The University of Illinois at Urbana-Champaign will evaluate the Hot Carbonate Absorption Process (Hot-CAP) process with crystallization-enabled high pressure stripping. The Hot-CAP is an absorption-based, post-combustion CO_2 technology that uses a carbonate salt (K_2CO_3 or Na_2CO_3) as a solvent. The process integrates a high temperature (70-80°C) CO_2 absorption column, a slurry-based high-pressure (up to 40atm) CO_2 stripping column, a crystallization unit to separate bicarbonate and recover the carbonate solvent, and a reclaimer to recover $CaSO_4$ as the byproduct of the SO_2 removal.[295]

A preliminary techno-economic evaluation shows that energy use with the Hot-CAP is about half that of a conventional MEA process. In a typical MEA process there are three components of heat: the heat of reaction, the sensible heat, and the stripping heat. The Hot-CAP reduces all three heat components.[296]

Because the bicarbonate slurry comes from the crystallizer, the stripping process is decoupled with, and thus independent of, the absorption process. The carbonate solution has a smaller heat of absorption than the MEA. With the inclusion of the heat of crystallization, the overall heat of reaction ranges between 7 and 17 kcal/mol CO_2 compared to 21 kcal/mol CO_2 for MEA. In addition, the use of the bicarbonate slurry results in a significant increase in the working capacity of the solvent.[297]

A higher working capacity reduces the energy required to heat the slurry, or the sensible heat. Finally, since the carbonate salt does not degrade at a high regeneration temperature, the Hot-CAP can be operated at higher pressures. A higher stripping pressure reduces the stripping heat as well as the compression work.[298]

The DOE's NETL provided $1,277,118 in 2011 to support this technology.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

Project Leader(s): Kunlei Liu
Weblink: caer.uky.edu/catalysis/home.shtml
Phone: 859.257.0293

Level of Funding: $1,955,078
Location: Lexington, KY
E. kunlei.liu@uky.edu

University of Kentucky-Center for Applied Energy Research

The University of Kentucky research team will develop a hybrid absorption solvent/catalytic membrane for post-combustion carbon dioxide capture process that can be retrofit onto existing coal-fired power plants.[299]

The membrane is a catalytic separator that couples nanofiltration separation and catalysis to produce a concentrated permeate. The membrane can be used with aqueous ammonium and some typical alkyl amines solutions.[300]

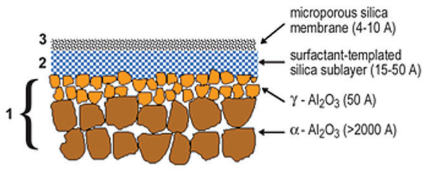
This catalytic membrane reactor could greatly reduce the energy penalty for carbon dioxide capture. Moreover, it could be conveniently integrated with traditional carbon capture processes.[301]

The DOE's ARPA-E provided $1,955,078 in April 2010 to support this technology.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): C. Jeffrey Brinker
Weblink: unm.edu/~solgel
Phone: 505.272.7627

Level of Funding: $886,827
Location: Albuquerque, NM
E. cjbrink@sandia.gov



Source: NETL

University of New Mexico

This completed University of New Mexico project was to develop a dual-function amine modified membrane capable of economically and efficiently removing CO_2 emissions from the flue gas of coal-fired power plants. The use of such an amine-modified membrane, with high CO_2 permeance and selectively, holds promise for reducing costs by avoiding the expensive absorber/stripper system required with existing amine-based technology.[302]

This dual-function membrane is prepared by a unique sol-gel dip-coating process for depositing a microporous amino-silicate membrane on a porous tubular ceramic support. It consists of a microporous inorganic siliceous matrix, with amine functional groups physically immobilized or covalently bonded on the membrane pore walls.[303]

Strong interactions between the permeating CO_2 molecules and the amine functional membrane pores will enhance surface diffusion of CO_2 on the pore wall of the membrane, subsequently blocking other gases.[304]

The new membrane is expected to exhibit higher CO_2 selectivity compared to prior membranes that separate gases based on differences in molecular size only.[305]

The DOE's NETL provided $886,827 in 2005 to support this technology.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006–12
PrizeCapital

Project Leader(s): Brandon M. Pavlish
Weblink: undeerc.org
Phone: 701.777.5065

Level of Funding: Unknown
Location: Grand Forks, ND
E. bpavlish@undeerc.org

University of North Dakota – EERC

The EERC's PCO2C Program is researching capture technologies to identify the most efficient, cleanest, and most cost-effective for implementation in the electric utility fleet or in CO_2 sequestration.[306]

Besides the EERC, the PCO2C Partnership includes the U.S. Department of Energy (DOE), the North Dakota Industrial Commission, and some 15 industrial partners.[307]

The first phase of the project began in July 2008 and wraps up in July 2010 as the project moves into Phase II. Phase I concentrated on designing and fabricating an oxygen-fired combustion technology and a postcombustion high-efficiency, flexible scrubber system, both for use on the EERC's existing 550,000-Btu/hr suspension-fired pilot-scale combustion test facility (CTF). The postcombustion system evaluated the performance of several CO_2-scrubbing solvents in flue gas streams derived from the combustion of selected fossil fuels, biomass, and blends. Phase II will test the most promising solvents as well as some novel technologies.[308]

PrizeCapital
Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Steve Benson
Weblink: engineering.und.edu/institute-for-energy-studies
Phone: 701.213.7070

Level of Funding: $3,690,000
Location: Grand Forks, ND
E. stevebenson@mail.und.nodak.edu

University of North Dakota – Institute for Energy Studies

The objective of this project is to scale up and demonstrate a hybrid solid sorbent technology, referred to as the CACHYSTM process, for CO_2 capture from coal combustion-derived flue gas.[309]

The technology involves a novel solid sorbent based on the following ideas: reduction of energy for sorbent regeneration, utilization of novel process chemistry, contactor conditions that minimize sorbent-CO_2 heat of reaction and promote fast CO_2 capture, and low-cost method of heat management.[310]

The project will develop key information for the CACHYS process-sorbent performance, energy for sorbent regeneration, physical properties of the sorbent, the integration of process components, sizing of equipment, and overall capital and operational cost of the integrated system.[311]

The DOE's ARPA-E provided $2,952,000 in August 2011 to support this work.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006–12
PrizeCapital

Project Leader(s): Joan Brennecke
Weblink: nd.edu/~jfb
Phone: 574.631.5847

Level of Funding: $2,559,563
Location: South Bend, IN
E. jfb@nd.edu

University of Notre Dame – Brennecke Research Group

A recent discovery by researchers at Notre Dame University have identified a class of ionic liquid materials which undergo a phase transition from solid phase to liquid when reacting with carbon dioxide.[257]

A detailed synthetic study of these new compounds will aim to identify materials that are best suited for post-combustion capture applications.[258]

The potential of these projects as a more economical means of CO_2 capture depends upon the efficient use of ILs as CO_2 absorbents in coal-fired power plants. Compared to existing amine-based technologies, these designs would reduce costs through higher CO_2 loading in the circulating liquid and lower heat requirements for regeneration.[259] Research has indicated that, for flue gas application, ILs have demonstrated SO_2 solubility 8 to 25 times that of CO_2 at the same partial pressure, thereby allowing this novel solvent to not only remove CO_2 but also serve as an SO_2 polishing step.[260]

Lower heats of regeneration are required with these materials because the heat of fusion during the phase change from liquid to solid reduces the amount of energy needed to release the carbon dioxide that is captured.[261]

DOE's ARPA-E provided $2,559,563 in April 2010 to support this effort.

Project Leader(s): Edward Maginn
Weblink: nd.edu/~ed/
Phone: 574.631.5687

Level of Funding: $434,076
Location: St. Joseph County, IN
E. ed@nd.edu

University of Notre Dame – Maginn Group

The University of Notre Dame is conducting the Ionic Liquids: Breakthrough Absorption Technology for Post-Combustion CO_2 Capture project (FC26-07NT43091), that builds on the work of its earlier project (FG26-04NT42122), to provide a comprehensive evaluation of the feasibility of using a novel class of compounds – ionic liquids (ILs) – for the capture of CO_2 from the flue gas of coal-fired power plants.[254]

Initial efforts focused on "proof-of-concept" exploration, followed by a laboratory-/bench-scale effort. ILs include a broad category of salts, typically containing an organic cation and either an inorganic or organic anion.[255]

Since ILs are physical solvents, less heat is required for regeneration compared to today's conventional chemical solvents. Task-specific ILs that contain amine functionality are being investigated to further improve CO_2 solubility.[256]

The DOE's NETL provided $434,076 to support this project between 2004 and 2007.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006–12
PrizeCapital

Project Leader(s): Deanna D'Alessandro
Weblink: sydney.edu.au/science/chemistry/~deanna
Phone: +61-2-9351-3777

Level of Funding: $20,000
Location: Sydney, Australia
E. deanna@chem.usyd.edu.au

University of Sydney

Splitting her work between California and Sydney, Dr. Deanna D'Alessandro has constructed crystals full of minute holes that can trap CO_2, and theoretically almost any gas.[312]

Dr. D'Alessandro's high-tech crystals are known as metal-organic frameworks, which are clusters of charged metal atoms linked by carbon-based groups. Their molecular structures are essentially similar to the molecular structures of seashells and microscopic marine plants called diatoms. One teaspoon of these molecular sponges has a surface area equivalent to a rugby field.[313]

The concept is not new, but Dr. D'Alessandro's crystals are more robust with molecular pores that could even be shaped using light. This gives them the ability to capture and release gases on cue.[314]

They can also withstand the hot, wet environments of power station flues that currently use carbon capture technology based around toxic chemicals. And which can require up to 40 per cent of the power generated by the station to successfully capture CO_2.[315]

The scientist was awarded the L'Oréal Australia For Women in Science Fellowship for her achievement, which will provide $20,000 worth of equipment, travel support and a summer vacation student to assist her research.[316]

The crystals may have other important applications including hydrogen storage, gas separation, and electrodes for sensors.[317]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): Gary T. Rochelle
Weblink: research.engr.utexas.edu/rochelle
Phone: 512.471.7230

Level of Funding: $2,262,325

Location: Austin, TX
E. gtr@che.utexas.edu

University of Texas at Austin

The University of Texas at Austin investigated an improved process for CO_2 capture by alkanolamine absorption that uses an alternative solvent, aqueous potassium carbonate (K_2CO_3) promoted by piperazine (PZ).[318]

The K_2CO_3/PZ system (5 molar K; 2.5 molar PZ) has an absorption rate 10–30% faster than a 30% solution of MEA and favorable equilibrium characteristics. A benefit is that oxygen is less soluble in K+/PZ solvents; however, piperazine is more expensive than MEA, so the economic impact of oxidative degradation will be about the same.[319]

If successful, this process would use less energy for CO_2 capture than the conventional monoethanolamine (MEA) scrubbing process. An improved capture system would mean a relative improvement in overall power plant efficiency.[320]

The project developed models to predict the performance of absorption/stripping of CO_2 using the improved solvent and perform a pilot plant study to validate the process models and define the range of feasible process operations.[321]

As part of the pilot plant study, a test with MEA was conducted as a baseline to compare CO_2 absorption and stripping performance with tests using the K_2CO_3/PZ solvent. Researchers also investigated key issues such as solvent degradation, solvent reclamation, corrosion, and alternative stripper configurations.[322]

The DOE's NETL provided $1,565,275 in 2002 to support the development of this technology.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006–12
PrizeCapital

Project Leader(s): Maciej Radosz
Weblink: wwweng.uwyo.edu/economic/sml/index.html
Phone: 307.766.4926

Level of Funding: Unknown
Location: Laramie, WY
E. radosz@uwyo.edu

University of Wyoming

The university is creating a low-pressure Carbon Filter Process (patent pending) to capture CO_2 from flue gas.[323]

This filter is filled with a low-cost carbonaceous sorbent, such as activated carbon or charcoal, which has a high affinity (and, hence, high capacity) to CO_2 but not to nitrogen (N_2). This, in turn, leads to a high CO_2/N_2 selectivity, especially at low pressures.[324]

The Carbon Filter Process proposed in this work can recover at least 90% of flue-gas CO_2 of 90%+ purity at a fraction of the cost normally associated with the conventional amine absorption process.[325]

The Carbon Filter Process requires neither expensive materials nor flue-gas compression or refrigeration, and it is easy to heat integrate with an existing or grassroots power plant without affecting the cost of the produced electricity too much.[326]

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Project Leader(s): George Hirasaki
Weblink: ruf.rice.edu/~che
Phone: 713.348.5416

Level of Funding: $960,811
Location: Houston, Texas
E. gjh@rice.edu

William Marshall Rice University

Researchers will construct and test at the bench-scale a novel CO_2 capture process that includes combining the absorber and stripper columns into a single integrated unit.[327]

The two functions of this integrated unit are separated by a ceramic membrane that enhances the capture of the CO_2 from the flue gas and the production of a concentrated stream of CO_2 for storage.[328]

A computer simulation model will be developed for the process, and the results will be used to optimize the properties of ceramics being used and the process operating conditions. The expected outcomes of this project include significant reduction in the capital and operating costs of the gas absorption process and the resulting increase in COE.[329]

In August 2011, the DOE provided $768,647 to support this technology.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

Works Cited »

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

1 Wald, Matthew. Broder, John. *Utility Shelves Ambitious Plan to Limit Carbon.* The New York Times. [13 July 2011]. [Online] Available: http://www.nytimes.com/2011/07/14/business/energy-environment/utility-shelves-plan-to-capture-carbon-dioxide.html
2 Peak, Matt. *Carbon Capture and Recycling Industry Overview.* Prize Capital, LLC. [2011]. [Online] Available: http://prizecapital.net/Prize_Capital/CCR_Industry_Overview_Report.html
3 Ibid.
4 Ibid.
5 Ibid.
6 Ibid.
7 Ibid.
8 Ibid.
9 See: "And the winner is..." by McKinsey & Company, available for download: http://mckinseyonsociety.com/capturing-the-promise-of-philanthropic-prizes/
10 *Carbon Capture Research*. The Department of Energy. [9 February 2011]. [Online] Available: http://www.fossil.energy.gov/programs/sequestration/capture/
11 *FAQ Information Portal: Carbon Capture*. The National Energy Technology Laboratory. The Department of Energy. [Online] Available: http://www.netl.doe.gov/technologies/carbon_seq/FAQs/carboncapture2.html
12 *Carbon Capture Research*. The Department of Energy. [9 February 2011]. [Online] Available: http://www.fossil.energy.gov/programs/sequestration/capture/
13 Figueroa, José et. al. *Advances in CO_2 capture technology—The U.S. Department of Energy's Carbon Sequestration Program.* The International Journal of Greenhouse Gas Control. [17 September 2007]. [Online] Available: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CO2%20Capture%20Paper.pdf
14 Ibid.
15 Ibid.
16 *Amines as Bases. Chemguide*. [Online] Available: http://www.chemguide.co.uk/organicprops/amines/base.html
17 Ibid.
18 *Carbon Dioxide (CO_2) Capture & Storage Initiative*. American Electric Power. [22 September 2008]. [Online] Available: http://www.aep.com/environmental/climatechange/carboncapture/docs/ChilledAmmonia9-22-08.pdf
19 *Mountaineer CCS Project Deemed a Success*. Power Engineering. [5 May 2011]. [Online] Available: http://www.power-eng.com/articles/2011/05/mountaineer-ccs-project-deemed-a-success.html
20 Ibid.
21 *Carbon Capture & Storage.* American Electric Power. [Online] Available: http://www.aep.com/environmental/climatechange/carboncapture/
22 *Carbon Capture Research.* The Department of Energy. [9 February 2011]. [Online] Available: http://www.fossil.energy.gov/programs/sequestration/capture/
23 Ibid.
24 *CCS For Coal Power Plant Sites with Low Energy and Cost Penalties.* Carbon Capture Journal. [18 December 2009]. [Online] Available: http://www.carboncapturejournal.com/displaynews.php?NewsID=496
25 *Carbon Capture Research.* The Department of Energy. [9 February 2011]. [Online] Available: http://www.fossil.energy.gov/programs/sequestration/capture/
26 Ibid.
27 Moore, Samuel K. *The Water Cost of Carbon Capture.* [June 2010]. [Online] Available: http://spectrum.ieee.org/energy/environment/the-water-cost-of-carbon-capture/0
28 Ibid.
29 *CCS For Coal Power Plant Sites with Low Energy and Cost Penalties.* Carbon Capture Journal. [18 December 2009]. [Online] Available: http://www.carboncapturejournal.com/displaynews.php?NewsID=496
30 Shuster, Erik. *Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements; 2009 Update.* The National Energy Technology Laboratory. [30 September 2009]. [Online] Available: http://www.netl.doe.gov/energy-analyses/pubs/2009%20Water%20Needs%20Analysis%20-%20Final%20(9-30-2009).pdf
31 *FAQ Information Portal: Carbon Capture*. *The National Energy Technology Laboratory.* The Department of Energy. [Online] Available: http://www.netl.doe.gov/technologies/carbon_seq/FAQs/carboncapture2.html
32 Figueroa, José et. al. *Advances in CO_2 capture technology—The U.S. Department of Energy's Carbon Sequestration Program.* The International Journal of Greenhouse Gas Control. [17 September 2007]. [Online] Available: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CO2%20Capture%20Paper.pdf
33 Ibid.
34 Ibid.
35 Ibid.
36 Ibid.
37 Ibid.
38 Ibid.
39 Ibid.
40 Ibid.
41 Ibid.
42 Ibid.
43 Ibid.
44 Ibid.
45 Ibid.
46 Ibid.
47 Ibid.
48 Ibid.
49 Ibid.
50 Davison, J., Freund, P., and Smith, A. *Putting Carbon Back Into the Ground.* IEA Greenhouse Gas R&D Programme. [February 2001]. [Online] Available: http://www.ieaghg.org/docs/general_publications/putcback.pdf
51 Kazama, S., Teramoto, T., and Haraya, K. *Carbon Dioxide and Nitrogen Transport Properties of Bis(Phenyl)Fluorene-Based Cardo Polymer Membranes.* The Journal of Membrane Science. [1 September 2002].
52 Bredesena, R., Jordal, K., and Bolland, A.. *High-Temperature Membranes in Power Generation with CO2 Capture.* Chemical Engineering and Processing[25 May 2004]. [Online] Available: http://folk.ntnu.no/obolland/pdf/Bredesen_Jordal_Bolland_HTmembranes_CO2_capture.pdf
53 Lin, Y.M., and Rei, M.H. *Process Development for Generating High Purity Hydrogen by Using Supported Palladium Membrane Reactor as Steam Reformer.* International Journal of Hydrogen Energy. [March 2000].
54 Feron, P.H.M., and Jansen, A.E. *CO_2 Separation with Polyolefin Membrane Contactors and Dedicated Absorption Liquids: Performances and Prospects.* Separation and Purification Technology. [1 June 2002].

55 *An Assessment of Carbon Capture Technology and Research Opportunities.* The Global Climate and Energy Project. [Spring, 2005]. [Online] Available: http://gcep.stanford.edu/pdfs/assessments/carbon_capture_assessment.pdf
56 Carapellucci, R., and Milazzo, A. *Carbon Dioxide Removal via a Membrane System in a Natural Gas Combined-Cycle Plant.* The Journal of Power and Energy. [1 June 2004].
57 *An Assessment of Carbon Capture Technology and Research Opportunities.* The Global Climate and Energy Project. [Spring, 2005]. [Online] Available: http://gcep.stanford.edu/pdfs/assessments/carbon_capture_assessment.pdf
58 Figueroa, José et. al. *Advances in CO_2 capture technology—The U.S. Department of Energy's Carbon Sequestration Program.* The International Journal of Greenhouse Gas Control. [17 September 2007]. [Online] Available: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CO2%20Capture%20Paper.pdf
59 Ibid.
60 *Carbon Dioxide Recovery from Flue Gas using Carbon-Supported Amine Sorbents Project No.: FG02-04ER83885 SBIR.* The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/amine.html
61 Ibid.
62 *A Low-Energy, Low-Cost Process for Stripping Carbon Dioxide from Absorbents Project No.: FG02-06ER84592 SBIR.* The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/stripping.html
63 Ibid.
64 *Technology.* Aker CleanCarbon Homepage. [Online] Available: http://www.akercleancarbon.com/section.cfm?path=418,456
65 Ibid.
66 Ibid.
67 *Akermin Wins $4.6 Million in Grants and Contracts.* Aker CleanCarbon Homepage. [15 August 2010]. [Online] Available: http://akermin.com/grants/
68 *CO_2 Capture by Sub-Ambient Membrane Operation Project No.: DE-FE0004278.* The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/sub-ambient-membrane.html
69 *A High Efficiency Inertial CO_2 Extraction System — ICES*. Advanced Research Projects Agency-Energy. [September 2010]. [Online] Available: http://arpa-e.energy.gov/LinkClick.aspx?fileticket=85IQIGTruiQ%3d&tabid=277
70 Ibid.
71 *Department of Energy Announces $41 Million Investment for Carbon Capture Development.* The Department of Energy. [25 August 2011]. [Online] Available: http://energy.gov/articles/department-energy-announces-41-million-investment-carbon-capture-development
72 *RWE, BASF and Linde: Breakthrough in Capturing Carbon from Flue Gas of Coal-fired Power Plants.* BASF Homepage. [3 September 2010]. [Online] Available: http://www.basf.com/group/pressrelease/P-10-395
73 Ibid.
74 *New Solvent Promises to Capture CCS Cost Savings.* businessGreen. [17 February 2011]. [Online] Available: http://www.businessgreen.com/bg/news/2027037/solvent-promises-capture-ccs-cost-savings
75 *RWE, BASF and Linde Claim Flue Gas CO_2 Capture 'Breakthrough'.* Carbon Capture Journal. [3 September 2010]. [Online] Available: http://www.carboncapturejournal.com/displaynews.php?NewsID=628&PHPSESSID=8po9arra47eqdcd7r3isi62hf2
76 *Department of Energy Announces $41 Million Investment for Carbon Capture Development*. The Department of Energy. [25 August 2011]. [Online] Available: http://energy.gov/articles/department-energy-announces-41-million-investment-carbon-capture-development
77 Ibid.
78 Haas, Anne. *Battelle Receives $2 Million Award to Test Energy Efficient Carbon Capture*. Pacific Northwest National Laboratory. [25 August 2011]. [Online] Available: http://www.pnnl.gov/news/release.aspx?id=885
79 *Department of Energy Announces $41 Million Investment for Carbon Capture Development*. The Department of Energy. [25 August 2011]. [Online] Available: http://energy.gov/articles/department-energy-announces-41-million-investment-carbon-capture-development
80 Haas, Anne. *Battelle Receives $2 Million Award to Test Energy Efficient Carbon Capture*. Pacific Northwest National Laboratory. [25 August 2011]. [Online] Available: http://www.pnnl.gov/news/release.aspx?id=885
81 Ricketts, Camille. *C12 Energy Captures $4.5M for Carbon Sequestration*. VentureBeat. [11 February 2009]. [Online] Available: http://venturebeat.com/2009/02/11/c12-energy-captures-45m-for-carbon-sequestration/
82 Garthwaite, Josie. *Sequoia Breaks Into Carbon Capture, Backs Stealthy C12 Energy*. Gigaom. [12 February 2009]. [Online] Available: http://gigaom.com/cleantech/sequoia-breaks-into-carbon-capture-backs-stealthy-c12-energy/
83 *Department of Energy Announces $41 Million Investment for Carbon Capture Development*. The Department of Energy. [25 August 2011]. [Online] Available: http://energy.gov/articles/department-energy-announces-41-million-investment-carbon-capture-development
84 Ibid.
85 *Gas Pressurized Stripping (GPS) Process-Based Technology*. Carbon Capture Scientific, LLC. [Online] Available: http://carboncapturescientific.com/technology.html#two
86 *Department of Energy Announces $41 Million Investment for Carbon Capture Development*. The Department of Energy. [25 August 2011]. [Online] Available: http://energy.gov/articles/department-energy-announces-41-million-investment-carbon-capture-development
87 *Air Capture – Frequently Asked Questions*. Carbon Engineering. [2011]. [Online] Available: http://www.carbonengineering.com/wp-content/uploads/2011/04/CarbonEngineering-AirCaptureFAQ.pdf
88 Ibid.
89 Ibid.
90 Ibid.
91 Ibid.
92 *Biomimetric Membrane Project No.: FC26-07NT43084*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/biomimetric.html
93 Ibid.
94 Ibid.
95 Ibid.
96 Figueroa, José et. al. *Advances in CO_2 capture technology—The U.S. Department of Energy's Carbon Sequestration Program*. The International Journal of Greenhouse Gas Control. [17 September 2007]. [Online] Available: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CO2%20Capture%20Paper.pdf
97 Climeworks Homepage. [Online] Available: http://www.climeworks.com/

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

98 *Climeworks Technology for Efficient CO2 Capture from Ambient Air*. Climeworks Homepage. [Online] Available: http://www.climeworks.com/capture_process/articles/capture_process.html
99 Ibid.
100 *Technology* Overview. CO2 Solution Homepage. [Online] Available: http://www.co2solution.com/en/technology-overview.php
101 Ibid.
102 Low Cost Biological Catalyst to Enable Efficient Carbon Dioxide (CO2) Capture. Advanced Research Projects Agency-Energy. [2010]. [Online] Available: http://arpa-e.energy.gov/LinkClick.aspx?fileticket=Esm28mWVGXI%3D&tabid=288
103 Ibid.
104 Ibid.
105 *Carbon Dioxide Capture from Large Point Sources Project No.: FG02-04ER83925 SBIR*. The national Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/largepoint.html
106 Ibid.
107 Ibid.
108 Figueroa, José et. al. *Advances in CO_2 capture technology—The U.S. Department of Energy's Carbon Sequestration Program*. The International Journal of Greenhouse Gas Control. [17 September 2007]. [Online] Available: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CO2%20Capture%20Paper.pdf
109 Ibid.
110 *Process* Description. Cansolv Homepage. [Online] Available: http://www.cansolv.com/en/co2capturedescription.ch2
111 *Econamine FG Plus Process*. Fluor Homepage. [Online] Available: http://www.fluor.com/econamine/Pages/efgprocess.aspx
112 Ibid.
113 Ibid.
114 Ibid.
115 Figueroa, José et. al. *Advances in CO_2 capture technology—The U.S. Department of Energy's Carbon Sequestration Program*. The International Journal of Greenhouse Gas Control. [17 September 2007]. [Online] Available: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CO2%20Capture%20Paper.pdf
116 *FuelCell Energy Awarded $3M to Evaluate DFC in Carbon Capture*. FuelCellToday. [4 October 2011]. [Online] Available: http://www.fuelcelltoday.com/news-events/news-archive/2011/october/fuelcell-energy-awarded-$3m-to-evaluate-dfc-in-carbon-capture
117 *FuelCell Energy receives DOE grant for carbon capture technology*. Energy Business Review. [5 October 2011]. [Online] Available: http://carbon.energy-business-review.com/news/fuelcell-energy-receives-doe-grant-for-carbon-capture-technology-051011
118 *Department of Energy Announces $41 Million Investment for Carbon Capture Development*. The Department of Energy. [25 August 2011]. [Online] Available: http://energy.gov/articles/department-energy-announces-41-million-investment-carbon-capture-development
119 Ibid.
120 Ibid.
121 *Hybrid Membrane/Absorption Process for Post-combustion CO_2 Capture*. The National Energy Technology Laboratory. [November 2011]. [Online] Available: http://www.netl.doe.gov/publications/factsheets/project/FE0004787.pdf
122 *Novel High Capacity Oligomers for Low Cost CO_2 Capture Project No.: DE-NT0005310.* The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/oligomers.html
123 Ibid.
124 Ibid.
125 *Bench-Scale Silicone Process for Low-Cost CO_2 Capture Project No.: FE0007502*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/solvent-ge.html
126 Ibid.
127 Ibid.
128 *Department of Energy Announces $41 Million Investment for Carbon Capture Development*. The Department of Energy. [25 August 2011]. [Online] Available: http://energy.gov/articles/department-energy-announces-41-million-investment-carbon-capture-development
129 Ibid.
130 Ibid.
131 *GE Global Research: CO_2 Capture Process Using Phase-Changing Absorbents*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/IMPACCT/CO2CaptureProcessUsingPhaseChangingAbsorbent.aspx
132 Ibid.
133 Ibid.
134 Gunther, Mark. *The Business of Cooling the Planet*. CNN Money. [7 October 2011]. [Online] Available: http://tech.fortune.cnn.com/2011/10/07/the-business-of-cooling-the-planet/
135 Siegle, Lucy. *Graciela Chichilnisky's Innovation: Carbon Capturing*. The Guardian. [13 November 2010]. [Online] Available: http://www.guardian.co.uk/environment/2010/nov/14/graciela-chichilnisky-carbon-capture-global-thermostat
136 *Connect With The ARPA-E Applicant Community*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/ConnectwiththeApplicantCommunity/CarbonCapture.aspx
137 Ibid.
138 Ibid.
139 *Department of Energy Announces $41 Million Investment for Carbon Capture Development*. The Department of Energy. [25 August 2011]. [Online] Available: http://www.fe.doe.gov/news/techlines/2011/11048-Carbon_Capture_Projects_Selected.html
140 Ibid.
141 *The VeloxoTherm™ Process*. Inventys Homepage. [Online] Available: http://www.inventysinc.com/technology/
142 Ibid.
143 Ibid.
144 Ibid.
145 *Novel Solvent System for CO_2 Capture*. The National Energy Technology Laboratory. [November 2011]. [Online] Available: http://www.netl.doe.gov/publications/factsheets/project/FE0005799.pdf
146 Ibid.
147 Ibid.
148 Company. Kilimanjaro Homepage. [Online] Available: http://www.kilimanjaroenergy.com/company/
149 Ibid.
150 *RECTISOL® Wash*. Linde Homepage. [Online] Available: http://www.linde-engineering.com/en/process_plants/hydrogen_and_synthesis_gas_plants/gas_processing_plants/rectisol_wash/index.html

151 Ibid.
152 Ibid.
153 Ibid.
154 *Membrane Process to Capture CO_2 from Power Plant Flue Gas*. The National Energy Technology Laboratory. [May 2009]. [Online] Available: http://www.netl.doe.gov/publications/factsheets/project/Proj593.pdf
155 Ibid.
156 Ibid.
157 Ibid.
158 Figueroa, José et. al. *Advances in CO_2 capture technology—The U.S. Department of Energy's Carbon Sequestration Program*. The International Journal of Greenhouse Gas Control. [17 September 2007]. [Online] Available: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CO2%20Capture%20Paper.pdf
159 Mitchell, Ronald. *Mitsubishi Heavy Industries' Carbon Capture Technology*. Carbon Capture Journal. [January/February 2008]. [Online] Available: http://www.precaution.org/lib/carbcapjournal_v1_n1.080101.pdf
160 Ibid.
161 *Nalco Company: Energy Efficient Capture Of CO_2 From Coal Flue Gas*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/OtherProjects/CarbonCapture/EnergyEfficientCaptureofCO2fromCoalFlueGas.aspx
162 Ibid.
163 *Energy Efficient Capture of CO_2 from Coal Flue Gas*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/LinkClick.aspx?fileticket=F1ltVUlpzZM%3d&tabid=206
164 Ibid.
165 Ibid.
166 *Connect With The ARPA-E Applicant Community*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/ConnectwiththeApplicantCommunity/CarbonCapture.aspx
167 Ibid.
168 Ibid.
169 Ibid.
170 *Low-Energy Solvents for CO_2 Capture Enabled by a Combination of Enzymes and Ultrasonics*. The National Energy Technology Laboratory. [November 2011]. [Online] Available: http://www.netl.doe.gov/publications/factsheets/project/FE0007741.pdf
171 Ibid.
172 Ibid.
173 *Carbon* Capture. Process Group Homepage. [Online] Available: http://www.processgroup.com.au/index.php?id=63
174 Ibid.
175 Ibid.
176 Ibid.
177 Ibid.
178 Carbon Nanotube Membranes for Energy-Efficient Carbon Sequestration. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/LinkClick.aspx?fileticket=XwQhkUHfz9E%3d&tabid=205
179 Ibid.
180 Ibid.
181 *Slipstream Development and Testing of Siemens POSTCAP Capture and Separation Technology Project No.: DE-FE0003714*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/siemens-postcap.html
182 Ibid.
183 Ibid.
184 *Sustainable Energy Solutions: Cryogenic Carbon Capture*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/IMPACCT/CryogenicCarbonCapture.aspx
185 *Cryogenic Carbon Capture*. Sustainable Energy Solutions Homepage. [Online] Available: http://www.sustainablees.com/index-4.html
186 *Flow Diagram*. Sustainable Energy Solutions Homepage. [Online] Available: http://www.sustainablees.com/index-4.2.html
187 Ibid.
188 *Sustainable Energy Solutions: Cryogenic Carbon Capture*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/IMPACCT/CryogenicCarbonCapture.aspx
189 *Low-cost Sorbent for Capturing CO2 Emissions Generated by Existing Coal-fired Power Plants*. The National Energy Technology Laboratory. [January 2011]. [Online] Available: http://www.netl.doe.gov/publications/factsheets/project/NT0005497.pdf
190 Ibid.
191 Ibid.
192 *Advanced Amine Solvent Formulation and Process Integration for Near-Term CO2 Capture Success Project No.: FG02-06ER84625 SBIR*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/adv-amine.html
193 Ibid.
194 Ibid.
195 Ibid.
196 *United Technologies Research Center: CO_2 Capture With Enzyme Synthetic Analogue*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/OtherProjects/CarbonCapture/CO2CapturewithEnzymeSyntheticAnalogue.aspx
197 Ibid.
198 Ibid.
199 Ibid.
200 *CO_2 Removal from Flue Gas Using Microporous Metal Organic Frameworks*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/publications/factsheets/project/NT43092.pdf
201 Ibid.
202 Ibid.
203 *Evaluation of Concentrated Piperazine for CO_2 Capture from Coal-Fired Flue Gas*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/publications/factsheets/project/FE0005654.pdf
204 Ibid.
205 Ibid.
206 *Department of Energy Announces $41 Million Investment for Carbon Capture Development*. The Department of Energy. [25 August 2011]. [Online] Available: http://energy.gov/articles/department-energy-announces-41-million-investment-carbon-capture-development
207 Ibid.
208 Ibid.
209 *Earth & Environmental Engineering, Columbia University: Chemical And Biological Catalytic Enhancement Of Weathering Of Silicate Minerals As Novel Carbon Capture And Storage Technology*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/IMPACCT/ChemicalandBiologicalCatalyticEnhancementofW.aspx
210 Ibid.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12

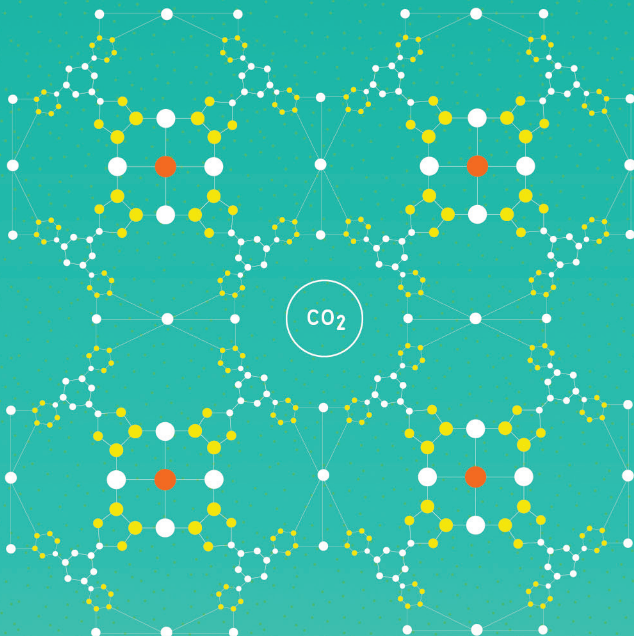
211 *Connect With The ARPA-E Applicant Community*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/ConnectwiththeApplicantCommunity/CarbonCapture.aspx
212 Ibid.
213 Ibid.
214 *Georgia Tech Research Corporation: High Performance MOF-Polymer Composite Membranes For CO_2 Capture*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/IMPACCT/HighPerformanceMOFpolymerCompositeMembranesf.aspx
215 Ibid.
216 *What We* Do. Sholl Research Group Homepage. [Online] Available: http://sholl.chbe.gatech.edu/research.htm
217 *Reversible Ionic Liquids as Double-Action Solvents for Efficient CO_2 Capture Project No.: DE-NT0005287*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/double-action.html
218 Ibid.
219 Ibid.
220 Ibid.
221 *Department of Energy Announces $41 Million Investment for Carbon Capture Development*. The Department of Energy. [25 August 2011]. [Online] Available: http://energy.gov/articles/department-energy-announces-41-million-investment-carbon-capture-development
222 Ibid.
223 *Nanometric Thin-Film Membranes Capture More Carbon Dioxide*. Capture Ready. [21 September 2010]. [Online] Available: http://www.captureready.com/en/Channels/News/showDetail.asp?objID=1966&isNew=
224 Ibid.
225 Ibid.
226 Ibid.
227 Ibid.
228 *CO_2 Capture from Flue Gas by Phase Transitional Absorption Project No.: FG26-05NT42488*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/transitional.html
229 Ibid.
230 *Air Capture Technology Ready by 2018 -UK Engineers*. AlertNet. [26 October 2011]. [Online] Available: http://www.thomsonreutersfoundation.com/alertnet/news/air-capture-technology-ready-by-2018--uk-engineers/
231 Ibid.
232 Ibid.
233 *Lawrence Berkeley National Laboratory: High-Throughput Discovery Of Robust Metal-Organic Frameworks For CO_2 Capture*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/IMPACCT/HighThroughputDiscoveryofRobustMetalOrganic.aspx
234 Ibid.
235 Ibid.
236 *Lawrence Livermore National Security, LLNS: Catalytic Improvement Of Solvent Capture Systems*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/IMPACCT/CatalyticImprovementofSolventCaptureSystems.aspx
237 *Lehigh University: Electric Field Swing Adsorption For Carbon Capture Applications*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/OtherProjects/CarbonCapture/ElectricFieldSwingAdsorptionforCarbonCapture.aspx
238 Ibid.
239 *Electric Field Swing Adsorption for Carbon Capture Applications*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/LinkClick.aspx?fileticket=jucaCHbekgk%3d&tabid=207
240 *Lehigh University: Electric Field Swing Adsorption For Carbon Capture Applications*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/OtherProjects/CarbonCapture/ElectricFieldSwingAdsorptionforCarbonCapture.aspx
241 *Massachusetts Institute Of Technology: Electrochemically Mediated Separation For Carbon Capture And Mitigation*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/IMPACCT/ElectrochemicallyMediatedSeparationforCarbonC.aspx
242 Ibid.
243 Ibid.
244 Figueroa, José et. al. *Advances in CO_2 capture technology—The U.S. Department of Energy's Carbon Sequestration Program*. The International Journal of Greenhouse Gas Control. [17 September 2007]. [Online] Available: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CO2%20Capture%20Paper.pdf
245 Ibid.
246 *NETL-Developed Process for Capturing CO_2 Emissions Wins National Award for Excellence in Technology Transfer*. The National Energy Technology Laboratory. [3 February 2011]. [Online] Available: http://www.fossil.energy.gov/news/techlines/2011/11009-NETL_Process_Wins_Award.html
247 Ibid.
248 Li, Yuandi. *Carbon Capture with Sawdust*. Royal Society of Chemistry. [18 March 2011]. [Online] Available: http://www.rsc.org/chemistryworld/News/2011/March/18031103.asp
249 Ibid.
250 Sevilla, Marta. Fuertes, Antonio B. *Sustainable Porous Carbons With A Superior Performance For CO_2 Capture*. [17 December 2010]. [Online] Available: http://pubs.rsc.org/en/content/articlelanding/2011/ee/c0ee00784f
251 *'All-Natural' Material Created To Capture Carbon*. Ecoseed. [26 September 2011]. [Online] Available: http://www.ecoseed.org/energy-efficiency-blog/carbon-capture-and-storage/article/78-carbon-capture-and-storage/11314-?tmpl=component
252 Ibid.
253 Ibid.
254 *Ionic Liquids Project No.: FC26-07NT43091*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/ionic.html
255 Ibid.
256 Ibid.
257 *University Of Notre Dame: CO_2 Capture With Ionic Liquids Involving Phase Change*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/IMPACCT/CO2CapturewithIonicLiquidsInvolvingPhaseCha.aspx
258 Ibid.
259 *Ionic Liquids Project No.: FC26-07NT43091*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/ionic.html
260 Figueroa, José et. al. *Advances in CO_2 capture technology—The U.S. Department of Energy's Carbon Sequestration Program*. The International Journal of Greenhouse Gas Control. [17 September 2007]. [Online] Available: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CO2%20Capture%20Paper.pdf

261 *University Of Notre Dame: CO_2 Capture With Ionic Liquids Involving Phase Change*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/IMPACCT/CO2CapturewithIonicLiquidsInvolvingPhaseCha.aspx
262 *Oak Ridge National Laboratory: High Performance CO_2 Scrubbing Based On Hollow Fiber-Supported Designer Ionic Liquid Sponges*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/IMPACCT/HighPerformanceCO2ScrubbingBasedonHollowFib.aspx
263 Ibid.
264 *Department of Energy Announces $41 Million Investment for Carbon Capture Development*. The Department of Energy. [25 August 2011]. [Online] Available: http://energy.gov/articles/department-energy-announces-41-million-investment-carbon-capture-development
265 Ibid.
266 Ibid.
267 *CO_2 Capture from Flue Gas Using Solid Molecular Basket Sorbents*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/publications/factsheets/project/FE0000458.pdf
268 Ibid.
269 *Dry Regenerable Sorbents Project No.: FC26-07NT43089*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/dry-regen.html
270 Ibid.
271 Figueroa, José et. al. *Advances in CO_2 capture technology—The U.S. Department of Energy's Carbon Sequestration Program*. The International Journal of Greenhouse Gas Control. [17 September 2007]. [Online] Available: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CO2%20Capture%20Paper.pdf
272 *CO_2 Capture Membrane Process for Power Plant Flue Gas Project No.: DE-NT0005313*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/membrane-process.html
273 Ibid.
274 *Research Triangle Institute (RTI International): Novel Non-Aqueous CO_2 Solvent-Based Capture Process With Substantially Reduced Energy Penalties*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/IMPACCT/NovelNonAqueousCO2SolventbasedCaptureProces.aspx
275 Ibid.
276 *Development of Novel Carbon Sorbents for CO_2 Capture*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/publications/factsheets/project/NT0005578.pdf
277 Ibid.
278 Ibid.
279 Ibid.
280 *Texas A&M University: Stimuli-Responsive Metal-Organic Frameworks For Energy-Efficient Post-Combustion Carbon Dioxide Capture*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/IMPACCT/StimuliresponsiveMetalOrganicFrameworksforEn.aspx
281 Ibid.
282 Ibid.
283 *Metal Monolithic Amine-Grafted Zeolites for CO_2 Capture Project No.: FC26-07NT43086*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/zeolite.html
284 Ibid.
285 Ibid.
286 Stark, Anne M. Speeding Up Mother Nature's Very Own CO_2 Mitigation Process. Lawrence Livermore National Laboratory. [19 January 2011]. [Online] Available: https://www.llnl.gov/news/newsreleases/2011/Jan/NR-11-01-03.html
287 Ibid.
288 Ibid.
289 Ibid.
290 *The Regents Of The University Of Colorado: Achieving A 10,000 Gpu Permeance For Post-Combustion Carbon Capture With Gelled Ionic Liquid-Based Membranes*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/IMPACCT/Achievinga10000GPUPermeanceforPostCombusti.aspx
291 Ibid.
292 *Development and Evaluation of a Novel Integrated Vacuum Carbonate Absorption Process Project No.: DE-NT0005498*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/vacuumcarbonate.html
293 Ibid.
294 Ibid.
295 *Bench-Scale Development of a Hot Carbonate Absorption Process with Crystallization-Enabled High Pressure Stripping for Post-Combustion CO_2 Capture Project No.: DE-FE0004360*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/bench-scale-dev.html
296 Ibid.
297 Ibid.
298 Ibid.
299 *University Of Kentucky Research Foundation: A Solvent-Membrane Hybrid Post-Combustion CO_2 Capture Process For Existing Coal-Fired Power Plants*. Advanced Research Projects Agency-Energy. [Online] Available: http://arpa-e.energy.gov/ProgramsProjects/IMPACCT/ASolventMembraneHybridPostcombustionCO2Capt.aspx
300 Ibid.
301 Ibid.
302 *Novel Dual Functional Membrane for Controlling Carbon Dioxide Emissions from Fossil Fueled Power Plants Project No.: FG26-04NT42120*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/dual-function.html
303 Ibid.
304 Ibid.
305 Ibid.
306 EERC Performs Cutting-Edge Research On CO2 Capture. University of North Dakota. [Online] Available: http://www.undeerc.org/homearticle.aspx?id=223
307 Ibid.
308 Ibid.
309 *Department of Energy Announces $41 Million Investment for Carbon Capture Development*. The Department of Energy. [25 August 2011]. [Online] Available: http://energy.gov/articles/department-energy-announces-41-million-investment-carbon-capture-development
310 Ibid.
311 Ibid.
312 Pearson, Caden. *Carbon Emissions Captured by Aussie Crystals*. The Epoch Times. [13 September 2010]. [Online] Available: http://www.theepochtimes.com/n2/content/view/42500/

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12
PrizeCapital

313 Ibid.
314 Ibid.
315 Ibid.
316 Ibid.
317 Ibid.
318 *Carbon Dioxide Capture by Absorption with Potassium Carbonate Project No.: FC26-02NT41440*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/potassium.html
319 Figueroa, José et. al. *Advances in CO_2 capture technology—The U.S. Department of Energy's Carbon Sequestration Program*. The International Journal of Greenhouse Gas Control. [17 September 2007]. [Online] Available: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CO2%20Capture%20Paper.pdf
320 *Carbon Dioxide Capture by Absorption with Potassium Carbonate Project No.: FC26-02NT41440*. The National Energy Technology Laboratory. [Online] Available: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/potassium.html
321 Ibid.
322 Ibid.
323 Radosz, Maciej et. al. Flue-Gas Carbon Capture on Carbonaceous Sorbents: Toward a Low-Cost Multifunctional Carbon Filter for "Green" Energy Producers. Industrial & Engineering Chemistry Research. [29 April 2008]. [Online] Available: http://pubs.acs.org/doi/abs/10.1021/ie0707974
324 Ibid.
325 Ibid.
326 Ibid.
327 *Department of Energy Announces $41 Million Investment for Carbon Capture Development*. The Department of Energy. [25 August 2011]. [Online] Available: http://energy.gov/articles/department-energy-announces-41-million-investment-carbon-capture-development
328 Ibid.
329 Ibid.

Not for Duplication or Distribution
Prize Capital is a Service Mark of Prize Capital, LLC. 2006-12



PrizeCapital

Prize Capital, LLC | 1616 Camino Del Mar, Del Mar, CA 92014 | 213.327.8935

Printed on 100% recycled content, 60% post-consumer waste, processed chlorine free and printed with vegetable based inks.