Carbon Capture Journal

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Norway breaks vicious cycle of inaction on CCS deployment

Bellona says that thanks to its consistent efforts the Norwegian government has decided to move forward with the country's three CO2 capture projects.

The capture projects represent three different industries: Yara, the world's largest ammonia production company, Norcem, Norway's sole cement producer, and Oslo's waste management and energy recovery CCS project Klemetsrud. This will thus add immense value for the development of CO2 capture technologies in Norway and throughout the EU.

Bellona has fought for the development of CO2 capture and storage in Norway and Europe for more than 20 years in order to deeply decarbonise industry and has insisted on the solution that the Ministry has now chosen to go for in a report from March 2015.

"Today's decision marks a historic milestone and an end to a vicious cycle that has been putting on hold progress towards the commercialisation of CCS technology in the EU" comments Jonas Helseth, Director of the Bellona's EU Office in Brussels.

Norway certainly holds the key to decarbonising European industry in that the Norwegian North Sea can store European CO2 emissions through the fossil age. The CCS project at hand aims at developing large facilities that can provide CO2 storage way beyond Norway's needs.

Lack of suitable storage sites has been a frequently used excuse for inaction with regards to CO2 storage and investment in CCS technology across the EU. Norway's move will help to break this cycle.

Ensuring an accessible storage for CO2 helps to remove much of the counterparty risk and thus makes an EU project much more likely. Not least this will significantly improve chances of funding for a CCS projects under the EU's Innovation Fund. Remaining below the 1.5 degree target will require the rest of the EU to follow in Norway's footsteps.

"It's our opinion that moving the CO2 capture focus from power production to traditional industry was absolutely the right choice for Norway" notes Helseth.

CCS: attaining climate goals, while retaining Europe's industrial base

Limiting global temperature rise below 1.5°C as agreed under the Paris Agreement will to a large extent depend on tackling emissions stemming from energy intensive industries which today account for one fifth of Europe's total emissions. Because energy-intensive industries including steel, cement and chemicals are reaching theoretical efficiency limits, the application of CCS technology currently constitutes the sole means to substantially reduce their emissions – and attain deep decarbonisation of these important industries.

When it comes to steel for example, at present the EU hosts 500 production sites, split between 23 EU countries which provide 328 000 direct jobs. In Europe one tonne steel produced emits ~ 1.3 tonnes of CO2. Deployment of CCS will be crucial for retaining these jobs and achieving deep cuts in emissions cost effectively.

Enhanced collaboration between Member States and regions to connect key emissions clusters to the storage hubs will help to further reduce the costs of deploying the vital technology.

What comes next?

Now it will be up to the next government to invest in full scale capture, transport and storage as the investment decision has been postponed until after next year's Parliamentary election. The plan is that Norway's commitment to at least one full scale CCS plant will be realised by the end of 2022.

Bellona's Brussels office too is actively working to bridge the gap between the EU's climate goals and industrial competitiveness. Next month Bellona will be hosting a report launch conference where speakers from European industry, labour unions and regional and European policy makers will describe their approach to enabling decarbonisation of industry, while maintaining competitiveness and advancing investment.

Report launch

On October 13, Bellona launched its report "Manufacturing our Future: Industries, European Regions, and Climate Action". The report concludes that Industrial CO2 Capture, Use and Storage (iCCUS) technologies provide a critical and cost-effective solution to reaching Europe's climate goals.

However, current EU and national policies have so far not given the needed signals for European industry to invest in CCUS projects, and more importantly, very few plans exist to put in place an enabling infrastructure for strategic industries. A societally and climactically disastrous choice is emerging: to decarbonise, or to retain industrial production and employment: This is a false choice.

"A change in approach is required to enable the decarbonisation of strategic European industries" notes Keith Whiriskey, Climate Technologies Manager at Bellona Europa and co-author of the report.

This new report outlines concepts for making industrial decarbonisation infrastructure and projects investible in Europe in the short term. Given the lead times for developing CO2 storage and transport solutions, Europe has no time to lose.

More information

www.bellona.org

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Front cover:

Toshiba's CO2 capture plant in Saga city, Japan. The installed plant has the capacity to capture 10 tons of CO2 per day from the flue gas of the waste incinerator

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Toshiba's CCS activities in Japan

Toshiba has been operating the Mikawa Post Combustion Capture pilot plant since 2009 and is now part of a major five year Government project to demonstrate sustainable CCS technology with a larger plant at the site, which will capture half of Mikawa's daily emissions. The technology is also already being used commercially at a waste incineration plant in Saga, Japan.

By Kensuke Suzuki, Toshiba Corporation

To provide solutions to the growing global needs for lower carbon emissions from thermal power plants, Toshiba Corporation's Thermal & Hydro Power Systems & Services Division started activities in the field of CCS in 2008.

In order to bridge the fruits of preceding R&D work to actual practical application and solution which could be presented and proposed to our potential customers, Toshiba first constructed its own carbon capture pilot plant facility at Mikawa Power Plant (49 MW coal fired power plant situated in Fukuoka, Japan, owned and operated by Toshiba subsidiary Sigma Power Ariake Co., Ltd.)

The pilot plant employs post combustion capture technology based on chemical absorption process. Using chemical absorbents which selectively capture CO2 in the flue gas at a certain condition in the absorber tower, and release it under a different condition in the stripper tower, CO2 is continuously separated from the flue gas of the thermal power plant.

Toshiba's CO2 capture plant in Saga city, Japan. The installed plant has the capacity to capture 10 tons of CO2 per day from the flue gas of the waste incinerator

The Mikawa Post Combustion Capture Pilot Plant was completed and commenced its operation in September 2009. Facility is capable of capturing 10 tons of CO2 per day from live flue gas of the coal fired Mikawa Power Plant, enabling verification of the performance, operability, maintainability of the technology employed.

Up to present, the pilot plant has accumulated more than 10,000 hours of operation on live flue gas (as of October 2016). During this time, verification of improvements made on the solvent system and required plant configuration, etc. has been conducted here continuously.

While normal testing at the plant is conducted using coal fired flue gas with 11 to 13% CO2 concentration, the pilot plant has been modified to enable recirculation of flue gas exiting the absorber tower (with low CO2 concentration) to the inlet of absorber. This enables dilution of the flue gas with CO2 concentration down to around 4%, which is similar to that of a natural gas fired combined cycle.

In addition, modification was also made on the stripper tower, whereby gas exiting the tower (with almost 100% CO2 concentration) is recirculated to the inlet of the absorber. This enables enrichment of the flue gas with CO2 concentration of around 30%, which is similar to that of some of the emissions from steel works.

Provided with this flexibility in testing and verification, the learning here at the pilot plant is widely leveraged and applied to planning of various carbon capture plant projects utilizing this technology, each with different customer needs.

From 2014 to 2015, Toshiba had been selected to work with Japan's Ministry of the Environment (MOE) under their "Feasibility Study for the Introduction of Sustainable CCS Technology". As part of this work which covers many aspects of the CCS chain, Toshiba was responsible for the investigation of the qualitative and quantitative aspects of amine emissions (amine as constituent of chemical absorbent and its degradation products) in the treated flue gas from outlet of absorber.

Toshiba utilized the capabilities of the Mikawa Post Combustion Capture Pilot Plant to support this work for MOE, and data and learnings gained here is to be utilized for providing guidance and direction regarding environmental impact assessment of this carbon capture technology.

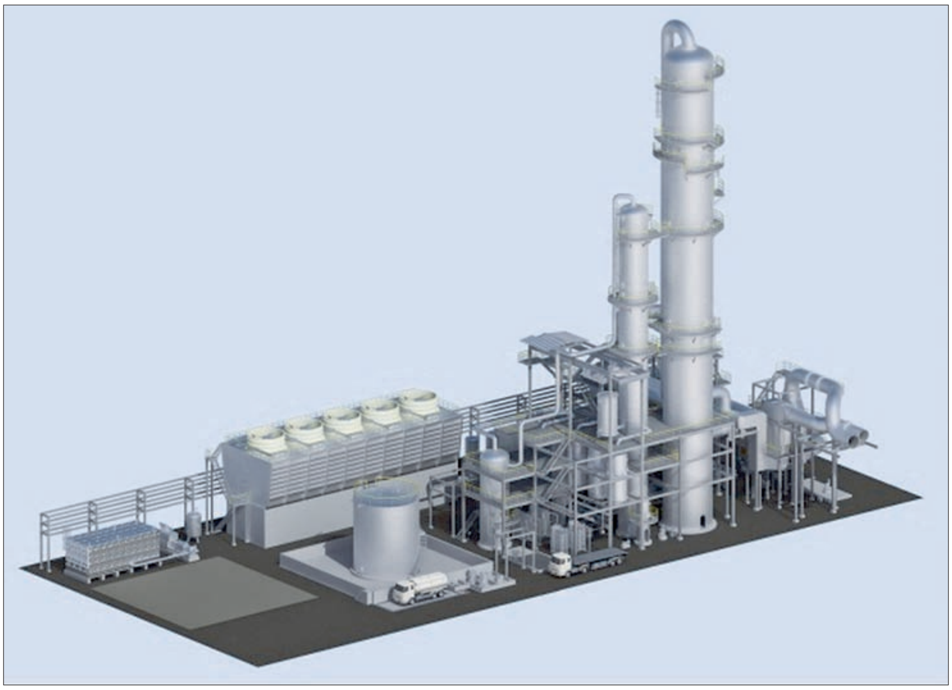
Through this activity, two very notable facts have become evident.

The first is about the learnings on the forms of amine emission. One form of emission comes in the shape of vapor, and the other as mist. Although every amine compounds included in the flue gas take the shape of these two forms, the existing ratio of these forms differs depending on the kind of amine compounds used, and is strongly affected by their characteristics, especially their vapor pressures. It has become clear that amine emission which comes in mist form is not easily separable by conventional methods such as water washing using packing beds.

The second is about the origin of amine mists. Using continuous aerosol counter and PTR-MS amine analyzer, the strong correlation between aerosol density at the inlet of absorber, aerosol density at the outlet of absorber, and amine concentration at the outlet of absorber has become clear. It has been confirmed also that fluctuation tendencies of the average aerosol size at the inlet of absorber (in nm-order size) and that at the outlet of absorber (in nm-order size) match well with each other. These facts indicate that the aerosol at the inlet of absorber act as nuclei of amine mist generated in the absorber.

Based on these findings and learnings, in July 2016, Toshiba along with Mizuho Information & Research Institute, and 11 other entities have been selected to carry out a major five-year project, the "Demonstration of Sustainable CCS Technology Project" sponsored by MOE. Under this project, Toshiba will construct a carbon capture facility designed to capture more than 500 tons of CO2 per day from the Mikawa Power Plant. This accounts to about 50% of its daily emissions.

The project will run from 2016 to 2020 and the technology's performance, cost and environmental impacts will be evaluated. The consortium led by the two companies will investigate an environmental impact assessment method for CCS, and use the results to develop policies and the framework necessary for the smooth introduction and deployment of CCS in Japan.



The carbon capture demonstration plant design

In addition, the Mikawa Power Plant is now being retrofitted to accommodate both coal- and biomass-fired power generation. When the demonstration facility is completed in 2020, it is likely to become one of the world's first power plants equipped with a large-scale carbon capture demonstration facility capable of capturing carbon dioxide from a biomass power plant.

In August 2016, Toshiba announced completion and commencement of a commercial-use post combustion carbon capture system applied to a municipal waste incineration plant in Saga, Japan. It is a first-of-a-kind application of the technology to the waste incineration process. The installed plant has the capacity to capture 10 tons of CO2 per day from the flue gas of the waste incinerator. The captured CO2 here is sold by the City of Saga to businesses in the area for use in crop cultivation and algae culture (Carbon Capture and Utilization).

Prior to the construction of this commercial plant, Toshiba installed a small pilot and test CCU system in the Saga plant in October 2013. This test system collected more than 8,000 hours of operational data on flue gas of the waste incinerator, which was used for verification of high purity separation and capture of CO2 that can be provided to agriculture, the cost of the capture operation.

The test findings confirmed that CCU system's separation and capture mechanism works with plant-specific flue gas impurities. These findings and results, together with the know-how and expertise gained at the Mikawa Pilot Plant, led up to the construction of the commercial plant.

Based on experience gained at the pilot plant as well as other commercial applications, Toshiba's Thermal & Hydro Power Systems & Services Division will continue to promote the expansion of high performance capture technology and its application not only inside Japan, but to the global market, with aims to build a low-carbon system that integrates this technology into high-efficiency thermal power plants.

More information

www.toshiba.co.jp

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I²CNER - efforts to achieve effective, safe CO2 storage

The International Institute for Carbon-Neutral Energy Research (I²CNER) is studying CO2 behavior from molecular to field scale to achieve better CO2 storage.

By Takeshi Tsuji, CO2 Storage Division, I²CNER, Kyushu University

CO2 storage division at I²CNER

At the CO2 Storage Division of I²CNER, we develop methods to characterize CO2 injection reservoirs to allow pre-injection site selection and post-injection predictions of the fate of CO2. We also monitor injected CO2 to help ensure safe and permanent CO2 sequestration.

To accomplish these goals, we are pursuing fundamental research to elucidate CO2 behavior over a wide range of scales (Figure 1). In particular, we are studying the influence of molecular-scale (or pore-scale) characteristics on field-scale CO2 behavior; i.e., determining the relationships between multi-scale phenomena. For example, the wettability of each mineral calculated at the molecular scale could influence the kilometer-scale CO2 behavior in a reservoir.

Here we report our recent work on the characterization of CO2 behavior from molecular to field scale.

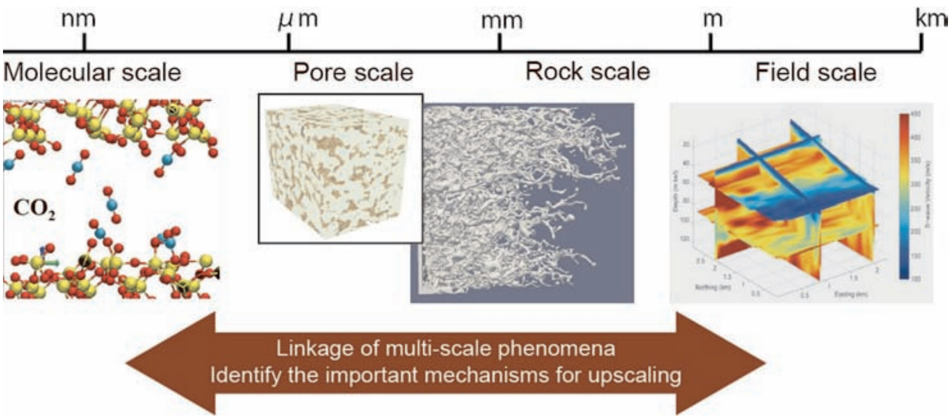

Figure 1. Injected CO2 behavior from the molecular scale to the field scale. We aim to understand the relationships between multi-scale phenomena

Molecular to pore scale

Modeling of CO2 mineralization

Mineralization (i.e., geochemical CO2 trapping) is considered a safe way to store CO2. This trapping mechanism converts CO2 to insoluble minerals (e.g., CaCO3) via geochemical interactions with rock and formation water.

It was believed until recently that CO2 mineralization takes several hundreds to thousands of years. However, the Iceland-based pilot project demonstrated that CO2 mineralization takes less than two years in basaltic rock. We have revealed the microscopic mechanism of mineralization through first-principles calculations (ab initio molecular dynamics simulations).

To do this, we calculated the reaction process between supercritical CO2 and host rock (e.g., igneous rock), and showed how carbonate ions () are generated on the surface of the host mineral (Figure 2). If suitable cations (e.g., Ca2+ or Mg2+) are present in the vicinity of , insoluble carbonate minerals will form. These kinds of cations are abundant in igneous rocks like basalt.

We have also investigated fluid mixtures of CO2 and hydrogen sulfide (H2S) by a similar approach because H2S is a major concomitant geothermal gas of CO2. The overall cost of CO2 capture and storage (CCS) could be lowered substantially by injecting a mixture rather than pure CO2.

This research provided microscopic insights into geochemical trapping of CO2. Our molecular dynamics simulations also revealed interfacial properties, such as wettability, of the fluid mixtures.

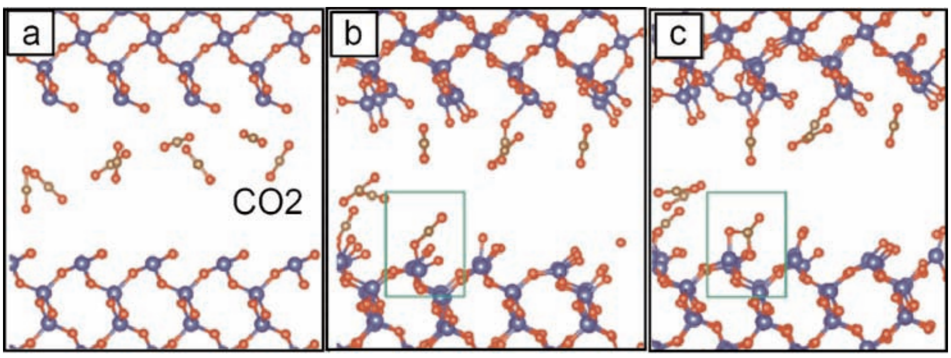

Figure 2. Example of an ab initio molecular dynamics simulation of a supercritical CO2 reaction, showing snapshots after (a) 0 fs (initial configuration), (b) 594 fs, and (c) 750 fs. The green frames in (b) and (c) indicate formation of ion

Accurate porous flow characterization by considering slip flow at the fluid–solid interface

Hydrological properties such as permeability play a major role in determining the storage capacity of a geological site. The typical length scale of pores available in these sites is of the order of a few micrometers. At this small scale, the slip effect starts to appear at the fluid–solid interface and affects the permeability of the rock.

We incorporated the slip effect into a lattice Boltzmann simulation by using a diffusively reflecting solid wall boundary condition. We used a simple homogeneous porous medium to validate that this boundary condition was capable of reproducing the effect of slip (Figure 3a).

An increased slip velocity inside the pore throat was obtained upon using an appropriate diffusively reflecting boundary condition (right in Figure 3a) compared with that using the conventional boundary condition (left in Figure 3a).

To evaluate the extent of the influence of slip on bulk properties like permeability, we calculated the permeability with different Knudsen numbers (Kn). Kn is defined as the ratio of the molecular mean free path to characteristic macroscopic length, and is inversely related to pore size. The rise in slip velocity results in increased permeability with decreasing pore size (Figure 3b). This effect is generally not considered in conventional numerical methods.

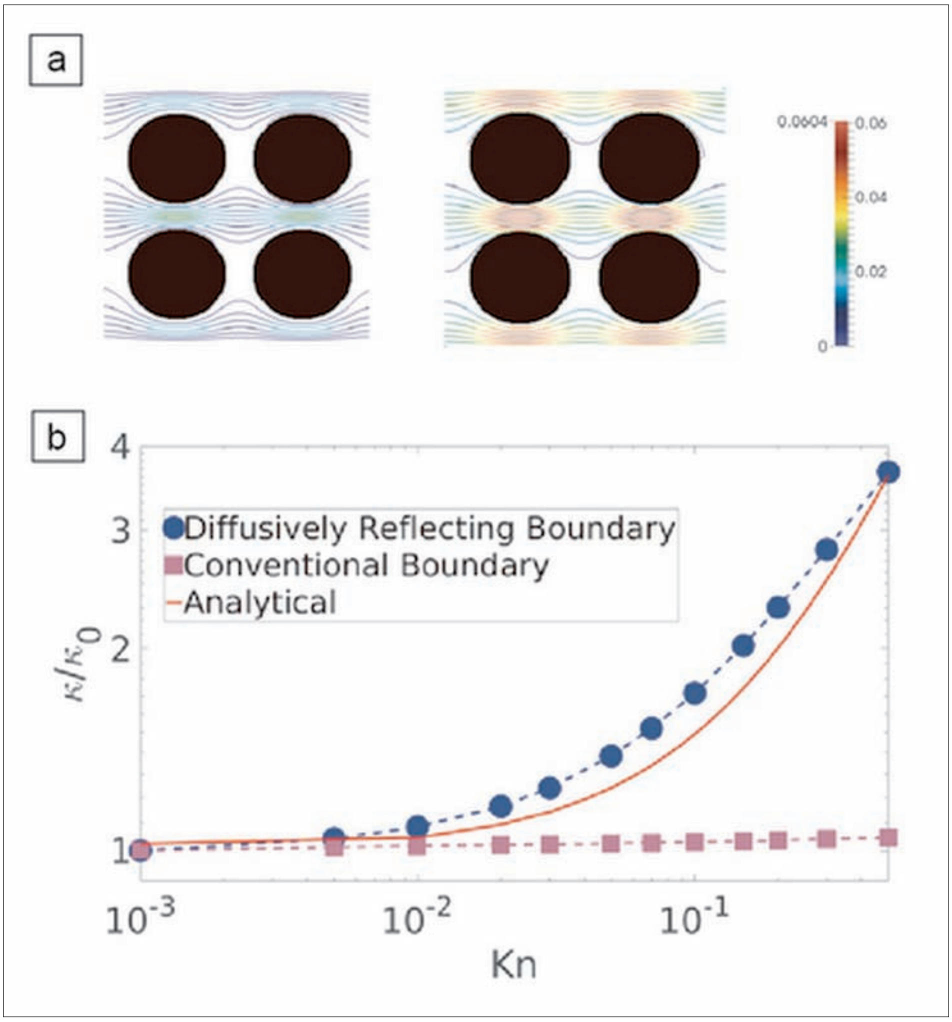

Figure 3. (a) Steady-state streamlines and fluid velocity using (left) a conventional boundary condition and (right) our boundary condition considering slip. (b) Permeability correction factor (κ/κ0) with respect to Knudsen number (Kn). The permeability predicted from our analysis agrees with analytical one

Pore to rock scale

Identifying suitable reservoir conditions for effective, safe CO2 storage

We have tried to identify suitable reservoir conditions (e.g., pressure) for effective, safe CO2 storage. The behavior and saturation of CO2 in a reservoir is influenced by many reservoir parameters, including the viscosity and density of the fluids, interfacial tension, pore structure, and other porous medium characteristics like wettability and surface roughness. Therefore, it is challenging to identify suitable conditions for CO2 storage.

We calculated CO2 displacements in 3D natural sandstone under various conditions using two-phase lattice Boltzmann simulations, and characterized the influence of reservoir conditions on CO2 and water flow (Figure 4a) [1]. The results of simulations conducted under more than 50 combinations of conditions were used to classify the resulting two-phase flow behaviors into typical fluid displacement patterns in plots of capillary number (Ca) against the viscosity ratio of CO2 to water (M). In addition, the saturation of the non-wetting phase (CO2) was calculated and mapped on the Ca–M diagrams.

In CCS, we should consider the domain of $M < 1$ (the areas indicated by red rectangles in the bottom panels of Figure 4). Our results demonstrated that CO2 saturation is controlled by Ca and M, and the optimum CO2 saturation scales with Ca and M (bottom of Figure 4a).

Similar analysis of a different type of rock (2D homogeneous model in Figure 4b) revealed that its CO2 saturation and behavior were quite different from those of 3D natural rock. These important differences between two-phase flow in 3D natural rock and the 2D homogeneous model could be caused by the heterogeneity of pore geometry and differences in pore connectivity.

Our approach provides useful information to determine suitable reservoir conditions for effective CO2 storage (e.g., high CO2 saturation) by quantifying CO2 behavior in a target reservoir rock under various conditions (i.e., saturation mapping on the Ca–M diagram).

Quantifying CO2 saturation in reservoirs from monitoring data

Time-lapse seismic surveys are suitable to monitor CO2 distributions within reservoirs, but it is difficult to quantify CO2 saturation from time-lapse seismic data. To estimate CO2 saturation from seismic velocity, the relationship between CO2 saturation and seismic velocity must be determined (Figure 5a). However, this relationship is difficult to quantify because the response of seismic velocity to CO2 saturation is affected by multiple factors, and is also influenced by the CO2 distribution in the pore spaces of rock (see Figure 4). Therefore, quantitative monitoring requires both hydrological and geophysical approaches.

We evaluated the influence of CO2 behavior within rock pores on the relationships between seismic velocity and CO2 saturation (Figure 5a) [2]. We conducted two computational studies with different injection pressures using (1) a two-phase lattice Boltzmann method to simulate CO2 injection (i.e., hydrologic simulation) and (2) wave propagation simulation with a finite difference approach to evaluate seismic velocity (i.e., elastic simulation).

We identified a difference in the relationships between seismic velocity and CO2 saturation in a few cases; i.e., lower seismic velocity was observed when Ca was high than when Ca was low at the same saturation (Figure 5a).

The difference in velocity response to CO2 saturation was controlled by CO2 distribution features. Ca (or the pressure gradient) depends on the distance from the injection well (Figure 5b). Low Ca values are expected far from the injection well and high ones near the well.

This study demonstrated that Ca at each reservoir location should be considered to accurately estimate CO2 saturation from seismic monitoring data.

Rock to field scale

Reservoir characterization in high resolution (application to the Tomakomai CCS project)

Geological heterogeneity influences CO2 behavior in reservoirs. In particular, if there are localized fractures in CO2 storage sites, they may behave as CO2 leakage paths. To detect localized heterogeneity in high resolution (i.e., downscaling), we developed an advanced seismic processing method using surface waves [3].

Our method allowed us to characterize local heterogeneity by integrating S-wave velocity and attenuation. We applied the method to 3D seismic data acquired at the Tomakomai CO2 storage site, Japan, and successfully extracted a high-resolution S-wave velocity structure and attenuation coefficient (Figure 6b and c, respectively).

From these results, we identified a geological boundary developed for northwest–southeast direction. This was the first demonstration of using surface waves to identify a 3D S-wave velocity distribution in a CO2 storage site.

Because the S-wave velocity reflects the strength of a formation, the estimated S-wave velocity distribution can be used to evaluate lithology strength for geomechanical simulation (prevention of a CO2 injection-induced earthquake).

The estimated heterogeneity also provides vital information for CO2 geological storage,

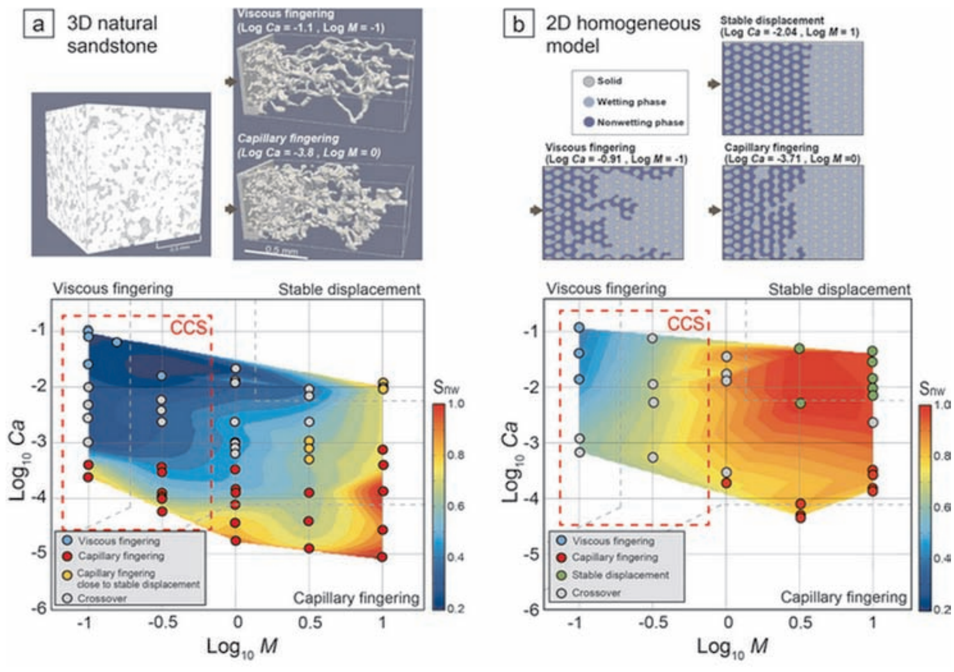

Figure 4. (a) 3D pore geometry of natural sandstone (top left), and CO2 behavior in 3D natural sandstone under viscous fingering and capillary fingering regimes (top right). The bottom panel shows the displacement pattern and CO2 saturation plotted on a diagram of capillary number Ca against viscosity ratio M [1]. The dots indicate the calculation conditions. The color map on the phase diagram shows the CO2 saturation. (b) CO2 behavior in the 2D homogeneous pore model under different conditions (top). The displacement pattern and CO2 saturation for the 2D homogeneous pore model are plotted on a diagram of Ca against M (bottom)

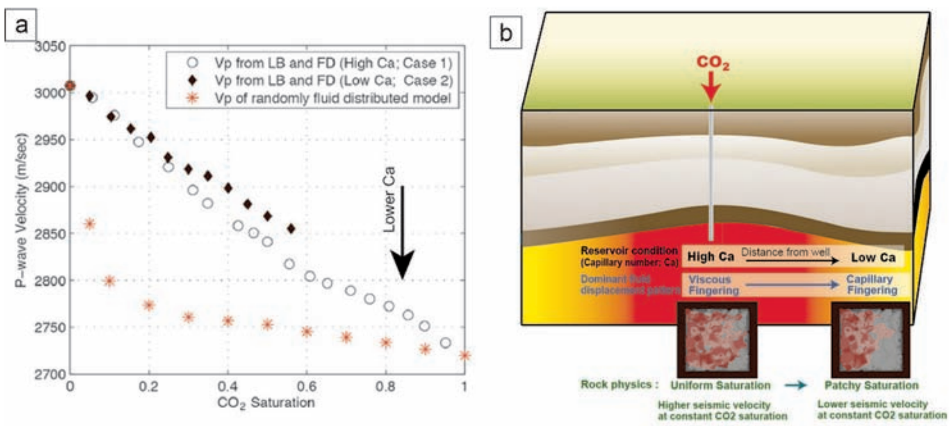

Figure 5. (a) Relationship between seismic velocity and CO2 saturation at different capillary numbers Ca [2]. These relationships were calculated by lattice Boltzmann method fluid flow simulations and dynamic wave propagation simulations. Circles indicate the results for higher Ca and diamonds those for lower Ca. Red asterisks show results for randomly distributed models. (b) Injected CO2 behavior under different reservoir conditions (Ca)

such as evaluation of CO2 leakage paths and permeability heterogeneity used in reservoir simulation.

Continuous, accurate monitoring system for injected CO2

In CCS, monitoring of injected CO2 is crucial to (a) predict the risk of CO2 leakage from storage reservoirs, (b) increase the efficiency of CO2 injection and lower its cost, and (c) lower the risk of injection-induced seismicity.

Time-lapse seismic surveys have been used to monitor the distribution and migration of injected CO2. However, the monitoring interval in time-lapse surveys is usually long because of the high cost of monitoring; it is generally too expensive to continuously monitor the injected CO2. However, continuous monitoring of dynamic CO2 behavior is crucial to detect incidents associated with CO2 injection (e.g., leakage).

We developed a seismic monitoring system using a continuous, controlled seismic source (Figure 7a) [4]. Our system monitored the shallow subsurface through temporal variation of surface-wave velocity.

Compared with conventional monitoring, our system is cost-effective with high temporal resolution and accuracy. Field experiments showed that hourly variation of surface-wave velocity could be monitored with better than 1% accuracy (Figure 7b).

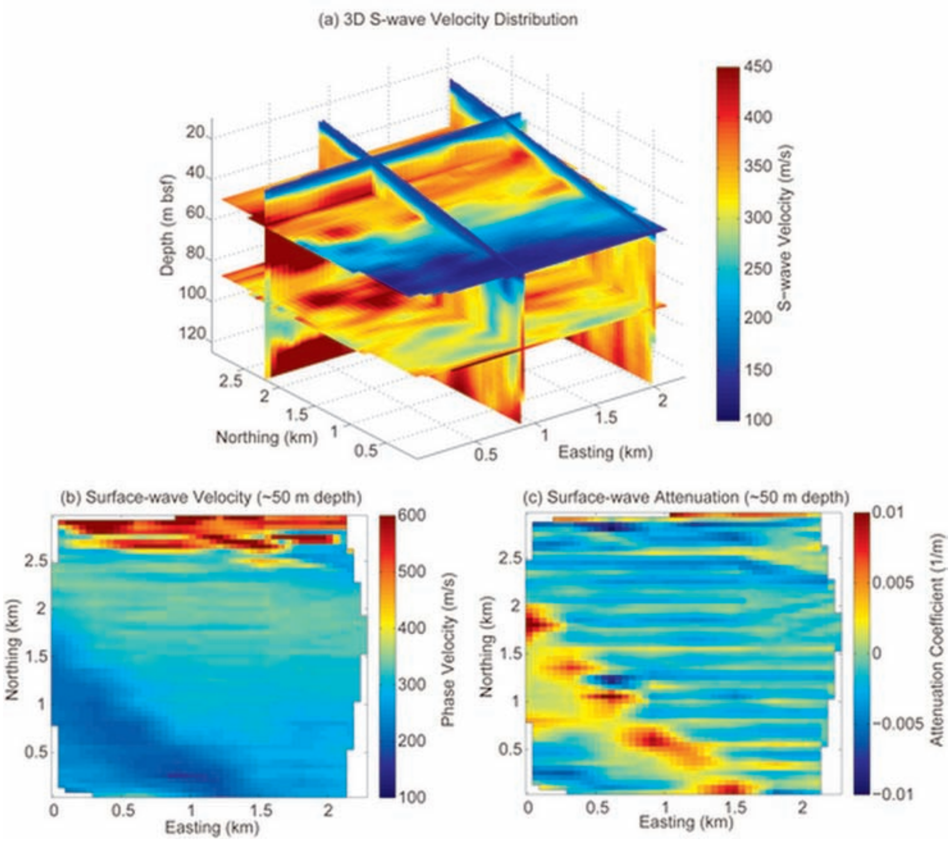

Figure 6. (a) The estimated 3D S-wave velocity model for the Tomakomai CO2 storage site. Horizontal slices (map views) of the estimated (b) surface-wave velocity and (c) attenuation ~50 m below the seafloor [3]

This temporal stability provides the possibility to detect changes in seismic velocities associated with CO2 leakage through fault zones. Recently, we used this monitoring system in the Aquistore CCS project in Canada, and clearly identified seasonal variation associated with the degree of freezing in shallow sediments.

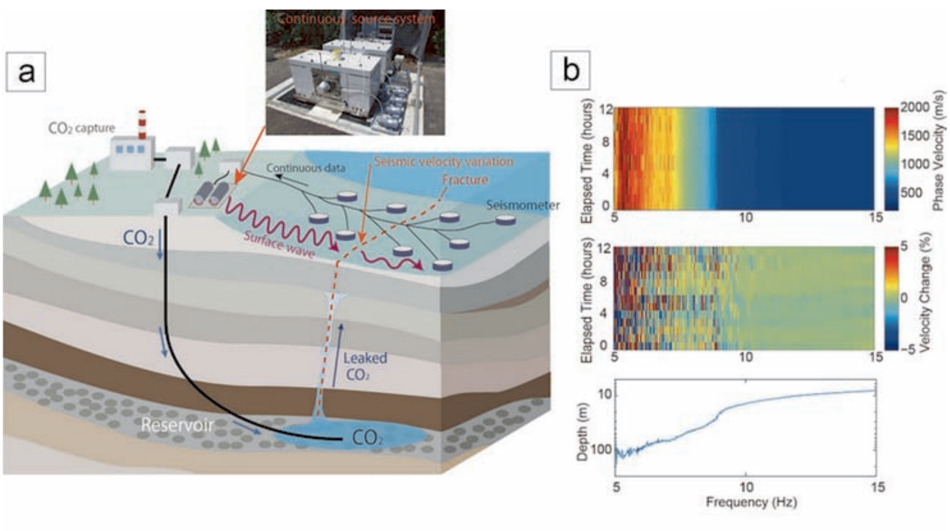

Figure 7. (a) Continuous seismic monitoring of injected CO2 and detection of leaked CO2. The photograph shows the monitoring device, which generates a continuous, accurate source signal. (b) Hourly variation of (upper) surface-wave velocity, (middle) velocity change for averaged velocities, and (lower) sensitive depth in field experiments [4]

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More information

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Skytree – commercialising direct air capture

Amsterdam company Skytree is finding ways to commercialise direct CO2 capture technology developed by the European Space Agency. Its first business is CO2 for aquariums.

Skytree, a company based in Amsterdam, Netherlands, is commercialising a CO2 direct capture technology developed by the European Space Agency – and has found its first business line in aquariums.

The European Space Agency spent 70m Euros over 15 years developing a technology, so it could separate CO2, breathed out by astronauts, out of the spaceship air. The technology will be implemented on the International Space Station in 2017.

Skytree was set up as a spin-off company from the European Space Agency, to find other commercial pathways for the technology. Alexander Gunkel, one of the founders of Skytree, previously worked at ESA.

The company has private investors and is making plans for a bigger round of investment shortly.

The company believes it has found its first market, providing equipment to aquarium owners so they can separate CO2 from their living room air and bubble it through the aquarium to stimulate plant growth, without needing CO2 supplied in bulky bottles.

Many aquarium owners like plants, but don't grow them because having a bottled CO2 supply is difficult to maintain and set-up, Mr Gunkel says.

A typical customer requirement is 10-50g of CO2 per day, for a medium size aquarium. The amount of CO2 required depends on the plants variety and quantity as well as the size of the aquarium.

Skytree is collaborating with one of the world's largest aquarium manufacturers, Eheim of Germany, with the technology. For the moment, Skytree will work on development and testing, but not the manufacturing.

This will be the "first commercially available consumer air capture in the world," Mr Gunkel says.

Skytree does not specify a cost, but the total cost of ownership would probably need to be similar to the Eur 200 to Eur 450 a year which customers typically spend on bottled CO2 for aquariums, unless customers were willing to pay more for the convenience of having CO2 taken from the air rather than delivered.

Skytree co-founders (from left to right) Max Beaumont, Bardia Alaee, Alexander Gunkel with the first aquarium prototype (+ cartridge) and CO2 sorbent

The company has developed a demonstration unit sized 20 x 20 x 10cm to provide CO2 to a standard rectangular aquarium between 70 to 150 liters.

CO2 in the water will also improve its quality for the fish, by adjusting the acidity level.

Oliver Knott, a well-known Germany aquarium designer has made some angel investment in Skytree, as well.

The technology

The technology captures CO2 from air by using a special plastic material which CO2 absorbs onto.

To maximise the absorbtion capacity, the plastic material is very porous, so a large surface area of material can be put into a small volume, with a low weight.

One gram of material has a surface area of 60m2, and a small aquarium unit can require 50g to 150g of material (so a massive 3,000m2 to 9000m2 of area).

The material is placed in a chamber. Air is allowed to enter the chamber, and then CO2 in air absorbs onto the material. Then the chamber is sealed and evacuated of air leaving CO2 absorbed onto the material.

Then the plastic material is heated to 80 to 90 degrees, which causes the CO2 to desorb from the material into the now empty chamber. The CO2 in the chamber can be moved by compressor into a CO2 cylinder, or wherever it needs to go.

As you may have guessed, the process of evacuating the chamber of air, and heating up the absorbent material, uses energy. If this energy is supplied conventionally (by fossil fuels) then the whole process will probably emit more CO2 (from generating electricity) than it separates out of the atmosphere.

But this does not mean that the technology is pointless. Perhaps it could be developed on a large scale, but with the heat being supplied from surplus heat from a power plant, or geothermal heat – and the compressor to create the vacuum running on hydroelectricity. If society is willing to spend money taking CO2 out of the air in future, such technologies will need to be considered.

Other applications

The company has been looking hard at other applications for the technology.

One idea is to supply CO_2 for "vertical farms", greenhouses where plants are grown stacked on top of each other, using artificial light because they cannot all see sunlight. A large amount of CO_2 is absorbed in a small space. These could be used for supermarkets to run their on-site 'farms' growing herbs – there are pilot projects going on.

There may be a market supplying CO_2 to remote, small scale water treatment facilities, where drinking water is generated using reverse osmosis, a water purification technology using a membrane. This is sometimes used on ships and offshore oil platforms.

Reverse osmosis can remove salt and any large molecules from water, so it is possible to drink seawater. But the filtration works so well that the resulting water does not contain any minerals at all, which makes it less healthy.

The minerals can be added back in, but they can't just be dissolved into the water. The standard way to do it is to use minerals which react with CO_2 to get into a form where they can be dissolved into the water.

Another possible business angle for the technology is in reducing CO_2 levels within buildings.

CO_2 levels can get high in buildings, if they have many people inside them breathing out CO_2, and poor ventilation.

Most building requirements say that CO_2 must be kept below 10,000 or 15,000 ppm. However some research shows that a CO_2 level above 800ppm can affect our cognitive functions, so there may be future legislation saying that this is the maximum CO_2 level, Mr Gunkel believes. This will lead to a market for technology which can extract CO_2 from air.

A further potential business angle is using CO_2 to make methanol, which can then be used as a fuel. This might be viable in (for example) a remote location, which would like to use liquid fuels, or have energy available around the clock, and has an intermittent supply of renewable energy to make them with. With its German research & development partner Gensoric this proposal won the prestigious SME-2 grant recently and is called "Willpower".

All of the projects have a good positive 'spin' to them – removing CO_2 from air and from within buildings, helping plants grow, making water more human to drink, and CO_2 is involved in all of those.

More information

www.skytree.eu

willpower-energy.com

Enabling direct carbon capture

Scientists at King Abdullah University of Science & Technology (KAUST) have developed new solid CO_2 capture materials.

Professor Mohamed Eddaoudi, associate director of the University's Advanced Membranes and Porous Materials Research Center, leads a team of researchers at KAUST who are developing porous solids called metal-organic frameworks (MOFs) for the selective removal of various gases from gas mixtures. Their latest breakthrough material can effectively take up carbon dioxide even when it is present at concentrations as low as 400 parts per million and opens possibilities for capturing CO_2 as it is generated.

MOFs contain metal ions or clusters that are held in place by organic molecules known as linkers. Altering the chemical composition and geometry of these two primary components can produce versions with varying and highly selective abilities to adsorb and store gases.

"The discovery of this latest material for capturing carbon dioxide is the result of about four to five years of work on this unique MOF platform," said Eddaoudi. He explained that the key challenge was to create something that could exceed the performance of existing options while also greatly reducing the energy requirements over the full cycle of operation.

The researchers' response was to develop a fluorine-containing MOF in which square-grid layers encompassing Ni(II) metal centers and pyrazine linkers are bridged via pillars composed of niobium, oxygen and the fluorine atoms1.

"The ability to control the distance between the fluorine atoms allowed us to create the ideal square-shaped pockets for trapping carbon dioxide molecules effectively and efficiently and giving our material such impressive performance," said Eddaoudi.

The location of carbon dioxide molecules inside the MOFs was visualized using X-ray diffraction equipment at the University of Stellenbosch in South Africa.

The ability to trap carbon dioxide when it is at very low concentrations makes the new material suitable for a wide range of applications, including the direct capture from air.

Eddaoudi explained that the MOF might be adapted for use in static industrial processes that generate carbon dioxide (such as cement factories), but could also be used on board vehicles such as trucks, cars and aircraft. Capturing the carbon dioxide as soon as it is emitted could be significantly more effective and efficient than going after it when it has mixed in with the atmosphere overall.

"We are now working to scale up the use of this material, allowing us to seek industry collaboration towards eventual commercialization," Eddaoudi said.

More information

www.kaust.edu.sa

CO2 Utilization: A Look Ahead

Finding ways to convert carbon dioxide from an energy and industrial sector waste product to a useful commodity could spur the development of new technologies, products, and industries while limiting emissions to the atmosphere of climate-altering pollutants.

By Fatima Maria Ahmad, C2ES

In 2016, U.S. policymakers demonstrated leadership in this area by introducing several bills that would provide commercial deployment incentives for carbon capture use and storage (CCUS) technology.i

While CO2 has been safely used for carbon dioxide enhanced oil recovery (CO2-EOR) for over 40 years in the United States, there is an increased focus on identifying options for re-use of CO2 for other purposes. Indeed, in July, Senators Heidi Heitkamp (D-ND) and Sheldon Whitehouse (D-RI) introduced a bill to extend 45Q (the major tax credit for CO2-EOR) that expressly expanded the use of the tax credit to allow it to apply to other forms of CO2 utilization.ii Recent scientific developments in CO2 re-use are promising but challenges will have to be overcome to achieve additional progress.

Looking forward, the new administration and new Congress will need to consider how best to incentivize continued research, development, and demonstration (RD&D) and commercial-scale deployment of CO2 utilization technology, especially as the U.S. begins to lay the foundation for a strategy of deep decarbonization by mid-century.

CO2-EOR: The Best Re-Use Option . . . Today

Since the 1970s, the U.S. independent oil and gas industry has led the world in CO2-EOR, mostly using natural CO2. Captured CO2 is used commercially in the U.S. to recover more oil from already developed oil fields. That CO2 can be then safely and permanently stored underground in those same oil and gas reservoirs. The U.S. produces 300,000 barrels per day, or nearly 3.5 percent of our annual domestic oil production, through this method.iii

Recent estimates suggest that in the coming years the oil and gas industry could technically produce between 56 – 106 billions of barrels of additional American oil from existing fields using CO2-EOR technology. iv This would involve the use of 22,270 – 33,050 million metric tons of CO2.v

The climate benefits of CO2-EOR are clear. Last fall, the International Energy Agency concluded that for every barrel of oil produced using manmade CO2, there is a net CO2 storage of 0.19 metric tons.vi This analysis includes the CO2 emissions from use of the oil and the impact of increased demand for oil due to lowered oil prices from the additional supply of oil.vii

In light of the economic and environmental benefits of CO2-EOR, the National Coal Council (a federal advisory committee to the Secretary of Energy) recently released a draft report concluding that CO2-EOR is the "most immediate, highest value opportunity to utilize the greatest volumes of anthropogenic CO2."viii

In addition to CO2-EOR, additional geologic re-use options for CO2 include CO2 shale, enhanced coal bed methane, enhanced water recovery, and enhanced geothermal. The National Coal Council concluded that these geologic options "have the greatest potential to advance CCUS by creating market demand for anthropogenic CO2."ix Certainly, a major benefit of reusing manmade CO2 is creating a revenue stream to offset the costs of capturing carbon dioxide.

Next Generation Uses of CO2: NRG COSIA Carbon X-Prize

Last fall, the $20 million Carbon X-Prize was launched after many years of collaboration between investors, utilities, and non-profit organizations who agreed that CO2 could be transformed from a liability to an asset.x

On October 17, 2016, the NRG COSIA Carbon X Prize announced 27 semifinalist teams from the U.S., Canada, China, India, Switzerland, and Scotland.xi Track A focuses on creating products from CO2 from coal power plants and Track B focuses on CO2 from natural gas plants. The semifinalists are developing a wide range of products, from minerals for concrete and other building ma-

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i See, e.g., H.R. 4622, 114th Cong. (2016) available at https://www.congress.gov/bill/114th-congress/house-bill/4622 ; H.R. 636, 114th Cong. (2016), available at https://www.congress.gov/amendment/114th-congress/senate-amendment/3645 ; S. 2012, 114th Cong. (2016), available at https://www.congress.gov/114/bills/s2012/BILLS-114s2012es.pdf ; H.R. 2883, 114th Cong. (2016), available at https://www.congress.gov/bill/114th-congress/house-bill/2883 ; S. 2305, 114th Cong. (2016), available at https://www.congress.gov/bill/114th-congress/senate-bill/2305

ii S. 3179, 114th Cong. (2016), available at https://www.congress.gov/bill/114th-congress/senate-bill/3179

iii Oil and Gas Journal Survey (2014).

iv National Coal Council, CO2 Building Blocks: Assessing CO2 Utilization Options 96 (Aug. 2016).

v Id.

vi IEA, Storing CO2 Through Enhanced Oil Recovery (2015), available at https://www.iea.org/publications/insights/insightpublications/CO2EOR_3Nov2015.pdf

vii Id.

viii National Coal Council, supra at 1.

ix Id at 20.

x Xprize Foundation. Carbon Conversion Landscape Analysis 5 (Dec. 2014); Prize Capital LLC. Commercializing the CO2-Asset Industry 17 (2013).

xi NRG COSIA Carbon X Prize, 27 Teams Advancing in $20M NRG COSIA Carbon Xprize (Oct. 17, 2016), available at http://carbon.xprize.org/press-release/27-teams-advancing-20m-nrg-cosia-carbon-xprize terials, to biofuels, paint, fertilizers, health supplements, and even toothpaste.xii There is a team re-using CO2 to develop carbon nanotubes, which can be used to make environmentally sustainable lithium-ion and sodium-ion batteries and teams creating CO2-based methanol, which is a potential drop-in fuel, meaning that it is interchangeable with existing petroleum-based fuels.xiii

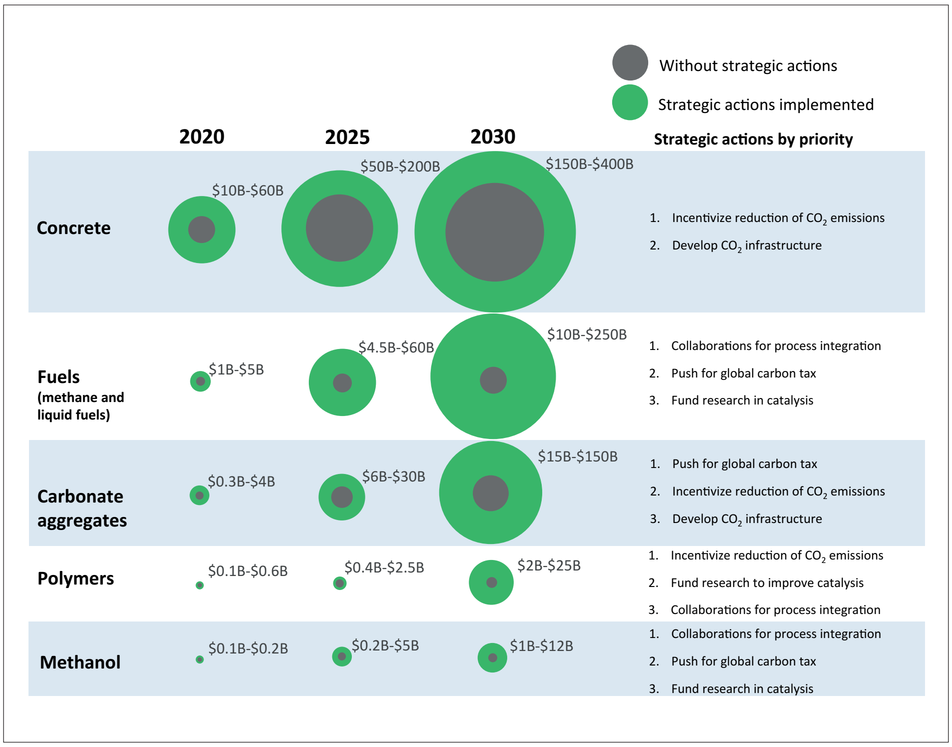
During Round 3, the teams will demonstrate their technologies at a larger scale under real world conditions using test centers adjacent to existing power plants. The winner of each track will be awarded a $7.5 million grand prize in March 2020.

Challenges: Technical, Market, and Policy

In general, the three main types of carbon capture are pre- and post-combustion and oxyfuel combustion.xiv Each of these includes a number of technologies, including but not limited to the use of solvents, sorbents, membranes, and carbonate fuel cells. Some carbon capture technologies have a much higher energy penalty than others. Putting aside the technological challenges related to capturing CO2, there are a number of technical challenges related to the re-use of captured CO2, including the following:xv

Processes need to be efficient in light of thermodynamic constraints. There is an energy penalty associated with the conversion of CO2 to other substances. The CO2 molecule is stable and breaking the bonds through a chemical or catalytic method often requires a large amount of energy, which affects the lifecycle analysis of emissions reduction. Innovators have explored using renewable energy for this task. If renewable energy prices continue to drop, that would enable greater use of such energy for conversion of CO2 through chemical or catalytic methods.

Due to the cost of transport, the re-use of CO2 will need to take place near sources of captured CO2, which is a geographic constraint.



Top five CCU product categories by market size (Taken from Global CO2 Initiative Draft Roadmap for Implementation of Carbon Dioxide Utilization Technologies)

Due to the volume of manmade CO2, re-use options need to be possible in many seasons and in various climates and on a commercial-scale.

Finally, one overarching technical challenge is the urgency of climate change – CO2 utilization options need to be able to be deployed on a commercial-scale quickly.

There are also a number of market challenges that have slowed down the creation of a market for CO2. Government investment has focused more on the capture side of CCUS than on the re-use aspect and it may be time for more emphasis on re-use. Between Fiscal Years 2005 and 2014, the U.S. Department of Energy invested $7.6 billion in carbon capture and storage and $100 million in beneficial re-use of CO2.xvi Many of the opportunities for re-use of CO2 will be competing with mature, high-volume manufacturing technologies that have been optimized for efficiency and have the confidence of customers.xvii

Additional market challenges include the following:

• Options for re-use of CO2 are highly diverse and it is not easy to compare their performance and benefits.xviii

• The potential economic benefits of CO2 conversion for re-use are largely unquantified because the technologies are in early stages of development.xix The climate benefits of re-

xii Paul Bunje and Marcius Extavour, Carbon Xprize Team Semi-Finalists to Transform CO2 Waste Into Building Materials, Biofuels, and Toothpaste (Oct. 17, 2016), available at http://carbon.xprize.org/news/blog/carbon-xprize-team-semi-finalists-transform-co2-waste-building-materials-biofuels

xiii Id.

xiv Global CCS Institute, Capture, available at https://www.globalccsinstitute.com/content/capture

xv Prize Capital LLC, supra at 66.

xvi Xprize Foundation, supra at 16.

xvii Id.

xviii Id at 17.

xix Id at 18.

xx Xprize Foundation, supra at 18.

use of CO2 are also not fully quantified.xx

• Utilities are not able to take on the technological or financial risk of investing in CO2 re-use options.xxi Legal and regulatory obstacles prevent testing of promising technologies on operating power plants.xxii As a result, utilities are also not regularly communicating with CO2 re-use innovators to inform the R&D process.

• Regulations on CO2 emissions are not stringent enough to independently drive the creation of a commodity market for CO2. xxiii

Certainly, products made from captured and re-used CO2 could be green-labeled and if the CO2-derived versions provided additional benefits not provided by existing options (such as for fuels, concrete, etc.) that would also help the CO2-derived products compete in the market.

With respect to business models, there may be some challenges that can be overcome by creative innovation. For example, power companies may be looking to enter into contracts to sell CO2 that are as long as the remaining useful life of the power plant (maybe 40 years), while re-users of CO2 may be looking to realize profits for investors within 10 years.xxiv

If re-users of CO2 are start-ups, utilities may be concerned about whether the companies will remain in business for the duration of power plant operations.xxv There is also a question regarding whether the potential market for products derived from CO2 is large enough to absorb the amount of CO2 that will need to be captured to meet our mid-century climate goals. Innovative business models will be needed to resolve these challenges.

There may also be a number of policy challenges. The international ASTM standards for materials like concrete may need to be revised to reflect new approaches. On the regulatory side, CO2-EOR and other geologic storage technologies are recognized under U.S. law for their emissions reduction benefits, including under the Clean Air Act Prevention of Significant Deterioration (PSD) permit program, the Standards of Performance for Greenhouse Gas Emissions from New, Modified, and Reconstructed Electric Utility Generating Units, and the Clean Power Plan.xxvi

The U.S. Environmental Protection Agency will need to review options for CO2 utilization to determine whether they are as effective as geologic storage for reducing CO2 emissions. With respect to the Clean Power Plan specifically, EPA must review evidence concerning “the ultimate fate of the captured CO2 and the degree to which the method permanently isolates the captured CO2 or displaces other CO2 emissions from the atmosphere.”xxvii

The Global CO2 Initiative Roadmap Project: Looking for Solutions

Researchers and industry experts are working on solutions to these technical, market, and policy challenges. The Global CO2 Initiative was launched in January 2016 with the goal of capturing 10 percent of annual global CO2 emissions and transforming them into valuable products. In October 2016, it determined that significant progress was made in CO2 utilization research over the past five years and concluded that “[m]omentum is favorable for four major markets – building materials, chemical intermediates, polymers, and fuels.”xxviii

In its roadmap, the Global CO2 Initiative identified five strategic actions to accelerate commercial deployment of CO2 utilization options:xxix

• First, policymakers should implement a price on carbon, increase mandates for renewable products and fuels, and incentivize continued emissions reductions.

• Second, research should be funded to decrease the cost of CO2 utilization.

• Third, production can be scaled-up through collaborations among researchers, entrepreneurs, governments and businesses for process integration of carbon capture, CO2 conversion, and hydrogen generation.

• Fourth, infrastructure is needed to link generators of CO2 with users of CO2 to ensure a reliable source of CO2. Finally, funders should explore applied research into long-shot technologies and applications with high CO2 abatement potential.

Conclusion

International agreements to reduce greenhouse gas emissions in 2016 demonstrate a global recognition of the need to reduce CO2 emissions. In order to meet mid-century climate goals, nations and other actors need to ramp up CO2 utilization quickly. The good news is that the pace of technological discovery is often surprising. Examples include the semiconductor industry and research in robotics.

Estimates for the global size of the CO2 utilization market by 2030 in carbonate aggregates, fuels (methane and liquid fuels), concrete, methanol, and polymers are as large as $700 billion, utilizing 7 billion metric tons of CO2 per year, which is equivalent to approximately 15 percent of current global CO2 emissions.xxx With appropriate policy incentives, the U.S. can take a leadership role in in CO2 utilization. The rewards will be great.

More information

www.c2es.org

www.globalco2initiative.org

xxi Id at 19.

xxii Prize Capital LLC. Commercializing the CO2-Asset Industry 111-12 (2013).

xxiii Xprize Foundation, supra at 19.

xxiv National Coal Council, supra at 2.

xxv Id.

xxvi Id at 2, 13-14.

xxvii 80 Fed. Reg. 64,662, 64,884 (Oct. 23, 2015).

xxviii Global CO2 Initiative, Draft Roadmap for Implementation of Carbon Dioxide Utilization Technologies 1 (Oct. 2016).

xxix Id at 2.

xxx Id at 3.

Making the macroeconomic case for CCS

The Centre for Energy Policy at the University of Strathclyde argues that the UK's decision to scrap its CCS commercialisation competition brings into sharp focus an urgent need to consider the economic service role of capture, transport and storage activities.

By Karen Turner and Julia Race

In July 2016 a spending review briefing by the National Audit Office noted that, while agreeing with the Department for Energy and Climate Change (DECC) that CCS is required to meet UK carbon targets, "HM Treasury raised concerns about the merits of the carbon capture and storage competition given fiscal constraints".[1]

At a recent UKCCSRC conference on 'Making the Case for CCS'[2], the Centre for Energy Policy (CEP) has argued that some key omissions in the information provided to HM Treasury (HMT) by DECC may have contributed to the decision to cancel the competition:

The wider economic and fiscal case was not made to provide a context for how investment and operational costs may impact industry, consumers and public budgets.

The near-term benefits were not argued (e.g. direct and supply chain employment in developing infrastructure).

The longer term benefits of establishing carbon capture, transport and storage as economic service activities (i.e. in addition to estimates of additional costs of running a decarbonised UK economy by 2050 in the absence of CCS[3]) were not considered.

There is a need to consider the case for CCS via the type of full social cost benefit analysis recommended by HMT for appraisal and evaluation in 'the Green Book'.[4] However, in order to inform this type of analysis there is a need to think more broadly about 'the economics of CCS'.

Analysis of the contribution of CCS in moving towards a decarbonised economy is most commonly made through the use of energy system models such as TIMES. However, this does not offer much insight in terms of what is involved in making this contribution happen.

Given high start-up costs and uncertainty over up-take and operational costs, it is natural to be concerned about cost effectiveness, particularly where costs to end consumers and the wider competitiveness of UK industry are in question.

On the other hand, economic system models, such as the computable general equilibrium (CGE) model used by HMT to assess the wider economic and fiscal impacts of a range of policy actions and/or changes in economic conditions[5], either do not include CCS or simply treat it as an 'end of pipe' technology that can be turned on or off at a cost.

The crucial point is that we need to think of CCS in broader terms. How would it actually be introduced, operated and regulated? CCS involves a chain of activities. First, capture must be carried out within the industrial or power generation plant generating CO2. Second, CO2 must be transported to the storage location (perhaps via some utilisation activity such as enhanced oil recovery, EOR). Third, CO2 must be stored (most likely off-shore in the UK case).

The latter two stages are likely to be external to the CO2 emitter and involve use of a common resource in the form of a transport and storage infrastructure. Thus, the question arises as to how different parts of the CCS chain may be initiated and operated. Emitters may be responsible for capture.

However, the high investment costs required for the transport stage, combined with the issue of management of storage capacity, imply that these elements are characterised by some element of 'natural monopoly', as is the case with, for example, electricity transmission or the rail network.

If we consider the essential nature of what CCS must do, this is a problem of disposing of a (largely) unwanted (unless there are CO2 utilisation opportunities) waste by-product of economic activity. An, albeit imperfect, analogy may be drawn with the waste collection, treatment and disposal industry, which is included in the Standard Industrial Classification of Economic Activities.[6]

As generators of waste, households and businesses 'capture' the waste they generate. However, they are not expected to transport and deal with the waste. Instead, they (directly or indirectly) make some form of payment to publicly or privately owned waste transport and management operations to do this (in a regulated environment).

As well as providing a valuable economic service activity context (where people are employed, GDP and tax revenues are created)

1. See page 7 of 'Sustainability in the Spending Review' published by the National Audit Office in July 2016 at https://www.nao.org.uk/wp-content/uploads/2016/07/Sustainability-in-the-Spending-Review.pdf.

2. See programme and downloads of presentations and posters at https://ukccsrc.ac.uk/news-events/events/making-case-ccs-edinburgh-biannual.

3. For example the CCSA report in reaching decarbonisation goals in the absence of CCS may cost the UK economy an additional £32bn per year or 1% of GDP by 2050. See http://www.ccsassociation.org/press-centre/reports-and-publications/delivering-ccs/.

4. See https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent.

5. For example, see HMT/HMRC analysis of the impacts of fuel duty reductions at https://www.gov.uk/government/publications/analysis-of-the-dynamic-effects-of-fuel-duty-reductions.

6. See file:///C:/Users/kkb12179/Downloads/sic2007explanatorynote_tcm77-223502%20(3).pdf, Section E, classifications 38 and 39 (page 38).

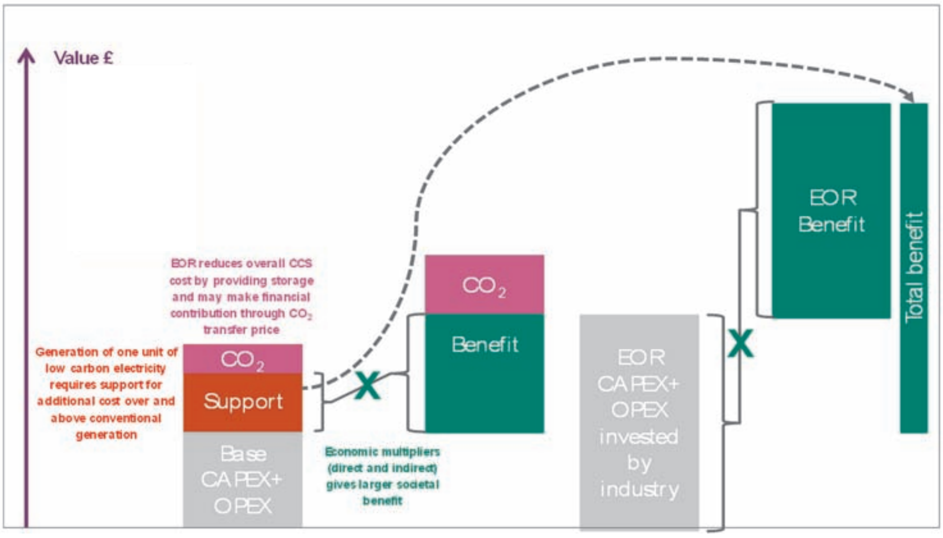
the waste analogy also provides a basis for considering the motivation for engaging in CCS from a human and/or environmental cost/risk perspective.

However, this also gives rise to a crucial problem: infrastructure has long been in place to dispose of waste because of very localised and immediate health concerns. In contrast, the problem of climate change is a global one that impacts over a longer time frame and potentially in a location remote from the source.

Thus, the economic case for collection and management of CO2 via CCS may need to be stronger. One potential source of near term economic benefits would be development of transport infrastructure. While the value of 'economic activity for its own sake' may be contested, it is true that particularly creation of jobs in direct and supply chain activity to facilitate major infrastructure developments (e.g. Hinkley Point) is valued by public and politicians alike.

Moreover, where infrastructure development is ultimately to enable a fuller stream of economic and social benefits (and where average costs of the enabled activity will decline over time) we generally accept the initial financial and other resource costs, and welcome even short-term job and other value creation associated with the development.

It then becomes crucial to assess how both average and marginal costs of the different elements of the CCS chain are likely to decline over time – through advances and evolution in technologies, learning by doing and economies of scale with fuller deployment (including CCS cluster opportunities) – and to identify a full set of potential benefits. Wider economic benefits are also likely to evolve over time as UK supply chains respond to the presence of CCS.



Capturing the impact of CCS linked to EOR through multipliers[7]

Capturing the impact of CCS linked to EOR through multipliers

For example, CEP has conducted preliminary research of potential multiplier impacts through UK supply chains of CCS linked to EOR. As shown in the Figure, multiplier analysis focuses on how direct spending (privately or via government support) in any one activity creates further benefits through output, employment and value-added generated in up-stream supply chains and through creation of any additional activity, for example where CO2 can be used as an input to other processes (particularly if this involves a transfer price). There are a number of factors governing how multiplier benefits are likely to evolve, including:

Capacity and capability of domestic supply chains to support investment and operational stages of capture, transport and/or storage activities (noting that, via the oil and gas industry, and linked service sectors, the UK already has skills/expertise and, to some extent, a physical infrastructure foundation for transport and storage).

Whether technologies are developed at home or abroad (with the former providing technology/service export opportunities).

Whether the development of (elements of) CCS capability and infrastructure enables retention of existing energy-intensive industries and potentially attracts new firms to UK locations.

The July 2016 spending review by the National Audit Office notes that the UK Government retains the belief that CCS is likely to be necessary and play a crucial role in the future energy system and low carbon economy. It is necessary, then, to quantify solidly grounded scenarios for the role that the capture, transport and storage elements can play in an economic service context.

Moreover, and to effectively consider the case for required policy support in the shorter term (to facilitate the long term contribution of CCS), it is necessary that this be done in the type of economy-wide CGE modelling and social cost-benefit framework that is familiar to and trusted by key policymakers in HMT and elsewhere.

This will involve inter-disciplinary research activity (involving collaboration between academia, industry, government and society) to ensure that both the wider economic and technological characteristics of capture, transport and storage elements are effectively represented, and that the results usefully inform the wider public debate on the future of CCS in the UK.

More information

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www.strath.ac.uk

7. Figure taken from report (pp31-35) at http://www.sccs.org.uk/images/expertise/reports/co2-eor-jip/SCCS-CO2-EOR-JIP-Report-SUMMARY.pdf

Projects and policy news

CCS climate change mitigation role reconfirmed in Paris agreement

www.globalccsinstitute.com

Carbon capture and storage (CCS) takes on even greater significance as a major climate change mitigation technology with the Paris climate change agreement entering into force.

Global CCS Institute Chief Executive, Brad Page, expressed optimism that new opportunities to accelerate the deployment of CCS will emerge as countries grapple with how to deliver their current and future emission objectives.

"With the legal commencement of the Paris Agreement taking effect today, it has taken just 10 months to achieve the same milestone that eluded the Kyoto Protocol for eight years. This bodes well for inclusive and comprehensive climate actions going forward.

Mr Page said the Intergovernmental Panel on Climate Change (IPCC) has indicated that containing the average global temperature rise to 2°C `and below' will be challenging even with the inclusion of CCS.

"We know, however, that without CCS, it is highly improbable that the world can ever deliver on the Paris Agreement's core climate goal."

Mr Page said it is clear that the Paris Agreement provides a high level of encouragement for nations to progressively strengthen their support for climate actions through the bottom-up, Nationally Determined Contributions (NDC) process. While the rapid ramping up of the deployment of renewables, nuclear and energy efficiency are all required, the continued large-scale use of fossil fuels cannot be ignored or wished away.

"With fossil fuels likely to account for more than 70% of total primary energy up to 2040 and beyond, CCS must feature increasingly as a mainstream mitigation option. Its adoption by many more countries is assured if the temperature targets in the Paris Agreement are to be achieved.

Mr Page said that one year on from the Paris conference, many nations appeared to be embracing the huge mitigation challenge that lies ahead. However none have as yet established targets that are capable of achieving the temperature objectives of the Paris Agreement.

"With a global geological storage potential of many thousands of gigatonnes of CO2, CCS offers more than just an attractive opportunity to manage CO2 emissions in the industrial and power sectors.

CCS also delivers important co-benefits including the control of many non-CO2 pollutants which currently threaten the health of many millions of people, especially in developing nations."

Mr Page said CCS is highly credentialed as an environmentally sound technology option within the UNFCCC's architecture and is already capturing and storing 24 Mt of CO2 every year.

"The challenge remains to fully support its mitigation potential in a way that not only safeguards the world against the dangers of climate change, but also ensures that climate action is achieved in a cost-effective and timely manner.

In practice, this means affording CCS similar levels of policy support and market opportunities as many other clean energy alternatives are currently receiving, and so that it can materially enhance the global clean energy outcome."

OGCI announces $1 billion investment in low emissions technologies

www.oilandgasclimateinitiative.com

The Oil and Gas Climate Initiative (OGCI) will invest $1 billion over the next ten years, to develop and accelerate the commercial deployment of low emissions technologies including CCS.

In a joint statement, the heads of the 10 oil and gas companies that comprise the OGCI said: "The creation of OGCI Climate Investments shows our collective determination to deliver technology on a large-scale that will create a step change to help tackle the climate challenge. We are personally committed to ensuring that by working with others our companies play a key role in reducing the emissions of greenhouse gases, while still providing the energy the world needs."

Through discussions with stakeholders and detailed technical work, the OGCI has identified two initial focus areas: accelerating the deployment of carbon capture, use and storage; and reducing methane emissions from the global oil and gas industry in order to maximize the climate benefits of natural gas. The OGCI believes that these are areas where the oil and gas industry has meaningful influence and where its collaborative work can have the greatest impact.

Beyond this, OGCI CI will make investments that support improving energy and operational efficiencies in energy-intensive industries. OGCI CI will also work closely with manufacturers to increase energy efficiency in all modes of transportation.

A CEO and management team for OGCI Climate Investments will be announced in the near future. The closing of OGCI Climate Investments is subject to customary conditions including regulatory clearances as required.

The Global CCS Institute commented, "The $1 billion investment in low-emissions technologies committed by OGCI's member companies reflects the confidence of the world's energy leadership in carbon capture and storage to mitigate climate change."

"Private sector investment, coupled with government support equivalent to that afforded to renewables, will fully realize the vital contribution of CCS technology to achieving the Paris Agreement's goal of limiting global warming to 2°. The transition to a low carbon future requires CCS, and OGCI's financial commitment will accelerate an affordable path to its widespread deployment."

Dr. Luke Warren, Chief Executive of the CCSA, commented, "Following Norway's recent announcement to push forward with three industrial CCS projects, as well as new projects such as the Petra Nova CCS plant in the US which is due to begin operation by the end of the year, the fund launched today by the OGCI shows that there is no lack of international interest in delivering CCS."

"This is a historical announcement by the heads of ten of the world's largest oil and gas companies and demonstrates their commitment to reducing their carbon footprint and playing an important role in meeting the Paris Agreement."

MENA's first Carbon Capture Utilisation & Storage (CCUS) project now on stream

www.masdar.ae

The CCUS plant developed by joint venture between Abu Dhabi National Oil Company (ADNOC) and Masdar will sequester up to 800,000 metric tons of C02 annually.

The first commercial-scale carbon capture,utilisation & storage (CCUS) facilityin the Middle East & North Africa (MENA) is now operational and aims to sequester up to 800,000 metric tons of carbon dioxide (CO2) per year, it was announced today.

His Excellency Dr Sultan Ahmed Al Jaber, UAE Minister of State, ADNOC CEO and Chairman of Masdar, officially unveiled the CCUS facility accompanied by a delegation of senior government and industry officials

Developed by Abu Dhabi's Carbon Capture Company Al Reyadah, a joint venture between Abu Dhabi National Oil Company (ADNOC) and Masdar, the Abu Dhabi Future Energy Company, the project harnesses CO2emitted by a major Abu Dhabi steel producer, Emirates Steel Industries (ESI), before injecting it as a substitute for rich gas into the emirate's oil reservoirs to help enhance their output.

Based in Abu Dhabi's Mussafah industrial area next to Emirates Steel Industries, Al Reyadah's inaugural CCUS project started construction in July 2013. The projectis one of only 22 large-scale CCUS ventures, either in operation or under construction worldwide, and the first to capture CO2 from an iron and steel works.

Al Reyadah, meaning 'leadership' in Arabic, is the first company in the MENA region focused on developing commercial-scale CCUS projects. The CCUS technology now deployed in Abu Dhabi will free up more natural gas for electricity generation, water desalination and other industrial uses while enhancing oil recovery.

The technology works in three stages. Carbon dioxide is first captured on site at the Emirates Steel manufacturing complex before being compressed and dehydrated. The third step involves conveying the CO2 via a 43-kilometre underground pipeline for Enhanced Oil Recovery (EOR) injection into ADNOC's NEB (Al Rumaitha) and Bab onshore oilfields.

A joint venture between ADNOC (51%) and Masdar (49%), Al Reyadah is potentially the first phase of an industrial-scale CCUS network aimed at reducing the carbon footprint of the Abu Dhabi economy and supporting the expansion of a low-carbon power generation industry.

FuelCell Energy and ExxonMobil pilot plant

www.fuelcellenergy.com

The James M. Barry Electric Generating Station will host pilot plant tests of the technology, which uses carbonate fuel cells to concentrate and capture carbon dioxide streams from power plants.

The tests at the 2.7 gigawatt mixed-use coal and gas-fired power plant operated by Southern Company subsidiary Alabama Power, will demonstrate carbon capture from natural gas-fired power generation under an agreement between FuelCell Energy and ExxonMobil announced in May, and from coal-fired power generation under a previously announced agreement between FuelCell Energy and the U.S. Dept. of Energy.

This fuel cell carbon capture solution could substantially reduce costs and lead to a more economical pathway toward large-scale carbon capture and sequestration globally.

"The fuel cell carbon capture solution we are advancing with ExxonMobil could be a game-changer in affordably reducing carbon dioxide emissions from coal and gas-fired power plants globally," said Chip Bottone, president and chief executive officer of FuelCell Energy, Inc.

"The carbonate fuel cell solution uses a proven global platform to generate power while capturing carbon dioxide."

Vijay Swarup, vice president for research and development at ExxonMobil Research and Engineering Company, said ExxonMobil scientists recognized an opportunity to pursue the novel approach to use carbonate fuel cells at natural gas power plants. Current carbon capture processes consume energy, which increases costs. But carbonate fuel cells generate electricity and hydrogen while capturing and concentrating carbon dioxide streams, which will reduce the cost of carbon capture.

The pilot plant tests will use FuelCell Energy's commercial DFC3000® carbonate fuel cell power system to concentrate and capture a portion of the carbon dioxide emissions from the power plant as part of the fuel cells' power generation process. Flue gas from power generation will be directed into the fuel cells' air intake system where it is combined with natural gas.

The fuel cells concentrate and capture carbon dioxide and also eliminate about 70 percent of smog-producing nitrogen oxide from coal, supporting federal and local clean air initiatives. Following capture, carbon dioxide will be compressed and cooled utilizing standard chilling equipment. Installation of the fuel cell plant will begin after completion of engineering studies that are already under way.

Results from the natural gas pilot test will help guide engineering studies for potential construction of a standalone pilot plant to test the technology at a larger scale, under FuelCell Energy's existing agreement with ExxonMobil.

The Barry generating station is located near Mobile in Bucks, Alabama, and has 2,657 megawatt total generating capacity from six units fueled by coal and natural gas. Southern Company and Alabama Power have previously conducted carbon capture research at the location and at another power plant in Wilsonville, Alabama, near Birmingham.

SNC-Lavalin appointed to ETI gas power with CCS project

www.eti.co.uk

www.snclavalin.com

The Energy Technologies Institute (ETI) has appointed engineering and construction group SNC-Lavalin to a new project to develop a generic business case for developing a gas-fired power plant fitted with Carbon Capture and Storage (CCS).

They will work with global infrastructure services firm AECOM and the University of Sheffield's Energy 2050 Institute on the nine month project, which will see the ETI invest £650,000.

The ETI's whole energy system modelling work has shown that CCS is one of the most cost effective technologies to help the UK meet its 2050 CO2 reduction targets. Without it the energy system cost in 2050 could be £30bn per annum higher.

Back in June 2015 the ETI launched a request for proposals for a Thermal Power with CCS (TPwCCS) project, which aimed to accelerate the development of a low cost, low risk 'Phase 2' CCS project which could follow on from the then Government-backed 'Phase 1' CCS commercialisation competition projects.

Following the Government's decision not to proceed with the competition the ETI has been reshaping the TPwCCS project to reflect the new circumstances. This new project will support the creation of a business case for a large scale gas with CCS power plant.

The business case will develop an outline scheme and a 'template' power plant design (Combined Cycle Gas Turbine (CCGT) with post combustion capture), identify potential sites in key UK industrial hubs and build a credible cost base for such a scheme, benchmarked as far as possible against actual project data and as-built plant.

Thus the project is wholly aligned with and will provide a critical evidence base for the vision set out in the recent Parliamentary Advisory Group on CCS report – "Lowest cost decarbonisation for the UK : the critical role of CCS".

Andrew Green, ETI CCS Programme Manager said, "There is broad consensus that the UK power system needs to be largely decarbonised by the early 2030s to enable any material decarbonisation of heat and transport to be viable thereafter. CCS has a key role to play in decarbonising the power sector, and with a strong history in oil, gas and power skills, the UK is well placed to lead the world in the development of CCS."

"Since the Government's decision not to proceed with the CCS competition we have carried out a range of different analyses around potential ways forward. They confirm that the most cost-effective and secure way to meet these needs is to move forward as soon as reasonably possible with a strategically-placed, large-scale gas with CCS power project. We were delighted that the way forward for CCS proposed by the Parliamentary Advisory Group on CCS in its recent report was fully aligned with our analysis, and we expect this project to provide further concrete evidence on the cost-effectiveness of CCS."

"Delay in the implementation of CCS could cost £1 – 2bn per annum in the 2020s, rising to £4 – 5bn by 2040."

"Stakeholders in CCS will need compelling evidence of the business case for a new power with CCS project which is why we are taking this project forward, to add to this evidence base."

New carbon capture and storage laboratory opens at Australian University

federation.edu.au

CO2CRC Limited and Federation University Australia have officially opened a new CCS laboratory at the University's Gippsland Campus.

The FedUni laboratory is part of the Australian CCS Research Laboratories Network (CCSNet). It is funded through a $2.3 million agreement between the Australian Government's Education Infrastructure Fund and CO2CRC Limited.

The new laboratory will conduct important research into a range of CCS technologies, with the aim of reducing the cost of implementation so as to make price-competitive carbon reduction options.

"The new laboratory's location at Federation University Australia's Gippsland Campus is particularly fitting, given that nearly 90 per cent of Australia's brown coal reserves are located here," Dr Vincent Verheyen, Director of the Carbon Technology Research Centre at Federation University Australia, said.

"The laboratory will make a significant contribution to the understanding and implementation of solvent-based post-combustion capture at Latrobe Valley Brown Coal power generation facilities.

"While the initial focus of the facilities will be on local flue gas, the knowledge gained will be relevant to other power generators and broadened to pre-combustion coal to product applications around the country and internationally," Dr Verheyen said.

Tania Constable, CO2CRC's CEO, believes that carbon capture storage can and should play a vital role in supporting the renewal of the Gippsland region and Federation University will play its part.

Ms Constable said: "CCS is the only proven and reliable technology to remove large scale emissions from power generation and industrial processes. The Gippsland Community's Plan for action highlights the potential of CCS. This means thousands of jobs for the Gippsland region and will remove over 10 per cent of Australia's emissions."

One of the goals of the Commonwealth Education Infrastructure Funded Centre will be to focus on undertaking future energy training and research towards environmentally neutral and costed effective carbon based technologies.

The facility will provide a community focal point for science on brown coal and related energy knowledge topics. It will provide energy education services to community groups and students from primary school to postgraduate level.

Report from the Global CCS Institute conference in Oslo

The Global Carbon Capture and Storage Institute (GCCSI) held their annual EMEA conference in Oslo on October 13, with a comprehensive round-up of carbon capture developments around the world, how politicians see it, and what is happening in Norway, the Netherlands and the UK.
By Karl Jeffery

Lord Nicholas Stern, Professor of Economics and Government at the London School of Economics, said that the world is currently in an "extraordinary moment", with a climate agenda agreed globally.

In that sense, the world is in a similar situation to where it was after the Second World War. "After World War 2 you had to come to the conclusion that a world where people didn't collaborate was destined for great trouble," he said.

He was speaking at the evening reception after the Global CCS Institute Europe, Middle East and Africa forum in Oslo on October 13, 2016.

"In Paris [in 2015], 195 countries, with no one dominant country, got together to make an agreement on anticipation of a problem. So it was a remarkable moment."

"The goals applied to everyone and were agreed by everybody. We didn't anticipate how fast it would move."

We had the US taking the lead, India ratifying in October [2016], and the EU a few days later.

Now, "we have a chance to ask the rulers of the world to step up to what they have promised to do."

"A key reason it happened [is that] we have an understanding of how we do this," he said.

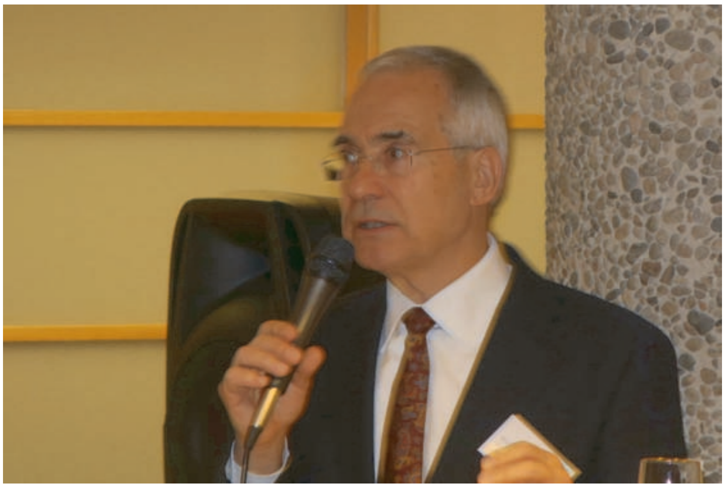
"Strong investment in sustainable infrastructure revives the world economy. It is not a trade-off between climate responsibility and growth, it is the only way to grow."

"We haven't won the argument yet, but we're moving that way."

Carbon capture and storage is centre stage in how the emissions cuts should be achieved, he said. "The International Energy Agency has argued that CCS is about 12 per cent of what we have to do."

"All of the UK Climate Change Committee reckon if you rule out CCS the extra cost would be £5bn a year."

"We have to be clear about the scale of reductions that are necessary. If we don't rise to this scale you can forget about two degrees [temperature rise]."



"I am optimistic about what we can do, I am not so optimistic about what we will do" - Lord Nicholas Stern

A carbon price of $40 a ton is "ludicrously low." But if carbon capture and storage can be done for $60 to $80 a ton, it ought to work "for any reasonable price of carbon," he said.

"The heating story has got too little focus," he said. "If we no longer use gas, we'd need to use hydrogen or heat pumps of some sort."

Also, carbon capture is capital intensive, so the cost of capital is fundamental.

A big question is how fast the costs of carbon capture can be brought down. Consider that solar power has brought its costs down by a factor of ten, not so much through technology development, but through more collaboration, he said.

It is important to get China and India involved in carbon capture. "A few years ago we got China involved. India is a bit behind but it's changing. There's real chance of talking to India. They are very important in the world and part of the scale story."

There was also talk in Paris about negative emissions. This can be done through growing more forests, and doing bioenergy with CCS, and air capture, although "you wouldn't want to bet the planet on air capture," he said.

Forests are only net negative while they are increasing, and they can't increase forever. So ultimately "It's only bioenergy and CCS which is net negative." And "you can't talk about bioenergy and CCS unless you have CCS".

Currently, there's a gap between the ambition to cut emissions and what is planned to do it, he said.

The way to fill the gap is to show that carbon capture and green energy "is the growth story of our future," he said.

"I am optimistic about what we can do, I am not so optimistic about what we will do. But it has to be on the back to very strong rational argument. "

Kamel Ben Naceur

Kamel Ben Naceur, director of Sustainability, Technology and Outlook with the International Energy Agency (IEA), noted that CCS is already falling behind on reaching the world's emission targets.

For the world to keep temperature rise under 2 degrees, we will need 500 megatons of CO2 a year to be sequestered by 2025 and 1,500 megatons per year by 2030.

But "if all projects known today were to proceed it would just be 74 megatonnes of CO2 a year," he said.

There are currently seven CCS projects under construction worldwide, in an increasingly diverse range of sectors, including coal, oil sands and steel, he said.

IEA is publishing a report called 'EOR plus', looking at how the concept of Enhanced Oil Recovery (EOR) can be extended to work together with carbon capture, he said.

Conventional EOR has a goal to maximise oil recovery, but 'EOR plus' has goals of both maximising oil recovery and maximising CO2 sequestration.

In IEA's two degree scenario [its imagined pathway to how we keep temperature rise to under 2 degrees], most coal power would be decarbonised, but not all of the gas, he said. So we would probably still see conventional gas power being used for heating.

The IEA considers that Norway has a "promising outlook" on carbon capture, and "in UK we hope to see re-emergence of CCS," he said.

One concern is the enormous number of people who have left the oil and gas industry due to the downturn, many to retire. This means that many people with geoscience expertise, which the carbon capture industry would need, are no longer available.

Oil and gas investment worldwide dropped 25 per cent between 2014 and 2015, and dropped another 24 per cent in 2016. "This is the first time it has dropped for 2 years running since the 1980s," he said. IEA predicts oil and gas investment will stay flat or show a slight decline going into 2017.

It is also worth noting how fast the price of renewable energy has dropped, by a factor of four over the past three years. Auction prices have dropped from around $80-100 per mwh to $30 per mwh. This is for both wind and solar PV, he said.

Mr Naceur noted that only 10 out of the 170 countries which signed up to the COP 21 Paris agreement mentioned CCS has part of their carbon capture plan, although there are 25 governments in the 'Carbon Sequestration Leadership Forum', a governmental carbon capture organisation.

The carbon capture story arguably began in 1987, with two Statoil scientists having a discussion over a beer, about options for handling CO2 from the Sleipner gas field, where the gas had a high CO2 content. "They issued a memo about the opportunity of using CO2 storage," he said. "Next year we celebrate 30 years of that beer."

Tim Bertels, Shell

Tim Bertels, CO2 Implementation Manager / Head of CCS, Shell, said that the company has now stored a million tons of CO2 in its Quest CCS project in Canada.

Quest is a joint venture with Chevron (20 per cent) and Marathon (20 per cent). It takes 35 per cent of the CO2 emissions from the Scotford upgrader, a facility which processes crude bitumen from oil sands. The C02 is stored 2km underground.

The CO2 was delivered "on time and below budget," he said. "So far it has been operating extremely well."

The system was built in modules, using methods usually used for offshore work, leading to a tighter, more integrated design. There wasn't a lot of space available for constructing the carbon capture plant.

Shell put a lot of activity in talking to the public. "You have to hear people's concerns and accept them as legitimate," he said. "We had a stakeholder engagement group."

It is important to make the effort to engage with people, otherwise you might find later that people come up with objections you had not anticipated, he said. People might trust the people they meet, even if they do not trust the company.

The pipeline for the project had to be built 'crooked' so it would only go through land where permission had been agreed.

The Quest project would not have worked without assistance from the government, which (in particular) provided clear and workable regulations on how the liability for storage would be managed.

In most carbon capture projects, the revenues do not end up covering the costs, and the challenge is to close the gap. In Quest, it was a great help that Shell was given double carbon credits, as an incentive to build a 'first of a kind' project, he said.

The non-governmental organisations (NGOs) have a spectrum of opinions on these projects. Some NGOs say "oil sands are not to our liking so we dont applaud CCS on oil sands," he said. "I believe any CO2 taken out of atmosphere which would otherwise be emitted is a good thing. But opinions are mixed."

Although Shell's Peterhead (UK) project was cancelled, the company got a "number of learnings" from it, so, "it is in a sense equally valuable," he said.

Mr Bertels was asked about his opinion on CO2 utilisation. "I think it's good to think about anything with CCS. But I see challenges around cost, scale of utilisation, and foot printing - not all utilisation has a negative footprint. There will be opportunities and we should pursue them."

"EOR CO2 is not easy in a low oil price environment. I wouldn't want to overestimate where we can deploy it. But EOR CO2 keeps running in US at $50 [oil price]."

"There is a similar sensitivity about CO2 EOR as there are is for oil sands. Some people say its additional oil so I don't support it. I am of a different opinion. The fact is CO2 EOrRdoes store a lot of CO2."

In terms of potential cost reduction, "I can say, from studies we did, there are gains to be made in every element of the value chain, you can reduce the cost," he said.

Financial metrics

Both Shell's Tim Bertels and Andy Read, from the Dutch ROAD project, said that the continued emphasis on pricing CCS in 'cost per ton of CO2' are not always helpful.

Power station operators are mainly interested in the price of electricity, and that is currently low due to the growth in subsidised renewables, Mr Read said. Some people say, "People only build what you can get a subsidy for."

And if you calculate the cost of carbon capture per megawatt hour of carbon free electricity, gas is cheaper, but if you calculate the cost per ton of CO2, coal power is cheaper, he said. But also it varies with different cases.

Shell's Tim Bertels agreed "we should be careful about euros per ton." For example, the first CCS project could set a pathway to create many more projects, and in this case the most important issue is the pathway, not the cost of the first project.

Perhaps in the long term, the carbon price will reach the cost of storing CO2, rather than the CO2 storage cost having to match the carbon price, he said.

More information

Presentations from the conference, and the GCCSI's own report, is online at:

http://bit.ly/GCCSIOslo

ROAD just needs one more agreement

The Dutch 'ROAD' project just needs one more agreement to be confirmed before it can start development, although the project size has been scaled down, said Andy Read, CO2 capture director

The Netherlands 'ROAD' (Rotterdam Opslag en Afvang Demonstratieproject) carbon capture project just needs one more signature before it can go ahead, said Andy Read, Capture Director with the Dutch "ROAD" Project.

There is one "heads of terms" agreement which the ROAD team need to pin down before starting, he said.

The ROAD team want to get all agreements in place before starting, to avoid a re-run of 2012, where the project team spent a large amount of money planning a project which did not ultimately go ahead, due to insufficient funding being available.

The project has been in 'slow mode' since 2012, with the team trying to plug a gap between funds available and the project anticipated capital and operating costs.

The project was originally planned to be funded by the carbon price (earning emission credits by sequestering CO2 which would otherwise be emitted). But now "we've given up on carbon price," he said.

But after 4 years of hard work, the ROAD team believe they are very close to being able to close the funding gap, he said. This has been achieved by downsizing the project so it can be built for less money, and planning to operate it for a shorter length of time.

The CO2 storage site has been changed from an offshore site operated by TAQA, to an onshore site operated by Oranje-Nassau Energie, with an injection point very close to the Maasvlakte power plant, which is the source of the CO2.

The CO2 will be transported 5km onshore, through a 24 inch pipeline, with no offshore pipeline needed.

The pressure has been reduced to 20 bar, which makes it easier to tie the system into an existing 20 bar CO2 system in Rotterdam providing CO2 for greenhouses in future, he said. The CO2 will be compressed to a higher pressure for injection at the injection site. This means that the injection temperature and pressure can be fully controlled, he said.

It makes sense for ROAD to stick with a coal power plant, because most gas power plants in Europe are not running at a high load, because their power is more expensive. To make gas power + CCS work, "you'd have to transform the power market". But coal power is running at a high load factor in most places, he said.

The coal power plant chosen is 1070 MW, 46 per cent efficient plant. The capture plant will capture the CO2 equivalent to 250 MW of power generation, with the size of the capture plant set by the size of the EU grant to build it. It will capture 90 per cent of the CO2, which equates to 1.1 megatonnes of CO2 per year.

The storage site, operated by Oranje-Nassau Energie, has capacity for 2-4 mt of CO2, which means it will be full in about 3 years, he said.

The storage site is also an oil and gas reservoir, which started production in 2014, with LPG, condensate and gas. It will be available for CO2 storage in about 2020.

With the condensate production, it would become an enhanced oil recovery project. But the amount of condensate available is a small part of a very small field, he said.

Revenues from the increased production will help cover operational costs. "But every little helps," he said.

Currently the project can be built using funds already committed, but there is no guaranteed funds available to run it, and abandon it at the end. It is something as a 'pay as you go' model, where the project will only operate so long as funds are available.

"We're trying to make each financing step an amount governments can swallow," he said.

There is already a CO2 industry in Rotterdam, taking CO2 from Shell's Pernis refinery to be pumped into greenhouses, and there are many greenhouses which do not have a CO2 supply.

All of this could be connected to ROAD. Also the CO2 network could be extended to nearby Antwerp, and use waste heat from industry and electricity from renewables.

There has been very strong political support "in some senses", with lawmakers agreeing to change the law for CO2 storage to make ROAD possible.

A headwind is a Dutch campaign to close down coal power plants, which would make the project impossible, he said.

The Dutch government is currently deciding which coal power plants will need to be closed down in order for the country to achieve its 2020 emission reduction goals, he said.

Perception by politicians

Probably the biggest factor in whether carbon capture and storage projects can get started is how it is perceived by politicians, because most projects are dependent on public support.

A panel session was held at the conference looking at how politicians see carbon capture. This is very important because carbon capture projects are usually dependent on large government support.

Per Rune Henriksen, member of the Storting (Norwegian legislative body) and the Norwegian Standing Committee on Energy and the Environment said that CCS is still "not regarded as a good solution by many politicians".

Chris Davies, a former Member of the European Parliament (where he played an active role in promoting carbon capture), recalled that in 2008, when he first started with CCS, "there were people coming to my office one after the other [with projects]. As carbon price fell away, the enthusiasm fell away," he said. Today, "in every national capital, there's no enthusiasm - and sometimes outright hostility."

Politicians think it is OK to cherry pick parts of the international climate change agreements they like, and disregard CCS, which the Intergovernmental Panel on Climate Change (IPCC) says is essential, Mr Davies said. Today, there is some enthusiasm from carbon capture from the European Commission but not from the national governments.

Ola Elvestuen, also a member of the Norwegian Storting and Chair of the Standing Committee on Energy and the Environment, said that the easiest way to get political support for carbon capture is to make a success of one project and then others will follow.

"It is difficult to commit large sums of money given that there hasn't been many successes," said Michael Schuetz, policy officer with the European Commission Directorate General (DG) for Energy.

Carbon capture "is a big upfront risk," he said. "Politicians need to see that something actually works before giving several hundred million more of taxpayers' money. Lots of people in Europe had their fingers burned with CCS."

"In renewables, the benefits are more equally distributed. [For example] People have shares, people rent land."

There was very little public noise after the UK carbon capture competition was cancelled - Lord Oxburgh (Photo ©Sverre Chr. Jarild)

Lord Oxburgh, from the UK House of Lords, asked where in Brussels the responsibility lies for meeting the 2050 emission reduction targets. If people are making objections to carbon capture investment, they should also have a responsibility for suggesting alternatives.

Mr Schuetz replied by saying that the responsibility [for actually achieving emission cuts] is with the member states.

The situation is different in Norway, said Per Rune Henriksen, member of the Norwegian Storting.

"Norwegian politicians realise this will be a costly process, we are ready to put up the sums needed to get going."

Ola Elvestuen, Member of the Storting, noted that in particular, politicians want to avoid being blamed for mistakes, one of which is not being in control of costs.

There was a time when costs for Norway's Technology Centre Mongstad project "were starting to run by themselves," he said.

Another issue, Lord Oxburgh pointed out, is that "no politician ever lost votes for cutting funding for CCS." There was very little public noise after the UK carbon capture competition was cancelled.

Per Rune Henriksen replied, "In Norway you can lose votes on cutting funding for CCS. And we shouldn't be so afraid of mistakes, that we don't do anything."

And if carbon capture does not succeed, politicians will need to tell the public that they have to walk rather than drive, and they will probably get blamed for that. "Maybe we have to talk about the alterative more and more," he said.

Ola Elvestuen said, "You don't win elections on climate change. It is something you do when you're in [a] position."

Lord Oxburgh said, "From a political point of view, you want to give people things they can be proud of. Once we have power stations with CCS we should put an additive in the emissions so it's green. People see they have something for their money."

Carbon capture in Norway

Norway is currently planning three ground-breaking carbon capture projects, taking CO2 from a cement factory, a fertiliser factory, and a waste incineration plant, and taking the CO2 to a single offshore storage site

Norway is currently planning a feasibility study for three ground-breaking carbon capture projects, covering cement manufacture, waste incineration and fertiliser manufacturer.

The projects are supported by government funds. The CO2 will probably be taken by ship to a single offshore storage site.

In his opening address, Brad Page, CEO of the Global CCS Institute, noted that carbon capture has support from all political parties in Norway, and the Sleipner CO2 Storage Project has now been injecting CO2 for 20 years.

Also Norway is a major contributor to the Carbon Sequestration Leadership Forum (CSLF), and it contributes to the CSLF's Trust Fund and the World Bank CCS Trust Fund.

Norway was one of only 10 countries in the world out of 170 which said it would use CCS to meet its COP21 targets.

Norway has kept going [with CCS], when other countries started and stopped," noted Lord Oxburgh, from the UK government House of Lords.

Ingvil Smines Tybring Gjedde, state secretary and deputy minister in the Norwegian Ministry of Petroleum and Energy, explained why CCS is seen as such a high priority in Norway.

Norway has agreed to reduce its CO2 emissions under the Paris (COP21) agreement; it has knowledge and skills relevant to carbon capture acquired through its offshore oil and gas activity.

Also, with Sleipner and Snøvhit, it has the only CCS projects on the European continental shelf, she said.

Norway also has Technology Centre Mongstad (TCM), "one of the world's largest and most advanced test centres," she said.

"Norway is keen to have a full scale carbon capture project" - Ingvil Smines Tybring Gjedde, state secretary and deputy minister in the Norwegian Ministry of Petroleum and Energy (Photo ©Sverre Chr. Jarild)

Three Norwegian projects

Norway is keen to have a full scale carbon capture project, Ms Tybring Gjedde said, and it will need to be in the industrial sector, because Norway does not have a lot of coal power (95 per cent of electricity production in Norway is hydroelectric).

Norway is planning a feasibility study to look at capturing carbon capture from three industrial sources - a cement manufacturing plant operated by Norcem, a fertilizer plant operated by Yara, and the Klementsrud waste incineration plant in Oslo.

The CO2 is most likely to be transported in ships rather than pipelines, because shipping "is considered most cost effective at this stage," she said.

The CO2 storage location is likely to be an offshore site called Smeaheia, connected by well and pipeline to an onshore terminal, she said.

"Studies show it's technically feasible at lower cost than previously anticipated," she said.

The project timeline is to select the engineering concept and initiate Front End Engineering and Design (FEED) in mid-2017, and make a final investment decision in 2019, with construction 2019 to 2022, when operation will start.

"We will need hundreds or thousands of CCS projects around the world in a few decades," she said.

Representatives of the three Norwegian projects were present at the conference.

Johnny Stuen, technology Manager for the Klementsrud waste incineration plant in Oslo, said that the idea of putting carbon capture on a waste incineration plant "has broad political support in Oslo".

CO2 in waste incineration comes from both plastics and biological waste (such as paper).

The CCS + biological waste is arguably a negative CO2 system, because CO2 is taken out of the atmosphere when the biological materials (such as trees) are grown.

It might be good to have regulation saying that all waste treatment should be done without CO2 emission, he said.

Liv Bjerge, senior project manager, with Norcem CO2 Capture Projects, talked about the plan to build a carbon capture plant at its Brevik plant in Norway, which is responsible for 800,000 tons of CO2 emitted per year.

The cement industry is responsible for 5-6 per cent of total global emissions, she said. Norcem is part of Heidelberg Cement, the second largest cement producer in the world and the only producer in Norway.

"We realise we need to find solutions," she said. "We have a vision by 2030 our product will be carbon neutral."

Norcem has already run a feasibility study to look at if it could do carbon capture from its flue gas, using amines from Aker Solutions, using waste heat from the cement plant and the CO2 compression train, with a capacity of 400,000 tons of CO2 / year.

The proposed carbon capture project could involve a 3,500 tank for liquid CO2, where it could be stored prior to being offloaded into a vessel. "This will be the first plant for cement," she said.

"We are ready for the next step and that's a field study. We've selected technology and vendor."

However the project is dependent on public support, she said.

Eystein Leren, head of Environmental Technologies Production R&D, Yara, said that Yara would like to set up "the first ultra-low CO2 ammonia plant in the world."

Yara is a Norwegian chemical company and one of the largest fertiliser producers in the world.

The fertiliser is made from ammonia, and the ammonia is made from combining nitrogen hydrogen. The CO2 emissions are made when hydrogen is made from natural gas.

Norwegian FEED project panel discussion. From left to right: Olav Skalmeraas , Vice President for Carbon Capture & Storage, Statoil ASA; John Kristian Økland , Project Manager, Gassco; Eystein Leren , Head of Environmental Technologies Production R&D, Yara; Liv Bjerge , Senior Project Manager, Norcem CO2 Capture Projects (hidden); Johnny Stuen , Technology Manager EGE/Klemetsrudanlegget AS (Photo ©Sverre Chr. Jarild)

There is also CO2 emitted from heating process, he said.

Yara has been capturing CO2 for many years, but the CO2 is ultimately emitted, because there hasn't been any way to store it, he said.

So far the only work to develop carbon capture has been a feasibility study, or a 'desktop' study, he said.

The project would not make commercial sense on its own, he said, and so depends on public support. There is no allowance for paying for CO2 emissions reflected in the price of ammonia.

CO2 transport

John Kristian Økland, project manager with Norwegian gas transport company Gassco, talked about his studies of CO2 transport by ship.

Gassco builds and operates a range of Norwegian gas transport infrastructure.

It has looked at three ship designs for CO2, at low, medium and high pressure.

The low pressure vessel carries CO2 at -50 degrees C and 7 bar pressure, where it is close to the 'triple point' that the CO2 is simultaneously gas, solid (dry ice) and liquid). The capacity is 6000 to 7000m3 and the density is highest, 1150 kg/m3. Because the pressure is low, less steel thickness is required, but the ship requires more insulation because the temperature is lower. Cooling the CO2 is energy consuming. This vessel is comparable to an LPG vessel, he said.

The medium pressure vessel carries CO2 at -25 degrees C and at 15 bar pressure. The capacity is 7400 to 7700m3. The CO2 has a density of 1050 kg/m3. The high pressure means a thicker wall, and the low temperature means some insulation is required. So it is energy consuming but not as much as the low pressure vessel.

The high pressure vessel carries CO2 at +10 degrees C and 45 bar, with vessel capacity of 7,000 to 12,000m3. The density is lowest, 870 kg/m3. The high pressure means that the most steel is needed to contain the gas. But very little insulation is needed. This the least energy consuming process. Also, the high pressure means that it is easier to offload the CO2 into a subsurface storage site, because less additional compression is needed.

Gassco has not yet selected which concept it would like to use, he said.

Statoil

Olav Skalmeraas, vice president for Carbon Capture and Storage with Statoil said that Statoil stressed the value of storing carbon dioxide in areas where the subsurface is already well understood, due to oil and gas activity.

To fully understand a CO2 storage site from a point of having no geological knowledge can take 8 years, he said, longer than it takes to build a carbon capture plant.

Statoil has developed CO2 monitoring systems for its storage sites in Sleipner and Snøhvit. Monitoring programs are very expensive, because you can need to continually monitor a site for 25 to 30 years after injection, he said.

There are three different engineering concepts which could work for CO2 storage, he said. You can inject CO2 directly from offshore, run a pipeline from a shore terminal to a subsea injection point, or tranship the CO2 to a permanent pressured injection ship.

“All concepts are feasible, some technology qualification needs to be done,” he said.

One point to note is that with Sleipner, the entire project has only one owner, and is all part of the same ‘value chain’, the need to produce CO2 free gas.

But in carbon capture and storage, there are different companies, with different income levels and reasons for doing it.

Currently, the carbon capture framework “is not attracting investors,” he said. “It is important to establish and prove commercial models to attract and not repel investors.”

Gassnova and TCM

Gassnova, the Norwegian state enterprise for carbon capture and storage, currently manages a Eur 25m annual budget for its “CLIMIT” research and development program, which has supported 300 projects so far.

It is also one of four owners of Technology Centre Mongstad (TCM), a centre for research of carbon capture technology. The other owners are Statoil, Shell and SASOL.

TCM has an actual carbon capture plant, which tests different ways of separating CO2 out of a flue gas. It has access to two CO2 rich gas streams, one from a gas power plant and one from a catalytic cracker (where the flue gas is similar to flue gas from a coal power plant). Seven companies have tested their technology at TCM so far.

There is a current agreement to operate TCM until 2017, and the plan is to find funding to operate for 3 years after that, she said.

Trude Sundset, CEO of Gassnova, is very pleased that the proposed carbon capture project on the Yara fertiliser plant will see CO2 emission fee hydrogen being created. “That’s a fascinating opportunity for the future,” she said.

Another proposed Norwegian project, taking CO2 from a waste incineration plant, could be considered a ‘negative CO2 plant’ because waste is 60 per cent biofuel (for example, paper). A negative CO2 plant is something “we desperately need,” she said.

In Gassnova’s analysis of the prices of building CCS projects, it found that three plants could be built for roughly twice the cost of building one, so “three for the price of two.”

In more detail, one source would enable the capturing of 400kt CO2 a year, three sources would capture 1300 kt CO2 a year.

The planning and investment costs for one source would be Eur 791m, for 3 sources would be Eur 1384m. The operating and maintenance costs for one source would be Eur 39m, for three sources would be Eur 98m.

Furthermore, the storage site to be developed in Smeaheia could also take CO2 from other parts of Europe.

There has already been Eur 40m committed in Norway’s 2017 national budget to a full scale demonstration plant, she said.

Using shipping will also give the system more flexibility than using pipelines, she said.

Roy Vardheim, CEO CO2 Technology Centre Mongstad (TCM) said that the centre has 3 main roles, to help technology vendors test and develop proprietary technology, to help universities develop non-proprietary technology, and act as a ‘global competence’ source.

Next year there will be a project with research organisations SINTEF and NTNU, to demonstrate ways of running the plant with predictive control systems, so it can be operated at lower cost, he said.

TCM is learning about better ways to prevent corrosion and reduce degradation of the solvents, he said.

It is also developing competence in better ways to manage emissions, understand the chemistry involved, and get better at simulation and modelling of the capture process.

The centre also offers operator training services, he said.

There is a growing interest in CO2 utilisation, and the centre has got involved by providing space in its parking lot for a company which is experimenting with growing algae in CO2 rich environment, he said.

Bellona

Frederic Hauge, president of environmental organisation Bellona, said he believes that carbon capture is crucial to achieve the Paris agreement, and is upset that other environmental organisations that don’t support it.

“The best way to fill up your [email] inbox is to accuse Greenpeace of not taking global warming seriously because they oppose CCS,” he said.

“To tell the poor people in the world, we've got to spend twice as much money to solve the climate (by not using CCS) so we have less for your welfare, that is very arrogant,” he said.

Bellona has been struggling with the Green party in Germany who also dislike CCS. “They are not very productive,” he said.

Mr Hauge believes that carbon capture should provide employment for 10,000 to 15,000 people working offshore in the Norwegian continental shelf from 2030 onwards, working with CO2 storage.

Norway could provide CO2 storage opportunities to other countries in Europe, or has he colourfully put it, “taking back all the sh** we sold to Europe and we make money once more.”

But nobody is really fighting for carbon capture, he said, the CCS community is just talking about getting the technology ‘accepted’, which is something different.

“It’s because the community is fragmented. We mislead politicians,” he said.

Modelling and exergetic analysis of an oxy-combustion CCS process

Renato P Cabral, a researcher at Imperial College London, is working on simulating an oxy-combustion process for a pulverised coal ultra-supercritical power plant using Aspen HYSYS process simulation software

Oxy-combustion is more suitable to new plants and has the added advantage of having improved efficiency and lower equipment size due to the lack of air nitrogen (N2) during the combustion reaction. In this process, the fuel is burned on a mixture of oxygen (O2) and recycled flue gas (RFG) which increases CO2 and water concentrations allowing for an easier separation of CO2.[1-3]

A cryogenic air separation unit was chosen for this study because it is the only proven technology, up to this date, to be able to satisfy the high demands of O2 from the coal power plant. In this unit air is compressed to 4.2 bar and then sent to a multiple stream heat exchanger where it is partially condensed against the cold products from the rectification units. This stream is then fed to a high-pressure (HP) column operating at 4.1 bar and -180°C where a pre-separation of air occurs into a N2 stream and an O2 enriched air stream.

These streams are fed to the low-pressure (LP) column operating at 1.1 bar and -188°C where further purification of O2 takes place. These columns are separated by a condenser/reboiler where N2 from the HP column condenses against boiling O2 from the LP column. With this configuration, it is possible to produce O2 with 98% w/w purity with a specific power consumption of 204 kWh/t_{O2} to be used as oxidant in the power plant.

The O2 produced is sent to an ultra-supercritical power plant to oxidize coal producing flue gas (FG) (CO2, water, sulphur oxides (SO_x)), and ashes. Nitrogen oxides (NO_x) are present in smaller amounts than under air-firing conditions since there are only small amounts of molecular N2 on the oxidant, and its formation is mainly due to nitrogen present in coal.

Hot FG is used in the boiler to heat pressurised water at 300 bar until supercritical state at 600°C and consequently drives a turbine to generate electricity. Steam leaves the turbine at low pressure and temperature and sent to a condenser. It is then pre-heated against bleeds taken from the turbine and sent to the boiler closing the Rankine cycle. The FG leaves the boiler at lower temperature and is used to pre-heat RFG on a regenerative heat exchanger, increasing the cycle efficiency, and it is then sent to a spray dryer to remove SO_x, baghouse filters to remove ashes, and cooled in a direct contact cooler.

Unrecycled FG is sent to a CO2 compression and purification unit (CPU)[4], where it is first compressed in three stages with intercooling and condensed water removal until 28 bar and 25°C. This stream is sent to multiple stream heat exchanger where it is cooled against the products of the rectification unit operating at 28 bar and -9°C, where 99.9% w/w purity CO2 leaves from the bottom of the unit, and a waste stream leaves from the top.

High-purity CO2 is further compressed to supercritical state at 120 bar and 39°C in a series of two compressors with intercooling and a pump to be sent for storage. An oxy-combustion process with gross power of 506MW and net power of 363MW was modelled, and had a gross efficiency of 47% (LHV) and net efficiency of 34% (LHV), with good validation against Integrated Environmental Control Model (IECM) program and data obtained from Callide Oxyfuel Project.[5]

A thermodynamic evaluation was performed on both the ASU and the CO2 CPU, and it was possible to observe that O2 separation was 25% efficient and CO2 separation was only 5% efficient when comparing with the minimum thermodynamic separation work. It can be observed that a small improvement in efficient on the CO2 CPU process will have a bigger impact on oxy-combustion efficiency than an improvement in the ASU.

An increase of 25% in separation efficiency for both the ASU and CO2 CPU leads to a 5% improvement in net efficiency, however it can also be observed that higher efficiencies can be obtained if the boiler is improved.

Because the CO2 CPU is the newer technology, it has a greater potential for improvement than the ASU and although improvements in the boiler would have a bigger improvement in efficiency. This would require newer materials to be developed which is unlikely in the short term.

An exergetic analysis was performed on the process and it can be observed that the boiler is the source of most losses, followed by the ASU and the feed-water heating train, where water is pre-heated before going back to the boiler. Because there is compression work being done at the ASU, this shows that there is the possibility of using low grade heat from air compression to pre-heat feed-water to the boiler, which would allow less bleeds from the turbines and more steam available to generate electricity.

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More information

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Modelling and exergetic analysis of an oxy-combustion CCS process

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INTRODUCTION

In order to limit climate change to "the well below 2 °C target" agreed on COP21, carbon capture and storage (CCS) is an extremely important technology as we are still reliant on fossil fuels for heat and power generation. Carbon dioxide (CO_2) reductions of as high as 90% can be achieved by applying CCS on CO_2 sources.[1]

Oxy-fuel combustion involves burning a fuel with a mixture of oxygen (O_2) with recycled flue gas (RFG) as opposed to air. This reduces the amount of nitrogen (N_2) in the flue gas (FG) while increasing CO_2 and water vapour concentrations, making it easier to obtain a pure stream of CO_2.[2-4]

This work presents a techno-exergetic analysis of a state-of-the-art oxy-CCS process, with the aim of identifying opportunities for efficiency improvements.

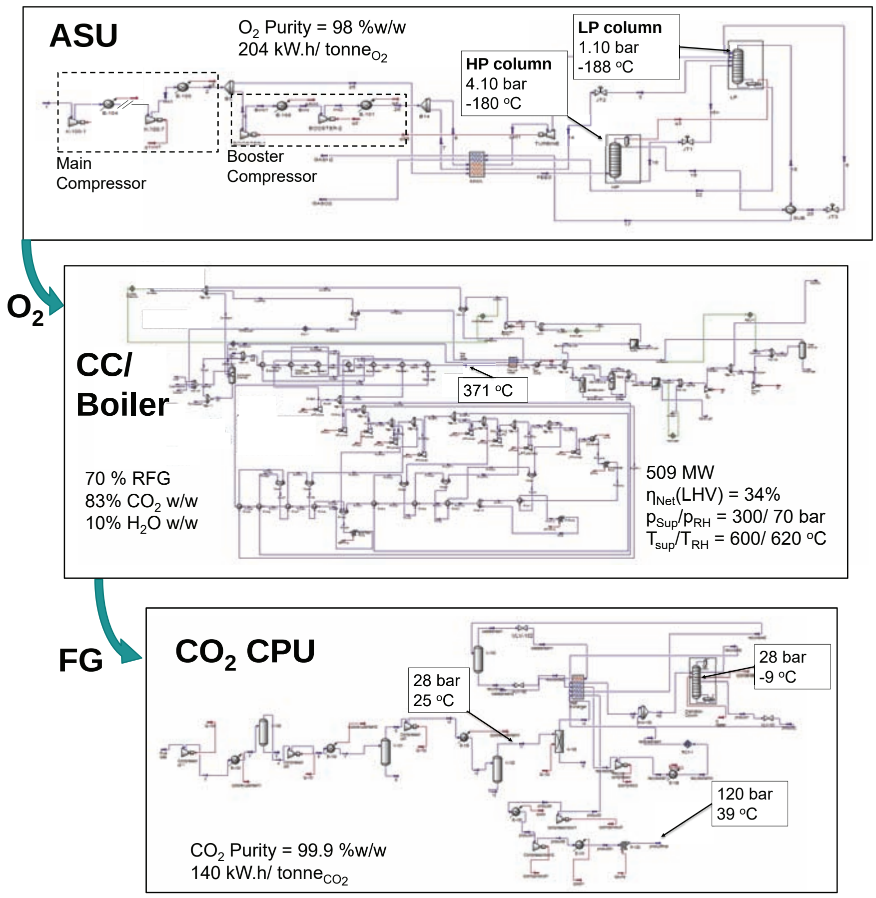

Figure 1 – Schematic representation of an oxy-combustion process. On the top, we see the Air Separation Unit (ASU) responsible for the production of oxygen required by the combustion chamber (middle), where coal combusts in a mixture of recycled flue gas (RFG) and pure O_2. After combustion, flue gas (FG) is passed through a boiler producing supercritical steam that expands to a turbine, generating power. Sulphur oxides (SO_x) and fly ash are removed from the FG prior to being recycled or sent to the CO_2 Compression and Purification Unit (CPU) (bottom)[6]. Here water is removed from the FG and CO_2 is purified to be sent for storage. This model has been validated with the literature, with data presented in Table 1 below.

Minimum thermodynamic separation work

$$W_{min} = \frac{RT}{n^{pure}_{O_2,CO_2}}[\textstyle\sum_{Out}(n^{Out}_{O_2,CO_2}\ln(y^{Out}_{O_2,CO_2})+n^{Out}_{1-(O_2,CO_2)}\ln(1-y^{Out}_{O_2,CO_2}))]-[\textstyle\sum_{In}(n^{In}_{O_2,CO_2}\ln(y^{In}_{O_2,CO_2})+n^{In}_{1-(O_2,CO_2)}\ln(1-y^{In}_{O_2,CO_2}))]$$

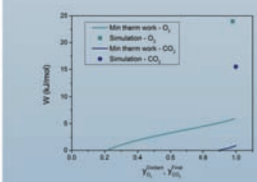

Figure 2 – Minimum thermodynamic separation work of O_2 from air and CO_2 from flue gas. O_2 separation efficiency is 25% and that of CO_2 is only 5%.

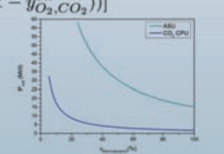

Figure 3 – Effect on parasitic power of ASU and CO_2 CPU improvement.

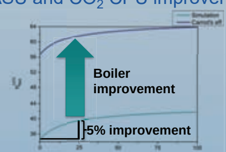

Figure 4 – Improvement on oxy-combustion efficiency. Note the 5% efficiency gain if separation is improved by 25%.

Exergetic analysis

$$LW = \textstyle\sum_{In}(n(h-T_0 s)+Q(1-\frac{T_0}{T_s})+W_s)-\sum_{Out}(n(h-T_0 s)+Q(1-\frac{T_0}{T_s})+W_s)$$

Boiler heat loss is the primary source of exergy destruction

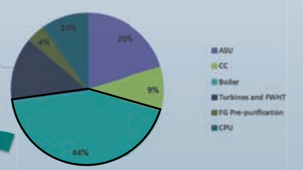

Figure 5 – Oxy-combustion process exergy loss

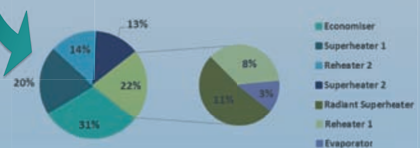

Figure 6 – Boiler exergy loss

Table 1 – Model validation exercise

Oxy-combustion	Model	IECM	Callide[5]
Gross Power [MW]	509	517	500
Net Power [MW]	363	396	345
Gross efficiency (LHV)	47%	46%	46%
Net efficiency (LHV)	34%	35%	32%
O_2 demand [kg/MWh]	605	653	632
Fuel Burned [kg/s]	40	40	54

Conclusions

- Successful simulation using Aspen HYSYS.
- 13% penalty between gross and net efficiency.
- Values in accordance with IECM and data obtained from Callide Oxyfuel project.
- Boiler improvement will have bigger impact on oxy-CCS net efficiency, however this will be hard to do.
- As compressors operate at near 90% efficiency, improvement from ASU and CO_2 CPU not likely to come from this.
- Reducing ASU power consumption by sending a greater amount of air to expander turbine.
- Improving heat integration between the processes are the most likely way of reducing efficiency loss.
- Using heat of compression to pre-heat boiler's feed-water, allowing less bleed on turbines and more steam for electricity generation.
- CO_2 CPU has possibility for bigger improvement, as it is a newer technology.
- CO_2 CPU offers the potential for greater reduction in power consumption.

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Science and Solutions for a Changing Planet

Grantham Institute
Climate Change and the Environment

Bubble-like liquid membrane to separate CO2

Sandia National Laboratories and the University of New Mexico (UNM) have created a powerful new way to capture carbon dioxide with a bubble-like membrane or 'Memzyme'.

CO2 is a primary greenhouse gas, and about 600 coal-fired power plants emitted more than a quarter of total U.S. CO2 emissions in 2015. When you include emissions from natural gas plants, the figure goes up to almost 40 percent. Current commercial technologies to capture these emissions use vats of expensive, amine-based liquids to absorb CO2. This method consumes about one third of the energy the plant generates and requires large, high-pressure facilities.

The Department of Energy has set a goal for a second-generation technology that captures 90 percent of CO2 emissions at a cost-effective $40 per ton by 2025. Sandia and UNM's new CO2 Memzyme is the first CO2 capture technology that could actually meet these national clean energy goals. The researchers received a patent for their innovation earlier this year.

It's still early days for the CO2 Memzyme, but based on laboratory-scale performance, "if we applied it to a single coal-fired power plant, then over one year we could avoid CO2emissions equivalent to planting 63 million trees and letting them grow for 10 years," said Susan Rempe, a Sandia computational biophysicist and one of the principal developers.

Membranes usually have either high flow rates without discriminating among molecules or high selectivity for a particular molecule and slow flow rates. Rempe; Ying-Bing Jiang, a chemical engineering research professor at UNM; and their teams joined forces to combine two recent, major technological advances to produce a membrane that is both 100 times faster in passing flue gas than any membrane on the market today and 10-100 times more selective for CO2 over nitrogen, the main component of flue gas.

Stabilized, bubble-like liquid membrane

One day Jiang was monitoring the capture of CO2 by a ceramic-based membrane using a soap bubble flow meter when he had a revolutionary thought: What if he could use a thin, watery membrane, like a soap bubble, to separate CO2 from flue gas that contains other molecules such as nitrogen and oxygen?

Thinner is faster when you're separating gases. Polymer-based CO2 capture membranes, which can be made of material similar to diapers, are like a row of tollbooths: They slow everything down to ensure only the right molecules get though. Then the molecules must travel long distances through the membrane to reach, say, the next row of tollbooths. A membrane half as thick means the molecules travel half the distance, which speeds up the separation process.

CO2 moves, or diffuses, from an area with a lot of it, such as flue gas from a plant that can be up to 15 percent CO2, to an area with very little. Diffusion is fastest in air, hence the rapid spread of popcorn aroma, and slowest through solids, which is why helium slowly diffuses through the solid walls of a balloon, causing it to deflate. Thus, diffusion through a liquid membrane would be 100 times faster than diffusion through a conventional solid membrane.

Soap bubbles are very thin – 200 times thinner than a human hair – but are fragile. Even the lightest touch can make them pop. Jiang and his postdoctoral fellow Yaqin Fu knew they would need to come up with a way to stabilize an ultra-thin membrane.

Luckily, his colleague Jeff Brinker, another principal developer who is a Sandia fellow and regent's professor at UNM, studies porous silica. B

y modifying Brinker's material, Jiang's team was able to produce a silica-based membrane support that stabilized a watery layer 10 times thinner than a soap bubble. By combining a relatively thick hydrophobic (water-fearing) layer and a thin hydrophilic (water-loving) layer, they made tiny nanopores that protect the watery membrane so it doesn't "pop" or leak out.

Sandia National Laboratories researcher Susan Rempe peers through bubbles. The CO2 Memzyme she helped design captures carbon dioxide from coal-fired power plants and is 10 times thinner than a soap bubble. (Photo by Randy Montoya)

Enzyme-saturated water accelerates CO2 absorption

Enzymes (the –zyme part of Memzyme; the mem– comes from membrane) are biological catalysts that speed up chemical reactions. Even the process of CO2 dissolving in water can be sped up by carbonic anhydrase, an enzyme that combines CO2 with water (H2O) to make super soluble bicarbonate (HCO3-) at an astounding rate of a million reactions per second. This enzyme can be found in our muscles, blood and lungs to help us get rid of CO2.

Rempe and her former postdoctoral fellow Dian Jiao were studying how CO2 dissolved in water, with and without this enzyme. They thought the enzyme could be combined with something like Jiang's watery membrane to speed up CO2 capture. An enzyme-loaded membrane is almost like an electronic toll collection system (such as E-ZPass). The enzyme speeds up the dissolving of CO2 into water by a factor of 10 million, without interacting with other gases such as nitrogen or oxygen. In other words, the liquid Memzyme takes up and releases CO2 only, fast enough that diffusion is unimpeded. This innovation makes the Memzyme more than 10 times more selective while maintaining an exceptionally high flow rate, or flux, compared to most competitors that use slower physical processes like diffusion through solids.

However, the nanopores in the membrane are very small, only a little wider than and a few times as tall as the enzyme itself. "What's happening to the enzyme under confinement? Does it change shape? Is it stable? Does it attach to the walls? How many enzymes are in there?" Rempe wondered.

Rempe and her postdoctoral fellow Juan Vanegas designed molecular simulations to model what happens to the enzyme in its little cubby to improve performance. Interestingly, the enzyme actually likes its "crowded" environment, perhaps because it mimics the environment inside our bodies. And more than one enzyme can squeeze into a nanopore, acting like runners in a relay passing off a CO2 baton. Because of the unique structure of the membrane, the enzymes stay dissolved and active at a concentration 50 times higher than competitors who use the enzyme just in water. That's like having 50 E-ZPass lanes instead of just one. Protected inside the nanopores, the enzyme is still efficient and lasts for months even at 140 degrees Fahrenheit.

Working toward a greener future

Having successfully tested the CO2 Memzyme at the laboratory scale, the Sandia-UNM team is looking for partners to help the technology mature. Each part of the membrane fabrication process can be scaled up, but the process needs to be optimized to make membranes for large power plants.

In addition, the team is looking into more stable alternatives to the common form of the enzyme, such as enzymes from thermophiles that live in Yellowstone National Park hot springs. Or the Memzyme could use different enzymes to purify other gases, such as by turning methane gas into soluble methanol to produce purified methane for use in the natural gas industry.

The CO2 Memzyme produces 99 percent pure CO2, which can be used in many industries. For example, U.S. oil companies buy 30 million tons of pure CO2 for enhanced oil recovery. The CO2 could be fed to algae in biofuel production, used in the chemical industry or even used to carbonate beverages.

"Partnership between theory and experiment, Sandia and UNM, has proven fruitful here, as it did in our earlier work on water purification membranes. Together we developed a membrane that has both high selectivity and fast flux for CO2. With optimization for industry, the Memzyme could be the solution we're looking for to make electricity both cheap and green," said Rempe.

More information

www.sandia.gov
www.unm.edu

Capture and utilisation news

EnCO2re moves to commercialise CO2 re-use for the plastics industry

enco2re.climate-kic.org

CO2 re-use programme seeks new industrial partners to turn CO2 emissions into a source of value for European industry.

An open innovation programme to replace petroleum with CO2 as a feedstock in the manufacture of plastics was launched at KFair in Düsseldorf. Led by Climate-KIC and Covestro, the EnCO2re programme has more than a dozen leading research partners in seven countries and is now ready to work with industrial partners to take CO2 re-use out of the laboratory and deploy it at scale.

The first commercial-scale applications of CO2 re-use could be polymers and chemical intermediates that are the basis of the plastics we use every day, including in our furniture, the panels that insulate our homes, and under the hood of our cars. Professor Charlotte Williams, Professor of Catalysis and Polymer Chemistry, Oxford University, said, "Industry and academia need to work hand in hand to solve the world's biggest challenges. Being part of EnCO2re helps us collaborate with some of the world's CO2 re-use experts toward a common goal. Only together we can move more quickly toward sustainable industrial processes."

EnCO2re's partners say that the CO2 re-use market has the potential to grow by more than 20 times its current size, reaching up to 3.7 billion tonnes per year – an amount equal to roughly 10% of global emissions. However, CO2 re-use technologies currently face technical, commercial and financial barriers to development and widespread deployment. EnCO2re is an innovation hub, partner network and market development programme aimed at breaking down those barriers.

Sira Saccani, Director of Sustainable Production Systems at Climate-KIC said, "Cooperation between research and industry is essential to commercialising breakthrough technologies, and CO2 re-use is no exception. Through the EnCO2re programme, Climate-KIC is bringing together top research institutes with industrial partners to turn CO2 from an environmental threat to a valuable industrial feedstock."

EnCO2re's aim is a balanced and prosperous large-scale market for re-used CO2 through the establishment of a CO2 value chain, beginning with a focus on polymers and chemical intermediates. EnCO2re already has active, world-class projects in two of the three main CO2-to-chemical conversion routes: catalysis and electrochemistry. It will be adding projects covering the biological route in 2017.

Catalysis and electrochemistry technologies are at different levels of readiness across the programme portfolio. Some are currently proof-of-concept, while others, like CroCO2PETs, are taking steps toward market readiness by working with producers to validate performance against the industry-standard properties of conventional materials.

Underpinning all projects is a rigorous, peer-reviewed examination of the life-cycle environmental impacts of CO2 re-use. Dr. Christoph Sievering, Head of Energy Strategy and Policy at Covestro said, "Cooperation between industry and science, in addition to active dialogue with society and policymakers, is essential to commercializing breakthrough technologies. Through CO2 re-use and other innovations, it's clear that industry can and will be part of the solution to climate change."

Transport and storage news

Quest project stores 1M tonnes CO2

www.strath.ac.uk

The Quest oil sands CCS project in Alberta Canada has captured and stored its first tonne of CO2 ahead of schedule.

Quest is the first CCS project applied to oil sands operations, and is run by the Athabasca Oil Sands Project joint-venture owners Shell Canada Energy (60 per cent), Chevron Canada Limited (20 per cent) and Marathon Oil Canada Corporation (20 per cent). The governments of Alberta and Canada provided C$745 million and C$120 million, respectively, in funding.

“The success we are seeing in Quest demonstrates that Canadians are at the forefront of carbon capture and storage technology, showing the world that we can develop real solutions to address climate change,” said Zoe Yujnovich, Executive Vice President, Oil Sands for Shell. “Not only is Quest capturing and storing CO2 emissions from our oil sands operations, but its technology can be applied to other industries around the world to significantly reduce their CO2 emissions.”

Quest has been working better than planned, both in preventing CO2 from entering the atmosphere and in safely storing that CO2 deep underground, since its start-up celebration last November. Both its capture technology and storage capability have helped Quest exceed its target of capturing one million tonnes of CO2 per year, and through careful study and monitoring, the subsurface geology is proving ideal for long-term, safe storage of CO2.

From the outset, any intellectual property or data generated by Quest has been publicly available, in collaboration with the governments of Alberta and Canada, to help bring down future costs of CCS and encourage wider use of the technology around the world. This means that others can take the detailed engineering plans, valued at C$100 million, to help build future CCS facilities.

“Supportive government policy was essential in getting Quest up and running and will continue to play a vital role in developing large-scale CCS projects globally,” added Yujnovich. “Together with government, we are sharing lessons learned through Quest to help bring down future costs of CCS globally. If Quest was built again today, we estimate that it would cost 20-30 per cent less to construct and operate thanks to a variety of factors including capital efficiency improvements and a lower cost environment.”

One of the lessons learned has pointed to how significant cost savings could be achieved through joint transportation and storage facilities. For example, another capture facility could be tied into the existing Quest pipeline for CO2 storage. Operating costs for Quest are also 30 per cent less than anticipated, mainly due to lower fixed costs and energy efficiency savings.

EERC and Hitachi improve CO2 storage estimation

www.undeerc.org

The Energy & Environmental Research Center (EERC) is working with NETL and Hitachi High Technologies America to improve assessment methods for estimating the storage capacity of CO2 in tight shale formations.

EERC researchers will develop advanced analytical techniques to better understand and quantify the distribution of clay minerals, organics, pore networks, and fractures in representative shale and tight rock samples. The analytical methods will be developed using imagery collected from a field emission scanning electron microscope (FESEM), which provides the high-resolution images necessary for detection and characterization of the formation.

"Although significant progress has been made globally to investigate the suitability of subsurface geologic sinks for CO2 storage, there is a lack of detailed geologic and petrophysical data needed to develop better techniques for assessing CO2 storage resources within unconventional formations," said Bethany Kurz, EERC Principal Hydrogeologist, Laboratory Analysis Group Lead.

Project participant and cosponsor Hitachi High Technologies America, Inc., will work alongside the EERC to improve the data processing and image analysis within the FESEM software. The project is funded by NETL with cost share provided by Hitachi.

The effects of CO2 exposure on shale samples will also be analyzed by scientists at NETL's CT Scanning Lab in Morgantown, West Virginia. NETL staff will also be involved to ensure that the project supports the goals of the Carbon Storage Program, which aims to improve the ability to predict CO2 storage capacity in geologic formations to within ±30%.

UN specifications for CO2 storage operational

www.unece.org

UNFC specifications for CO2 storage have been approved.

United Nations Economic Commission for Europe (UNECE) has worked to develop specifications for the application of the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC) to injection projects for geological storage. The specifications are now operational following approval by UNECE’s Committee on Sustainable Energy.

According to the International Energy Agency (IEA), through 2050 CCS could provide 13 percent of global emissions reductions (around 6 billion tonnes of carbon dioxide (CO2) emissions per year).

If the world is to develop the underground storage capacity needed to receive those volumes of CO2 in that timeframe, it will be essential to improve our understanding of the geological, technical, and socio-economic parameters of alternative storage projects.

The work on geological storage is essential for possible future development of CCS as a reliable estimate of CO2 storage capacity is an important consideration when selecting storage sites.

The specifications were prepared by a task force of the UNECE Expert Group on Resource Classification that is led by Karin Ask, Corporate Reserves Manager for Statoil. The task force comprises representatives from the British Geological Survey, CCOP, Global CCS Institute, Illinois State Geological Survey, King Abdullah Petroleum Studies and Research Centre, Norwegian Petroleum Directorate, OMV and Shell.

The IEA was also a key contributor. These specifications will help industry, policymakers and regulators structure the permitting needed for CO2 storage.

Storage storage everywhere, but where to start?

In the UK, there have been several full chain CCS projects which have completed FEED studies including offshore storage development plans, however so far none of these projects have progressed beyond FEED and the UK government's decision to close the commercialisation programme in November 2015 appears to have been taken largely on the grounds of perceived cost effectiveness.

By Alan James, Managing Director, Pale Blue Dot

Earlier this year, Pale Blue Dot Energy (along with partners Axis Well Technology and Costain) completed a comprehensive 12 month study progressing the development of the UK's strategic carbon dioxide storage resource. Commissioned by the Energy Technologies Institute with DECC funding, the study focussed on the acceleration of strategically important CO2 storage capacity in the UK offshore area.

The work used a platform of the CO2Stored database which contains an inventory of almost 600 potential storage sites to select twenty promising storage sites. From this group a diverse portfolio of five storage sites were selected. Whilst the study has confirmed previous findings regarding the huge potential capacity of the UK offshore for CO2 storage, the key new finding is that with careful selection, the UK requirements for CO2 Storage through to perhaps 2070 could be fulfilled by only 8 storage sites representing perhaps only 2% of the total UK Continental Shelf (UKCS) CO2 storage resource potential. The key question now is not about whether there is enough capacity, but how cost effectively it can be mobilised.

Alongside the detailed knowledge transfer package from UK FEED projects, these sites characterise one of the most comprehensive and mature CO2 storage potential propositions available within the public domain.

The project succeeded in progressing the appraisal of five substantial stores, well-placed in relation to the UK's major emission sources, towards readiness for final investment decision (FID) so that prospective capture projects will have a range of storage options 30 years into the future.

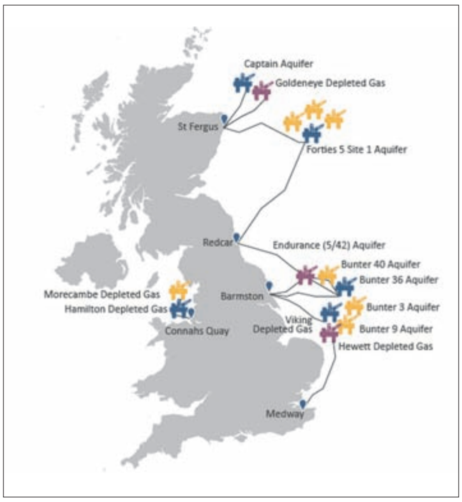
The detailed characterisation and development planning has significantly de-risked these stores and the results are transferable to storage developers wishing to progress the more capital intensive parts of the development programme. By selecting geological storage sites (depleted oil and gas fields and saline aquifers) that already have had a great deal of information gathered and analysis completed through oil and gas exploration and production activities, the UK storage proposition could be available for injection from the early 2020's.

Very significantly, three of the five new sites considered would not require any further appraisal drilling. This is a significant factor and serves to reduce the time required from identification to Final Investment Decision to between two and four years.

The analysis suggested that with 42% of UKCS saline aquifer storage resource lying within open saline aquifers, then much more work was required around the consenting of these sites which generally do not have clearly defined lateral boundaries. The work also highlighted the significance of Storage Efficiency and how efforts to increase this can have an immediate and positive impact on overall cost effectiveness.

Finally, the report found that whilst infrastructure re-use might look like a very attractive cost reduction strategy initially, the high cost of offshore platform modifications coupled with infrastructure which is generally significantly older than its original design life, severely restricts the re-use opportunities of oil and gas infrastructure. There are a few key exceptions where hydrocarbon operational life has been very short.

This has left around three pipelines in the Central North Sea and even fewer platforms, as potential re-use targets for CCS where operational life extensions of between 10 and 40 years will be required. This picture is further complicated by the commercial intricacies surrounding the decommissioning process.



This may sometimes motivate an existing owner towards CCS activities if there are re-use opportunities, in order to significantly defer and potentially totally defray decommissioning expenditure, but where new developers would find a new CCS development a much simpler and more cost effective option.

At present there is a real risk that the current low oil price environment will encourage petroleum operators to exploit this low cost opportunity to fulfil their license responsibilities and decommission infrastructure quickly. In some circumstances this will impact some of the infrastructure that could be re-used for CCS and could raise the cost hurdle for CCS by up to £100m or more for a storage site.

At a time when the full focus of the CCS industry is on cost reduction, OGA and BEIS should be carefully considering these issues in a joined up integrated way to ensure that this key infrastructure is not put beyond re-use.

Further details about the project and its results can be found at the Pale Blu Dot website.

More information

www.pale-blu.com

Berkeley lab digs deep for clean energy

Scientists at Lawrence Berkeley National Laboratory are studying rock fracturing to accelerate advances in energy production and waste storage technologies.

About a mile beneath the Earth's surface in an old gold mine, Lawrence Berkeley National Laboratory (Berkeley Lab) scientists have built an observatory to study how rocks fracture. The knowledge they gain could ultimately help reduce greenhouse gas emissions and accelerate deployment of clean energy technologies.

The observatory is part of a Department of Energy (DOE) initiative that seeks to address challenges associated with the use of the subsurface for energy extraction and waste storage. Dubbed SubTER—or Subsurface Technology and Engineering Research, Development and Demonstration Crosscut—the initiative recognizes that the United States currently relies on the subsurface for more than 80 percent of its energy needs and that adaptive control of subsurface fractures and fluid flow is a crosscutting challenge that has the potential to transform energy production and waste storage strategies.

Berkeley Lab researchers have deployed various tools to collect data on the boreholes they drilled at kISMET, a rock observatory a mile underground at the Sanford Underground Research Facility in South Dakota. (Credit: Matthew Kapust, Sanford Underground Research Facility)

"As important as the subsurface is for U.S. energy strategy, our understanding of how the subsurface responds to common perturbations, such as those caused by pulling fluids out or pushing fluids in, is quite crude," said Susan Hubbard, an Associate Director of Berkeley Lab who helps lead the SubTER National Laboratory team. "We're not able to manipulate the subsurface with the control that can guarantee that we're not only maximizing energy production or waste storage, but that we're also protecting our environment—including minimizing greenhouse gas emissions, impacts to groundwater, and induced seismicity. That's a significant gap."

Grand Challenge: Controlling the Subsurface

Scientists at several of the Department of Energy's national labs are contributing to SubTER, which was launched last year after Energy Secretary Ernest Moniz identified adaptive control of the subsurface as one of the DOE's "grand challenges."

"We know the subsurface will still be a big part of our energy strategy for many decades to come," said Hubbard. "We launched this initiative with the recognition that, whether it's old energy strategies like oil and gas or new strategies like enhanced geothermal or carbon capture and sequestration, we have to really gain control of the subsurface."

One key to gaining control is understanding how rocks fracture, in order to control it or prevent it, depending on the application. "We're concerned with the ability of fluids to move through cracks and pores," said Berkeley Lab geologist Patrick Dobson. "For some applications, such as engineered geothermal systems, you want fluids to move in order to mine the heat from the subsurface, so you want to create fractures. In others, such as carbon capture and sequestration, we're more interested in making sure fractures don't grow."

To gain a predictive understanding of fracture control, Berkeley Lab is leading a SubTER project to develop an underground observatory and to conduct integrated experiments and geophysical imaging. The underground observatory is located at the Sanford Underground Research Facility (SURF) in South Dakota, the site of a former gold mine that is now primarily a research lab for particle physics. The Berkeley Lab team chose one part of the facility at 4,850 feet below ground to set up their observatory, dubbed kISMET, for permeability [k] and Induced Seismicity Management for Energy Technologies.

Getting Energy By Understanding Rocks

Co-led by Dobson and Berkeley Lab geologist Curt Oldenburg, the kISMET team has drilled and cored four 50-meter-deep monitoring boreholes and a 100-meter-deep experimental borehole. "We are essentially trying to understand the relationship between the stress field, rock fabric, and fracturing," Oldenburg said.

The scientists injected small amounts of water into the rock at very high pressure until the rock fractured. "We are looking at the pressure which creates a new fracture, and the flow rate and volume of water that goes into the fracture to estimate its size," Oldenburg said. "Then we go back with borehole logging tools to determine the orientation of the fracture. At the same time, we are carrying out some detailed monitoring of the fracturing process. In particular, we are measuring the rock electrical resistivity in near-real time and the rock seismic properties. We are also measuring microseismicity associated with the fracturing."

Berkeley Lab geologists Patrick Dobson (left) and Curt Oldenburg (right) along with Bill Roggenthen (center) of the South Dakota School of Mines and Technology at the kISMET site in the Sanford Underground Research Facility prior to drilling. (Photo courtesy Curt Oldenburg)

The kISMET experiments are most relevant for Enhanced Geothermal Systems (EGS), a clean energy technology where underground fractures are engineered in hot rocks in the subsurface in order to inject water and extract heat. EGS has the potential to generate enough clean energy to power millions of homes, but scientists still need better methods for managing rock permeability.

The rock at the Sanford Lab is similar to the deep crystalline rock found in many geothermal systems. "One of the key challenges is understanding the state of stress of the rock, which is likely to govern the direction in which the rock is likely to break and where it will do so," Dobson said.

Besides geothermal energy, kISMET will be relevant to a number of other applications. "Fractures and their relation to stress and rock fabric are very important to carbon sequestration, oil and gas, and nuclear waste isolation because fluid flow often occurs preferentially in fractures," Oldenburg said.

The experiments could also be useful for better understanding the seismicity that results from disposal of large volumes of water produced by unconventional oil and gas wells created by "fracking"; the injection of wastewater has been known to result in small earthquakes. "At kISMET, our sensitive instrumentation will be able to detect microseismicity associated with our water injection experiments," Oldenburg said. "We can learn about detecting and locating microseismic events in deep crystalline rock from our highly controlled experiments."

Besides kISMET, DOE recently announced it would invest $11.5 million in eight SubTER projects focused on advancing geothermal energy and carbon storage technologies. Berkeley Lab scientists will participate in two of them, including a $684,000 project to deploy and validate GPUSA Inc.'s carbon dioxide monitoring system and a $1.5 million project to use passive seismic emission tomography to advance the imaging and characterization of geothermal permeability at the San Emidio geothermal field in Nevada.

Berkeley Lab scientist Yuxin Wu at kISMET (Credit: Matthew Kapust, Sanford Underground Research Facility)

Berkeley Lab's geophysical imaging capabilities are just one of the strengths they are bringing to the challenge of adaptive control of the subsurface. "We have a full range of fundamental through applied geoscience expertise," Hubbard said. "At the fundamental side, we have the ability to explore how hydrological, geomechanical, and geochemical components interact to yield a composite response to a perturbation. On the applied side, we are able to use our Geosciences Measurement Facility to test theory, sensors, and models under relevant pressure and temperature subsurface conditions."

"This range of capabilities is needed to advance our ability to manipulate the subsurface with confidence."

More information

www.lbl.gov

www.sanfordlab.org