carbon capture journal

Mar / Apr 2013 Issue 32

DOE and Archer Daniels Midland Illinois project

Energy Technologies Institute - leading UK CCS research

Whole-chain CCS system modelling

Koch-Glitsch - internals for post-combustion carbon capture plants

DNV KEMA - guidance for managing the risks of CO2 handling

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Front cover: DOE and ADM Illinois project: the CO2 is divided into four parallel streams that each feed a 4-stage, 2424 kW reciprocating compressor as shown

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DOE and ADM Illinois project advances

The United States Department of Energy (DOE) and Archer Daniels Midland Company (ADM) has made significant progress in the development and construction of the largest carbon capture, utilization, and storage (CCUS) project in the U.S.

By Sai Gollakota (National Energy Technology Laboratory, U.S. Department of Energy) and Scott McDonald (Archer Daniels Midland Company)

The large-scale industrial CCUS project, also referred to as the Illinois ICCS project, is being demonstrated at the ADM's agricultural processing and biofuels complex in Decatur, Illinois. It is cost shared with funds from the American Recovery and Reinvestment Act of 2009, is being demonstrated under the DOE's Industrial Carbon Capture and Storage (ICCS) program.

The Office of Fossil Energy's National Energy Technology Laboratory (NETL) manages the project, which receives $141.4 million in Recovery Act funding and another $66.5 million in private sector cost-sharing. The project team members are ADM, DOE, Schlumberger Carbon Services, University of Illinois-Illinois State Geological Survey (ISGS), and Richland Community College (RCC).

The project will demonstrate an integrated system for capturing CO2 from ADM's ethanol plant and geologically storing it in the Mount Simon Sandstone, a saline reservoir that covers portions of the Midwest including central and southern Illinois. The CO2 is produced as a co-product during the processing of corn to fuel-grade ethanol.

The project scope includes the design, construction, and integrated operation of CO2 capture, compression, dehydration, and injection facilities. Additionally the project will develop and implement a monitoring, verification, and accounting program for the stored CO2.

The technology demonstrated and the lessons learned from this project will aid the development of the regional CCUS industry related to CO2 capture and transport infrastructure for enhanced oil recovery in the depleted oilfields in the Illinois Basin.

The project partners

NETL and ADM Partnership

NETL is part of the DOE's national laboratory system and it is owned and operated by the DOE. NETL implements a broad range of energy and environmental research and development programs in the areas of coal, natural gas, and oil technologies, and CCUS. NETL is developing a portfolio of safe, cost-effective, commercial-scale CCUS technologies for deployment by the industry. NETL also conducts analyses of energy systems and international energy issues.

Archer Daniels Midland Company (ADM) global headquarters is located in Decatur, Illinois. Its more than 265 processing plants and 30000 employees convert corn, oilseeds, wheat, and cocoa into products for food, animal feed, chemicals and energy uses. The net sales of ADM in fiscal year 2012 were $89 billion.

ADM, as part of its comprehensive strategy for energy sustainability and environmental responsibility, is implementing the Illinois ICCS project to reduce carbon footprint of industrial processes, e.g., by permanently storing the CO2 generated during ethanol production in deep underground rock formations, rather than releasing it into the atmosphere. Successful demonstration of this cutting-edge technology will have significant implications for commercialization of CCUS

ADM is already operating the first DOE-sponsored CCUS project in Decatur. This project, led by ISGS, is referred to as the Illinois Basin-Decatur Project (IBDP). This is a large-volume, saline reservoir sequestration test that will inject one million tonnes of CO2 over a period of three years. IBDP has completed construction of a 1000 tonnes per day CO2 compression and dehydration facility, drilled and completed the associated injection and deep monitoring wells, and established an extensive CO2 monitoring program.

The injection well is located adjacent to ADM's Decatur ethanol plant. The IBDP has compiled extensive geologic data for this CO2 storage site. The IBDP completed one year of successful operation and injected over 320000 tonnes of CO2 into the Mt. Simon Sandstone. The injection will continue for another two years, followed by three years of post-injection monitoring.

ADM's experience from the IBDP project enabled expanding the CCUS capability to that of a commercial-scale operation (907000 tonnes per year) in the second project, i.e., Illinois ICCS project. To reach commercial scale, upon completion of the

IBDP injection operations in the fall of 2014, ADM will integrate the IBDP compression and dehydration facilities with the new facilities constructed under the Illinois ICCS project.

At its October 2012 annual meeting in Perth, Australia, the Carbon Sequestration Leadership Forum, an international carbon storage organization, officially recognized the Illinois ICCS project and the IBDP for advancing CCUS technologies.

Illinois ICCS Project Objectives

The project will demonstrate an integrated system for collecting CO2 from an ethanol plant and geologically sequestering it in a saline reservoir:

• Design, construct, and operate a new CO2 collection, compression, and dehydration facility capable of delivering up to 2000 tonnes of CO2 per day to the injection site.

• Integrate the new facility with an existing 1000 tonnes of CO2 per day compression and dehydration facility to achieve a total CO2 capacity of up to 3000 tonnes of CO2 per day.

• Design, construct, and operate a storage site capable of accepting up to 3000 tonnes of CO2 per day. Implement deep subsurface and near surface monitoring of the stored CO2.

CO2 Capture, Compression, and Dehydration

The following is a brief description of the new CO2 capture, compression, and dehydration facility being constructed under the Illinois ICCS project. The CO2 produced during the ethanol fermentation process is a high purity CO2 stream (greater than 99% purity on a moisture free basis), with water content less than 3% by weight.

First the CO2 coming off the fermentation tanks is directed to a water wash column to remove any entrained ethanol or other water soluble components. Next the water saturated CO2 exits the top of the scrubber at near atmospheric pressure and 37.8oC and is transported via a 0.91 m diameter pipeline to a collection facility where is passes through a water separator before being compressed to 0.24 MPa using a 2238 kW 4-stage gas blower.

After compression, the CO2 is cooled from 93.3°C to 35°C using a 3370 kW plate and frame heat exchanger. Next, a separator removes any free water produced during cooling and the CO2 stream is transported through a 0.61 m diameter, 457 m long pipeline to a compression and dehydration facility.

At this facility, the gas is divided into four parallel streams that each feed a 4-stage, 2424 kW reciprocating compressor resulting in a total compression capacity in excess of 2000 tonnes per day.

After compression, the CO2 is sent to a glycol dehydration unit - the glycol removes water from the CO2 by physical absorption and the rich glycol (water saturated) exits the bottom of the column

Each compressor has six cylinders; two cylinders for the 1st stage, two cylinders for the 2nd stage, one cylinder for the 3rd stage, and one cylinder for the 4th stage of compression. After each stage of compression, the interstage gas is cooled to 35°C using condensing water which is then removed by an interstage separator.

During the 1st stage, CO2 is compressed to 0.52 MPa with a discharge temperature of 145°C. During the 2nd stage CO2 is compressed to 1.71 MPa with a discharge temperature of 156°C. In the 3rd stage, CO2 is compressed to 4.1 MPa and 123°C. At this point, after cooling and free water separation, 95% of the water entering the process has been removed through compression and cooling.

After the 3rd stage of compression, the four CO2 streams are recombined and sent to the triethylene glycol (glycol) dehydration unit. The combined CO2 stream enters the bottom of the glycol contactor where it is contacted with the lean glycol (water free) introduced at the top of the unit. The glycol removes water from the CO2 by physical absorption and the rich glycol (water saturated) exits the bottom of the column.

The dry CO2 stream leaves the top of the contactor and passes through an outlet cooler, which cools the gas to 35°C before returning to the compression section. The glycol regenerator consists of a column, an overhead condenser, and a natural gas fired reboiler. In this column, the glycol is thermally regenerated by hot vapor stripping the water from the liquid phase.

After the CO2 leaves the dehydration section, it splits into four streams each stream returning to the 4th stage of the reciprocating compressor where it is compressed to 9.8 MPa and 133°C. After this stage, CO2 is cooled to 35°C.

Finally, the dehydrated CO2, which has less than 0.005% moisture by weight (>99.9% CO2 purity), will be further compressed up to 15.8 MPa using a 298 kW centrifugal booster pump and transported 1610 m through an 0.2 m diameter pipeline to the injection wellhead. The injection operations will be conducted adjacent to the ethanol plant on a site owned by ADM. The injection wellhead conditions will comply with the permit requirements.

CO2 Injection

This project will store CO2 in the Mt. Simon Sandstone, an extensive saline reservoir in the Illinois Basin with the capacity to store billions of tons of CO2. Saline reservoirs are layers of porous rock that are saturated with brine (a concentrated salt solution). Mt. Simon Sandstone is a clean sedimentary rock dominated by silicate minerals and lacking significant amounts of clay minerals (which typically clog pores and reduce porosity), resulting in highly favorable porosity and permeability features for CO2 storage.

The Illinois ICCS project will initially

inject CO2 into the Mt. Simon Sandstone at a rate of 1500 tonnes per day. The IBDP will also inject CO2 at a rate of 1000 tonnes per day during this period. The Illinois ICCS project's injection rate can be increased up to 3000 tonnes per day once the IBDP completes injection operations in the fall of 2014. Each project will have a separate injection well and the distance between the two wells will be approximately 1128 m.

At the injection location, the top of the Mt. Simon Sandstone is at a depth of 1677 m below the surface and has a thickness of 457 m. The CO2 will be injected into the lower Mt. Simon at a depth of about 2134 m. Carbon dioxide injection will occur at depths far below the Underground Source of Drinking Water level thus ensuring the safety of these water sources.

The Mt. Simon Sandstone is overlain by the 152 m thick Eau Claire formation, of which the bottom 61 m is primarily shale. The low-porosity Eau Claire Shale acts as the primary cap rock seal preventing upward migration of CO2 from the Mt. Simon Sandstone. Two other shale formations, the Maquoketa Shale and the New Albany Shale, are present at shallower depths and act as secondary and tertiary seals, respectively. The base of the Mt. Simon Sandstone is underlain by Precambrian igneous bedrock (granite basement).

Monitoring the Stored CO2

The Illinois ICCS project will implement a robust plan to monitor CO2 migration and to protect groundwater sources. The monitoring efforts will employ methods to provide an accurate accounting of the stored CO2 and a high level of confidence that it will remain permanently stored deep underground. The monitoring plan includes near surface and deep subsurface activities.

The near-surface monitoring includes soil CO2 flux measurements to monitor changes in CO2 concentrations and shallow groundwater sampling for geochemical analysis. The deep-subsurface monitoring includes geophysical (seismic) surveys and passive seismic surveys in the above cap rock seal locations and geophysical surveys, geochemical sampling, and pressure and temperature monitoring in the injection zone.

A baseline 3D surface seismic data acquisition and analysis, performed by ISGS and Schlumberger Carbon Services, did not indicate any seismically resolvable faults in the reservoir or in the cap rock seal at the proposed Illinois ICCS injection site. A lack of geologic faults offers greater certainty that the injected CO2 will be stratigraphically trapped in the Mt. Simon Sandstone.

National Sequestration Education Center

Public education and outreach on CCUS is an integral part of this ICCS project. The project team is conducting an integrated communication, outreach, training, and education initiative, which is engaging stakeholders in understanding CCUS.

To promote knowledge sharing in CCUS, a 1390 sq m center containing classrooms, training and laboratory facilities, called the National Sequestration Education Center, was established at RCC in September 2012. RCC is implementing a new associate degree program, first in the U.S., with an emphasis on CCUS (i.e., Associate of Applied Science in Engineering Technology with Sequestration Specialty and Associate of Science with Sequestration Concentration, a university transfer degree).

Project Schedule and Status

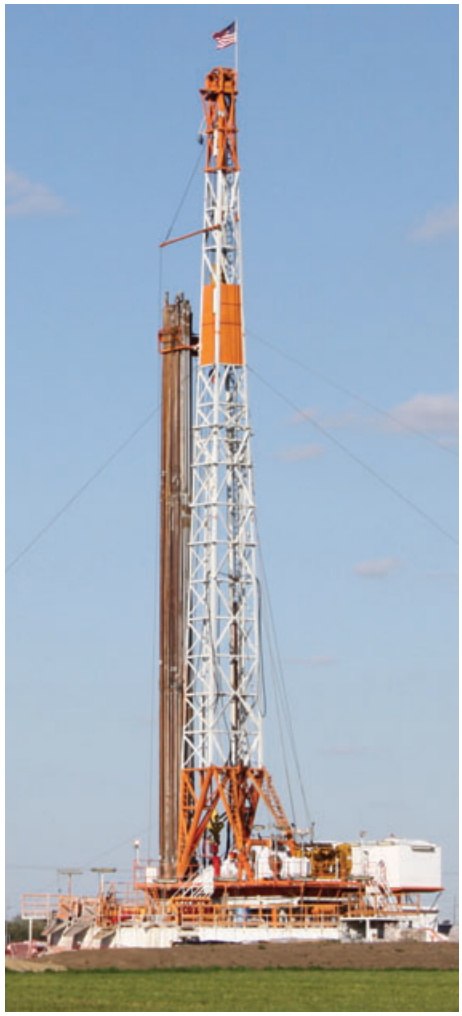
The Illinois ICCS project construction was initiated in May 2011. Detailed design and mechanical installation of the compression and dehydration equipment have been completed, and piping, electrical, and instrumentation installation is in progress. A 2207 m deep monitoring well and a 1084 m deep geophysical well were drilled. U.S. Environmental Protection Agency Region 5 is reviewing ADM's application for injection well permit approval, i.e., Underground Injection Control permit to construct and to operate Class VI injection well for the purpose of geologic sequestration of CO2.

The project is scheduled to commission and startup in 2013. Initially the project plans to operate at an injection rate of 580000 tonnes per year, and achieve the target injection rate of 907000 tonnes per year in the fall of 2014 when IBDP completes its operations. Project completion date for the DOE funding period is September 30, 2015.

Broader Benefits of the Project

Because all of the captured CO2 is produced from biologic fermentation, a significant feature of the Illinois ICCS project is its "negative carbon footprint," meaning that the storage results in a net reduction of atmospheric CO2. Successful implementation of this project could:

- Facilitate exploration of long-term CO2 utilization options, such as enhanced oil recovery in the Illinois Basin and carbonate-based chemicals production;
- Develop a market for the CCUS technology in the U.S. for some of the approximately 200 fuel grade ethanol plants that have access to geologic storage.
- Develop a market for utilization of U.S. geologic saline storage capacity of CO2 that is estimated to range from 1700 to 20000 billion tonnes.



Drilling the monitoring well

Acknowledgement

The Illinois ICCS project, being implemented under the DOE Award No. DE-FE-0001547, is administered by the Office of Fossil Energy and managed by NETL. The contributions of the following team leads are acknowledged in project implementation: Dr. Robert Finley (ISGS), Eric Berlin (Schlumberger Carbon Services), and Dr. Douglas Brauer (RCC).

More information

www.netl.doe.gov
www.adm.com

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Accelerating CCS implementation in the UK

The Energy Technologies Institute (ETI) sees Carbon Capture and Storage (CCS) as one of the UK's big priority development areas for any future low carbon focused energy system. ETI Programme Manager for CCS, Andrew Green, explains.

The ETI - a public private partnership focused on the acceleration of the development of affordable, secure and sustainable energy technologies - has developed its Energy System Modelling Environment (ESME) to inform its strategy.

ESME is a national energy system design tool, which integrates power, heat, transport and infrastructure, searching for the lowest cost solution. ESME shows that CCS forms a major part of cost-effective energy system scenarios through to 2050. Furthermore, if CCS was not available, the cost of the energy system would be around £42bn per annum higher. To put it another way, without a successful CCS industry the cost of all forms of energy in 2050 would be two pence per kWh higher. These numbers point to an energy system-wide value of CCS. This is a view of CCS extending beyond low carbon electricity generation to include CCS with biomass, gasification applications that could produce hydrogen for transport and industrial uses.

By applying CCS to biomass, we could effectively work to remove CO2 from the atmosphere by creating 'negative emissions'. Successful development could offset our continued use of gas and liquid fuels in specific parts of domestic heating and transport sectors where their replacement is likely to be particularly difficult and expensive.

CCS creates a potentially huge opportunity to save energy system costs if it is adopted early enough, but there are significant challenges. Capturing CO2 at large scale incurs significant costs and storage of CO2 has long planning times when selecting, appraising, drilling, testing and constructing potential sites, all of which could take up to 10 years or more.

Although at first glance CCS appears an expensive addition to power generation, it is one of the most important strategic levers we can use if seeking to follow a path of decarbonisation. The opportunity costs associated with delivering a sustainable future energy system with CCS, ranged against the cost of doing so without it, far outweigh the absolute cost of CCS.

The ETI is managing a series of projects it has commissioned and funded that aims to accelerate the implementation of CCS technology on fossil-fuel fired power stations and other major stationary CO2 sources in the UK, by demonstrating innovative technology which reduces the capital and operating costs of capture processes. In tandem with this work, the ETI is also working to reduce the risks and costs of storage through greater understanding and knowledge of storage assets and the monitoring of their potential operation. These are outlined below.

UK Storage Appraisal Project (UKSAP)

Launched in October 2009, the ETI's UK Storage Appraisal (UKSAP) project has delivered a realistic, defensible and fully auditable assessment of potential CO2 storage capacity in the UK.

This £4m project involved Senergy Alternative Energy Ltd, the British Geological Survey (BGS), the Scottish Centre for Carbon Storage (University of Edinburgh, Heriot-Watt University), Durham University, GeoPressure Technology Ltd, Geospatial Research Ltd, Imperial College London, RPS Energy and Element Energy Ltd. Last year we agreed a licence with The Crown Estate (TCE) and BGS to host and further develop the online database of mapped UK offshore carbon dioxide storage capacity produced through the project.

Launched to the public later this year, the web-enabled database – the first of its type anywhere in the world – will contain live, geological data, storage estimates, risk assessments and the economics of nearly 600 potential CO2 storage units of depleted oil and gas reservoirs, and saline aquifers around the UK. This will enable interested stakeholders to access information about the level of storage resource available to assist informed decisions related to the roll out of CCS in the UK.

Next Generation Capture Technologies

The ETI has invested in two types of next generation capture technologies – coal and gas. In 2011, the ETI invested £3.5m in the front-end engineering design for a unit to demonstrate coal capture technology. This project is aimed at pre-combustion carbon capture applications, involving CO2 removal by physical separation.

Costain has produced a front end engineering design for a coal capture demonstration unit, working with the University of Edinburgh and Imperial College, London.

"CCS creates a potentially huge opportunity to save energy system costs if it is adopted early enough" - Andrew Green, ETI Programme Manager for CCS

Then last year we commissioned and funded a consortium to deliver a project which will see a 5MW carbon capture gas demonstration plant capable of capturing up to 95% of CO2 emissions designed, built and tested by 2016. The project could see more than £20m being invested to develop and verify advanced carbon capture technology. The technology will be designed to be used on new-build Combined Cycle Gas Turbine (CCGT) power stations or to retrofit CCS onto existing stations.

The technology that will be employed by the consortium of Inventys, Howden, Doosan Power Systems and MAST Carbon International is based around post combustion capture using a structured carbon adsorbent, housed within a rotating bed. An initial assessment by the ETI suggests that the technology could potentially reduce the typical cost of electricity by 13 per cent when compared to current CCS technology. The first phase of the project has seen a £1.6m investment in a small-scale demonstrator prototype, laboratory work and techno-economic assessments to confirm the projected benefits.

CCS Modelling Tool Kit

This is a £3m project that will help support the future design, operation and roll-out of cost effective CCS systems in the UK.

The two-and-a-half year long project launched in September 2011 is creating a modelling tool-kit capable of simulating the operation of all aspects of the CCS chain,

from capture and transport to storage.

This involves modelling technology provider Process Systems Enterprise (PSE), energy consultancy E4tech, and industrial partners EDF Energy, E.ON, Rolls-Royce and Petrofac – a company who expect to be involved in transporting and storing CO2 in the future. The project will result in a commercial modelling tool-kit built on PSE's gPROMS modelling platform.

The Tool-kit will be used to support initial conceptual designs and eventual detailed design and operation of CCS systems by helping to identify and understand system-wide operational issues such as the effects of power station ramp-up or ramp-down on downstream storage operation, or the effect of downstream disturbances on power generation.

See the article titled, "Whole-chain system modelling" in this issue for more details.

CCS Mineralisation

This £1.4m project, launched in May 2010 and completed last year carried out a detailed study of the availability and distribution of suitable minerals across the UK along with the technologies that could be used to economically capture and store CO2 emissions.

Minerals and CO2 can react together to permanently store CO2 as a solid carbonate product, which can then be safely stored, used as an aggregate or turned into useful end products such as bricks or filler for concrete.

The consortium involved Caterpillar, BGS and the University of Nottingham.

The objective was to investigate the potential for CCS by mineralisation to mitigate at least 2% of current UK CO2 emissions and 2% of worldwide emissions over a 100-year period.

The project found that there is an abundance of suitable minerals available in the UK and worldwide to meet these mitigation targets. However significant challenges remain to make the capture process economically attractive and to reduce its energy use. Significant niche opportunities exist where waste materials can be used as feedstock and/or the process produces value-added products, but markets would not be at a level required to meet the mitigation targets.

High Hydrogen

This £2m project is designed to advance the safe design and operation of gas turbines, reciprocating engines and combined heat & power systems using hydrogen-based fuels.

Through new modeling and large-scale experimental work this project is identifying the bounds of safe design and operation of high efficiency CCGT (combined cycle gas turbine) and CHP (combined heat and power) systems operating on a range of fuels with high and variable concentrations of hydrogen.

The aim of the project is to increase the range of fuels that can be safely used in power and heat generating plant.

The project involves the Health and Safety Laboratory (HSL), an agency of the Health and Safety Executive, in collaboration with Imperial Consultants, the consulting arm of Imperial College.

Appraisal of Saline Formations

In 2012 the ETI invested £2m into a project with National Grid to carry out the UK's first drilling assessment of a saline formation site for the storage of carbon dioxide, at a site 70km off Flamborough Head in Yorkshire.

The project represents a major step forward in the creation of a CCS industry in the UK.

National Grid will lead the drilling programme, starting in May, at the identified saline formation, a layer of porous sandstone rock over 1km below the seabed. The operation, using standard oil and gas drilling activities, will involve drilling up to two wells in the seabed to gather data to confirm that carbon dioxide can be safely and permanently stored at the site, while also confirming the scale and economics of the store.

Existing information has confirmed the store is very large and capable of storing carbon dioxide from several sources over a number of decades. The site is close to the shore and, importantly, near to two major clusters of carbon dioxide emitters in the UK making it an ideal storage location.

Mobilising private sector finance for CCS in the UK

In November 2012 the ETI, in collaboration with the Ecofin Research Foundation, published a report 'Carbon Capture and Storage – Mobilising private sector finance for CCS in the UK'. This found that successful CCS deployment could be a huge economic prize for the UK in its low carbon transition – cutting the annual cost of meeting the country's carbon targets by up to 1% of GDP by 2050.

Project to assess flexible power generation systems

The ETI launched a project in late February to increase the understanding of the economics and potential use of energy systems involving low carbon hydrogen production, storage and flexible turbine technology.

Led by global engineering and construction company Foster Wheeler, in collaboration with the British Geological Survey, the £300,000 five-month project will assess the economics of flexible power generation systems which involve the production of hydrogen from coal, biomass or natural gas, its intermediate storage (for example, in underground salt caverns) and production of power in flexible turbines. It will also look to map suitable hydrogen storage salt cavern sites in and around the UK. The sites - which tend to be located inland or up to 25 miles off the UK coastline - will need to be of sufficient size, depth, location and quality before they can be considered for hydrogen storage.

CCS Measurement Monitoring and Validation

This project will deliver a system to provide assurance that carbon dioxide stored deep underground beneath the sea bed is secure.

ETI analysis has identified that a key knowledge gap is for proven systems capable of detecting and measuring any leak in the shallow subsurface and the marine environment of storage sites. Although leakage is expected to be very unlikely, such systems will be important to any supply chain to provide assurance to regulators, storage providers and other stakeholders for the storage sector. An announcement on who will carry out the project for the ETI is expected in the Spring.

Next steps

Although CCS appears an expensive addition to power generation, it is one of the most important strategic levers the country could use for any decarbonisation of its economy. To move the industry forward, making early CCS projects investable and economically attractive is a key priority. Given the opportunities it offers, the technology around CCS requires major investment now to build its economic viability and help extend its role in any future UK energy system design. However nobody is immune to the fact that the investment case to support development has to be made clearly.

CCS is policy dependent so investors are sensitive but the exploration of public-private partnerships and co-ordination mechanisms can help to provide a financial solution. Newly developed technology which reduces costs and accelerates deployment for new builds and retrofits by 2030 is therefore a critical challenge.

More information

For details of all the ETI's CCS projects, visit www.eti.co.uk

Three days to change the world

CCS Information and Planning Symposium

May 21-23, 2013 • Regina, Saskatchewan, Canada

The Boundary Dam Integrated Carbon Capture and Storage Demonstration Project is advancing rapidly. It's one of the world's largest carbon capture and storage facilities, and the very first to employ fully integrated post combustion CCS technology in a commercial scale coal-fired plant.

The project has generated a wealth of CCS knowledge that has never before existed. Now, the SaskPower CCS Global Consortium is preparing to bring Boundary Dam to the world.

Knowledge is power.

Join us for three days in May for our inaugural information and planning symposium to help shape SaskPower's CCS Global Consortium. This is a content rich event showcasing the knowledge of our Boundary Dam CCS project and the benefits of becoming a Consortium member. For those with a vested interest in the future of CCS, this is the very knowledge that is making a technical, environmental and economic case for the sustainable use of coal.

Organizations interested in joining the Consortium are encouraged to attend this symposium. To receive an invitation visit **saskpowerccsconsortium.com** and complete the Expression of Interest form.

SaskPower
Powering the future

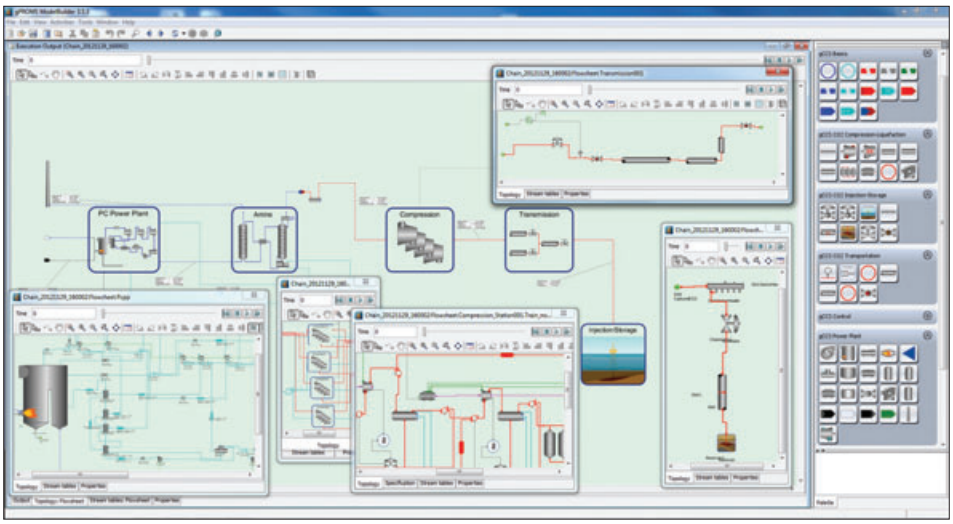
Whole-chain CCS system modelling

With many diverse stakeholders involved it is important to have a common basis for making decisiosn that works across the whole CCS value chain. In a UK Energy Technologies Institute (ETI) commissioned project, PSE has developed enabling technology to help accelerate commercialisation and manage technology risk.

By Mark Matzopoulos, Process Systems Enterprise Ltd

With the commercialisation of carbon capture & storage (CCS) given significant impetus by the announcement of the shortlist for the £1bn DECC award, UK CCS stakeholders will be required to address and resolve design and operability details from generation to storage at a commercial scale for the first time.

While CCS seems like 'new technology', there is little that is new in terms of individual CCS chain components. Indeed, conventional power stations, amine-based CO2 capture plants, pipelines and compressors have been part of the power and process industry world for decades and are well understood. Although it is spread out geographically, a CCS chain has less complexity than a small chemical plant.



The gCCS CCS system modelling environment

Challenges: interoperability at a system level

There are, however, still significant challenges in the commercial implementations of CCS. Many of these arise from the fact that the whole chain – and, eventually, whole CO2 transportation network – needs to be considered as a single system in order to make design and operation decisions that satisfactorily address the commercial imperatives and risk requirements of the various stakeholders along the chain. Even a cursory analysis shows that design and operating decisions at the power plant can have a significant effect on storage providers at the other end of the chain, and vice versa.

Many challenges relate to the difficulty of investigating these system-wide interactions, resolving the techno-economic tradeoffs that inevitably arise – which are affected by both design and operating decisions, and may require both steady-state and dynamic analysis – and proving that the whole system will work satisfactorily under a range of current and future scenarios. Underpinning all of this is the challenge of getting stakeholders with very different natures and commercial interests, working practices, technologies and tools – for example, power generation and oil companies – to work together.

Many decisions come down to tradeoffs between these diverse stakeholders. For example, power generators and storage providers both maintain that their requirements are simple. Generators simply want all their CO2 to be removed as they produce it. Storage providers, on the other hand, want a steady flowrate of CO2 with constant composition. Technically, it would be possible to achieve both of these requirements, although at the considerable cost of building a very large buffer storage at some central location and routing all CO2 via this. Obviously this is not a practical solution.

One (capital-intensive) option is to provide sufficient installed compression capacity to handle all flowrate eventualities. An alternative is to provide 'rich solvent' buffer storage at the capture plant in order to peak-shave by allowing some processing to take place at off-peak generation time, for example during the night; depending on peak electricity prices, the cost of solvent and the amount of buffering required, this might improve overall generation economics.

Another option would be to allow fluctuation in flowrates within certain bounds while imposing stringent limits on impurities, moving the onus from compression and storage providers to upstream gas treatment. Each of these options could involve significant capital and operating costs for one of the parties involved, depending on the specifics of operation.

It is evident from this single example that the decision space is complex. Not only is it necessary to determine realistic costs in each case in order to negotiate suitable commercial terms, but important technical considerations also need to be taken into account in these decisions. What is the effect of strongly fluctuating flow on well operation, for example? Does the consequent likelihood of two-phase flow impose risks of its own? How much buffering will a given CO2 pipeline allow, given pressure limits and taking into account other likely demands? It is no use resolving the economics at the expense of creating new technical risks; indeed it is almost impossible to separate the technical and economic aspects of such decisions.

A common basis for techno-economic decisions across the chain

What is clear is that some common basis for providing decision support is absolutely essential. Robin Irons, from E.ON's CCS Innovation Centre, sums up the situation when he says: "we need tools that enable us to look at the whole system simultaneously so that we can answer questions and make decisions based on accurate numbers".

This was echoed by Andrew Green, CCS Programme Manager at the Energy Technologies Institute (ETI), whose members comprise BP, Caterpillar, EDF, E.ON,

Rolls-Royce and Shell and the UK government. "Our members identified system modelling as a key enabling technology for the commercialisation of CCS", he says. "It is an essential tool for understanding interoperability of the components in the system, managing trade-offs and mitigating risks".

Investigation quickly shows that there is a lack of tools that cover the whole system to an adequate level of fidelity. Many simulation tools – such as PROATES®, PROMAX®, Aspen Plus® and OLGA® – have been and are currently used in power station design, amine plant design, compressor design, and analysis of transmission and injection operations. While very effective in resolving the current set of challenges, they are used mostly for single areas within the chain.

A challenge for interoperability analysis is that different companies along the CCS chain tend to use different simulation software packages, some of which have a very industry-specific focus. Even if the underlying assumptions and approach of these software packages were compatible, the software architecture of most simulation software does not allow easy interoperation. This is particularly true for dynamic simulation, which is a key requirement for analysis of flexible power generation.

The ETI responded by setting out to commission a project to produce a 'CCS system modelling tool-kit'. Says Green, "We asked respondents for proposals to create a commercially-supported CCS system modelling package capable of being used not only by individual stakeholders along the chain, but also for government policymakers and others that need to quantify options based on the whole chain or networks."

CCS system modelling tool-kit project

The result was a £3m project commissioned and co-funded by the ETI and project participants, comprising E.ON, EDF, Rolls-Royce, Petrofac (via its subsidiary CO2DeepStore), Process Systems Enterprise (PSE) and E4tech. The project is aimed at delivering a robust, fully integrated tool-kit that can be used by CCS stakeholders across the whole CCS chain. In parallel PSE is developing the commercial software product, known as gCCS, which will ensure that the outputs from the project will be made widely available and supported and further developed into the future.

Industrial input is from E.ON and EDF on the power generation side, Rolls-Royce for compression, and Petrofac/CO2DeepStore for the transmission and injection aspects. The project is managed by energy consultancy E4tech. PSE's gPROMS advanced process modelling platform provides the modelling software basis, with the company providing much of the modelling expertise for creation of models that cover operations across the chain.

Because of the requirement for many stakeholders to be able to model areas of the chain beyond their own specific processes (for example, a key requirement for power generators is the ability to investigate the effects on their operation of amine and compression systems attached to their plants), an early conclusion was that it is necessary for such a tool to provide process models for the whole chain. This is also useful – indeed essential – for groups who require a whole-chain view, such as engineering companies or government departments who need to quantify policy decisions.

"We are now at the stage where high-fidelity models are required in order to deliver true commercial value and provide accurate quantification of risk."

Thus gCCS is being constructed with a full complement of models for conventional generation (pulverised coal and combined cycle gas turbine), new generation (gasification and oxyfuel), solvent-based carbon capture, compression, transmission and injection. In addition, it is possible to incorporate models of other plants, such as air separation units, using existing capabilities of the gPROMS platform, or to create custom models that can be incorporated within the environment. Using the tool it will be possible to look at single areas such as amine plants in detail; investigate partial-chain operations – for example, power generation, capture and compression; or analyse interactions across the whole chain and eventually – when this becomes necessary – whole network.

The individual process models are mostly implemented to what conventional process simulators consider to be medium-to-high fidelity: multicomponent streams; equilibrium methods for vapour-liquid separation; comprehensive compressor models allowing multi-stage, multi-section compressors with manufacturers' curves; and distributed pipeline models for construction of pipeline networks that can take elevation into account. The capture models use rate-based techniques for accurate quantification of chemical and physical capture in order to quantify energy penalties accurately and allow meaningful analysis of transient operations.

Says Chief Architect of gCCS Prof. Costas Pantelides, MD of PSE and a Professor of Chemical Engineering at Imperial College, "When you are seeking to make design and operating decisions, assess interoperability across whole CCS chains and perform economic optimisation, it is no use working with approximate or empirical models. We are now at the stage where high-fidelity models are required in order to deliver true commercial value and provide accurate quantification of risk."

gCCS also allows external packages to be interfaced to the core environment, in order to simplify interoperability analysis while allowing companies to preserve existing workflows where necessary. For example, E.ON can use models of power plants constructed in its PROATES® package directly within gCCS.

"This allows us to integrate our proprietary models – most already validated at commercial scale – into gCCS to accurately represent the operation of a complete CCS chain within a much wider framework (e.g. transportation networks connecting various CO2 sources and sinks). This will provide valuable information to evaluate potential opportunities and challenges for future CCS projects, in particular those where multiple CO2 sources (i.e. CO2 clusters) are located" says David Peralta-Solorio, who is managing E.ON's contribution to this project on behalf of the CCS Team at E.ON New Build & Technology.

Accelerating new technology for efficiency improvement

While the individual components along the chain may be well understood, in many case there is much scope for improvement in the individual systems. Solvent-based CO2 capture may be well understood, but there is a significant body of ongoing work to design and prove new solvents that improve process economics and reduce energy penalty.

Because of the inherent challenges of solvent-based processes, much R&D effort is being put into developing alternatives. These need to be scaled up, demonstrated and proven industrially; model-based techniques can accelerate all of these, including management of technology risk inherent in new designs. Likewise there are many questions around the design of pipelines and compression system for CO2 with significant impurities, as well as aspects of gasification processes that need to be proven in power generation scenarios.

A key to the gCCS framework is that it provides and advanced custom modelling capability, meaning that it is easy to add models of new processes and combine them with existing flowsheeting components.

Prof. Pantelides adds "We are working with universities and SMEs throughout the UK to provide services and tools to accelerate development of capture processes, and bring models of these into the gCCS framework. In the future we also hope to persuade vendors of capture processes, gasifiers and other equipment that it makes sense to have models of their equipment and processes that can be used for rapid analysis of integration issues, and also as sales tools."

Current status

Half-way through the 30-month project, much has been achieved. The project team recently demonstrated a whole-chain model, built from a pulverised-coal power plant model constructed by E.ON, with compressions system input by Rolls-Royce, coupled with other components such as transmission and injection systems. Work is currently progressing with EDF on a dynamic CCGT demonstration, and the software is being rolled out to the initial users within the participating organisations.

Alfredo Ramos, head of PSE's CCS strategic business and project manager of the gCCS development team, says "the fact that we are starting from a well-established process modelling platform is an enormous advantage. This means that the flowsheeting framework, steady-state and dynamic modelling, custom modelling and optimisation capabilities are already there. Our main task is to develop fit-for-purpose model content and tailor the environment for CCS users."

"Given the challenges of this type of simulation", says Ramos, "we were pleased to see that following a short training course E.ON was able to build a model of the power plant, and Rolls-Royce a model of the compression train, and then the two groups were able to combine these and create a whole-chain model within a few days."

The future

The ETI-commissioned project is due for completion in March 2014, after which gCCS will be maintained, supported and further developed by PSE.

"We intend to create a broad system modelling 'ecosystem' for CCS", says Pantelides. "The more people who are using the environment the better for the whole industry".

PSE is engaging with universities to provide tools for the considerable academic research activity into CCS currently underway in UK universities. "We see strong mutual benefits: CCS PhD students will be able to concentrate on their real research topics rather than spend the first 6 months creating a power plant model from scratch; we can also provide a route for dissemination of their results to industry. In return they provide an early test bed for the gCCS tool before we go out to industry on a large scale."

A test for success will be the application of gCCS on the DECC competition FEED studies. "We are talking to several of the projects", says Ramos, "and look forward to seeing the benefits of the system modelling approach being proven in real industrial applications."

More information

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Understanding potential health risks and their cost implications

Based on an Industrial Economics (IEc) report titled, "Valuation of potential risks arising from a model, commercial-scale CCS project site," Jeffrey Price, Bluewave Resources and Sarah Wade, Wade, have produced a report outlining an approach to estimating the financial impact of risks to human health and the environment from CCS projects.

The approach consists of a financial simulation model using a combination of site-specific and more generic data.

It was tested using a case study based on a proposed CCS project, the Jewett FutureGen project in the United States. Results calculated the average costs associated with the risks for a well-sited and operated CCS project at $0.15/tonne CO2, which is less than roughly 0.4 per cent of estimated project costs.

This approach is flexible in that it could be applied, with some modification, to other CCS projects. It could also be applied at different stages of a project, although the degree of confidence in the results is commensurate with the quality and specificity of available data. As better and more site-specific data are obtained during project development, confidence in the results would increase.

The study concludes that the financial risks associated with CCS projects can be quantified by standard analytical techniques. This challenges the widespread misperception that the costs associated with the risks of CCS cannot be quantified. It further shows how uncertainty can be explicitly taken into account.

It demonstrates that well-sited and well-operated CCS projects can be expected to result in a relatively small potential financial risk for damages to human health and the environment compared to both the planned project costs and the benefits of such projects. Choice of the site is critical. Site characteristics – both the geologic factors that affect risk and the potential exposure of humans and the environment – are major determinants of risks. Although the results are based on a single early-stage project using generalized data, they give insight into the likely range of damage costs that can be expected at well-selected and operated projects.

The application of the approach used in this study can help developers of CCS projects better site and design their projects to mitigate risk and confidently make investment decision. This information can be used by regulators and project developers to inform regulatory and permitting decisions and to establish regulatory timeframes and financial assurance mechanisms. The financial community can use this information to better evaluate project investments. Perhaps most importantly, this information can be shared with the public to build confidence in projects.

Download the full report at:
www.globalccsinstitute.com

Internals for carbon capture plants

Koch-Glitsch is using its extensive experience to design cost-effective, energy efficient internals for post-combustion capture columns that still give optimum performance even for towers exceeding 20m diameter.

Traditional vs. Post Combustion CO2 Capture Design

For many years, various industries, such as fertilizer and gas processing, have used processes to remove carbon dioxide from gas streams. The majority of these processes use a chemical solvent (amine, hot carbonate, and so forth) or physical solvent (propylene glycols or chilled methanol) in an absorption tower that contains either trays or packing for contacting the solvent with the acid gas in the gas stream. Over the years, Koch-Glitsch engineers have worked on hundreds of these columns and have developed industry leading design knowledge for the internals these towers need.

Post combustion CO2 capture processes present new challenges to the designers of mass transfer internals due to the differences in operating conditions compared to traditional CO2 absorption.

Traditional acid gas removal processes operate at high pressure with the result that even relatively low CO2 concentrations in the gas have a high partial pressure. In most traditional acid gas removal systems, the actual solvent recirculation is significantly more than the theoretical minimum solvent rate. These two factors allow even relatively low technology equipment to provide reasonable performance. In a post-combustion CO2 capture plant, CO2 is removed from the flue gas at slightly higher than atmospheric pressure. Even at inlet concentrations of 10-15% CO2, the resulting partial pressure will be relatively low.

To minimize the parasitic energy demand required to regenerate the solvent it is crucial to minimize the solvent recirculation rate.

• Under these conditions, any maldistribution of liquid or vapor can cause a pinch between the operating and equilibrium line and will result in exit gas with higher CO2 levels than desired.

• Increasing the solvent recirculation rate above the desired design rate will result in a significant increase in the parasitic energy demand. This phenomena is illustrated in Figure 2.

The design requirements for column internals in post-combustion CO2 capture plants are, therefore, significantly more difficult than those for conventional acid gas removal plants. These additional requirements are well understood by Koch-Glitsch engineers. Using INTALOX™ Packed Tower Internals technology, which has been proven in numerous packed super fractionators, Koch-Glitsch can provide you with the internals to minimize the parasitic energy demand of the regenerator.

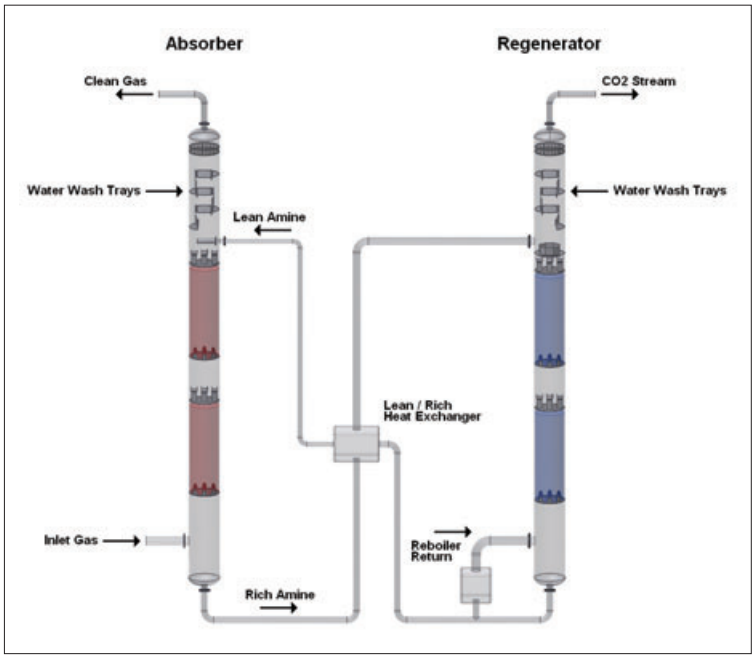

Figure 1 - Absorber and regenerator columns and piping

Size Matters

Commercial-scale post combustion carbon dioxide absorbers and regenerators will be very large because of the volumes of flue gas emanating from power plants. Tower diameters exceeding 20 m (65 ft) will not be unusual. The large dimensions present several challenges:

- Supporting the weight of packed beds and tower internals
- Proper leveling of liquid distributors to ensure good distribution
- Providing good vapor distribution
- Installing equipment in large diameter towers

Koch-Glitsch has extensive experience handling each of these challenges.

Liquid Distribution

INTALOX™ high performance liquid distributors apply the following ideal attributes:

- Uniform distribution over the entire cross sectional area of the tower
- Proper operation through the operating flow range
- Low vapor phase pressure drop
- Resistance to plugging or fouling
- Optimal use of vessel height

Good liquid distribution depends on equal liquid levels throughout the distributor. Orifice flow is directly proportional to the liquid head above it and can be uneven if the distributor is not precisely leveled.

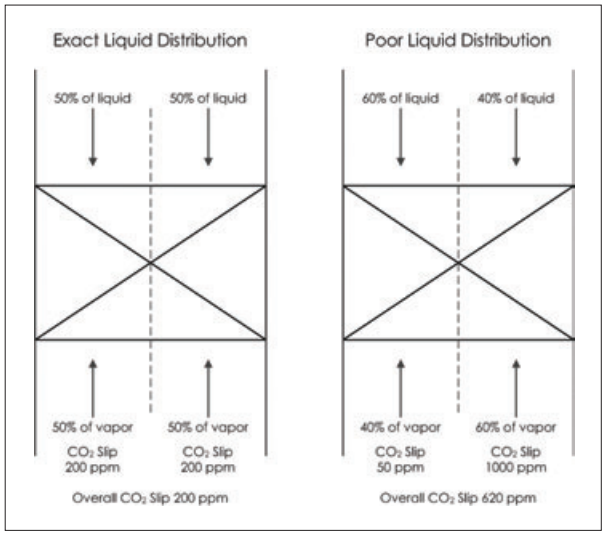

Figure 2 - Any maldistribution of liquid or vapor can cause a pinch between the operating and equilibrium line and will result in exit gas with higher CO2 levels than desired

Koch-Glitsch offers trough distributors with discrete drip points or enhanced baffles that are easily and accurately leveled. Both distributors can be supported directly on the structured packing.

This approach is beneficial for extremely large towers where mechanical deflection becomes an issue. Independent leveling mechanisms for each part of the distributor ensure point to point liquid flows are within the criteria for good liquid distribution.

This strategy has been applied to many critical distillations in tower diameters up to 12 m (40 ft.) and proven on Koch-Glitsch's liquid distributor test facility.

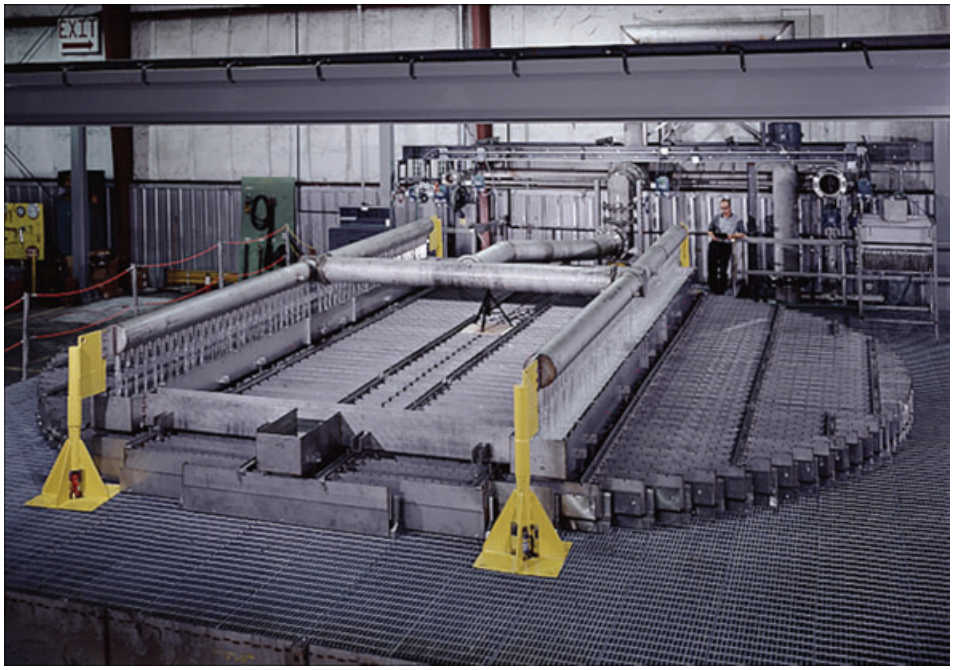

Figure 3 - Test of 12.2 m (40 ft) diameter High Performance INTALOX™ Model 156 Liquid Distributor

Vapor Distribution

Good vapor distribution is essential to achieve superior separation efficiency. Poor vapor distribution can lead to vapor/liquid channeling and reduced packing efficiency. Distributing the inlet gas evenly across the entire tower cross section in a very large tower is challenging.

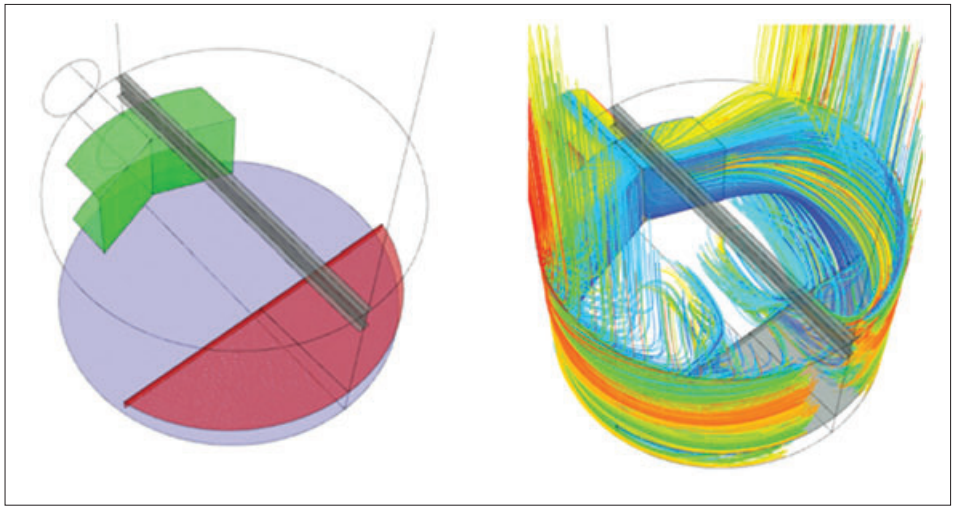

Figure 4 - Koch-Glitsch uses computational fluid dynamics (CFD) modeling technology to analyze the performance of existing equipment or to develop new designs

Koch-Glitsch uses computational fluid dynamics (CFD) modeling technology to analyze the performance of existing equipment or to develop new designs. Computer modeling of the three dimensional configuration of the column internals provides detailed predictions of fluid flow. Using this comprehensive approach with patented vapor distribution technology has proven very successful in towers as large as 15 m (50 ft.).

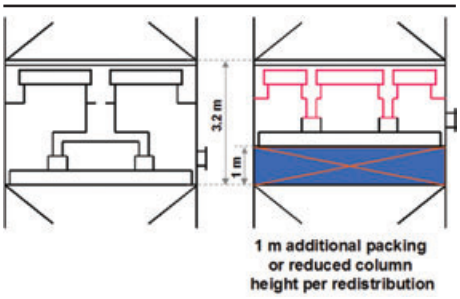

Figure 5 - Mixing drum vs. collector

Liquid Mixing

In the absorber column, the required packing volume is likely to be split into two or more beds. Even in columns with excellent liquid and gas distribution, small differences will exist in the liquid to vapor ratio. These differences will result in variations in the CO2 content in the solvent across the column.

To ensure these variations do not cause a pinch further down the column, any liquid coming from a higher bed must be thoroughly mixed before being distributed to the lower bed. The column height necessary to perform this mixing can be very expensive in columns with large cross sectional area. Historically mixing between packed beds has been done using mixing chambers or tanks that take up valuable column height.

Koch-Glitsch has developed a patented Cross Mixing Vane Collector that can minimize the space required for liquid mixing, which can result in significant vessel cost savings. As illustrated in Fig. 5, liquid from all points in the column is strategically moved to provide complete mixing prior to delivery to the bed below.

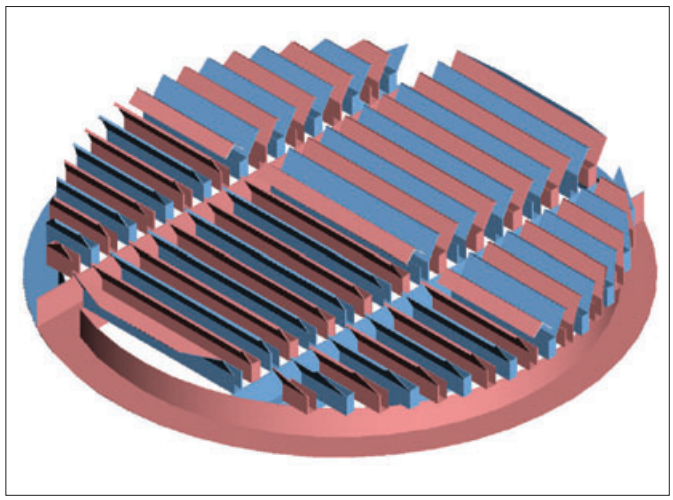

Figure 6 - Koch-Glitsch has developed a patented Cross Mixing Vane Collector that can minimize the space required for liquid mixing, which can result in significant vessel cost savings.

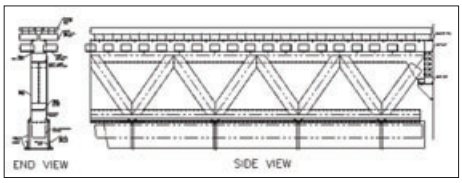

Figure 6 - The patent pending FLOW-THRU™ truss design combines the functions of support truss and liquid collector

An alternative to the Cross Mixing Vane Collector is an integrated internals design concept. The patent pending FLOW-THRU™ truss design combines the functions of support truss and liquid collector. The weight of packed beds in CO2 capture systems can exceed 300 metric tons (330 tons). To support the weight, allow free passage of vapor and liquid, and keep costs down requires unique beam designs with a minimized footprint and lower material usage.

The combined functionality of the FLOW-THRU™ truss design allows for a more robust structure without consuming valuable cross-sectional area for capacity and is better suited to higher liquid flow rates. The concept also allows for a reduction of 1-1.5 m (3.28-4.92 ft) of vessel height at each liquid redistribution point.

Hydraulic benefits include prevention of mechanical deflection induced mal-distribution, reduced liquid gradients and reduced leakage.

Equipment Installation

Installing tower packing and internals is a specialized job that requires knowledge of the equipment and years of experience. Very large towers make this job even more difficult. Koch Specialty Plant Services, Inc. (KSPS) has performed thousands of tower revamps and new installations around the world, including towers up to 15 m (50 ft) in diameter.

This experience ensures proper installation so there are no column performance issues on start-up. Combined with equipment from Koch-Glitsch, KSPS can provide turnkey services that include engineering, material procurement, project management, and field erection of vessels.

Research and Development

Reliable tower designs depend on accurate performance data developed in the laboratory. Koch-Glitsch has constructed a 1.7 m (5.5 ft) diameter commercial scale distillation tower to provide better performance characterization of trays and packing.

In addition, a complete CO2 capture pilot unit is available for testing a wide variety of solvents. The use of these facilities reduces technical risk and allows for the advancement of overall tower performance.

Conclusion

Although Post Combustion Carbon Capture provides challenges for the design of mass transfer internals, Koch-Glitsch engineers, using the wealth of experience available within the organization, are able to supply cost effective, energy efficient column internals.

In fact, this has been demonstrated by a number of Post Combustion Carbon Capture pilot and demonstration units that are operating with Koch-Glitsch internals installed in them.

By having comparative performance data in the same system and operating conditions for columns of 50 mm (2 in) diameter to in excess of 15 m (50 ft) diameter, Koch-Glitsch can effectively produce tower internals arrangements that will provide you with optimum performance even in the largest of towers.

Figure 7 - Commercial scale distillation towers used to test performance of a wide range of equipment including trays, packing and vapour and liquid distribution services

Figure 8 - A complete CO2 capture pilot unit is available for testing a wide variety of solvents

More information

Visit the website to review the latest in mass transfer internals technology:
www.koch-glitsch.com

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Power from gas + CCS at 54% efficiency?

Engineers at Technology Centre Mongstad of Norway believe that it might be possible to generate electricity from gas with CCS at 54 per cent efficiency – compared to 59 per cent efficiency for a gas turbine without CCS.

Technology Centre Mongstad (TCM), the world's largest CO2 capture research facility based in Norway, is currently enabling electricity to be generated from gas, with carbon capture, at 50-51 per cent efficiency.

TCM is connected to a nearby gas electric power plant.

TCM Engineers think that 52 per cent should be achieveable and 53-54 per cent possible. Bear in mind that the record efficiency for a gas power plant without CCS is currently around 59 per cent.

If there is a 51 per cent efficiency using CCS, this means that around 16 per cent of the electrical power, which would otherwise be available for electricity, is being used to run the capture plant ((59-51)/51= 0.156).

This is a lot of power, but still less than the 30 per cent power requirement estimates of early carbon capture plants.

TCM is engaging in intensive research to try to improve the 51 per cent figure.

Olav Falk-Pedersen, Technology Manager at Mongstad, believes that it might be possible to run the plant at 54 per cent efficiency, which would mean that the capture plant is drawing just 8.5 per cent of the electrical power ((59-54)/59=0.084).

If this could be achieved, it would make a massive reduction to the overall cost of CCS and improvement to its viability.

Oil and coal prices are constantly changing, but if (for example) the coal price per megajoule was to drop to 9 per cent less than the gas price (due to it being easier to get planning permission to build new gas plants than coal plants, and a surplus of coal in the US due to the shale gas boom), then it could be equally viable to construct a coal power station with CCS, as a gas power station without CCS.

Since it is currently viable to build gas plants without CCS, that would mean that a coal plant with CCS is economically viable.

There are the capital costs to take into consideration, but the main cost over the lifetime of the plant is the cost of the fuel.

Mr Falk-Pedersen believes that 52 per cent efficiency is "achievable".

Technology Centre Mongstad

Technology Centre Mongstad

Technology Centre Mongstad claims to be the world's largest facility for testing and improving CO2 capture, with an investment budget of 6bn NOK (approx. USD $1billion).

It is designed to capture 100,000 tonnes of CO2 per year. It is a joint venture between the Norwegian state, Statoil, Shell and Sasol.

The plant receives effluent gas from a Statoil oil refinery and a gas fired power station. The gas power plant has CO2 of 3.5 per cent and the refinery cracker has CO2 of 13 per cent.

The capture plant is still 200 times smaller than a capture plant that would be required to capture all the CO2 from a large coal power station, which can emit 20m tons of CO2 per year, but if the technology works efficiently at 100,000 tons a year that is a great step towards a 20m tons a year plant.

TCM is testing two carbon capture processes, chilled ammonia from Alstom and an amine process from Aker Clean Carbon. They are both post-combustion capture with solvents, designed to capture 85 per cent of the CO2 in the flue gas.

Aker Solutions builds its plant at its own factory in modules which can then be brought to the site and put together – this is because it does a lot of construction work for offshore facilities, and modular construction is much more practical for offshore construction if the plant can be built onshore rather than offshore. All of its modules can be delivered to Mongstad on barges.

Alstom goes for the on-site construction approach, which might be less expensive.

People often ask of Alstom and Aker are competing to see whose technology is best, but Mr Falk-Pedersen says that both companies are winners because they are learning more about their own technology.

Research

The research work is learning how the operation of a carbon capture plant can be fine-tuned for maximum efficiency, separation, purity, reliability, long life, maintainability, and construction.

It is working out how to get the best balance between energy requirement, amount of CO2 separated, and purity of the output stream.

It is learning how to keep the plant running reliably for long periods of time, and how to maintain the quality of the solvents so they can be reused over and over again and do not degrade.

The challenge is to "close the heat and mass balance," Mr Falk-Pedersen says, or in other words keep all flows into and out of the system in a steady state and measure energy consumption per ton of CO2 removed and other important key performance parameters with a high accuracy.. This way, the plant can be operated most efficiently.

You can do lots of theoretical studies and simulations about how the plant should

run, but it is all slightly different when you do it for real.

An important parameter is the capture rate, how much of the CO2 in the gas stream going into the plant should be separated from the exhaust gas which comes out. The plant is designed for a capture rate of between 50 to 95 per cent.

You could argue that there isn't much point to a plant which can only capture 50 per cent of the CO2 going in – but the energy costs of getting a 95 per cent capture might be so high, you might choose a lower capture rate.

The plant has a very stable (constant) exhaust gas as its input flow in terms of its composition. The input flow rate can be varied between 20,000 and 60,000m3 an hour. There is possibility to add air to the input flow, so you can experiment with a stream with an even lower CO2 concentration.

Research is also going into working out the best packing type for the absorber, and the optimum height of the absorption tower.

The researchers take 100 manual samples a day from the plant, and analyse them for concentrations of different substances, sometimes at levels of parts per billion. They also collect data from around 4,000 measuring points.

"People are working hard to see how we can totally optimise the process," he said.

The centre will be open for other companies to test their carbon capture equipment in early 2014, and Mitsubishi, Hitachi, Siemens and A ker are already showing interest. They will be able to test the technologies in our amine plant and see how well it can function in a larger scale capture plant.

Perhaps most importantly, if the centre can prove that carbon capture can work, then coal power companies (when asked by regulators if they will put carbon capture on their new coal plant) will no longer be able to reply that the carbon capture technology does not exist.

The project is planned to run for 5 years at least, and after that might be used to also research other capture technology (other than post combustion).

More information
www.mongstad.com

DNV KEMA – help manage risks of CO2

DNV KEMA, together with 16 organisations involved in CCS, has published a comprehensive guidance document on CO2 handling, to help people get a better understanding of the risks, and help improve public confidence that the risks have been managed.

Did you know that a rupture of a vessel containing CO2 could escalate to create a "Boiling Liquid Expanding Vapour Explosion (BLEVE)?"

DNV says, "The probability of this occurring is believed to be extremely low but CO2 system designers should be aware of the potential."

Do you know the hazardous limit of CO2 in air? (7 per cent, in case you were wondering – compared to 0.07 per cent for hydrogen sulphide).

Did you know that liquid CO2 is an excellent solvent which can break down lubricants and damage seals?

These are some of the points covered in CO2RISKMAN, a guidance for how to handle CO2 in a carbon capture and storage system (between the capture plant and subsurface injection facility), which has been put together by energy consultancy DNV KEMA and is available for download free of charge from www.dnvkema.com/ccs.

The guidance has been written at 4 different levels, ranging from level 1, a concise executive summary, to level 4, a 300 page in-depth knowledge source with separate sections for each link in the chain. The level 4 guidance has chapters for capture facilities, online pipelines, submarine pipelines, wells, offshore injection facilities, intermediate storage, ships used to carry CO2.

The guidance describes possible causes of hazards, escalation routes and possible consequences. It also provides guidance on hazard identification, risk assessment and how to bring risks down to an acceptable level.

The guidance follows a 15 months joint industry research project which began in August 2011, with support from 16 industry and regulator organisations. The plan is to update the guidance after a few years, when more knowledge is available.

Organisations involved in the research include gases company Air Liquide, Norwegian pipeline operator Gassco, engineering contractor AMEC, oil companies Chevron, Shell and Maersk Oil, power company E.ON, UK power transmission organisation National Grid, Norwegian CCS research centre Gassnova, the Norwegian Petroleum Safety Authority, the UK government's Environment Agency and Health and Safety Executive, the Scottish Environment Protection Agency, the International Energy Authority Greenhouse Gas Research program (IEAGHG), the Global CCS Institute, and the Institute for Studies and Power Engineering (ISPE - Romania).

The companies in the research group had complementary expertise. For example, Air Liquide has strength in handling liquid CO2, and AMEC has strength in pipelines.

Some of these organisations are in competition with each other, but they also recognise that all of the industry gains from a better understanding of the risks of CO2 handling.

It follows other joint industry projects organised by DNV, covering the capture process (CO2CAPTURE), pipeline transportation (CO2PIPETRANS), wells (CO2WELLS) and storage (CO2QUALSTORE).

The risks of CO2 handling are very different to the risks of CO2 storage, which are mainly about making a good assessment of a storage site, says Kaare Helle, head of CCS business development DNV KEMA.

The guidance could also be used as a basis for certification – a safety organisation, regulator or consultancy could certify a CO2 project as having thoroughly examined a CO2 system for hazards, based on information in the guidance, and taken adequate steps to address the associated risks.

The right balance

DNV aims to find the right balance between making sure people are aware of the risks so that they can be effectively managed and also making sure people are not too worried about the risks that nothing gets done.

"Raising awareness and providing information on potential hazards helps CCS projects manage their risks but it can also create concern amongst other stakeholders, stakeholders who may not have been aware of the potential hazards in the first place" says Hamish Holt, CO2RISKMAN project manager and principal consultant at DNV. "The CO2RISKMAN guidance tries to strike an appropriate balance by providing detailed information on potential CO2 hazards in a factual, non-alarmist way, along with risk reduction measures which CCS projects can consider."

A key statement in the guidance is that there is no reason why major accident risks

from a CO2 handling system within a CCS operation cannot be "low and well within acceptable limits," but to achieve this will require the application of existing rigorous hazard management processes combined with an adequate understanding of the properties and behaviours of CO2.

"A significant leak from a large inventory CO2 handling system has the potential to be life threatening to people caught within the ensuing dispersing cloud or could pose local environmental harm," it says.

Competence

Industry can get better at reducing risks as it gains experience with CO2 – but to put that another way, one of the biggest risks from CO2 handling today stems from the industry's lack of experience with it.

There is much considerable experience in the US in handling large quantities of naturally occurring CO2, where it has been used for enhanced oil recovery for a long time, but "there is much less experience handling very large quantities of CO2 outside the US," says Hamish Holt.

"With the introduction of CCS this will change. CCS engineers, project management, system operators, hazard management specialists, and others who have a key role in delivering a safe operation need to have adequate understanding of the potential CO2 hazards so that they can effectively manage the associated risks."

The CCS industry needs to take the existing technologies, experience and practises, ensure they are suitable for CCS, and then integrate the various links in the chain together.

Risks of CO2

Here are some of the risks of CO2 presented at an overview level.

If any water enters a CO2 system, it can form carbonic acid, which can corrode carbon steel (for example in the pipeline).

If as part of the CO2 capture process significant levels of hydrogen, nitrogen or other substances are mixed with the CO2, it can have an effect on the phase calculations (the temperatures and pressures at which CO2 becomes liquid or solid).

If a CO2 system is depressurised, there can be very cold temperatures.

It can be toxic if people breathe air with CO2 concentrations at above 5-7 per cent. This compares with dangerous limits of hydrogen sulphide at 0.07 per cent and nitrogen at 35 per cent.

For risk assessment, it is important to bear in mind that there is not much historical data about leaks, and not much release modelling work has been done.

CO2 is heavier than air (and so won't rise up and out of the way as hydrogen and natural gas release would).

If there is a failure upstream, which allows an impurity into the CO2 stream, it can cause problems downstream.

Liquid CO2 is an excellent solvent, which is capable of breaking down some lubricants and damage seals, so you have to ensure the materials you choose are suitable.

If CO2 is depressurised, it can cool down to -78°C -78 degrees and freeze - and frozen CO2 could also block CO2 pipelines.

CO2 density is also sensitive to temperature changes especially close to critical point conditions (i.e. 31°C and 74 bars). This can lead to system over pressurisation with a relatively small change in CO2 temperature.

There is "considerable knowledge" on managing risks associated with cracks in natural gas pipelines, and this knowledge is being used for CO2 pipeline design.

carbon capture journal

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Global CCS Institute Status of CCS update

The Global CCS Institute January update identified 72 Large Scale Integrated Projects around the world, down three projects from the 75 reported in October 2012.

Since the Institute's last report, one project has made a positive final investment decision (FID). This brings the total number of projects operating or under construction ('Execute') to 17 and their total capture capacity to more than 37 million tonnes of CO2 per annum (Mtpa) (refer Figure 2). The remaining 55 LSIPs are in the planning stages of development and have a potential capture capacity of around 104 Mtpa. A steadily increasing number of LSIPs remains needed for the world to meet global climate mitigation objectives.

Three projects have been removed from the Institute's LSIP listing due to being considered cancelled or on hold:

• the PurGen One project in New Jersey, United States (US), at the 'Define' stage;

• the Eemshaven CCS project in the Netherlands, at the 'Evaluate' stage; and

• Pegasus Rotterdam project in the Netherlands, at the 'Evaluate' stage.

In November 2012, Northwest Upgrading Inc. announced it had made an FID on its Alberta Carbon Trunk Line (ACTL) with North West Sturgeon Refinery CO2 Stream9 project. Construction is expected to break ground in early 2013; the plant is scheduled to commence operations in 2015. Around 2.6 Mtpa of CO2 will be captured at the new build North West Sturgeon Refinery in Alberta, Canada, and sold for EOR. The announcement highlights the strength of the Canadian CCS industry and, more specifi cally, in the province of Alberta. The Quest project, which was confirmed just a month earlier, is also located in Alberta.

The Institute estimates that up to four additional LSIPs could reach an FID in the first half of 2013, of which three plan to use the captured CO2 for EOR:

• Summit Power's Texas Clean Energy Project and the NRG Energy Parish CCS Project, both in Texas (US);

• Masdar and Emirates Steel Industries' ESI CCS Project in Abu Dhabi (United Arab Emirates); and

• Rotterdam Opslag en Afvang Demonstratieproject (ROAD) (the Netherlands), developed by a joint venture of E.ON Benelux and GDF Suez Group.

In a signifi cant setback to CCS demonstration targets in Europe, no CCS projects were awarded funding under the much anticipated first round of the European Commission's (EC) NER300 competition.

Outcomes from UNFCCC conference in Doha

The establishment and refinement of the arrangements for CCS in the Clean Development Mechanism (CDM) help create the institutional arrangements necessary for CCS as a mitigation option and enhance industry and public confidence in CCS.

During the United Nations Framework Convention on Climate Change (UNFCCC) conference held in Doha, Qatar, from 26 November to 8 December 2012, two outstanding CCS issues under the CDM negotiations were dealt with at the 8th session of the Conference of the Parties serving as the Meeting of the Parties to the Kyoto Protocol (CMP 8).

The two issues were first outlined at the Meeting of the Parties in 2011, after which the Subsidiary Body for Scientific and Technological Advice (SBSTA) was tasked to:

i. further explore the eligibility of CCS projects that involve the transport of CO2 from one country to another or which involve geological storage sites that are located in more than one country; and

ii. the establishment of a global reserve of certified emission reduction units for CCS projects (in addition to the agreed temporary reserve of five per cent).

The CMP decided in Doha that it could not make a definitive decision on either of these issues, and that more time was needed to generate learning-by-doing spill-overs from non-transboundary CCS projects in the CDM first. The CMP agreed to consider these issues pending further recommendations from the SBSTA's 45th session, scheduled for 2016. While this means that transboundary CCS projects will not be allowed to be registered in the CDM for the time being, the modalities and procedures adopted in 2011 remain fully intact and operational.

The CMP welcomed the work being undertaken by the CDM's Executive Board to adopt documents that provide for the inclusion of CCS projects, and formally acknowledged that transboundary CCS projects would ultimately merit inclusion under the CDM.

Despite these outstanding issues, there appears to be nothing of a procedural nature stopping non-transboundary CCS project proponents from applying to have their projects registered under the CDM. While most CDM commentators would suggest that it may take some time for CCS projects to be fully rewarded under the CDM, the mechanism (and other project–based schemes) is generally recognised as a necessary and important source of additional funding for CCS projects in developing countries.

Figure 1 - Comparison overview of LSIPs by asset lifecycle stage15 (©GCCSI)

Policy, projects and regulation news

Air Products' phase one carbon capture project onstream in Texas

www.airproducts.com

Phase One of its two stage carbon capture project in Port Arthur, Texas is onstream.

Ultimately, the project will capture approximately one million tons of carbon dioxide (CO2) annually to be recovered, purified by Air Products, and transported by Air Products via a pipeline owned by Denbury Green Pipeline-Texas, LLC for injection into the Denbury Onshore operated West Hastings Unit, an enhanced oil recovery project in Texas.

Air Products designed, constructed, and is now operating Phase One of a system to capture CO2 from one of its steam methane reformers (SMR) located within the Valero Port Arthur Refinery. The CO2 removal technology has been retrofitted to the SMR, which produces hydrogen to assist in the making of cleaner burning transportation fuels by refinery customers on Air Products' Gulf Coast hydrogen pipeline network. Phase Two, involving a second Air Products' SMR at the site, is to be onstream in April 2013.

"We have successfully launched Phase One and would like to congratulate all of our project collaborators on the achievement. We are now focused on getting Phase Two onstream and completing the project as designed. This novel and technology-leading project would not have occurred without the support and involvement of DOE," said Wilbur Mok, vice president, North America Tonnage Gases for Air Products.

DOE stated in its announcement that, "This event marks a milestone in DOE's ICCS program: progressing beyond research and development to a demonstration scale that can be readily replicated and deployed into commercial practice within the industry. Goals of the ICCS program are to mitigate climate change through carbon capture, utilization and storage; create jobs; and position the United States as a world leader in carbon-capture technologies."

DOE provided a significant portion of the funding (66%) for the over $400 million project. In June 2010, Air Products was selected to receive $253 million in funding from DOE through the National Energy Technology Laboratory under the ICCS Program, which is funded by the American Recovery and Reinvestment Act (ARRA) for this project.

It later received an additional $30 million from DOE through the ARRA for final engineering, design, construction, and project operation through September 2015. Air Products' project was the only industrial gas company led undertaking selected by DOE, and one of only three projects receiving additional funding towards a commercial demonstration project.

DOE has estimated that Air Products' Port Arthur Project will assist in the recovery of 1.6-3.1 million additional barrels of domestic oil annually. DOE's announcement stated that when an oil well begins "playing out," not enough oil is pumped to make it worthwhile to continue using the well, and the well is closed or "shut-in," even though much of the original oil in the field remains in the formation.

Several methods of enhanced oil recovery have been developed to recover this remaining oil, including pumping CO2 down to the oil reservoir. In the Port Arthur project, a monitoring, verification, and accounting program will ensure that the injected CO2 remains underground, safely and permanently trapped in the same geologic formation that confined the oil brought to the surface in the demonstration.

Air Products' Port Arthur hydrogen production facility hosting the CO2 project is part of its Gulf Coast hydrogen plant and pipeline supply network, the world's largest system of its kind, serving multiple refinery and petrochemical operations in the region. The pipeline stretches from the Houston Ship Channel in Texas to New Orleans, Louisiana.

In August it began supplying over 1.2 billion cubic feet of hydrogen per day to refinery and petrochemical customers. Air Products had operated two hydrogen pipeline systems in Texas and Louisiana before joining them with the new 180-mile segment. The 600-mile pipeline span is fed by over 20 Air Products hydrogen production facilities.

First tonne of CO2 captured at RWE npower pilot project

www.rwe.com

RWE npower's carbon capture pilot plant at Aberthaw Power Station in Wales, UK has commenced commissioning with live flue gas, successfully capturing its first tonne of CO2.

The plant pilots carbon capture technology designed by Cansolv Technologies (part of the Shell Group). When commissioning is complete, the plant will capture around 50 tonnes per day of CO2 from Aberthaw's flue gases (which equates to the amount of CO2 produced by 3MW of electricity generation).

The start of 2013 marked the launch of RWE Generation, a new pan-European approach to the management of RWE's power station fleet across Germany, the Netherlands and the UK. By the end of 2013, it is expected that Aberthaw will be the last of RWE npower's current fleet operating on coal.

Kevin Nix, Head of Hard Coal and Gas, UK, RWE Generation, said: "This pilot plant at Aberthaw will provide invaluable data on the viability of capturing carbon at an industrial scale, and help RWE to better understand how this technology could be used to reduce carbon emissions at coal-fired power stations."

Matthias Hartung, CEO, RWE Generation, said: "RWE now has more installed renewable energy capacity and a larger and more efficient gas-fired power station fleet than any other energy company in the UK, and has invested more into new energy technologies for Britain than anyone else over the last few years.

"The carbon capture pilot plant is another step on the road to giving us the choice of technologies we need to create a modern, efficient and diverse energy portfolio that is capable of guaranteeing continuity of supply, while reducing costs and carbon emissions."

During the R&D programme, RWE will optimise the performance of the technology, and use the facility to better understand the practical implications of operating a full-scale carbon capture facility in conjunction with normal power plant operations.

The environmental performance of the process will also be assessed, and during the programme RWE will be working with the Environment Agency to track and evaluate the environmental aspects of carbon capture technology for coal-fired power stations.

DNV KEMA launches CO2MPETENCY and risk management guidance

www.dnvkema.com/ccs

A new knowledge management component will help build and share competency around CO2 management and CCS projects, while the risk management guidance will help gain public confidence that CCS can be delivered in a safe and responsible manner through knowledge-based, consistent and robust hazard management

Two new components from DNV KEMA will help accelerate CCS development.

The new CO2MPETENCYservice supports:

- Learning in CO2 management projects: developing and implementing lessons learning at key milestones and critical points on the project timeline;

- Learning between CO2 management projects: enabling connections between projects and the identification, capture and sharing of good practices, joint problem solving and exchange of lessons learned between concurrent projects;

- Learning from CO2 management projects: the targeted capture, validation and dissemination of project knowledge to inform a wider community of practice and future projects.

The new risk management guidance, developed over 15 months through a joint industry project with support from 16 industry and regulator organizations, provides a comprehensive reference source for Carbon Capture and Storage (CCS) projects and operations across the world.

CO2MPETENCY

"Every day, in CO2 management and CCS projects around the world new experiences, lessons and solutions are developed. Some of this knowledge is documented and captured in systems; some of it is held by project staff, partners and contractors. Much of the knowledge is private and defines competitive advantage, but we believe that part of it will, when shared, benefit all of us," says Michael Carpenter, principal consultant at DNV KEMA's CCS Unit in Oslo, Norway.

According to Eelco Kruizinga, CO2MPETENCY project manager and principal consultant at DNV the new project learning service can help to "De-risk CCS by learning together how to manage the risks associated with capture, transport and storage of CO2 and to develop standards that define safe and economical industry practice; Accelerate technology development through sharing of what works and what doesn't, the CO2 management and CCS industry can advance more quickly through technology readiness levels in existing and new areas; Build public confidence through dissemination of the evidence gathered about the feasibility and safety of alternative CO2 management strategies, including CCS.

"Experience happens by itself, but learning from it at an organisational level requires a facilitated and systematic approach in order to become a reality. DNV KEMA has a unique methodology and track record for doing this and is well-positioned to support the CO2 management and CCS industries," adds Kaare Helle, business development manager at DNV KEMA's CCS Unit in Oslo, Norway.

"We do this through various means such as benchmarking performance of CCS activities to enable sharing and learning, capturing expertise to safeguard against knowledge loss and developing topical communities of practice," adds Helle.

Risk Management

In August 2011 DNV KEMA initiated the CO2 Risk Management (CO2RISKMAN) Joint Industry Project to develop a publicly-available guidance on major accident risk management of the carbon dioxide (CO2) stream within CSS projects. This guidance is now complete and provides the CCS industry with clear and comprehensive information to help in the development of effective CO2 risk management across the whole CCS chain from capture facilities through to underground injection.

"There is no reason why the major accident risks from a CO2 handling system within a CCS operation cannot be low and well within acceptable limits but to achieve this will require the application of existing rigorous hazard management processes combined with an adequate understanding of the properties and behaviours of CO2" says Hamish Holt CO2RISKMAN project manager, and principal consultant at DNV.

"A significant leak from a large inventory CO2 handling system has the potential to be life threatening to people caught within the ensuing dispersing cloud or could pose local environmental harm. In the same way as the risks from other better known hazards are managed, the risks from the CO2 stream also need to be well managed and the new guidance will help this happen," he adds.

Research may encourage low carbon innovation

www.cmc-nce.ca

Researchers in Canada are developing economic models that aim to reduce the economic costs associated with implementing policies to reduce carbon dioxide emissions and encourage low-carbon innovation.

A key goal of the project is to encourage low-carbon innovation by showing both the positive and negative impacts of policies.

"The idea is to try to develop some models regarding carbon policy that can tell a story from a sound academic basis rather than the extreme views on both sides," says one of the lead investigators, Dr. Randall Wigle, associate director of the PhD Program in Global Governance in the Department of Economics at the Balsillie School of International Affairs (BSIA) at Wilfrid Laurier.

Dr. Wigle and his team from BSIA, the University of Calgary and the University of Ottawa will receive $400,000 over two years from Carbon Management Canada (CMC-NCE), a national Network of Centres of Excellence supporting game-changing research to reduce CO2 emissions in the fossil energy industry as well as from other large stationary emitters. The award is part of CMC-NCE's third round of funding which saw a total of $3.75 awarded to eight projects.

Wigle and his team are using general equilibrium models to examine the multitude of factors that will be affected by a policies to reduce carbon dioxide emissions.

"You start from the simple things," he says. "Chemicals and refining and steel production are going to be affected a lot and the service sector won't be affected very much. We try to keep track of all these interrelations so we can give an answer at the end of the day."

The team, which includes University of Wisconsin-Madison Professor Tom Rutherford, an international leader in computational equilibrium modelling, will build on existing models supplied by Environment Canada.

"There are a number of features that are already in the model that we want to refine," says Wigle. "We are hoping to look at the impacts of alternative policy measures and the interaction of demographic change and Canada's fiscal change, as it relates to climate policy."

He says there are improvements in modeling techniques as well as better data available to help answer questions about the effects of carbon policy on the economy.

"With a modest carbon tax or, selling allowances at a very modest price—even if you sell a subset of the allowances at a pretty modest price—still you could be talking a fair amount of revenue, like billions."

TCM launches CCS test centre network

www.tcmda.com

CO2 Technology Centre Mongstad (TCM) has taken the initiative to form an international test centre network for carbon capture test facilities around the world to share knowledge to accelerate the commercialisation of technology.

The key aims of the CCS Test Centre Network are to share knowledge of technological developments, construction and operational experience, establish performance indicators, and promote technology standardization.

Overall the network will establish a level playing field for technology vendors to reduce costs, plus technical, environmental and financial risks associated with CCS.

CCS is the only technology that can significantly reduce CO2 emissions from fossil fuel combustion in power stations and industrial processes, by up to 90 per cent.

Commenting on the establishment of the test centre network, Tore Amundsen, CEO of Gassnova and Chairman of CO2 Technology Centre Mongstad, said:

"This is absolutely the right time to launch this knowledge sharing network. Every day, in test centres around the world, we see advancements in CCS technology with new experiences, lessons and solutions being developed. However, this knowledge is often not shared because there has been no appropriate forum for doing so. This network will change that for the benefit of everyone."

The eight founding members of the Test Centre Network are CO2 Technology Centre Mongstad (Norway), National Carbon Capture Center (Alabama, US), Southern Company's 25 megawatt CCS demonstration facility (Alabama, US), SaskPower,

J-Power (Japan), ENEL Engineering and Research (IT), E.ON (Germany) and Doosan Power Systems (UK). The Network is open for further large CCS test centers and therefore publicly invites them to join.

The key aims of the network are to:

1. Gain public confidence: enabling test centres to build on good practice from around the world and communicate successes to the public and wider CCS community.

2. Address regulator concerns: enabling test centres to individually address concerns of regulators and influence regulatory arenas by using the collective thinking and experience of network members.

3. Improve organizational efficiency: by providing members with a global network of experts and expertise to facilitate mutual problem solving around organisational issues.

4. Safeguard our people: by sharing good practice in Health, Safety and Environment (HSE), to protect staff, assets and the environment.

5. Accelerate technology development: By harmonising the testing requirements, the network will create a level playing field that will help break down barriers to successful uptake of capture technologies.

Summit Power and Linde to develop natural gas power plants with carbon capture

www.summitpower.com

Summit Power Group and The Linde Group have teamed up to develop commercial-scale natural gas-fired power plants that will capture up to ninety percent of the CO2 that would otherwise have been emitted.

The new power plants will combine well-established and commercially proven natural gas-fired power plant technology with proven carbon capture technology.

A typical gas-fired power plant with carbon capture developed by Summit and Linde will produce approximately 250 megawatts (MW) of net electric power, enough to provide electricity for 250,000 homes, and will capture up to 750,000 tons of CO2 annually.

"In the U.S. and abroad, the electric power sector is making a 'dash for gas,'" said Donald Paul Hodel, Summit's Chairman Emeritus and former U.S. Secretary of Energy. "Technology is ready to capture the CO2 that gas-fired power plants produce, and Summit, in partnership with Linde, is ready to develop those plants, just as Summit has developed thousands of megawatts of conventional gas-fired power plants in the past."

Both Summit and Linde are already active in developing power projects with CO2 capture where the CO2 can be either geologically sequestered in depleted gas fields and deep saline formations, or injected into depleting oilfields. Summit is currently developing two major coal gasification projects that will capture 90% of the CO2 they produce, namely the Texas Clean Energy Project (TCEP) in the United States and the Captain Clean Energy Project (CCEP) in the United Kingdom.

Linde is a major technology provider, engineering and construction contractor, and long-term operations and maintenance provider to TCEP. Based on their extensive cooperation, Linde and Summit are now expanding their focus to this new and promising field of natural gas based CO2 capture.

"Merely increasing reliance on natural gas is not a sufficient carbon-reduction strategy for the hydrocarbon sector of the global power industry," said Professor Dr. Aldo Belloni, member of the Executive Board of Linde AG. "It is still necessary, valuable, and eminently feasible to capture and geologically sequester the carbon dioxide that natural gas-fired plants would otherwise emit, just as it is with coal-based plants. Linde has the capability to achieve this and is ready to deploy it at commercial scale."

Outside the U.S., current carbon capture and sequestration (CCS) policies tend to favor depleted gas fields and deep saline formations as geological "sinks" for the captured CO2. However, in many U.S. oilfield locations the volume of CO2 captured from a typical natural gas-fired power plant can also be used to produce an additional 1.5 to 2.5 million barrels of oil per year.

Injection of CO2 for enhanced oil recovery (EOR) hence reduces CO2 emissions to the atmosphere as well as increases available oil reserves. Any CO2 that comes to the surface with the produced oil is re-compressed and re-injected, ultimately remaining trapped underground.

The resulting oil does not add to total world oil consumption or demand, but instead replaces the equivalent volume of oil produced by other means.

Summit and Linde have identified several suitable U.S. locations for this new type of power plant. Key locations are those where the ultra-low carbon electric power can be sold to utilities and large consumers, and suitable geological sequestration sites are available for the injection of CO2 underground. Revenue earned from the productive use of captured CO2, for example in oilfields, will reduce and in some cases may eliminate any environmental cost premium that CO2 capture imposes on power plants.

The two companies plan to announce their first such project in the coming months.

FutureGen 2.0 moves to Phase II

www.futuregenalliance.org

Following the successful completion of the first phase, the Energy Department today announced the beginning of Phase II of project development with a new cooperative agreement between the FutureGen Industrial Alliance and the Department of Energy.

In cooperation with the FutureGen project partners, the Department of Energy is investing in the upgrade of a coal-fired power plant in Meredosia, Illinois with oxy-combustion technology to capture more than 1 million tons of CO2 each year—more than 90 percent of the plant's carbon emissions. Other emissions will also be reduced to near-zero levels. Instead of capturing CO2 in the presence of a large amount of nitrogen, the oxy-combustion approach extracts the oxygen from air before combustion, greatly reducing the cost of carbon capture at the exhaust stack.

This project will test oxygen separation technology and exhaust processing technology after combustion at power plant scales. Using proven pipeline technology, the CO2 will then be safely transported and securely stored underground at a nearby storage site. This groundbreaking project will help pave the way for other cleaner and more sustainable advanced coal-burning power plants.

The completion of the FutureGen 2.0 project's first phase included important technical and financial milestones like the identification of a sequestration site in Morgan County, preliminary characterization and test drilling, and a commitment from the Illinois Commerce Commission to cover the FutureGen 2.0 project's output under its power purchasing plans.

The cooperative agreement announced with the FutureGen Industrial Alliance will build on these successes to begin preliminary design, pre-construction and engineering for the retrofitted, near-zero emission coal-fired power plant.

Capture and utilisation news

Carbon sponge could soak up coal emissions

www.monash.edu.au

Emissions from coal power stations could be drastically reduced by a new, energy-efficient material that adsorbs large amounts of carbon dioxide, then releases it when exposed to sunlight.

In a study published today in Angewandte Chemie, Monash University and CSIRO scientists for the first time discovered a photosensitive metal organic framework (MOF) – a class of materials known for their exceptional capacity to store gases. This has created a powerful and cost-effective new tool to capture and store, or potentially recycle, carbon dioxide.

By using sunlight to release the stored carbon, the new material overcomes the problems of expense and inefficiency associated with current, energy-intensive methods of carbon capture. Current technologies use liquid capture materials that are then heated in a prolonged process to release the carbon dioxide for storage.

Associate Professor Bradley Ladewig of the Monash Department of Chemical Engineering said the MOF was an exciting development in emissions reduction technology.

"For the first time, this has opened up the opportunity to design carbon capture systems that use sunlight to trigger the release of carbon dioxide," Associate Professor Ladewig said.

"This is a step-change in carbon capture technologies."

A promising and novel class of materials, MOFs are clusters of metal atoms connected by organic molecules. Due to their extremely high internal surface area - that could cover an entire football field in a single gram - they can store large volumes of gas.

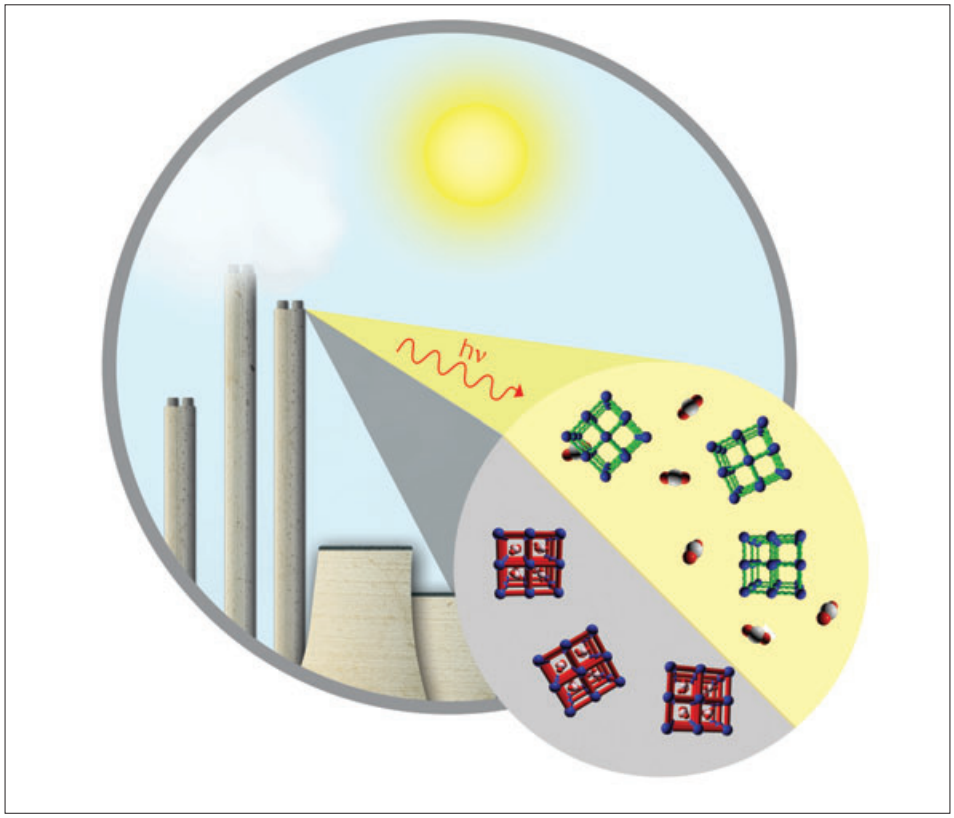
PhD student Richelle Lyndon and lead author of the paper said the technology, known as dynamic photo-switching was accomplished using light-sensitive azobenzene molecules.

"The MOF can release the adsorbed carbon dioxide when irradiated with light found in sunlight, just like wringing out a sponge," Ms Lyndon said.

"The MOF we discovered had a particular affinity for carbon dioxide. However, the light responsive molecules could potentially be combined with other MOFs, making the capture and release technology appropriate for other gases."

The researchers, led by Professor Matthew Hill of CSIRO, will now optimise the material to increase the efficiency of carbon dioxide to levels suitable for an industrial environment.

The study was supported by the Science and Industry Endowment Fund.



Monash University scientists have developed a material that traps CO2 and releases it when exposed to sunlight

Costain CCS projects financed through Government programme

www.costain.com

Costain has secured financial support from the Department of Environment and Climate Change (DECC) through a £20M programme for finding novel solutions to reduce the cost of carbon capture.

Costain has been selected to develop two innovative technologies which aim to reduce the cost of low-carbon electricity generation through reducing the cost associated with carbon capture, and will work in cooperation with renowned UK universities.

In collaboration with the University of Edinburgh, Costain will investigate a novel concept for the design and construction of cheaper absorber columns to be used for post-combustion carbon capture in coal and gas power plants.

An improved oxyfuel capture technology will also be developed together with the University of Edinburgh and the University of Leeds, which will study innovative carbon dioxide separation and compression technology.

Currently Costain is also developing unique next generation Carbon Capture technology together with the Energy Technologies Institute, which is expected to improve efficiencies and reduce capital cost for power generation in Integrated Gasification Combined Cycle power plants, while achieving a very high carbon capture rate of 95%.

CO2 Solutions receives $4.7 Million from Canadian government

www.co2solutions.com

The Harper Government has made a $4.7 million investment through the ecoENERGY Innovation Initiative to support the development of its carbon capture technology in the Alberta oil sands.

CO2 Solutions is developing carbon capture technology for use in oil sands production, including in-situ methods such as Steam Assisted Gravity Drainage (SAGD), and bitumen upgrading. Results from the project will also support the broader application of the Company's technology in other natural gas combustion sources, such as gas-

fired power plants. CO2 Solutions' management anticipates the overall cost of the project to be $7.5 million.

"This project will demonstrate our technology's ability to cost-effectively address a critical environmental challenge facing the oil sands," stated Glenn Kelly, President and CEO of CO2 Solutions. "The results from this project will also enable us to apply our technology to other large sources of natural gas combustion emissions, including the rapidly growing number of natural gas-fired power plants."

Unconventional oil production methods, such as SAGD used in the oil sands, have a somewhat higher carbon footprint than conventional oil production methods. Both industry and government are focused on ways to reduce emissions from the oil sands, with carbon capture being a key option. However, the cost of conventional carbon capture and sequestration systems is high for broad commercial deployment.

CO2 Solutions' says its technology lowers the cost barrier by taking advantage of a powerful naturally occurring enzyme, carbonic anhydrase which regulates CO2 management in all living organisms. The technology can be retrofitted to existing carbon capture systems as well as installed in new emissions sources.

Additional funds for the project are being obtained through grants from Alberta's Climate Change and Emissions Corporation (CCEMC), previously announced on October 31, 2012. The balance of the project's costs will be funded by CO2 Solutions and partnership capital from private entities.

Toolset for CCS computational modelling by U.S. Government

www.acceleratecarboncapture.org

A suite of 21 computational tools and models to help enable rapid development and deployment of new carbon capture technologies is now available from the Carbon Capture Simulation Initiative (CCSI).

The toolset developed by CCSI, a public-private partnership led by the Office of Fossil Energy's (FE) National Energy Technology Laboratory (NETL), will help meet an urgent need by industry to take carbon capture concepts from the laboratory to the power plant more quickly, at lower cost and with reduced risk.

The total cost savings that could be realized by using the CCSI toolset to scale up and widely deploy a carbon capture technology is estimated at approximately $500 million. The tools are expected to make it easier for U.S. utilities to meet carbon capture requirements if and when they are enacted and can help technology companies doing business in countries where controls are already in place.

Carbon capture, utilization and storage (CCUS) technologies are considered by many energy experts as an essential option for helping meet aggressive carbon dioxide (CO2) emission-reduction levels while allowing the continued use of coal, the largest source of electric power and an important component of economic growth.

The current release, available a year ahead of the original release date, includes tools to help identify promising concepts more quickly; reduce the time to design and troubleshoot new systems; and quantify the uncertainty of model predictions; as well as tools with new capabilities, such as creating reduced-order models from reacting multiphase flow simulations and running thousands of process simulations concurrently for optimization and uncertainty quantification.

The CCSI toolset works with commercial and open-source software currently in use by industry and includes new, highly versatile software tools developed to fill technology gaps. In addition to helping with carbon capture technologies, the tools can be used to accelerate technology development for refining, chemicals production and oil and natural gas production.

CCSI was formed to provide technology developers and plant operators a validated suite models and simulation tools that could dramatically reduce the 20-30 years of time usually required for commercial technology development. "The CCSI toolset delivers new capabilities for integrating multiscale modeling, optimization and uncertainty quantification, which will significantly impact the way carbon capture processes are developed," said NETL's David Miller, CCSI technical lead.

DOE sponsored project at Ohio University tests CCS with chemical looping

www.fossil.energy.gov

Researchers at The Ohio State University (OSU) have successfully completed more than 200 hours of continuous operation of their patented Coal-Direct Chemical Looping (CDCL) technology - a one-step process to produce both electric power and high-purity carbon dioxide (CO2).

The test, led by OSU Professor Liang-Shih Fan, represents the longest integrated operation of chemical looping technology anywhere in the world to date.

The test was conducted at OSU's 25 kilowatt thermal (kWt) CDCL combustion sub-pilot unit under the auspices of DOE's Carbon Capture Program, which is developing innovative environmental control technologies to foster the use of the nation's vast coal reserves. Managed by the Office of Fossil Energy's National Energy Technology Laboratory, the program's specific goal is to develop CO2 capture and compression technologies that can reduce the capital cost and energy penalty of CO2 capture by more than half—equivalent to CO2 capture at less than $40 per metric ton—when integrated into a new or existing coal fired power plant. The successful test moves chemical-looping a step closer to full scale.

Chemical looping is an advanced technology that offers several advantages over traditional combustion. In a chemical-looping system, a metal oxide, such as an iron oxide, provides the oxygen for combustion. The metal oxide releases its oxygen in a fuel reactor with a reducing atmosphere, and the oxygen reacts with the fuel. The reduced metal cycles back to an oxidation chamber where the metal oxide is regenerated by contact with air. The metal oxide is then reintroduced into the fuel reactor, thus completing the loop. Since CO2 separation occurs simultaneously with coal conversion, chemical looping offers a low-cost scheme for carbon capture. The process can produce power, synthesis gas, or hydrogen in addition to high-purity CO2.

OSU reports that the CDCL plant's 200+ hours of operation, using metallurgical coke and subbituminous and lignite coals, shows the robustness of its novel moving-bed design and non-mechanical valve operation. The combination resulted in nearly 100 percent solid fuel conversion and a CO2 stream more than 99 percent pure, making it applicable to CO2 enhanced oil recovery operations.

The OSU project is expected to benefit the DOE Carbon Capture Program by identifying oxygen carriers and a chemical looping process having the potential to control multiple pollutants, including sulfur dioxide (SO2) and nitrogen oxides (NOx), along with CO2. OSU research aims to identify potential barriers and optimize the CDCL technology and provide realistic data for future technological and economic analysis.

In addition to DOE, OSU is partnering on the project with the Ohio Department of Development, Babcock & Wilcox Power Generation Group, Inc., CONSOL Energy Inc., and Clear Skies Consulting LLC.

In a related project, DOE's National Carbon Capture Center in Wilsonville, Ala., will serve as the host site for the construction and operation of a fully integrated 250 kWt pressurized syngas chemical looping pilot unit starting this year.

Transport and storage news

National Grid sets date for UK drilling test programme

www.nationalgrid.com

National Grid has signed an Agreement for Lease with the Crown Estates to enable the UK's first carbon dioxide appraisal well to be drilled at a storage site in the southern North Sea 70km off Flamborough Head in Yorkshire.

The drilling will be the first ever offshore test of carbon dioxide storage potential in the UK and will start as early as May this year.

The saline aquifer site which is about 1km below the sea bed will initially support carbon capture and storage projects in the Yorkshire and Humber region – currently the area of the UK that produces most CO2.

"The appraisal drilling is the culmination of a three year work programme which has been largely funded by the EU and National Grid," said Jim Ward, Head of CCS at National Grid. "Our work to date has confirmed that the site is very large and capable of storing carbon dioxide from both power generation and industrial sources, including the Don Valley Power Project and the White Rose Project."

"The site is close to the shore, and importantly, near to the UK's largest clusters of carbon dioxide emitters, making it the ideal location to safely and permanently store carbon dioxide. The drilling will confirm the extent to which the site is capable of storing CO2 from regional power stations and industrial sites."

National Grid believes it will be much more cost effective to deploy CCS with a common, pipeline and storage infrastructure into which several carbon emitters in a region can connect – a so called 'cluster'. This view is also shared by DECC's CCS Cost Reduction Task Force.

Micro CT Scanner to further carbon capture research

www.curtin.edu.au

A new Micro CT Scanner installed at Curtin University in Australia will help researchers understand how CO2 behaves in geological reservoirs.

The capability of the scanner will be the most advanced in Australia for obtaining high-resolution physical detail of how CO2 and other greenhouse gases pass through a selected reservoir, at temperatures and pressures typical of greenhouse gas geo-sequestration conditions.

Professor Brian Evans, Director Oil and Gas Projects at Curtin and part of the National Geosequestration Laboratory Science Committee, said the scanner would allow researchers to determine more precisely the storage capacity and dependability of particular formations under a wide range of conditions.

"While Australia has completed first-class research in this area, there are still gaps in knowledge about the most technical aspects of geosequestration," Professor Evans said. "Precisely how CO2 moves when it interacts with certain porous rocks is not yet fully understood."

Dr Stefan Iglauer, from Curtin's Department of Petroleum Engineering, is leading the work on generating simulated reservoir conditions that will be integrated into the Micro CT scanner. He will study factors that influence CO2 geosequestration in a range of storage rocks in Australia.

"Understanding how CO2 moves and behaves at a high-resolution 3D micrometre-level will help to address some of the residual uncertainties around geosequestration, and thus improve public acceptance which is currently the main obstacle to large scale Carbon Capture and Storage implementation and CO2 emission reduction," Dr Iglauer said.

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Want to be at the forefront of the exploration of technologies to mitigate dangerous climate change? At the University of Edinburgh, we offer 2 Streams - Carbon Capture and Storage MSc & Carbon Capture and Storage (Engineering). This means that we can offer you the chance to really focus your studies on your unique areas of interest and career aspirations.

Why now? With commercial-scale demonstration projects being considered across the world and a number of companies in a broad range of industrial sectors developing increasingly large teams of people to develop and deliver these projects, now is the time to study this exciting, dynamic discipline!

Why Edinburgh? The University has strong links and affiliations with a range of organisations in the energy industry which offer support to the programme. Support has has included hosting site visits and research projects, providing guest lecturers, and granting bursaries.

What next? Graduates will be well-placed to pursue careers in: business, industry, government, NGOs (Stream 1) and low carbon energy production from fossil fuels through CCS and conventional power generation (Stream 2).

'I chose to come to the University of Edinburgh because it is the only place in the world to do an MSc in Carbon Capture and Storage. Am I glad I decided to come to Edinburgh? Absolutely! ... [Edinburgh] offers a FANTASTIC student experience. The facilities are good and the opportunity for a postgraduate student to get involved in the University life is great... Edinburgh is a beautiful place and there is something different to do every weekend. On the academic side, the department of GeoSciences offers brilliant industry links. The range of courses available to us is huge, from economics to thermodynamics... I am positive I made the right decision.'

Katie Vowles - MSc CCS 2010-11 (Technical Analyst at Gemcom Software International)

W: www.ed.ac.uk/geosciences/masters/ccs

THE UNIVERSITY of EDINBURGH

Status of CCS projects

The status of large-scale integrated projects data courtesy of the Global CCS Institute

For the full list, with the latest data as it becomes available, please download a spreadsheet at:
www.globalccsinstitute.com/data/status-ccs-project-database

Asset Lifecycle Stage	Project Name	Description
Operate	**Century Plant**	Occidental Petroleum, in partnership with Sandridge Energy, is operating a gas processing plant in West Texas that at present can capture 5 Mtpa of carbon dioxide for use in enhanced oil recovery. Capture capacity will be increased to 8.5 Mtpa in 2012.
Operate	**Enid Fertilizer CO2-EOR Project**	Since 1982, the Enid Fertilizer plant has sent around 680,000 tonnes per annum of carbon dioxide to be used in enhanced oil recovery operations in Oklahoma.
Operate	**Great Plains Synfuel Plant and Weyburn-Midale Project**	About 3 Mtpa of carbon dioxide is captured from the Great Plains Synfuel plant in North Dakota. Since 2000 the carbon dioxide has been transported by pipeline into Canada for enhanced oil recovery in the Weyburn Field, and since 2005 in Midale Field.
Operate	**In Salah CO2 Storage**	In Salah is a fully operational CCS project in Algeria. Since 2004, around 1 million tonnes per annum of carbon dioxide are separated from produced gas, transported by pipeline and injected for storage in a deep saline formation.
Operate	**Shute Creek Gas Processing Facility**	Around 7 million tonnes per annum of carbon dioxide are recovered from ExxonMobil's Shute Creek gas processing plant in Wyoming, and transported by pipeline to various oil fields for enhanced oil recovery. This project has been operational since 1986.
Operate	**Sleipner CO2 Injection**	Sleipner is the second largest gas development in the North Sea. Carbon dioxide is separated from produced gas at Sleipner T and reinjected into a deep saline formation above the hydrocarbon reservoir zone. This project has been in operation since 1996.
Operate	**Snøhvit CO2 Injection**	The Snøhvit offshore gas field and related CCS activities have been in operation since 2007. Carbon dioxide separated from the gas produced at an onshore liquid natural gas plant is reinjected into a deep saline formation below the reservoir zones.
Operate	**Val Verde Natural Gas Plants**	This operating enhanced oil recovery project uses carbon dioxide sourced from the Mitchell, Gray Ranch, Puckett, Pikes Peak and Terrell gas processing plants and transported via the Val Verde and CRC pipelines.
Execute	**Air Products Steam Methane Reformer EOR Project**	This project in construction will capture more than 1 million tonnes per year of carbon dioxide from two steam methane reformers to be transported via Denbury's Midwest pipeline to the Hastings and Oyster Bayou oil fields for enhanced oil recovery.
Execute	**Alberta Carbon Trunk Line ("ACTL") with Agrium CO2 Stream**	Agrium's fertiliser plant in Alberta is currently being retrofitted with a carbon dioxide capture unit. Around 585,000 tonnes per annum of carbon dioxide will be captured and transported via the Alberta Carbon Trunk Line (ACTL) for enhanced oil recovery.
Execute	**Alberta Carbon Trunk Line ("ACTL") with North West Sturgeon Refinery CO2 Stream**	Up to 1.2 million tonnes per annum of carbon dioxide will be captured at this new heavy oil upgrader in Alberta. In partnership with Enhance Energy, the carbon dioxide will be transported via the Alberta Carbon Trunk Line (ACTL) for enhanced oil recovery.
Execute	**Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project**	SaskPower is currently retrofitting a coal-based power generator with carbon capture technology near Estevan, Saskatchewan. When fully operational in 2014, this project will capture around 1 million tonnes per annum of carbon dioxide.
Execute	**Gorgon Carbon Dioxide Injection Project**	This component of a larger gas production and LNG processing project will inject 3.4 to 4.1 million tonnes of carbon dioxide per annum into a deep geologic formation. Construction is under way after a final investment decision was made in September 2009.
Execute	**Illinois Industrial Carbon Capture and Storage Project**	The project will capture around 1 million tonnes per annum of carbon dioxide from ethanol production. Carbon dioxide will be stored approximately 2.1 km underground in the Mount Simon Sandstone, a deep saline formation.
Execute	**Kemper County IGCC Project**	Mississippi Power (Southern Company) is constructing an air-blown 582 Mwe IGCC plant using a coal-based transport gasifier. Up to 3.5 million tonnes per annum of carbon dioxide will be captured at the plant and used for enhanced oil recovery.
Execute	**Lost Cabin Gas Plant**	This project will retrofit the Lost Cabin natural gas processing plant in Wyoming with CCS facilities, capturing around 1 million tonnes per annum of carbon dioxide to be used for enhanced oil recovery.
Execute	**Quest**	Quest will capture up to 1.2 million tonnes of carbon dioxide per annum from the Scotford upgrader, and transport it by pipeline for injection into a deep saline formation.
Define	**Belchatów CCS**	PGE EBSA intends to integrate a carbon capture plant into a new built 858 MW unit at the Bełchatów Power Plant, capturing around 1.8 million tonnes per annum of carbon dioxide.
Define	**Coffeyville Gasification Plant**	CVR Energy is developing a new compression facility at its fertiliser plant in Kansas. The plant currently produces approximately 850,000 tonnes of carbon dioxide which will be transported to the mid-continental region for use in enhanced oil recovery.

State / District	Country	Volume CO_2	Operation Date	Facility Details	Capture Type	Transport Length	Transport Type	Storage Type	Project URL
Texas	UNITED STATES	8.4 Mtpa	2010	Natural Gas Processing	Pre-Combustion (Gas Processing)	256 km	Onshore to onshore pipeline	Enhanced Oil Recovery	www.oxy.com/
Oklahoma	UNITED STATES	0.68 Mtpa	1982	Fertiliser Production	Pre-Combustion	225 km	Onshore to onshore pipeline	Enhanced Oil Recovery	www.kochfertilizer.com/
Saskatchewan	CANADA	3 Mtpa	2000	Synthetic Natural Gas	Pre-Combustion	315 km	Onshore to onshore pipeline	Enhanced Oil Recovery	www.cenovus.com/
Wilaya de Ouargla	ALGERIA	1 Mtpa	2004	Natural Gas Processing	Pre-Combustion (Gas Processing)	14 km	Onshore to onshore pipeline	Onshore Deep Saline Formations	www.insalahco2.com/
Wyoming	UNITED STATES	7 Mtpa	1986	Natural Gas Processing	Pre-Combustion (Gas Processing)	190 km	Onshore to onshore pipeline	Enhanced Oil Recovery	www.exxonmobil.com
North Sea	NORWAY	1 Mtpa	1996	Natural Gas Processing	Pre-Combustion (Gas Processing)	0 km	Direct injection	Offshore Deep Saline Formations	www.statoil.com/en/
Barents Sea	NORWAY	0.7 Mtpa	2008	Natural Gas Processing	Pre-Combustion (Gas Processing)	152 km	Onshore to offshore pipeline	Offshore Deep Saline Formations	www.statoil.com/en/
Texas	UNITED STATES	1.3 Mtpa	1972	Natural Gas Processing	Pre-Combustion (Gas Processing)	132 km	Onshore to onshore pipeline	Enhanced Oil Recovery	www.exxonmobil.com/
Texas	UNITED STATES	1 Mtpa	2013	Hydrogen Production	Post-Combustion	101 – 150 km	Onshore to onshore pipeline	Enhanced Oil Recovery	www.airproducts.com/
Alberta	CANADA	Up to 0.59 Mtpa (initially 0.29	2014	Fertiliser Production	Pre-Combustion	240 km	Onshore to onshore pipeline	Enhanced Oil Recovery	www.agrium.com/
Alberta	CANADA	1.2 Mtpa	2015	Oil Refining	Pre-Combustion	240 km	Onshore to onshore pipeline	Enhanced Oil Recovery	www.northwestupgrading.com/
Saskatchewan	CANADA	1 Mtpa	2014	Power Generation	Post-Combustion	100 km	Onshore to onshore pipeline	Enhanced Oil Recovery	www.saskpower.com/
Western Australia	AUSTRALIA	3.4 - 4.1Mtpa	2015	Natural Gas Processing	Pre-Combustion (Gas Processing)	7 km	Onshore to onshore pipeline	Onshore Deep Saline Formations	www.chevronaustralia.com
Illinois	UNITED STATES	1 Mtpa	2013	Chemical Production	Industrial Separation	1.6 km	Onshore to onshore pipeline	Onshore Deep Saline Formations	www.adm.com/
Mississippi	UNITED STATES	3.5 Mtpa	2014	Power Generation	Pre-Combustion	75 km	Onshore to onshore pipeline	Enhanced Oil Recovery	www.mississippipower.com/
Wyoming	UNITED STATES	1 Mtpa	2013	Natural Gas Processing	Pre-Combustion (Gas Processing)	Not specified	Onshore to onshore pipeline	Enhanced Oil Recovery	www.conocophillips.com/
Alberta	CANADA	1.08 Mtpa	2015	Hydrogen Production	Pre-Combustion	84 km	Onshore to onshore pipeline	Onshore Deep Saline Formations	www.shell.ca/
Łódź	POLAND	1.6 - 1.8 Mtpa	2017	Power Generation	Post-Combustion	101 – 150 km	Onshore to onshore pipeline	Onshore Deep Saline Formations	www.bot.pl/
Kansas	UNITED STATES	0.85 Mtpa	2013	Fertiliser Production	Pre-Combustion	112 km	Onshore to onshore pipeline	Enhanced Oil Recovery	www.cvrenergy.com/

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