# Carbon Capture Journal

## CCS in Europe

Decarbonization in the Ukraine

Understanding the long term fate of underground CO2

Improving CO2 storage using a hospital scanner

May / June 2016 Issue 51

# UK CCS Research Centre meeting - the future of CCS post Paris

International team publishes paper on CCS pilot funding

NIST could help keep sequestered carbon from blowin' in the wind

Berkeley lab develops new highly permeable carbon capture membrane

Lessons from Mars: Space science plays a key role informing terrestrial CCS

# Is 2 degrees still attainable? Probably not without negative emissions tech

**The signing of the Paris agreement should not be seen as an achievement in itself - without urgent policy action and rapid development of BECCS it will not achieve the 2 degree target, let alone 1.5**

**Keith Forward, Editor**

Despite an 'aspirational' target of limiting warming to 1.5 degrees, and commitments from some of the world's largest carbon emitters, there is a danger that the agreement in Paris will simply push back more effective solutions for at least the next decade.

There is still no appetite for the sort of drastic measures that are really needed to keep temperatures below 2 degrees, and by generating the perception among leaders, business and the public that something has already been achieved, there is a real possibility that little will change.

While the intention is there, it has so far been impossible to convert the talk into concrete action at a scale and pace that will affect the outcome.

The agreement relies on Nationally Determined Contributions to CO2 emissions reduction and negative emissions technology deployed on a vast scale after 2050 to achieve even a 2 degree target.

"Analyses of Intended Nationally Determined Contributions (INDCs to become NDCs once the Paris Agreement is ratified) put us on a trajectory to a temperature rise of between 2.7 and 3.5°C," says Ciara O'Connor of the UK CCS Research Centre.

"If the Paris Agreement doesn't come into force until 2020, the first review of NDCs won't take place for eight years, by which time we will have blown the 1.5°C 'aspirational' target."

China is a key indicator of what will or will not be achieved. It intends to continue the large-scale use of coal for power production, and has included clean coal technologies including carbon capture in its climate plan.

However while it is obviously keen to export the technology, it is unclear to what extent it will expect the West to contribute to actually deploying CCS in its domestic market.

"UN Secretary General, Ban-Ki moon emphasised that the Paris Agreement is the first universal agreement on climate change and the first one to have such a large number of signatures in one day. 171 countries signed the agreement this morning in NY and 15 of them also deposited their instruments of ratification," says Milagros Miranda, WCA Policy Director in a World Coal Association blog. "China announced that it will ratify the agreement by September this year."

"For the agreement to get into force, it needs the ratification of at least 55 parties that represent at least 55% of global emissions. China is responsible for 20% of global carbon emissions, so the announcement was celebrated as a hopeful and encouraging sign. Francois Hollande, President of France, called the European Union to sign and to ratify the agreement in 2016 to accelerate the entry into force of the Agreement."

"As many leaders stressed, the ratification and the implementation of the agreement are the major challenges ahead. This is only the beginning of the process, as was observed by many speakers, and it is time for concrete actions."

So far, while investing in the technology, China has only committed to building one integrated large-scale CCS project by 2020, as part of a U.S.-China agreement, and several smaller plants.

Sam Gomersall of Pale Blue Dot, a UK-based energy consultancy, is positive about the potential.

"China has the largest CO2 emissions of any nation, but considerable academic and engineering effort is being invested in CCS and carbon reduction. Combined with China's political commitment and planning for CCS, China will soon be at the forefront of this globally important technology. The story of this evolution to low carbon power in China deserves wider recognition."

## BECCS

The reliance on BECCS (Bio-energy with CCS) was not made apparent, says Kevin Anderson, Professor of energy and climate change at the Tyndall Centre for Climate Change Research in Manchester.

"The unquestioned reliance on negative emission technologies to deliver on the Paris goals is the greatest threat to the Agreement. Yet BECCS, or even negative emission technologies, received no direct reference throughout the thirty-two-page Paris Agreement. Despite this, the framing of the 2°C and (even more) the 1.5°C, goals, is fundamentally premised on the massive uptake of BECCS sometime in the latter half of the century. Disturbingly, this reliance on BECCS is also the case for most of the temperature estimates (e.g. 2.7°C) ascribed to the national pledges (INDCs) prior to the Paris COP."

"The sheer scale of the BECCS assumption underpinning the Agreement is breath taking – decades of ongoing planting and harvesting of energy crops over an area the size of one to three times that of India. At the same time the aviation industry anticipates fuelling its planes with bio-fuel, the shipping industry is seriously considering biomass to power its ships and the chemical sector sees biomass as a potential feedstock. And then there are 9 billion or so human mouths to feed. Surely this critical assumption deserved serious attention within the Agreement?"

"As it stands, the expedient and ubiquitous use of speculative negative emissions to expand the available 2°C carbon budgets, implies a deeply entrenched and systemic bias in favour of delivering politically palatable rather than scientifically balanced emission scenarios."

The UK is a case in point. It's carbon budget relies on BECCS contributing to emissions reduction from 2035, with a resultant repurposing of land use for growing biomass, which means CCS projects coming online in the 2020s. Ambitious? Maybe.

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*Front cover: Delegates at the UKCCSRC Manchester Biannual on April 13-14 discussed CCS post Paris and the reliance of climate targets on negative emissions technologies such as Bio-energy with CCS (BECCS)*


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# Ukrainian economics and the potential for decarbonization and growth

**Deep decarbonization could present economic opportunity to Ukrainian business in the heavily coal dependent and politically wobbly country, allowing it to gain a toehold on a progressive climate technology in the post-Paris Climate Summit world, Bellona told a working group in Kiev.**

The event, hosted by Bellona, drew leading Ukrainian environmentalists, and business and government leaders.

The UN Intergovernmental Panel on Climate Change has identified Carbon Capture and Storage as a critical climate technology if the world is to hold to a 2C temperature rise over preindustrial levels, all the more so if the goal of stopping warming at 1.5 C, as presented at the December UN climate summit in Paris, is to be realistic.

For this to happen, prior assumptions about CCS as a technology only applicable to power production have to be rethought.

As Jonas Helseth, director of Bellona Europa, told the roundtable discussion, Ukrainian industry across the board is ripe for CCS deployment – and numerous business opportunities could help foster that growth.

Currently, CCS has made inroads in the North American market. Saskatchewan, Canada's Boundary Dam project has operated since 2014 and is catching more than 90 percent of the CO2 emitted by the aged coal plant. Though the initial outlay for its first CCS unit was €1 billion, SaskaPower, the plant's operator, says the next unit they install will cost 30 percent less. The trapped CO2 is stored in underground geological deposits.

Similar projects are underway in the Southern US states of Texas and Mississippi. Only Europe is lagging behind.

But Helseth emphasized in Kiev that CCS offers a host of carbon reduction benefits for industry as well – which makes its broad adoption all the more pressing when the world's temperature rose 0.6 C over the last year.

"We therefore suggest implementing deep decarbonization and realizing a complex of measures including widening the sphere of application for renewable energy sources, raising the coefficient of energy efficiency and lowering emissions at industrial facilities and power stations run on fossil fuels," said Helseth.

The latter, he said, are the biggest emitters of CO2. But other critical areas to slash CO2 emissions are gas fired electric plants, as well as other huge sectors of Ukrainian industry, like steel mills and cement factories. Worldwide, cement and steel production together account for more than 10 percent of greenhouse gas emissions – 5 to 8 percent from cement and 5 percent from steel.

Outfitting these staple Ukrainian industries with CCS would not only lower emissions but constitute an investment in an overall low carbon economy.

Of course, major overhauls in Ukraine's infrastructure would have to proceed major CCS efforts, said Helseth, and a pricey endeavor especially if any given plant is building CO2 storage and CO2 pipelines only for itself.

The cost can be spread, he said, if, for instance, several industries go in on it together, like a cement factory, a chemical refinery or electrical station sharing the same infrastructure, and thus the cost.

Further, he said, "There are profits for private capital in this technology: We don't just reduce the volume of CO2 emissions, but also can inject it into old boreholes and increase their intensification." This process, known as enhanced oil recovery, can squeeze the last out of wells thought to no longer be productive.

*"Ukrainian industry across the board is ripe for CCS deployment" - Jonas Helseth, Director of Belllona Europa (Photo: Bellona)*

## Going green European-style

Another effective strategy for Ukraine discussed by the roundtable would be the adoption of energy-saving technologies that have swept Europe.

In Norway, for instance, 25 percent of car owners drive electric vehicles, making the world leader in EV use per capita.

Keith Whiriskey, Bellona Europa's project manager for climate technologies, explained to the roundtable the perspectives for renewable energies in Ukraine. According to expert forecasts, he said, some 200,000 wind turbines will operated in Europe by 2050, and the power produced by these turbines will grow to 650 Gigawatts.

Solar power, he said, was seeing similar trends: Solar stations could end up producing 1.5 Gigawatts of electrical energy that could be stored in batteries occupying more space than all the roads in Europe. This is creating a demand for implementing yet more energy-saving projects, and companies producing wind turbines and solar panels are poised for an economic boom.

Of equal importance in Europe is outfitting an infrastructure for EV car charging, where forecasts say charging costs are expected to drop significantly.

According to Goldman Sachs, battery production costs should drop by two times, while their range from a single charge should increase by two to three times. This will encourage a sales growth in electric cars reaching 41 million units per year by 2040, or 25 percent of the entire auto market, the investment firm reported.

"France will soon launch a massive project to harness electric energy produced on roads," said Whiriskey. "The Netherlands is undertaking a similar plan that will generate energy from traffic in bike lanes. In coming years, we'll also be able to buy paint thanks to which not only walls but roofs of houses will provide warmth and light."

The roundtable also addressed how attractive the investment climate in Ukraine is for foreign companies. Viktoria Shtets, head specialist with Ukraine's Department of Climate Policy, put the question of foreign interest in Ukrainian energy markets to Helseth.

He pointed out that the question applied not only for Norway, but Europe as a whole.

"Here we need to speak not only about the attractiveness of the investment climate, but of socially oriented business," said Helseth. "It's important to bring to the public problems we will encounter as a result of unlimited CO2 emissions into the atmosphere and global warming."

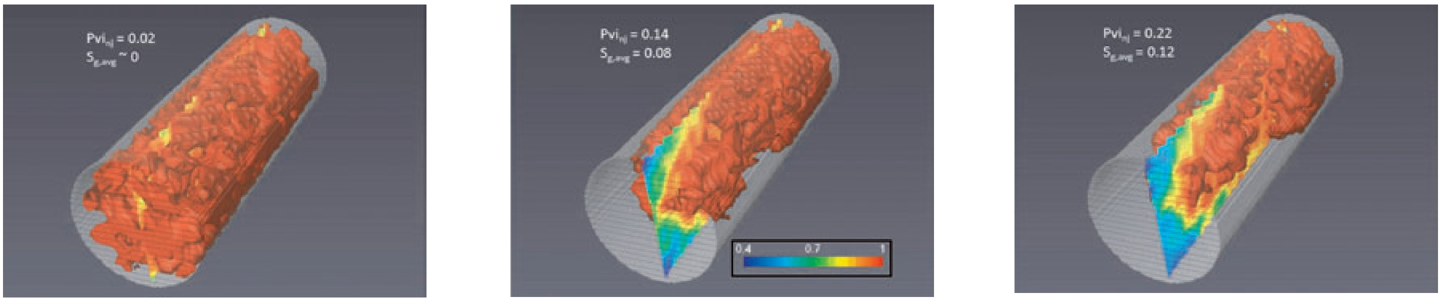
"Otherwise it will be simply impossible to avoid environmental and climactic catastrophe," he said.

### More information

www.bellona.org

# Improving CO2 storage using a hospital scanner

**Researchers at the University of Bergen (UiB) have identified PET scanning as an effective tool for improved oil production and CO2 storage.**




*Spatial 3D water distribution visualized with PET in a tilted sandstone core plug during liquid CO2 (μ=0.074 mPa·s; ρ=818 kg/m3) injection with a constant volumetric rate (Q = 2.5 cm3/h - NC = 7.6·10-10, P = 9 MPa, T = 23 °C). As CO2 migrates upwards, CO2 flow paths form along the edges and water remains in the center. A CO2 saturation of 0.23 was observed in the middle of the core, but a CO2 saturation gradient was present at steady-state (2.54 pore volumes CO2 injected). An isosurface (in red) shows distribution of 100% water saturation. Small deviations in pore volume injected and gas saturation is caused by dissolution of CO2 and compression of injection fluid.*

PET scans are well known from the health service and the researchers were investigating further uses for this technology, to try and promote more climate-friendly oil production – including improved CO2 storage.

"Using PET scans improves our understanding of the mechanisms behind CO2 storage and show the possibilities for a more effective use of CO2 in oil production, and also to measure CO2 leakage," says associate professor Martin A. Fernø at the Department of Physics and Technology (IFT), University of Bergen (UiB).

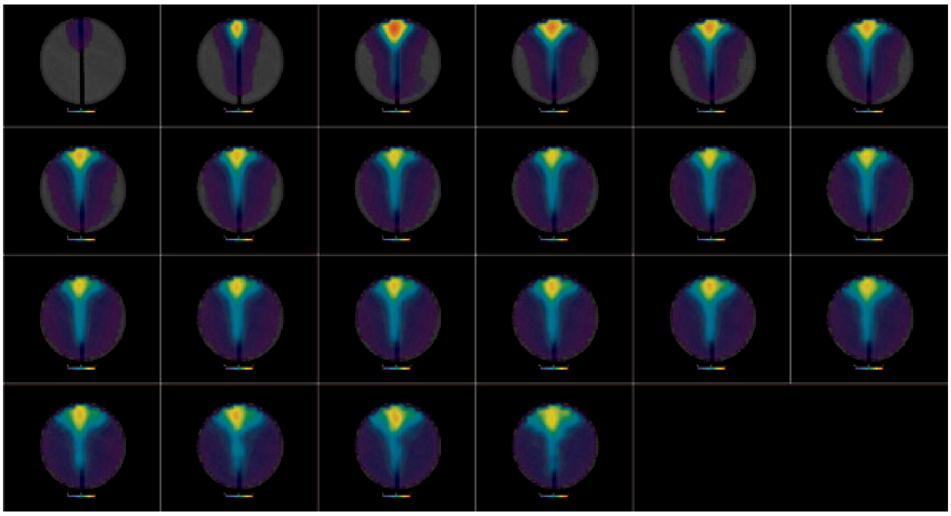
## From Texas to the North Sea

Since November 2015, the reservoir physics community at IFT have coordinated the five year long research project CO2 Foam EOR Field Pilots, led by Professor Arne Graue. The project is a part of the CLIMIT programme, supported by the Research Council of Norway.

"The main goal of this project is to understand the physics behind displacement and to develop a new technology for synchronous CO2 storage and a more effective oil production by using CO2 foam," Graue says.

To achieve necessary knowledge on CO2 injections, for combined storage and oil production in the North Sea in the future, the researchers will attempt a step by step scaling up from the laboratory to small oil fields in the American states of Mississippi and Texas.

"We want fast and cost-effective scientific findings, leading to a field test project on the Norwegian continental shelf. This is why we are doing tests in smaller fields in Texas, where CO2 is commercially available and the necessary infrastructure exists," says Graue.



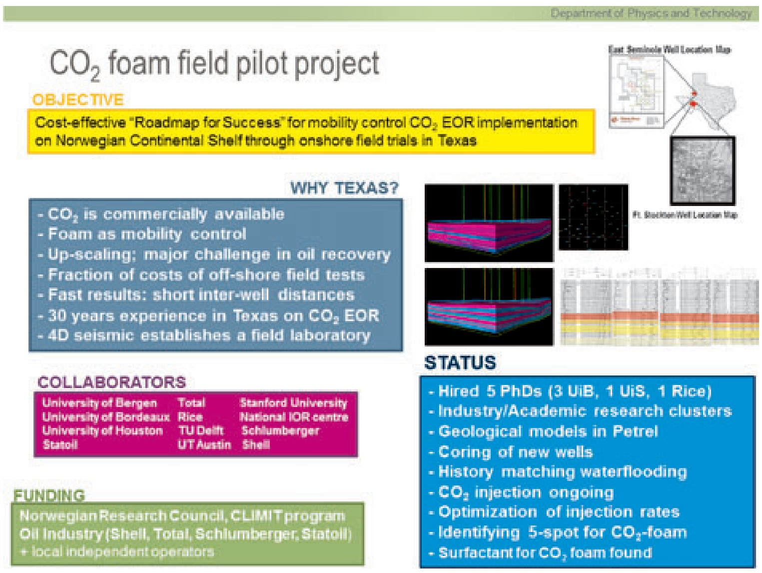
*Visualization of diffusive CO2 transport and mixing in a fractured (1mm constant fracture aperture held open with a spacer) oil-saturated (n-Decane) cylindrical Bentheim sandstone core plug. Explicit CO2 tracking was utilized in fractured, high-permeable [ =0.22, K=1.2 D] Bentheim sandstone to determine an effective diffusion coefficient directly from PET CO2 tracking data (Fig. 2) during miscible CO2 flow (P = 8.3 MPa, T = 25°C, Q = 0.15 cm3/min). The fracture was held open with a constant aperture of 0.5 mm using a spacer to assure a high conduit flow path to limit viscous forces. Transverse CO2 transport from the CO2 saturated longitudinal fracture to the completely oil saturated (n-Decane) matrix occurred by molecular diffusion only*

## Radioactive CO2

The researchers believe that PET scans could become an important tool to evaluate storage capacity and potential for extraction. By using PET and radioactive tracers, the researchers can show the flow of liquid or gas in the rock. Radioactive CO2 is pumped into rock samples from the reservoirs where the CO2 is to be stored.

"By testing different imaging techniques like MRI, CT and PET, we found that a combination of PET and CT is optimal for our purposes," says Fernø.

Fernø has recently published two articles on these discoveries in the scientific magazines Water Resources Research and Geophysical Research Letters (GRL).




The articles are results of pioneer research in the use of CO2 marked by radioactive C11 for visualizing the CO2 flow in porous rock under high pressure.

"The studies concluded that PET is especially suitable for visualizing the liquid flow in rock with high density, which is very difficult by other methods," Fernø explains.

Simultaneously, as part of the new research project, the use of CO2 foam is being studied to achieve a more effective oil production and CO2 storage. By mixing foam from soap and CO2, the gas flow will decrease, and the gas will spread more widely in the reservoir. The mechanisms behind the formation of foam and the reduction in gas flow, will be studied using the PET technique.

"The result of creating more CO2 foam, is increased CO2 storage, and increased oil production, by injecting CO2 into old reservoirs," says Fernø.

## Enthusiasm in the industry

The CO2 Foam EOR Field Pilots project includes 11 universities and 10 oil companies from five countries. The research collaboration focuses on new possibilities in making oil and gas production greener, by reducing CO2 emissions by simultaneous storage.

"The international research environments on petroleum are all very interested in this project. In particular, they find it positive that so many leading universities in this field of research can collaborate within this project," says Graue.

"The oil industry is also very excited about the project. The coal industry in the USA also support the project, and contribute with man-made CO2 to the field tests in addition to financial support, " Graue says.

"The support from the Research Council of Norway´s CLIMIT programme has been vital for the realisation of our research," says Graue.

The oil industry is also contributing to the pilot study by providing an oil field, financial support and internal expertise.

## More information

**www.uib.no/en/ift**

# Understanding the long-term fate of geologically stored CO2

Funded by the European Commission's Seventh Framework Programme (FP7), the ULTimateCO2 project had two clear goals: to significantly advance knowledge of processes that may affect the long-term fate of geologically stored CO2 and to provide state-of-the-art guidance on techniques for predicting the long-term performance of a storage site.

Running from 2011-2015, the project was coordinated by BRGM and united 12 partners from research institutes, academia and industry, as well as other experts in the field. The innovative research carried out by ULTimateCO2 focused on the three key elements of a storage site – reservoir, caprock and wellbore – based on a truly multidisciplinary approach:

• Laboratory experiments, including innovative experiments at the Underground Rock Laboratory at Mont Terri in Switzerland, where a life-size section of a well was reproduced in a typical clay formation and subjected to stresses similar to those experienced by a deep well used in CO2 storage

• Numerical modelling, including extending the model beyond the CO2 storage site permit area so that it incorporated not only the CO2 plume and its extension from the injection point (<10 km), but the entire sedimentary basin – 10s to 100s of km away

• Field data from both natural and industrial oil and gas field analogues in order to incorporate real-life examples of CO2 which is already 'stored' securely in nature.

These results were then merged and transposed into a 3D model at sedimentary basin scale in order to give an even greater understanding of the long-term fate of CO2 and the key physical and chemical processes involved.

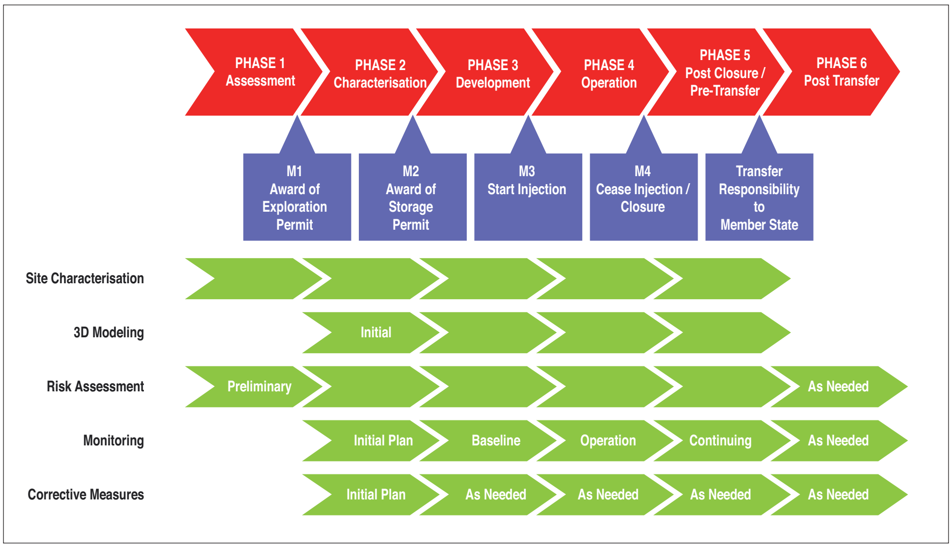



*Figure 1 - Simple CO2 storage project lifecycle, showing the main stages and permit milestones*

## Supporting the fulfilment of the CCS Directive

The European Directive on the geological storage of CO2 (2009/31/EC), known as the 'CCS Directive', has established a legal framework for the geological storage of CO2. In order to promote coherent implementation of the Directive throughout the EU, four Guidance Documents (GDs) have been produced. The GDs contain much helpful advice for assessing the long-term fate of geologically stored CO2 – particularly Guidance Document 3 which concerns the transfer of responsibility to the Competent Authority, in line with the CCS Directive (Phases 5 and 6 in Figure ES-1). "The CCS Directive calls for the operator to demonstrate that "all available evidence indicates that the stored CO2 will be completely and permanently contained".

The Directive also suggests that operators can demonstrate containment by meeting at least the three requirements or high-level criteria noted in Article 18(2): a. the conformity of the actual behaviour of the injected CO2 with the modelled behaviour; b. the absence of any detectable leakage; c. that the storage site is evolving towards a situation of long-term stability."

The conclusions of the ULTimateCO2 project are designed to complement the CCS Directive's Guidance Documents in addressing the transfer of responsibility from operators to the Competent Authority.

## Applying ULTimateCO2 findings to a real CO2 storage situation

An accurate understanding of the long-term fate of CO2 is important, especially for the national Competent Authority or regulator who will eventually take over responsibility of the site after CO2 injection ceases and the storage site is formally closed (see Figure 1). Before this transfer can take place, site operators must provide sufficient evidence to satisfy the Competent Authority that there is no detectable leakage and that the injected CO2 is permanently and securely stored.

Although ULTimateCO2 focuses on long-term issues, the conclusions are also relevant to other stages of a storage project lifecycle – from the characterization and monitoring of the reservoir geology, through to the CO2 injection, as well as site closure and transfer of responsibility to the Competent Authority.

In short, the results of ULTimateCO2 can be used to:

• Enhance confidence in long-term predictions for CO2 geological storage

• Better ensure a permanent and safe storage of CO2

• Improve well design and sealing properties, thereby reducing the risk of leakage

• Better identify any long-term risk of leakage via the caprock

• Enhance the efficiency of numerical simulation tools used to make long-term predictions for CO2 behaviour

• Help operators and regulators to complete the Transfer of Responsibility (Phase 6 in Figure 1).

The geological settings studied in ULTimateCO2 were the European North Sea (offshore) and the eastern part of the Paris Basin in France (onshore). The reservoir rocks (both industrial and natural analogues) studied were sandstones, which means certain geochemical processes that are specific to sandstone reservoirs might be different in carbonate reservoirs.

ULTimateCO2 did not focus on either monitoring or risk assessment since this has been covered by other projects. Nevertheless, its conclusions will contribute to the understanding of long-term risks associated with storage and the robustness of the methodology for designing monitoring plans.

It is also the first time the issue of uncertainty has been assessed in the context of long-term numerical predictions for CO2 geological storage. A general approach has been put forward, but please note that this was based on a limited number of specific scenarios.

## Key conlusions

• CO2 injected into a storage site can change its nature over time – for example, by dissolving in water (as in a bottle of sparkling water) or reacting chemically with rocks to produce minerals.

• Modelling of trapping mechanisms in realistic storage scenarios revealed that more than 50% of CO2 remains in a supercritical form several decades after site closure. However, it is still trapped within the structure, as demonstrated by the vast CO2-fields that already exist in nature. Studies of natural analogues – and confirmed by numerical predictions – also reveal that mineral trapping is limited in sandstone reservoirs typically used for CO2 storage.

• This highlights the importance of having control of CO2 migration through the combined use of modelling predictions and real-time monitoring once CO2 is injected into the reservoir. Conformity between modelling and monitoring is more challenging for geochemical processes (such as mineral dissolution due to acidification) for which further research is required.

• ULTimateCO2 has developed advanced numerical modelling techniques which show the importance of basin-scale models in predicting the long-term evolution of CO2 – not only at reservoir scale (100s of metres), but at basin scale (100s of kilometres) – in terms of pressure impact. As basin models are not an obligation for operators such models could be undertaken at regional or national level, with the support of government funds, in order to help operators predict the evolution of CO2 storage after site closure.

• When a typical caprock (e.g. Opalinus Clay) was tested for resistance to various fault rupture mechanisms at the Mont Terri Underground Rock Laboratory, the caprock showed a low risk of failure. These results are specific to experimental conditions and extrapolations to real-life situations should be taken with necessary caution. An improvement in protocols for evaluating the resistance of such geomaterials should therefore be developed in order to validate scientific investigations.

• When the test well at Mont Terri was put in contact with brine acidified with dissolved CO2 for over a year, the CO2 had a low impact on well integrity. However, the well had a high sensitivity to pressure and temperature variations, meaning that the 'history' of the well will strongly influence its integrity. Efforts should therefore be made to develop a geophysical tool to improve the evaluation of abandoned wells which appear to be the main risk for leakage pathways.

• In general, the integrity of caprock and wells showed a tendency to self-heal in the presence of CO2.

• Evidence from real site operations, such as CO2 storage or oil and gas production, show that predicting leakage risk from the storage complex is difficult due to the complexity of the underground geology, mineralogy and history of the natural processes involved. Nevertheless, risks identified were considered to be either low or very low.

• In summary, ULTimateCO2 research confirmed that the impact of long-term CO2 storage is low – no critical thresholds were reached in terms of pressure, fault reactivation or the development of CO2 flux/flow. While uncertainty should be factored in when looking at long time scales, the migration of the CO2 plume was limited.

### CO2 trapping mechanisms

• Structural: CO2 becomes trapped beneath a layer of impermeable caprock which acts as a seal

• Residual: CO2 becomes trapped in the tiny pore spaces of the porous rocks and cannot move

• Dissolution: CO2 dissolves into the water and, being heavier than the water around it, sinks to the bottom of the formation, trapping it indefinitely

• Mineral: The dissolved CO2 reacts chemically with the rocks to produce minerals

### More information

This article summarises the report which is available in full here:

ULTimateCO2, 2016. ULTimateCO2 Understanding the long-term fate of geologically stored CO2: Learnings and conclusions from a 4-year research project. Deliverable D7.14 of the FP7 ULTimateCO2 project. Available from http://ultimateco2.eu. 80 pp.

# International team publishes paper on CCS pilot funding

The Coal Utilization Research Council (CURC) and Japan's New Energy and Industrial Technology Development Organization (NEDO) have released a study titled, "Analysis of Options for Funding Large Pilot Scale Testing of Advanced Fossil-Based Power Generation Technologies with Carbon Capture."

The paper is the product of an effort led by CURC pursuant to a contract with NEDO of Japan and as a component of the continuing collaboration between NEDO and the U.S. Department of Energy. Other participants to the study include Natural Resources Canada and the Korean Institute of Energy Research of the Republic of Korea.

"With global climate threats on the rise and increasing use of fossil fuels to generate electricity especially in the developing world, the need for cost-effective carbon capture and storage (CCS) technology could not be greater. The study documents the global CCS development efforts underway and the enormous challenges to further progress," states the Washington, D.C. representative of NEDO – Hiro Hatada.

David Mohler, Deputy Assistant Secretary for Clean Coal and Carbon Management of the U.S. Department of Energy commented: "A number of technologies under development, including several supported by the Department, are ready for pilot scale application. Government and industry support are essential to the execution of this next technology step. The white paper describes the challenges we are facing and also emphasizes the need for international cooperation and collaboration if we are to accelerate efforts in time to meet U.S. and global climate goals."

The paper describes the status of technology demonstrations worldwide and provides a list of lessons learned from both successful and abandoned CCS technology projects. Significantly, government and industry efforts to develop carbon dioxide capture and storage technology appears to be waning.

Findings in the report document only three on-going coal related CCS demonstrations underway, all being pursued in North America. Until recently, scores of CCS projects had been announced but pursuit has been slowed or abandoned.

## Overview of the study

The study was segregated into four tasks:

Task One: The Overview of the Study

- briefly describing the purpose of the study and general findings and conclusions

Task Two: Lessons Learned from CCS Demonstration and Large Pilot Projects

- a review and analysis of significant projects undertaken, or abandoned, worldwide in order to generate a set of "lessons learned" which can be considered in the future to better insure successful technology initiatives

Task Three: Factors Impacting Private Sector Investment in Large Pilot CCS Projects

- in addition to the technology risks involved in the development of CCS at the pilot plant stage, the author reviews and analyzes the very significant economic risks associated with CCS technologies and the inadequacy of current economic and regulatory incentives that might encourage development at the pilot scale level

Task Four: Options for Funding Large Pilot Scale Testing of Advanced Fossil-Based Power Generation Technologies with Carbon Capture and Storage

- in order to develop a knowledge base that could be used to evaluate opportunities for multinational collaboration as a means to fund large pilot projects the author examines country-specific information about large pilot plant interest, legal and regulatory conditions, and financial incentives for technology development in Canada, Japan, the Republic of Korea, and the United States with the goal of compiling an initial "baseline" of understanding from which a subsequent assessment (that is, a follow-on study) can then be undertaken to consider mechanisms or models that might be used by multiple countries to support common projects.

"Substantially greater financial and other national resource commitments must be made worldwide if we are to realize the promise of developing carbon capture technologies," said Shannon Angielski, Executive Director of CURC. "This study draws attention to the fact that abundant and inexpensive natural gas, regulatory uncertainty facing the coal industry and flat electricity demand have combined all at once to greatly soften interest in technology development in the U.S."

The report follows a 2015 workshop conducted by CURC that addressed U.S. industry viewpoints on what is necessary to develop advanced fossil-based power generation with CCS at a large pilot scale. A companion white paper to the study released today is expected to be drafted for release in 2017. That paper is intended to set forth specific recommendations to facilitate financial and other contributions from multiple countries and organizations in order to plan, construct and operate international CCS pilot plant projects.

## More information

The Coal Utilization Research Council (CURC) is an organization of coal-using utilities, coal producers, equipment suppliers, universities, and several state government entities interested and involved in the use of coal resources and the development of coal-based technologies

**www.coal.org**

# UK Government should set power sector carbon intensity target

**A UK Energy and Climate Change Committee report says the Government should accept the recommendation of its climate change advisers in setting the level of the fifth carbon budget (covering the period 2028-32) and set a power sector carbon intensity target of 100 gCO2/kWh for 2030 to provide certainty for investors.**

The level of four carbon budgets have so far been set in law, covering the period up to 2027. The UK is currently on track to meet the first three carbon budgets but there are questions about whether adequate policies are in place to meet the emissions reductions needed in the late 2020s under the fourth carbon budget period. As required by the Act, the Secretary of State must set the level of the fifth carbon budget (for the period from 2028 to 2032) by 30 June 2016.

Energy and Climate Change Select Committee Chair Angus MacNeil MP, said, "We can see no basis for downgrading the UK's ambition to reduce emissions of climate-changing greenhouse gases. Indeed, to meet targets agreed at the Paris climate talks to keep temperature rises below 1.5 degrees, we may in the future need to cut emissions deeper and faster."

"Meeting our Climate Change Act targets and commitments made in Paris will require action across the board. But decarbonising our power sector is – along with energy efficiency – the most cost-effective way of reducing our emissions. It will also be vital in reducing emissions from the heat sector and from transport, as we electrify our rail network and road vehicles."

"The UK can't afford any further delays when it comes to replacing dirty power stations with cleaner forms of generation. Investors need certainty and setting a decarbonisation target for the electricity sector would signal the Government's commitment to phasing out fossil fuels."

"Should the Government deviate from the Committee on Climate Change's advice for the fifth carbon budget, we will be looking carefully for a robust evidence-base on any alternative level proposed."

The Committee on Climate Change (CCC) published its advice on the level for the fifth carbon budget on 26 November 2015. It recommended that the budget should be set at 1,765 million metric tons of carbon dioxide equivalent (MtCO2e), including 40 MtCO2e emissions from international shipping, which the CCC recommended including in the budget for the first time.

The Climate Change Act commits the UK to reducing carbon emissions by at least 80% by 2050, compared to 1990 levels. To meet this target, the UK Government sets carbon budgets, or caps in emissions, for each five-year period between 2008 and 2050. The budgets are important stepping stones on the path to 2050 and provide the certainty needed for policy decisions and investment to take place.

The level at which a carbon budget is set must be fixed in legislation "not later than 30th June in the 12th year before the beginning of the period in question". The Secretary of State must therefore set the level of the fifth carbon budget (covering the period from 2028 to 2032) by 30 June 2016. The Secretary of State must now set the carbon budget by laying a draft statutory instrument before Parliament.

If the Government chooses to set the budget at a different level from that recommended by the CCC, the Act requires the Secretary of State to "also publish a statement setting out the reasons for that decision"..

## MPs recommendations

• The fifth carbon budget should include emissions from international shipping, as advised by the CCC. We also urge the Government to work with international partners to secure an agreed international mechanism for controlling international aviation emissions.

• In the light of the climate agreement in Paris, the CCC and the Government must carry out further analyses as to what levels of emissions reduction may be required in the future to meet the more ambitious goal of limiting global temperature increase to 1.5 degrees Celsius.

• It is important that genuine action takes place in the power sector, not least as electrification of other sectors such as heat and transport becomes more prominent. The Government should set a power sector carbon intensity target of 100 gCO2/kWh for 2030 to provide the investment certainty needed.

• Uncertainties about the UK's share of the EU Emissions Trading System (ETS) cap for the period of the fifth carbon budget result in uncertainties in the share of the budget for the non-traded sectors such as heat, transport and buildings. We support the CCC's approach to dealing with the problem, that is to fix the net carbon budget for the traded sector at 590 MtCO2e over 2028–2032, thereby limiting emissions for the non-traded sector. However this support is conditional on Government clearly explaining how any discrepancies will be dealt with once the UK's share of the EU ETS cap is known.

## More information

The report can be downloaded here:
**www.parliament.uk**

# Lessons from Mars: Space science plays a key role informing terrestrial CCS

In July 2016 the Royal Society hosts their annual summer science exhibition in London, where scientists demonstrate cutting edge research to the public. Adrienne Macartney, from the School of Geographical and Earth Sciences, University of Glasgow, is designing an exhibit to explain how the exploration of Mars, and other planets, can inform strategies for carbon managementon Earth.

Mineral carbon sequestration is emerging as an effective method of carbon capture and storage (CCS). The precipitation of carbonate minerals that are stable over geological time-frames potentially provides a long term advantage over alternative CCS methods.

However, the technology and science remains at the pilot stage, and several countries, including Iceland, Norway and the USA, are experimenting with mineral CCS. . Natural processes of mineral carbon sequestration have recently been observed on Mars, and may have been partly responsible for the loss of the planet's early atmosphere.

The Royal Society exhibit highlights the important insights that studying other planets can provide into terrestrial climate change and CCS. The exhibit is a collaboration between the UK Space Agency, the British Geological Survey, the Natural History Museum London, the University of Glasgow and the Scottish Universities Environmental Research Centre (SUERC).

When atmospheric CO2 dissolves into an aqueous fluid and comes into contact with silicate rocks, it can cause them to release cations which react with the CO2 to precipitate a variety of secondary minerals such as carbonates. Olivine is the silicate mineral most susceptible to dissolution and replacement, therefore olivine-rich rocks such as basalt, serpentine and mantle peridotite carbonate most efficiently.

These rock types are common on Earth, particularly in ophiolites: pieces of oceanic crust which have been transported and obducted onto a continental plate. Ophiolites are highly out of chemical equilibrium with their 'new' environment and so react relatively rapidly. Nonetheless, natural mineral carbon sequestration is a slow process, occurring over geological timeframes.

## Geoengineering on Earth

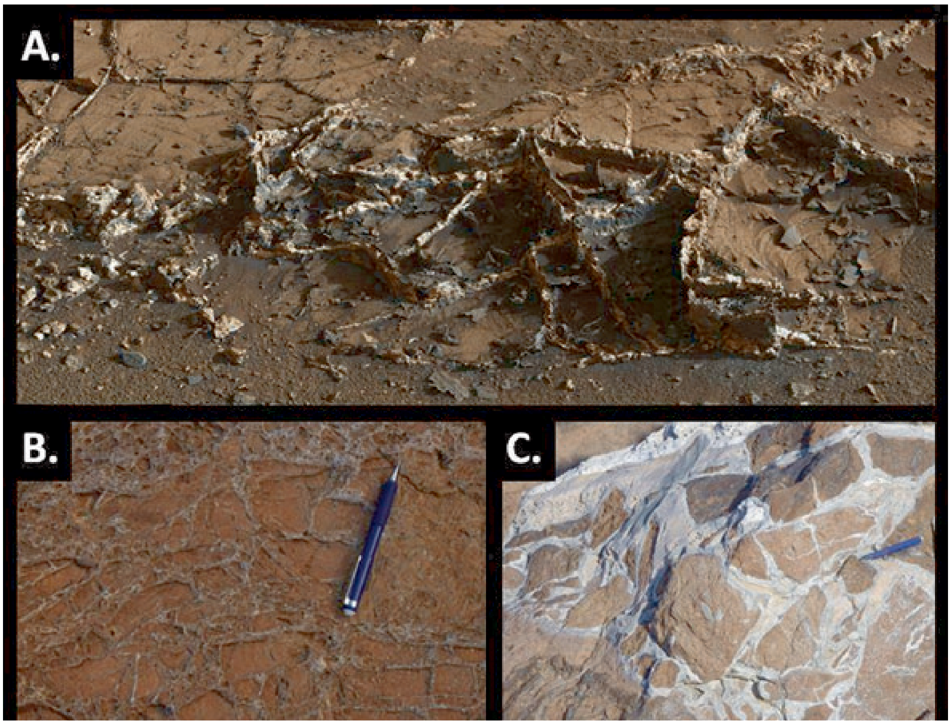



*Figure 1. Secondary mineral precipitation in veins surrounded by silicate rock. A. Mars, 'Garden City', lower Mt Sharp, taken by NASA Curiosity rover. Credit: NASA/JPL-Caltech/MSSS. B. C. Earth, Semail ophiolite, Oman. Credit: Dr Elisabeth Streit Falk [13]*

To accelerate mineral carbon sequestration to rates useful for industrial processes and reducing the effects of anthropogenic climate change, researchers have discovered that a fluid supercritical in CO2 and ~180°C is optimum, although lower temperatures of ~30°C can also work [1].

The fluid is injected down a borehole to the desired rock formation, usually a porous rock type with an impermeable cap rock above for containment. Carbonation is exothermic, and when combined with rocks at depth which are already hot due to the geothermal gradient, the heat produced can be sufficient to allow carbonation to become self-sustaining [1].

Furthermore, the reaction causes significant expansion of the host rock, up to 44%, through hydration [1], and this process instigates fracturing that exposes fresh mineral surfaces for continued reaction.

Mineral carbon sequestration potentially provides a safe, auditable, long term CCS solution, and has other benefits such as forming commercially valuable by-products, such as iron, nickel and chromium. If the CO2 is sequestered into in-situ rock formations then the need, and cost, of quarrying and transportation of reaction feed stocks is also negated.

Many questions remain inadequately resolved on the carbonation process, however, such as fully understanding the reaction pathways, implementing the pathways with sufficient speed to be industrially applicable, and quantitatively estimating CO2 mineralisation capacities and rates more precisely. Further research is clearly required to advance mineral carbon sequestration into a mainstream commercially viable solution for carbon management.

## Discoveries on Mars

Information on Mars geology comes from many sources. On the ground Mars exploration rovers conduct physical analysis of soil, dust, rocks and landscape geology. Orbiting satellites detect chemistry and image morphological features. Another key source is through meteorites that have been ejected from the Martian crust by impacts and have later landed on Earth.

A great body of evidence now supports the idea that liquid water flowed on the ancient Martian surface. However, under the current thin atmosphere of 0.06 bars and sub-zero temperatures, long term surface water is unsupportable [2], although temporary saline flow is likely [3]. This contradiction between ancient water rich Mars and present-day dry Mars suggests that the planet's atmosphere was once much denser than at present, maybe a bar or more, and probably predominantly CO2 in composition [4]. This denser atmosphere would have warmed the surface enough to allow sufficient water flow to form the observed terrain features, such as river channels and lake beds. So what happened to this atmosphere?

Researchers have proposed that the atmosphere was partly lost to space [5], partly stored as CO2 ice in the polar regions [6], and partly sequestered into the crust as carbonate minerals [7]. Carbonates have now been discovered in a variety of Martian settings: within meteorites [8, 9, 10], by the Mars reconnaissance orbiter satellite [11], and also by the Spirit rover in 2010 finding carbonates in the Comanche outcrops [12].

The study of rock stratigraphy, mineral compositions, associated structural and geomorphological deformations, seismicity, and a host of other chemical and geological lines of enquiry allow us to form an understanding of how the carbonates behave on Mars, and provide insights into the planet's atmospheric and geological history. By combining these Martian lessons with laboratory geochemical experiments and by using terrestrial comparative analysis, such as ophiolites, it becomes possible to use carbon dynamics on Mars to suggest solutions to terrestrial carbon problems, and vice versa.

## The value of space and planetary science research and investment

The social and industrial value of planetary, space science, and meteorite research, is often poorly recognised by the general public. Chemical or geological data gleaned from a meteorite can be regarded as esoteric, and of interest only to a small specialist academic field. The motivation for expensive robotic missions exploring Martian desert landscapes can be attributed to national pride and high technology demonstrations alone.

The reality is that investment into planetary science research provides results that are immediately relevant to problems on Earth. Mineral carbon sequestration represents a prime example of this. Many unresolved questions in industrial CCS may find their solutions in unexpected places, such as results from Mars exploration.

The resolution of these questions provides commercial assets, streamlines industrial procedures, assists in satisfying increasingly legally binding international carbon targets, and ultimately protects citizens from the loss of life and significant cost associated with climate change. Planetary research is directly relevant to peoples lives, and it is a field where a modest financial investment can go a long way. To find out more, please come along and visit the Royal Society summer science exhibition on the 5th-10th July in London, or contact the author directly.

## References

[1] Keleman P. B., Matter J. (2008). 'In situ carbonation of peridotite for CO2 storage.' Proceedings of the National Academy of Sciences of the United States of America. 105(45):17295-17300.

[2] Richardson M. I., Mischna M. A. (2005). 'Long-term evolution of transient liquid water on Mars.' Journal of Geophysical Research 110(E03003).

[3] McEwen A. S., Ojha L., Dundas C. M., Mattson S. S., Byrne S., Wray J. J., Cull S. C., Murchie S. L., Thomas N., Gulick V. C. (2011). 'Seasonal flow on warm Martian slopes.' Science 333(6043):740-743.

[4] Ramirez R. M., Kopparapu R., Zugger M. E., Robinson T. T., Freedman R., Kasting J. F. (2014). 'Warming early Mars with CO2 and H2.' Nature Geoscience 7:59-63.

[5] Niles P. B., Michalski J. (2011). 'Evolution of CO2 and H2O on Mars: a cold early history?' 42nd Lunar and Planetary Science Conference 2471.

[6] Phillips, R.J., Davis, B.J., Tanaka, K.L., Byrne, S., Mellon, M.T., Putzig, N.E., Haberle, R.M., Kahre, M.A., Campbell, B.A., Carter, L.M., Smith, I.B., Holt, J.W., Smrekar, S,E., Nunes, D.C., Plaut, J.J., Egan, A. F., Titus, T.N. and Seu, R. (2011). 'Massive CO2 ice deposits sequestered in the South polar layered deposits of Mars.' Science 332, 838-841

[7] Ehlmann B. L., Edwards C. S., (2014). 'Mineralogy of the Martian surface.' Annual Review of Earth and Planetary Sciences 42:291-315.

[8] Mittlefehldt D.W. (1994). 'ALH84001, a cumulate orthopyroxenite member of the Martian meteorite clan.' Meteoritics & Planetary Science 29(2):214-221.

[9] Tomkinson T., Lee M. R., Mark D. F., Smith C. L. (2013). 'Sequestration of Martian CO2 by mineral carbonation.' Nature Communication 4:2662.

[10] Grady M. M., Wright I. P. (1994). 'Martians come out of the closet'. Nature 369:356.

[11] Jain N., Chauhan P. (2014). 'Study of phyllosilicates and carbonates from the Capri Chasma region of Valles Marineris on Mars based on Mars Reconnaissance Orbiter-Compact Reconnaissance Imaging Spectrometer for Mars (MRO-CRISM) observations.' Icarus 250:7-17.

[12] Morris R. V., Ruff S. W., Gellert R., Ming D. W., Arvidson R. E., Clark B. C., Golden D. C., Siebach K., Klingelhöfer G., Schröder C., Fleischer I., Yen A. S., Squyres S. W. (2010). 'Identification of Carbonate-Rich Outcrops on Mars by the Spirit Rover.' Science 329(5990):421-424.

[13] Falk E. S., Kelemen P. B. (2015). 'Geochemistry and petrology of listvenite in the Samail ophiolite, Sultanate of Oman: Complete carbonation of peridotite during ophiolite emplacement.' Geochim. Cosmochim. Acta 160:70-90.

### More information

The full details of the Royal Society summer science exhibition can be found here:

**https://royalsociety.org/events/2016/07/summer-science**

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Special thanks to Cairn Productions for exhibit video support:

**www.cairnproduction.co.uk**

# Projects and policy news

## Brad Page: political courage needed to achieve climate targets

**www.globalccsinstitute.com**

**Bold policy commitments from political leaders are the only route to achieving the ambitious targets of the Paris Climate Agreement, according to Brad Page, Chief Executive Officer of the Global CCS Institute.**

With 155 countries indicating their intention to sign the historic agreement, Mr Page has called for urgent action to address carbon dioxide (CO2) emissions through proven carbon capture and storage (CCS) technology.

"In order to meet these demanding climate targets in the real world, we've got to reduce emissions from every possible sector of the global economy, and we've got to do it urgently and without bias," said Mr Page.

"All low carbon technologies must be part of the conversation – including renewables, nuclear power, energy efficiency, and CCS.

"Achieving these ambitious targets will require many acts of political courage over the next three decades, and an unwavering commitment to deep international collaboration on technological advancement, policy design, and funding.

"Globally, more than 2,400 new coal-fired power stations are already planned for construction by the year 2030. This says nothing of the hundreds of existing facilities that will still be in operation for the coming decades ahead. CCS is vital to limiting the emissions that are effectively already locked in by these facilities.

"Even replacing unabated coal power with gas is insufficient for the world to limit greenhouse gas emissions sufficiently to meet its own nominated targets. Gas-fired power plants still require CCS in order to realise their full emissions reduction potential.

"In light of these realities, it's important to acknowledge that global CCS investment since 2007 has been less than US$20billion.

"For the sake of comparison, renewable power generation technologies have benefitted from investment of around 100 times that amount over the same period, due to policy disparity.

"Outside of the power sector, one quarter (25 percent) of the world's CO2 emissions result from industrial sectors such as iron and steel, cement, petrochemicals refining, and chemicals and fertiliser manufacturing.

"CCS is the only technology that can achieve large reductions in emissions from these industrial processes.

"As we have seen from the success of the COP21 negotiations, the only way the world will achieve effective action on climate change is through a determined long-term commitment to international collaboration."

*"All low carbon technologies must be part of the conversation – including renewables, nuclear power, energy efficiency, and CCS." - Brad Page, Chief Executive Officer of the Global CCS Institute*

## ETI calls for more emphasis on carbon capture and storage and bioenergy in Fifth Carbon Budget

**www.eti.co.uk**

**The UK Energy Technologies Institute has called for greater emphasis on progressing CCS and building a UK bioenergy sector in the next 15 years if the UK is to meet its targets for decarbonising its energy system in the most cost effective way.**

The call was made by Chief Executive Dr David Clarke who gave evidence to the Energy and Climate Change Select Committee's inquiry into Setting the Fifth Carbon Budget yesterday (Wednesday 16 March).

Dr Clarke said:

"We support the Committee on Climate Change's recommendations and they are an important step on the pathway to 2050 but any delays in implementing key technologies will inevitably lead to cost increases. The 5thCarbon Budget recognises the significance of heat and transport as well as power generation but we need to get CCS back on track, we need to get nuclear moving and there needs to be more emphasis on bioenergy.

He said that delays in implementing CCS or new nuclear would lead to extra efforts and costs being needed in early decarbonisation of the heat sector. Long term policies and signals were also needed to encourage development of sustainably grown biomass crops in the UK. Short rotation forestry used for biomass has a growing time of at least 10 years so if we want a meaningful supply of UK sources crops by 2030 we need policy decisions soon that will encourage farmers to start planting."

In its written response the ETI said it agrees with the Committee on Climate Change's (CCC) advice on the level of the Fifth Carbon Budget and points out that its own analysis of the most cost effective pathway for a UK low carbon energy transition, points to a 2030 level of UK emissions very similar to that recommended by the CCC in its advice to the government.

However, the ETI's own whole energy system analysis highlights some areas that might want to be considered to complement the advice suggested by the CCC.

These include:

A stronger emphasis on the importance of progress in CCS before 2030– the CCC's advice implies that the importance of CCS mainly relates to achieving the UK's 2050 targets. ETI analysis also shows that it is a technology vitally important for minimising costs and risks associated with the UK's decarbonisation pathway even in the period before 2030. The success or failure to deploy CCS in the UK will have a fundamental influence on the decisions and costs around long-term infrastructure and energy system architecture, so ETI feels it is vital (and prudent) to achieve greater clarity on this before 2030. ETI would advise the government that it should give priority and emphasis to promoting commercial scale deployment of CCS before 2030 as a cost reduction demonstration measure, as recommended in a recent submission to the Energy and Climate Change select committee.

A stronger emphasis on building a UK bioenergy sector in the period to 2030 – ETI analysis points to the importance of bioenergy as one of the two (alongside CCS) most important system-wide opportunities to reduce CO2 emissions cost-effectively. ETI modelling highlights Bioenergy could provide up to 10% of the UK's primary energy needs by 2050, with the majority of this sourced domestically thereby substantially reducing the costs of meeting carbon targets and significantly growing the agricultural bio-crop industry in the UK. ETI would advise the government to give the development of the UK bioenergy sector a greater emphasis.

A measured approach to the decarbonisation of transport, particularly light transport pre-2030 – the ETI agrees with the CCC's advice around the need to continue efficiency improvement in vehicles by shifting towards ultra-low emission (e.g. electric and plug in hybrid) vehicles. ETI would caution that a rush to decarbonise transport, particularly light transport, could risk imposing significantly higher costs on UK consumers and businesses.

## Tomakomai integrated CCS project coming online in Japan

**www.globalccsinstitute.com**

**www.japanccs.com**

Carbon dioxide from a hydrogen production unit in an oil refinery will be captured and purified, before compression and subsequent injection into offshore geological formations.

The Global CCS Institute welcomed the launch of the Tomakomai CCS Project, and congratulated the Government of Japan on successful completion of Japan's first integrated CCS facility.

"Japan has demonstrated great leadership on the world stage, and several of the world's 15 operational large scale CCS projects were made possible with the inclusion of Japanese technology," said Brad Page, CEO of the Global CCS Institute.

"By working closely with its leading industry partners, the Japanese Government's collaboration is helping to ensure CCS projects around the world benefit from the expertise and experience of Japanese companies developing important technologies.

"The Government of Japan, and in particular the Ministry of Economy, Trade and Industry, is to be commended for its ongoing commitment to meeting its climate targets through a mix of low-carbon technologies, including CCS," said Mr Page.

Mr Page said the Tomakomai CCS Project was important to the global CCS industry for several reasons.

"CCS has a vital role to play as part of the overall technology mix required to meet the internationally agreed goal of limiting the impact of global warming to well-below two degrees.

"It is very appropriate that Japan is now home to its own fully integrated CCS project. The operation of the Tomakomai CCS Project will see at least one hundred thousand tonnes of CO2 captured, compressed and stored, per year, for three years.

"This notable demonstration project will provide Japan with important knowledge that will help drive the next phase of development for CCS in Japan.

"It is also the first fully integrated project using carbon capture, compression, transport, and geologic storage technology on a hydrogen production facility in the region, which is essential for demonstrating the growing range of applications for industrial CCS," said Mr Page.

Currently, most of the world's hydrogen is used either as ammonia feedstock in fertiliser production, or for converting heavy petroleum sources such as tar sands and oil shale into lighter fuels.

While hydrogen itself is often touted as a 'clean fuel', there are no naturally occurring sources of pure hydrogen.

Global hydrogen production depends heavily on fossil fuels including natural gas, oil and coal, which are processed to produce pure hydrogen. Carbon dioxide is an unavoidable byproduct of the industrial production of hydrogen. CCS is the solution to avoiding these emissions.ling increasing CO2 emissions worldwide."

## Integrating coal-to-hydrogen with carbon capture

**www.research-innovation.ed.ac.uk**

**Researchers at Edinburgh University have found a way of improving ultrapure hydrogen production yield and reducing energy consumption for carbon capture and compression.**

Academics at the University of Edinburgh, in collaboration with researchers at Yonsei University, South Korea, have developed a process that improves the production rate of high purity hydrogen (H2).

This breakthrough will provide a significant step-change for a broad range of chemical engineering and industrial applications where there is significant demand for the gas, in, for example, low carbon hydrogen-based heat and power production, across large-scale industrial plants, or powering the next generation of hydrogen fuel cells used in hybrid and electric vehicles.

The University of Edinburgh's commercialisation arm, Edinburgh Research & Innovation (ERI), is now seeking industry partners to license this technology for development into commercially viable application.

Until now, the primary form of hydrogen production has been by natural gas (methane) steam reforming. During this process, the hydrocarbons in the gas are converted at high temperature into a hydrogen-rich mixture of gases. The hydrogen is then separated out during an additional process step.

Natural Gas is generally used as raw material for the production of commercial, ultrapure hydrogen (99.9+ % H2 purity). However, the demands to produce high purity hydrogen from cheaper raw materials such as coal and biomass continue to increase.

The University of Edinburgh research found that such solid-to-H2 processes is not economically feasible against the conventional methane-to-H2 process due to an intrinsically very low hydrogen yield.

Moreover, this is required to produce low carbon hydrogen by implementing a carbon capture unit to fossil fuels H2 plants.

Dr Hyungwoong Ahn, a Senior Lecturer in Chemical Engineering from the University of Edinburgh's School of Engineering, reveals how, through a series of adopted processes, the research uncovered ways to produce the low carbon hydrogen from coal that improves on this ultra-pure hydrogen yield:

"By integrating a coal-to-hydrogen process with carbon capture, the hydrogen yield per unit coal feed can be greatly improved using the carbon capture unit used on a synthesis gas stream generated by coal gasification. This helps to improve the hydrogen yield by greater and more efficient use of the H2 Pressure Swing Absorption (PSA) tail gas – an important separation process for gases and applied widely in gas purification and gas recovery."

The research team identified the core invention was to split the PSA tail gas into three sub-streams and use them accordingly (i) as a supplementary fuel for a carbon gas capture unit to improve its sorbent regeneration; (ii) as an additional feed to shift reactors to boost the hydrogen yield by converting more carbon to hydrogen and (iii) as fuel from drying coal instead of using synthesis gas.

John Jeffrey, ERI's business development executive, commented, "This breakthrough now allows us to look for industrial and commercialisation partners who see the clear advantages in this research. The production of high-purity hydrogen and the efficiency of the process, from start to finish, will amount to an improvement in hydrogen production yield by more than 2% further to what would be expected of a solid-to-H2 process with CO2 capture and a total auxiliary power consumption reduction by around 7%. These can be viewed as significant savings depending on the output of the processing plant."

## Arup appointed to undertake carbon capture storage study

**www.arup.com**

**Arup has been appointed by Summit Power Caledonia UK to provide environmental and permitting advice for the Caledonia Clean Energy Project in Grangemouth, Scotland.**

Summit has been awarded £4.2m of funding from Scottish Government and the Department of Energy and Climate Change (DECC) to undertake a feasibility study for a circa 570 MW Carbon Capture and Storage (CCS) generation plant.

Stephen Kerr, Caledonia Clean Energy Project Director, Summit, said, "We are pleased to appoint Arup based on their wide ranging energy sector knowledge and the local expertise of their team in Scotland. They will contribute to demonstrating how the Caledonia Clean Energy Project can deliver extremely low carbon generation at an affordable cost in the UK while delivering a step-change reduction in Scotland's greenhouse gas emissions."

Arup will be working closely with Summit to provide a number of services including advising on the planning and environmental requirements and potential constraints that will inform project feasibility. The firm will be specifically responsible for conducting environmental risk assessments including air quality, ecological receptors, cooling water options, feedstock delivery as well as landscape and visual impacts.

It will also assist the development of a stakeholder and engagement strategy with reports and recommendations to be submitted to Summit later this year for assessment.

Clare Lavelle, Head of Energy Consultancy, Arup, said, "CCS technology is a critical technology in enabling Scotland and the UK to achieve secure, affordable and low carbon electricity generation. We are delighted to work on behalf of Summit on a project that is essential to demonstrating the viability of the Scottish and UK Carbon Capture sector. Our technical expertise comes from working across the energy sectors in thermal and renewable generation as well as supporting offshore projects in the North Sea allowing us to provide the best possible advice for Summit - we look forward to the next stages of the project."

Arup has worked on a number of CCS commissions across the UK and Europe supporting energy operators and Government with services from economic studies, outline design, project management and contract management through to technology strategies.

## Japan establishes geological storage research association

**www.rite.or.jp/en**

**The Geological Carbon Dioxide Storage Technology Research Association has been founded in Kyoto, Japan.**

The Geological Carbon dioxide Storage Technology Research Association will promote the development of technologies related to large-scale CCS (1 million tons/year) at suitable storage sites in Japan, as well as the improvement of social awareness and acceptance of CCS.

It is a collaboration between OYO CORPORATION, INPEX CORPORATION, Japan Petroleum Exploration Co., Ltd., TAISEI CORPORATION, ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY and the Research Institute of Innovative Technology for the Earth. It will be based within the Research Institute of Innovative Technology for the Earth in Kyoto.

Technical efforts targeting the commercialization of CCS at the Geological Carbon dioxide Storage Technology Research Association will include:

- Establishment of safety management technologies for large-scale CCS

- Establishment of effective injection technologies for large-scale subsurface storage

- Development of criteria and standards for improved CCS awareness

## SCCS wins £2.8m government funding

**www.sccs.org.uk**

**Scientists from the Scottish Carbon Capture & Storage (SCCS) research partnership have competitively won a 70% share of a £4 million fund for research into technology to support UK industry's efforts to reduce CO2 emissions.**

Researchers from SCCS will lead three out of four projects being funded by EPSRC's Research Challenges in Industrial CCS fund, and will work closely with industry partners on developing flexible and cost-effective CO2 capture technologies.

The partnership has stressed the importance of tackling industry's CO2 emissions as part of climate action for several years, and has a track record of research, knowledge exchange and workshops developed with the needs of industry, academia and policymakers in mind.

EPSRC's funding is part of the RCUK Energy Programme, which provides support for emerging energy technologies, including CCS.

The projects have secured £2.8m from the EPSRC call and include:

**Versatile adsorption processes for the capture of carbon dioxide from industrial sources – FlexICCS (£1.1m project)**

Principal Investigator: Prof Stefano Brandani, University of Edinburgh, School of Engineering

This project team comprises scientists exclusively from the SCCS partnership. The project will be led by the University of Edinburgh, with researchers from the University of St Andrews alongside industry partners Air Products and Chemicals, INEOS, Lotte Chemical, Diageo, Howden Group Technology and Tees Valley Unlimited. The project is also supported by the Scottish Environment Protection Agency.

The team will explore adsorption-based CO2 capture, developing new materials tailored to various processes found in industry. The aim is to produce two or three options that can be adjusted easily for different applications, thereby reducing overall costs by mass production of the units rather than developing ad hoc solutions for each system.

John Baker, senior technologist at Lotte Chemical, said: "Understanding how CCS technologies are evolving and how costs will come down will determine when industry adopts and implements the technology."

**A compact CO2 capture process to combat industrial emissions (£1.2m project)**

Principal Investigator: Dr Xianfeng Fan, University of Edinburgh, School of Engineering

This project, led by the University of Edinburgh, is a collaboration of scientists from the university with Newcastle University, the University of Hull and industry partners Global Technology/SK innovation, Ferrite Microwave Technologies, Tan Delta Microwaves Ltd, Carbon Clean Solutions Ltd and the UK-China (Guangdong) CCUS Centre.

The team will focus on issues surrounding amine solvents for CO2 capture, such as process efficiency, the size of equipment required and high capital and operating costs. The researchers aim to meet these challenges by combining two technologies – rotating packed bed absorption and microwave-assisted regeneration – which will enable small and flexible capture devices to be installed at a wide range of industrial sites.

Dr Xianfeng Fan said: "CO2 emissions from industry are typically from a number of small, low concentration sources with a wide range of flue gas compositions and impurity profiles. That means it's useful to have several compact and flexible capture units, with low operating and capital costs and high efficiency. Our work will combine two technologies that will enable such devices to be installed at a wide range of industrial sites."

# UK CCS Research Centre meeting discusses the future of CCS

The UKCCSRC Manchester Biennial, CCS in the UK: moving forward, focussed on the development of a UK CCS sector post Paris and the recent cancellation of the UK's CCS Competition. One emphasis was on BECCS - Bio energy with CCS - to achieve negative emissions, an essential part of the plan to limit global warming to 2 degrees.

## What does Paris mean for CCS?

One of the really important things about the Paris agreement is that it is technology neutral, said **Tim Dixon**, Manager Technical Programme, IEAGHG, which has not always been the case.

There were several difficult years, he said, when it was uncertain whether CCS would be included as part of the Clean Development Mechanism, and the resolution of that was an important step in the acceptance of the technology. Since then, the focus has been more on projects and demonstrations.

The fifth IPCC Synthesis Report has been very positive, he said, making clear that CCS works and is available and is an essential part of the solution, and emphasising the need for negative emissions technology in the latter part of the century. The sensitivity analysis was also important, concluding that without CCS the average costs of achieving 450ppm atmospheric CO2 rise by an average of 138% and only 4 of the scenarios could achieve that figure at all without CCS. The IPCC will produce a special report by 2018 on the 1.5 degree scenario.

There is also an increasing concern about 'unburnable' carbon, fossil fuel reserves that cannot be used in a 2 degree scenario. Of course, there is a solution to that problem, he said, and it is CCS. "The financial sector should be more interested in funding CCS demonstrations to derisk fossil fuel assets."

The conversation on CCS has moved on, he concluded, from "is it safe, does it work?" to "how do we do it?"

## IPCC scenarios rely on time travel and negative emissions

**Kevin Anderson**, Professor of energy and climate change at the Tyndall Centre for Climate Change Research in Manchester, said that the underlying assumptions of the Paris agreement are based on speculative technology and the 1.5 degree target will already be blown before any agreement is ratified

The two triumphs of the agreement, he said, were an acceptance of the science of climate change by global leaders and to limit warming to 2 degrees (and aim for 1.5) 'in accordance with best science and on the basis of equity'. However there was no mention of fossil fuels or decarbonisation and shipping and aviation were exempted. In order to achieve its aims, "We have to drastically reduce energy demand in the short term."


*The conversation has moved on from "is it safe, does it work?" to "how do we do it?" - Tim Dixon, Manager Technical Programme, IEAGHG*

The whole edifice relies on negative emissions, he said, but it was hardly mentioned in the agreement. "The scale is breathtaking, BECCS (Bio-energy with CCS) relies on planting and harvesting energy crops on an area one to three times the size of India over decades."

Of the 113 scenarios with a "likely" chance (66% or better) of 2°C (with 3 removed due to incomplete data), 107 (95%) assume the successful and large-scale uptake of negative emission technologies. The remaining 6 scenarios all adopt a global emissions peak of around 2010. Extending the probability to a 50% chance of 2°C paints a similar picture. Of the additional 287 scenarios, 237 (83%) include negative emissions, with all the remaining scenarios assuming the successful implementation of a stringent and global mitigation regime in 2010.

"The complete set of 400 IPCC scenarios for a 50% or better chance of 2°C assume either an ability to travel back in time or the successful and large-scale uptake of speculative negative emission technologies. A significant proportion of the scenarios are dependent on both time travel and geo-engineering."

The 1.5 degree target was disingenuous, he said, and a sop to poorer nations to get the agreement through. Two degrees will still be very dangerous, and the 66% chance is already blown, and the 50% carbon budget relies on a warlike footing for emissions reduction. BECCS is a way to kick the need for action into the long grass, he said. Two degrees is still possible but it will take significant action now.

"If the top 10% of global emitters reduced their footprint to the level of the average European, that would be a one third reduction of global emissions. We could also introduce performance standards for cars now but we're not prepared to do it."

CCS has a role for poorer countries, he said, as is just about fits in their carbon budgets as a bridging technology, but for rich countries emissions will still be too high.

## More information

Proceedings of the event will be available:
**www.ukccsrc.ac.uk**

# UK Parliamentary CCS meeting looks at Teesside

**A meeting of the UK's Carbon Capture and Storage All Party Parliamentary Group (APPG) took place on March 24, looking at developments with industrial CCS, particularly at Teesside.**

The UK's Carbon Capture and Storage All Party Parliamentary Group had a meeting at the UK Houses of Parliament, London, on March 24, looking at CCS developments at Teesside, among other areas.

The meeting was chaired by Alex Cunningham MP, Labour's Member of Parliament for Stockton North, which includes Teesside.

Neil Kenley, Director of Business Investment at Tees Valley Unlimited, presented the latest developments with the Teesside Collective project, a group of Teesside companies with an ambition to set up a shared CCS facility in the region.

Teesside's ambition is to be "the first industrial cluster in Europe to get CCS off the ground," he said.

There could be a coal power generating plant CCS as part of the cluster, he said.

UK heavy industries are coming under pressure to reduce CO2 emissions both from their customers and under the EU ETS scheme, he said. But also if the costs of production in the UK become much higher than elsewhere in the world, companies could easily leave.

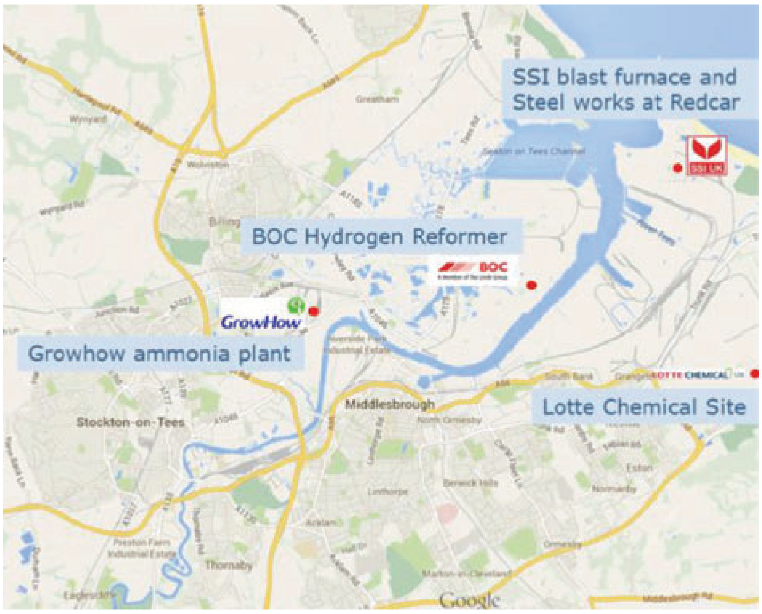
As a consequence, UK customers would import product into the UK from elsewhere. The manufacture of this product would emit the same amount of CO2 as before, so there would be no overall reduction in CO2 emissions, but a loss in UK jobs.

There are 4,000 employees in Teesside directly, a further 12,000 in the supply chain, and the 'gross value added' has been calculated at £89k / employee.

90 to 95 per cent of the companies are foreign owned – which perhaps makes it more possible that owners will move their production elsewhere if UK regulation makes the UK operations more expensive, he said.

Because many of the processes themselves emit CO2, it isn't possible to eliminate their CO2 emissions by running the plant on decarbonised electricity (for example electricity from wind). The only way to do it is to use carbon capture and storage.

Teesside is also looking at the growing hydrogen economy – perhaps it can generate hydrogen from natural gas, send the CO2 to be stored, and sell the carbon free hydrogen.




*Lotte Chemical's plant is one of the sites that could form part of a CCS Network in Teesside*

It is possible that a CO2 infrastructure could also be connected with industrial facilities in Humberside (70 miles to the South) or Grangemouth (200 miles to the North).

There is already a small CO2 industry in Teesside – Europe's largest biomass to ethanol plant produces CO2 as a by-product. This is then cleaned and sold for use in soft drinks.

The question still remains for how to pay for it, though. "We are working to try to identify mechanisms government could put in place," he said.

## Lotte Chemical

John Baker, site senior technologist with Teesside company Lotte Chemical UK, presented his company's perspective on carbon emissions.

Lotte manufactures PET, a plastic used to make bottles, including for soft drinks companies.

The boards of Lotte's customers are demanding more sustainable product," he said.

"Most major listed companies produce Corporate Sustainability Reports where they list performance and targets. Often the targets are about more sustainable supply," he said.

"If a packaging company make the same amount of product using less energy or less raw material, or pollute less, they could be regarded as more sustainable."

So it is possible that Lotte could win business preferentially if its PET was produced with no CO2 emissions – and conversely it could lose business to a competitor able to produce zero CO2 PET.

Lotte is not big enough to consider its own carbon capture and storage scheme, he said, but perhaps it could work as part of a CO2 cluster.

However government will probably need to cover the costs of the CCS infrastructure, he said.

## Scottish Enterprise

Chris Bryceland, Senior Executive - CCS and Thermal Generation with Scottish Enterprise, said that there has been 3 projects to try to get carbon capture going in North East Scotland.

Let's recap - BP's £500m project in Peterhead, scrapped in 2007; Longannet in Fife, scrapped in 2011; and Shell's Peterhead project, probably shelved after government pulled funding in 2015.

"What we need is projects," he said.

The biggest hope currently is the Summit Power project in Grangemouth, an industrial carbon capture and storage project. This could link to Peterhead, and pipelines offshore.

There is an existing pipeline from Grangemouth to Peterhead, known as "Feeder 10", which would be available. It "couldn't be better positioned," he said.

However doing industrial CCS in Grangemouth would be very complex, with many different CO2 sources, he said.

Scottish Enterprise is considering pushing harder to get North Sea oil companies to consider using CO2 for enhanced oil recovery.

"We think it's viable in the North Sea and maybe needs a higher oil price," he said.

A further concern is that offshore oil and gas infrastructure, would could be used for CO2 storage, might get decommissioned.

## Industrial decarbonisation

Stephen Rippon from the UK's Department of Energy and Climate Change (DECC) presented the latest with the DECC / BIS (Department of Business Innovation and Skills) "Industrial Decarbonisation Roadmaps," the UK's plans for heavy industries to stop emitting CO2.

Carbon capture is a "key technology" for many of the roadmaps, he said.

And "energy intensive industries are 'clearly crucial' for the UK economically," he said. So it is important that the costs of reducing CO2 emissions should not make UK industry uncompetitive with production in areas which do not have the same rules.

Industries targeted under the "Roadmaps" include cement, ceramics, chemicals, steel, paper and refining, he said.

Consultancy WSP Parsons Brinckherhoff was brought in to work on it, with an aim to identify the maximum "technical potential" for reducing CO2 emissions, and what technologies would help.

Technologies to decarbonise could include providing decarbonised electricity, using biomass fuel, providing heat by electricity, and carbon capture.

The biggest clusters of heavy industry, and CO2 emissions, are Teesside, Humberside, Merseyside, South Wales and Grangemouth.

The plan is to publish an 'action plan' by the end of 2016. The roadmaps look as far as 2050.

There continue to be concerns from industry that CO2 charges will make their industries uncompetitive. A question was raised along these lines by Richard Leese of the Mineral Products Association, a trade association for aggregates and cement.

If it makes UK cement more expensive, and consequently the market imports 'standard carbon emission' cement from outside the EU, there will be no benefit in terms of overall high carbon emissions, Mr Leese said.

Mr Rippon replied that DECC aims to make targeted 'relief' to industries which are threatened by the costs of buying carbon emission credits under the EU Emissions Trading Scheme. "Our aim is to make sure relief is in place targeted as well as it can be," he said.

### More information

Attendee list, presentations and official minutes of the meeting are online at:

**www.ccsassociation.org/appg-ccs**

# UKCCSRC Poster Prize winners

**The following articles summarise the prize winning projects of a poster competition at the UK CCS Research Centre meeting.**

The winners were **Clara Heuberger** and **Clea Kolster** from Imperial College London and **Thomas Spitz** from the University of Edinburgh.

The projects were respectively:

• An integrated multi-scale approach for low carbon energy system design

• Impacts of fluctuating and realistic CO2 supply on safe storage of CO2

• CCS power stations at the interface of CO2 transport and electricity transmission networks: How to deal with the dual set of requirements?

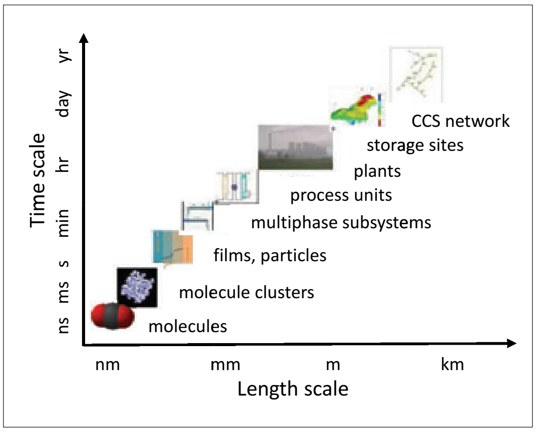
UKCCSRC Director Jon Gibbins presented the ECR Poster Prize to the three winners at the Manchester Biannual on Thursday 14 April 2016.

*Thomas Spitz, Clara Heuberger and Clea Kolster*

# An integrated multi-scale approach for low carbon energy system design

Clara Heuberger[1,2], Maria T. Mota-Martinez[2,3], Evgenia Mechleri[1,2], Niall Mac Dowell[1,2]
1. Centre for Environmental Policy, 2. Centre for Process System Engineering, and 3. Department of Chemical Engineering, Imperial College London

The decarbonisation of the power generation sector implies an unprecedented rate of change in the transition to an energy system balancing the trilemma of carbon avoidance, cost, and security. The development of power technologies which are suitable and appropriate to meet the required emission targets, while maintaining operational and supply security is imperative. Additionally, tools which are able to assess the applicability and the value of power technologies to the system as a whole are essential for a reliable and least-cost transition.



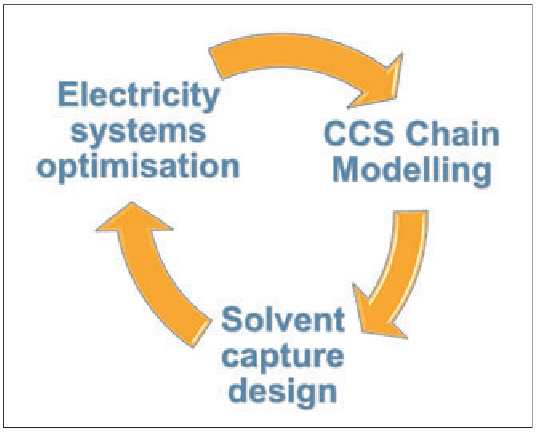




*Figure 1: Multi-scale approach to whole-systems (left) and CCS chain design and optimisation (right)*

The design and optimisation of a low carbon energy system requires an integrated multi-scale approach to ensure coherent decision making across the entire length chain – from the molecular scale to the whole energy system scale. This concept is illustrated in Figure 1 below.

From a bottom-up perspective, we aim to understand the impact of solvent and sorbent properties on the performance of CCS processes, and thereafter on the efficiency of the power plant with which this process is integrated. Thereafter, the CCS-power plant needs to integrate efficiently with the electricity system and ensure that it provides value on the energy systems level.

Similarly, from a top down perspective, we aim to identify the required design and operating parameters (cost, efficiency, etc.) of a given technology in order for it to provide the most value to the energy system at a given level of deployment. In other words, we quantify how much CCS technologies need to cost and how efficient they need to be within a given electricity market, such as that in the UK. We then follow this down to the detailed process design level and thereafter to sorbent/solvent design.

This approach is particularly powerful when used to evaluate novel technologies. In a top-down view, we gain insight into the type of power plant parameters which have a market-level impact. We can then focus on improving those features which show the greatest return upon deployment of the technology. In this way, we aim to work with device/lab-scale technology developers and provide insight into the design modifications which will maximise the deployment potential of this technology. Thus, we aim to bridge the gap between the lab and the energy system.

Short descriptions of the ongoing work at the molecular, process and system scales follow.

Starting on the electricity systems level, we have developed a new metric for technology valuation and comparison. Traditional metrics describing the cost of a given power source, such as the Levelised Cost of Electricity (LCOE), treat electricity as a homogeneous product. The operational challenges associated with integrating intermittent generating capacity into an existing system are neglected, as well as the ability of a power plant to provide ancillary services such as voltage and frequency control. Whilst the LCOE metric was entirely appropriate for the energy system of the 20th century, which was almost entirely composed of dispatchable thermal power plants, it is no longer appropriate for the diverse energy system of the 21st century.

In order to capture the challenges energy systems planning is facing today, we have developed a new metric based on the value that a given technology provides via a whole electricity systems optimisation. The "System Value" (SV) metric quantifies the value of a given power technology to the electricity system taking the systems dynamics and conditions explicitly into account.

Centrepiece of the SV approach is a mixed-integer linear program which simultaneously optimises system design (i.e., the type and amount of generating capacity) and the unit-wise dispatch schedule (i.e., the mode-dependent operation) of power generators subject to environmental, security, and detailed technical constraints. The SV of a particular technology is defined as the marginal change in total electricity generation cost (capital, energy, ancillary services) arising from the addition of a capacity unit of that technology.

We show that the value of a given technology is a function of the existing capacity mix, i.e., the composition of the incumbent energy system into which it is integrated, and that this value continues to evolve as a function of the changing energy landscape. In this way, we consequently overcome the shortcomings of the traditional LCOE metric by using a whole-system perspective. Through whole-systems modelling, we gain understanding about the market-level importance of a technology's operational characteristics (e.g. flexibility, efficiency, carbon intensity) and their impact on the optimal capacity mix.

We apply the proposed framework to assess and quantify the value of Carbon Capture and Storage (CCS) equipped power plants in the future UK power system. We note that our methodology is generic and modular, and with the relevant information on electricity demand and intermittent generating power profiles can be easily tailored to another energy system.

A key conclusion of our work thus far is that the availability of CCS power plants can significantly reduce total system cost as a function of deployment level and the underlying system conditions. The special feature of providing firm capacity and low-carbon electricity combined with a flexible and dispatchable operation makes CCS power plants particularly valuable in combination with intermittent renewable power generation and under tight emission limits.

The possibility to assess the detailed power plant level behaviour and characteristics in order to increase the value to the power system further is a key idea of the presented multi-scale approach. By incorporating new plant designs and features into the energy systems optimisation model and System Value concept, we are able to identify market-level implications and the value of a new power generating technology to the energy systems.

The link to the high level energy system analysis is provided by process systems engineering, modelling, simulation and optimisation.

The process systems engineering (PSE) approach is an essential tool for understanding interoperability of the components in the system, managing trade-offs and mitigating risks. It helps to understand the new technology, the interactions between the elements of the CCS chain, the trade-offs up and down the CCS chain and take these into account in component and system design. Moreover, through the detailed modelling we can optimise the design and operation of the elements of the chain taking into account upstream and downstream operational scenarios and also investigate future capacity scenarios. With this tool we can therefore minimise technology risks and accelerate adoption of commercial scale CCS.

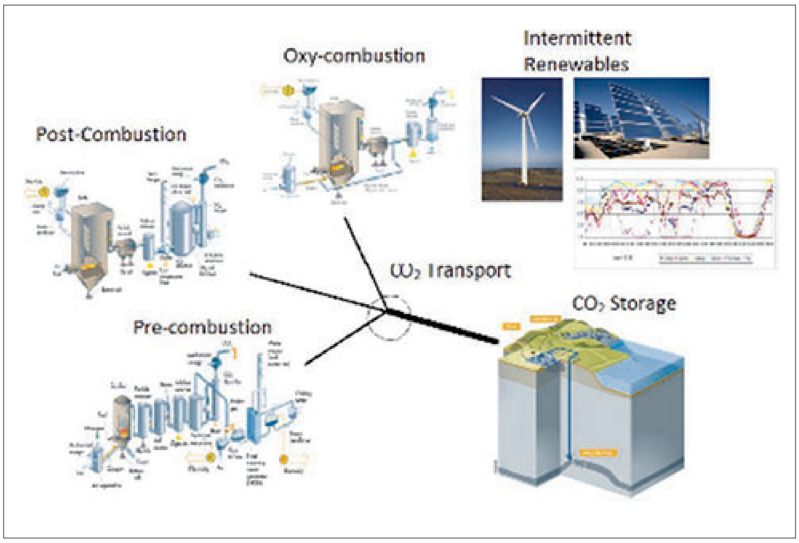



*Figure 2: The "CCS-network": a multi-source-to-sink, decarbonised energy network with decarbonised fossil fuels interacting with intermittent sources of renewable energy*

At the intermediate level of our multi-scale modelling approach, the aim of the PSE aspect of our work is to assess the operational flexibility of each link in the CCS chain, and to identify which links are rate-limiting in terms of the whole-system flexibility. In order to do so, we have developed a suite of dynamic models of decarbonised fossil fuel-based energy generation and used them to describe the interaction of decarbonised fossil fuels interacting with intermittent renewables. A key tool used here is the gCCS toolkit in gPROMS. These models describe the whole CCS chain from power (coal and gas fired power plants), compression, transport, injection and storage.

However, this is not as simple as it sounds! In the integrated design, the interactions between the upstream and downstream components of the CCS chain will imply modifications in each component of the chain, which requires the formulation and solution of a design optimisation problem.

In order to assess the capacity of the whole-system for flexible operation with a view to identifying flexibility-limiting links in the CCS chain, we will quantify the differences in performance obtained from a CCS chain in which each "link" is individually optimised and subsequently integrated vs. the performance of a CCS chain in which all links are simultaneously optimised as part of a whole-systems optimisation approach.x

Starting from the upper level of the CCS chain, i.e the integrated power and capture plant, we are exploring different types of flexible operation. We are investigating the different ways of integration of a power plant with the capture plant, aiming at decoupling their interference so that the power plant is able to operate based on the electricity market without the limitations imposed by the capture unit.

At this point however we should not neglect the effect of the downstream components of the chain i.e, compression, transport and storage and how they will react with these flexible operating patterns. The limitations imposed in the compression section and how to deal with possibly zero loads during the daily operation, in the transport section due to changes to temperature and pressure of the transported carbon dioxide (CO2) leading to phase changes and also in the injection site with different characteristics and variable injectivity rates, are some of the challenges that need to be addressed in the design and operation of the flexible CCS chain.

At the molecular level, a process-performance indexed aims to design an improved or new solvent, by evaluating and optimising the values of its thermophysical properties on the cost of the carbon capture. The process performance using the newly designed solvent will be further integrated with the higher level models, evaluating the effect on the whole CCS chain and the energy system.

One of the challenges to fully implement CCS technology is the high cost of the capture process. The current most mature technology to separate the CO2 from the flue gas in the chemisorption in aqueous solution of alkanolmaines, e.g. monotheanolamine (MEA). The process was developed by the gas industry and it has been widely implemented for gas sweetening, i.e., the separation of CO2 and other acid gases such as hydrogen sulphide from natural gas. The main advantages of aqueous alkanolmines is the rapid kinetic reactions with CO2 and the relatively inexpensive cost of the solvent.

However, several operating challenges are encountered. Alkanolamines irreversibly react with some impurities frequently encountered in the flue gas. Moreover, they present a relatively high volatility that results in considerable solvent loses. However, the main issue of this technology is the high energy requirements in the solvent regeneration step of the aqueous alkanolamine because of i) the strong chemical bond between the CO2 and the amine, ii) the large heat capacity of water, iii) the heat of vapourisation of water. This results in high operating costs and a substantial reduction of the efficiency of the hosting power plant, as evaluated in the intermediate level of our approach.

The chemical absorption of CO2 in aqueous alkanolamines has been extensively investigated and the process conditions have been significantly optimised. Yet, the cost related with the capture is too high. Therefore, the only prospect to further reduce the cost and improve the efficiency of carbon capture is finding an alternative solvent that would overcome the inconveniences presented by aqueous alkanolamines. It should be a non-volatile solvent, with low enthalpy of absorption and desorption, high chemical stability and ideally water-free.

Ionic liquids are promising replacements of aqueous alkanolamines for carbon capture. They are composed of large organic cations, viz. imidazolium, pyridinium, pyrrolidinium, ammonium, etc., and inorganic or organic anions. They are liquid at or close to room temperature thanks to the low ionic interactions as a result of their large size and their flexibility on the conformational distribution of the ions. Most of the ionic liquids present extraordinary properties such as negligible vapour pressure, high thermal and chemical stability and high CO2 loading.

The modification of the chemical structure of the ions and the introduction of functional chemical groups provides a mechanism to tune the properties of the ionic liquid accordingly to match the properties required for each of the potential applications. The vast potential combinations of cations and anions to form task-specific ionic liquids provides a substantial opportunity for chemical design of a perfect solvent for carbon capture. In fact, the potential ionic liquids are so large that we need a systematic methodology to discern the ionic liquids that are suitable.

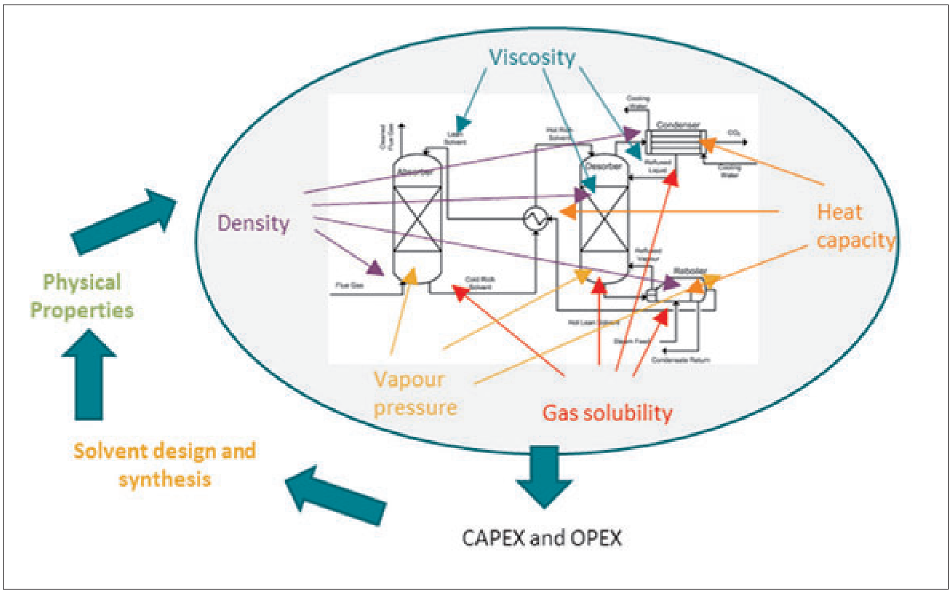



*Figure 3: Iterative design of an optimized solvent for carbon capture based on the thermophysical properties that maximise the process performance*

The application of the ionic liquids as alternative solvents for carbon capture is not new. Over a hundred ionic liquids have been investigated as potential solvents for carbon capture in the last years. However, most the efforts have been directed towards finding the ionic liquid that would optimise a certain property. It is common to claim that a particular ionic liquid is a promising solvent for carbon capture, but that assertion is based on the measurement of a limited number of properties, mainly CO2 solubility. As an example, it has been found that those ionic liquids containing fluorine atoms or nitrile and amine functional groups exhibit an excellent CO2 solubility. Nevertheless, some of them were extremely viscous or they decomposed with the presence of water at high temperatures and therefore being unfeasible for their industrial deployment.

The fact that a certain solvent presents a higher CO2 solubility it does not necessarily correlate with their suitability for a process. Other properties such as viscosity, enthalpy of solution, or heat capacity pay a significant role in the process performance and consequently in the cost of carbon capture as shown in Figure 3, but these properties are usually ignored. This imposes a priori constrain on the material development because of the existing gap between the chemical structure of the solvent and its correlation with the efficiency of the process and consequently with its real cost.

Therefore, at the molecular level of the integrated approach we are aiming to design of an optimum chemical structure of an ionic liquid that would minimize the cost of the carbon capture. Simultaneously, the carbon capture will be able to adequately integrate within the flexible operating CCS chain studied in the intermediate level. For this purpose, we have developed a tractable process modelling tool in gPROMS that reflects the complex relation between the molecular structure of ionic liquids and their process performance.

We will then re-design the benchmark detailed models to achieve these goals and have the “ideal” decarbonised technologies of the future. This integrated approach then dictate the technical characteristics that the standalone or integrated power and capture model, should have in order to gain a higher value in the energy mix of the future.

## More information

The poster on the next page summarises the research.

**www.imperial.ac.uk**

Imperial College London

Centre for Process Systems Engineering

cep

# An integrated multi-scale approach for low carbon energy system design

**Clara F. Heuberger[1,2], Maria T. Mota-Martinez[2,3], Evgenia D. Mechleri[1,2] and Niall Mac Dowell[1,2]**

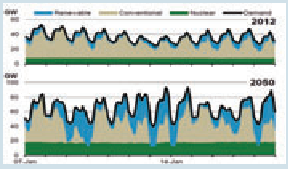
**[1]Centre for Environmental Policy [2]Centre for Process System Engineering, and [3]Department of Chemical Engineering, Imperial College London.**

## Approach and Aim of research

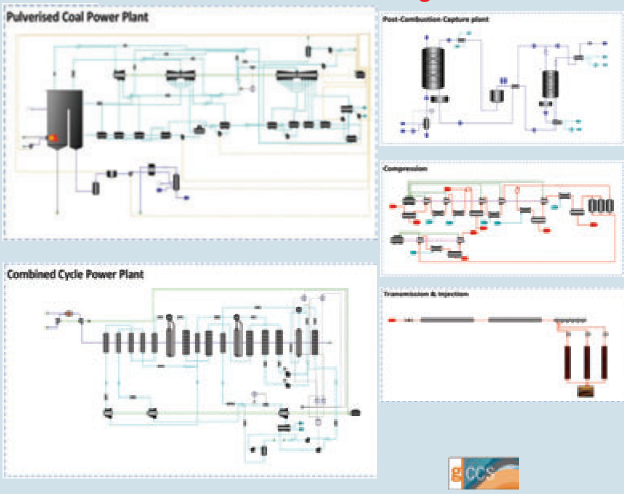
In the design of low carbon energy systems, decisions made at one scale markedly affect system behaviour at other length scales. This work develops an integrated, multi-scale systems design, optimisation and simulation framework wherein molecular level insight is fed up to process and subsequently whole system scales.

- On the system scale the "System Value" (SV) metric, quantifies the value of a given technology to the electricity system.
- On an process scale, we model the whole CCS chain, from power to storage using the gCCS toolkit in gPROMS.
- On the molecular scale, a process-performance index aims to design an improved new solvent, by evaluating and optimising the values of the thermophysical properties of an ideal solvent based upon monetised and non-monetised indexes.

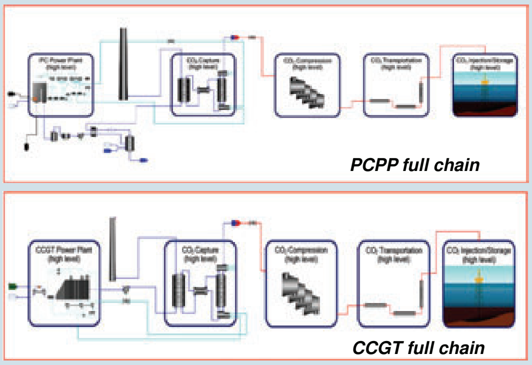
## Energy systems modelling




## Detailed CCS chain modelling




## High level CCS chain modelling



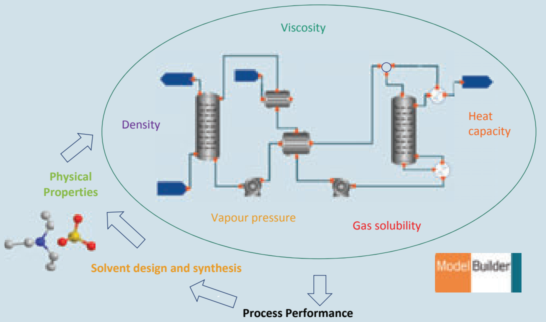

## $CO_2$ storage

## Flexibility Study

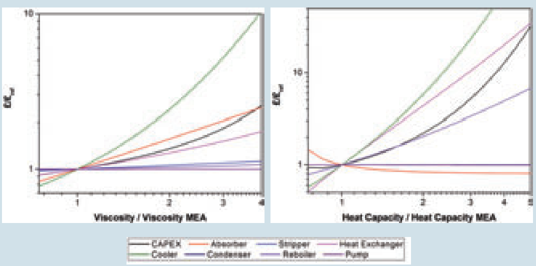
- Perform a quantitative assessment of the flexibility of the CCS chain
- Identify which links aid and limit system flexibility
- Develop a list of Key Performance Indicators (KPI's) for whole-system flexibility
- Develop a flexible CCS chain to adapt to the energy system

## Solvent Design based on process performance

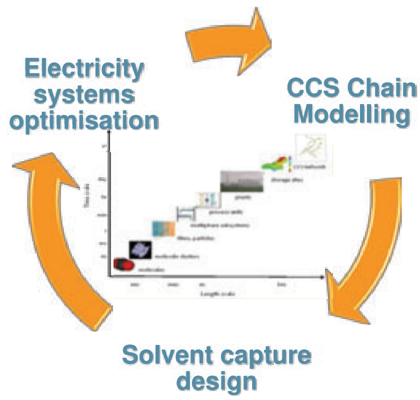
Chemical characteristics of the solvent impact the physical properties, which in turn affect the process performance and subsequently the cost of the carbon capture process.




Process-performance indexes are used to design task-specific solvents.




Physical properties of the newly design solvent should be kept within optimized ranges to reduce the cost.



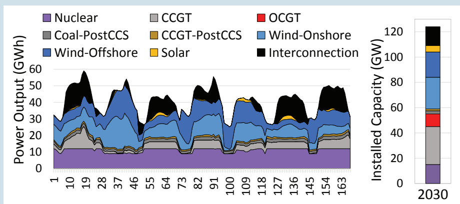

## Conclusions and Future Work

- Through integrated multi-scale modelling we can develop disruptive low-carbon technology designs.
- Model integration enable us to re-design and enhance the detailed models and develop "ideal" low-carbon technologies of the future.
- This integrated approach can dictate the technical characteristics that the stand-alone or integrated power and capture model, should have in order to gain a high-value energy mix of the future.

## Electricity systems optimisation

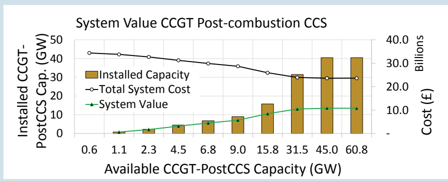
MILP for simultaneous system design and scheduling

- Technologies $i \in I; ic, ir, is \subset I$
- Operational modes $m \in M$
- Time steps $t \in T$
- Spatial zones $z \in Z$

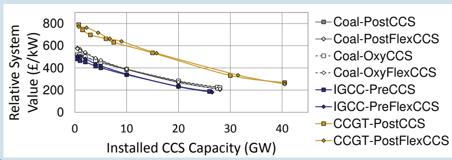



## Systemic Technology Valuation

The **System Value (SV)** of a technology quantifies the incremental change in total system costs caused by deployment within the electricity system.




The SV and is a function of the technology's characteristics and the prevalent system conditions.




## Acknowledgements

The authors gratefully acknowledge the financial support of the grant EP/M001369/1MESMERISE-CCS, the UKCCSRC for the grant UKCCSRC-C2-199 and the IEA Greenhouse Gas R&D Program (IEAGHG).

# Impacts of realistic and varying rates of CO2 injection on safe CO2 storage in the Bunter Sandstone of the Southern North Sea

Clea Kolster[1,2,3], Simeon Agada[4], Sam Krevor[4], Niall Mac Dowell[2,3]
1. Grantham Institute for Climate Change and the Environment, Imperial College London, 2. Centre for Environmental Policy, Imperial College, 3. Centre for Process Systems Engineering, Imperial College, 4. Department of Earth Science and Engineering, Imperial College

Carbon capture and storage (CCS), in spite of recent changes to UK government financing, is still recognized as (MacDowell and Staffell)a key technology to reduce CO2 emissions in the UK and around the world. Nevertheless, deployment remains slow and one of the main remaining challenges is the understanding of the dynamic behavior of a potential reservoir in response to realistic CO2 injection rates.

The UK Continental Shelf area is believed to have ample storage capacity offshore, of which one of largest storage sinks would be the Bunter Sandstone in the Southern North Sea. As CCS coupled with fossil fuel powered plants is likely to stand alongside intermittent renewable energy these CO2 injection rates will most likely vary over time. By coupling the reservoir response to varying rates of CO2 capture, we aim to provide a feedback loop from CO2 storage to the market supply of CO2.

In order to conduct this analysis, we collaborate with the British Geological Survey to obtain a coarsened geological model of the Bunter Sandstone saline aquifer and conduct dynamic simulations of CO2 injection into the reservoir in commercial reservoir simulator, Eclipse. The reservoir model is heterogeneous with an average permeability of 100mD and hysteresis is incorporated (Survey).

The study assumes that the field has closed boundaries and contains 12 injection sites. We do not consider reservoir management techniques such as brine production. Limiting the bottomhole pressure at each injection site to 75% of the lithostatic pressure imposes a conservative constraint minimizing risk to fracturing of the sealing caprocks.

As a first part of the study we assume a baseline injection rate of 2MT CO2/year in each injection site, hence a total of 24MT CO2/year into the whole field injected at a constant rate. We assume a total period of injection of 50 years to suit the scope of this study in terms of CCS deployment. The latter injection rate equates to the approximate output from Drax coal-firing power plant.

This injection rate response is compared with the effect of varying the rate by 1.8 and 0.2 times 2MT CO2/year. In a first simulation, we start out by injecting 0.4MT CO2/year in each injection site for 5 years and then injecting at 3.6MT CO2/year in each injection site for 5 years and continuing along this pattern for a total of 50 years of injection. This sequence is then repeated, but instead starts at the higher injection rate bound and fluctuates up and down every 5 years.

We observe in all three cases of simulation that, for an initial start up period, the injection rates desired are not achieved, and the rates remain pressure constrained due to the limit set on the bottom hole pressure at each site. This results in a cumulative injection of CO2 over 50 years that is between 100 and 200 MT below the desired total injection. In addition, we find that starting at a lower injection rate, rather than a very high injection rate, allows for a higher overall cumulative injection.

Following this analysis, we take three realistic scenarios of CO2 injection rates assuming the deployment of 3 coal+CCS plants with capture rates starting in 2030 as described in MacDowell & Staffell 2016 (MacDowell and Staffell). It is assumed that the CO2 is distributed evenly in all 12 injection sites.

The first scenario assumes that 12MT CO2 is the desired injection rate in 2030 and declines gradually over 50 years as a result of increased predicted capacity factor of renewable energy. The second scenario assumes a gradual increase of CO2 injection rate to 12MT CO2/year peaking in 2050 and the final scenario assumes a constant rate of CO2 injection of 11MT CO2/year.

All three scenarios have the same total amount of desired CO2 injection over 50 years. From these three scenarios, we observed a delay in order to reach the actual de-

# Impacts of fluctuating and realistic $CO_2$ supply on safe $CO_2$ storage development in the Bunter Sandstone of the Southern North Sea

Clea Kolster[1,2,3], Simeon Agada[4], Hayley Vosper[5], Gareth Williams[5], Sam Krevor[4], Niall Mac Dowell[1,2]|
[1] Centre for Environmental Policy, [2]Centre for Process Systems Engineering, [3] Grantham Institute for Climate Change and the Environment, [4]Department of Earth Science and Engineering, [5]British Geological Survey

## How $CO_2$ market supply affects $CO_2$ storage in the UK?

- CCS is still recognized as a key technology for reducing UK emissions
- Fossil fuel powered plants+CCS will likely stand alongside intermittent sources of renewable energy
- Market supply of $CO_2$ to storage will therefore vary depending on the energy needs
- The Bunter Sandstone is considered to be **one of the largest storage sinks in the UK**
- In order to accelerate deployment of CCS it is vital to have a thorough understanding of :
  - o The UK's storage capacity
  - o Dynamic reservoir behaviour in response to varying rates of $CO_2$ injection
- By showing the effect of varying injection rates on storage capacity we provide a **feedback loop to the market and capture rates of $CO_2$**.

## Geological Model of the Bunter Sandstone Saline Aquifer Formation in the Southern North Sea

Figure 1: Map showing some of the UK's major sedimentary basins [1]

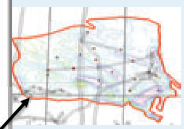


Figure 2: Map showing the field considered for this study including the injection sites marked by red dots

- Geological model developed by the BGS
- Dynamic simulation of $CO_2$ injection for storage
- Heterogeneous reservoir model with average permeability of 100 mD
- Hysteresis incorporated
- The reservoir is assumed to have closed boundaries with the exception of an **outcrop to the seabed**
- 12 injection sites modelled for safe injection
- Bottomhole pressure limit set for each injection site to equal 75% of lithostatic pressure at that point in order to avoid risk of caprock fracture
- Baseline injection rate is 2MT$CO_2$/year/injection site

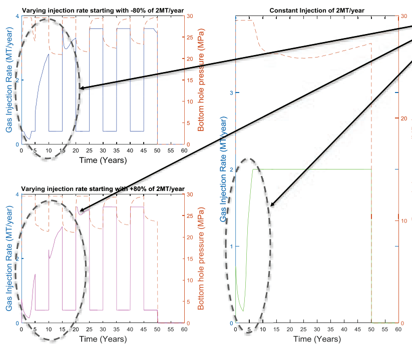
## How do varying $CO_2$ injection rates affect $CO_2$ storage capacity

Right figure:
Test injection of $CO_2$ at a rate of **2MT/year in each injection site**

Top left figure:
Test injection of $CO_2$ at varying rates by trying to **inject initially 80% less than 2 MT/year/injection site for 5 years** then 80% more for 5 years, repeatedly for a total of 50 years of injection

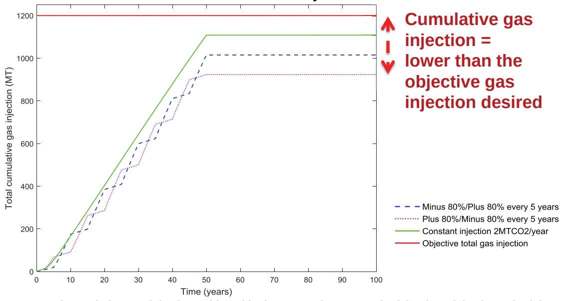
Bottom left figure:
Test the same as above but **starting with 80% more than 2 MT/year/injection** site for 5 years

**→Injecting $CO_2$ into the reservoir triggers a start up delay before the objective $CO_2$ injection desired is reached**




Figures 3-5: Results of actual gas injection rate and bottom hole pressure at Injection site 1 for three schedules of $CO_2$ injection

**Identifying a start up issue for injection:** initial injection rate **limited** by pressure build up reaching the bottom hole pressure limit set for safe injection




**Cumulative gas injection = lower than the objective gas injection desired**

Figure 6: Total cumulative gas injection achieved in the reservoir as a result of the three injection schedules compared with the total desired cumulative $CO_2$ injection over 50 years of injection and 50 years of monitoring

## The effect of realistic predictions of future $CO_2$ storage injection rate changes - starting in 2030 - on the Bunter Sandstone reservoir injectivity:

How quickly will the reservoir be able to respond to $CO_2$ market supply?

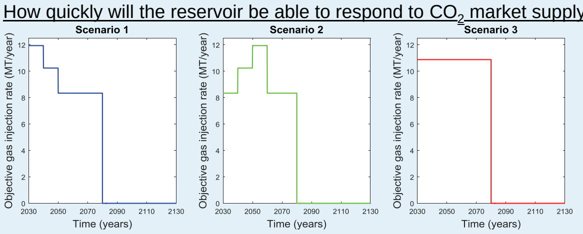
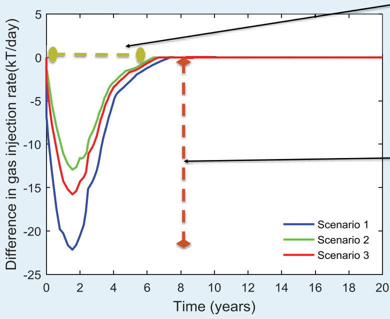



Figure 7-9: Objective gas injection rate into the reservoir's 12 injection sites in MT/year for a base case scenario starting with three coal+CCS units deployed in 2030 and reducing the $CO_2$ capture rate with increasing capacity factor (Scenario 1), for a second scenario with gradual increase in $CO_2$ injection rate (Scenario 2) and for an average constant injection rate (Scenario 3) based on predictions by Mac Dowell & Staffell 2016 [2].




**Start up time** delay to reach objective injection rate

**Difference** in actual $CO_2$ injection rate into the reservoir and objective injection rate

Figure 10: The difference in $CO_2$ gas injection rate that is actually obtained and the objective gas injection rate for the three scenarios described

## How is injectivity defined?

Injectivity index II:

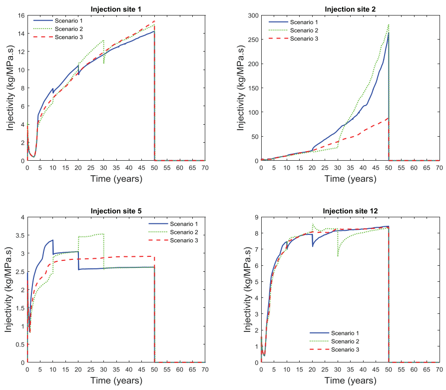
$$II = \frac{Q}{P_{bhp} - P_{av}} \quad [5]$$

$Q$: injection rate (kg/s),

$P_{bhp}$: flowing bottom hole pressure at the point of injection (MPa),

$P_{av}$: the average pressure in the reservoir (MPa)

**→Injectivity is the ability to inject $CO_2$ at a given rate at a safe injection pressure**




Figures 11-14: Injectivity of each realistic scenario for four characteristic injection sites with year zero corresponding to 2030

## CONCLUSIONS

1. There is a delay in reaching the desired $CO_2$ injection rate into the reservoir **= start up time**
2. Starting at a lower injection rate and **ramping up gradually over time** results in **higher cumulative injection of $CO_2$ achieved** (see Figure 10) due to:
   - Less pressure build up
   - Lower initial injection rate objectives
3. **Mismatch** between the time to achieve $CO_2$ capture supply and the time to achieve adequate reservoir injectivity for $CO_2$ storage
4. Lack of initial **reservoir injectivity** creates a **feedback signal to the $CO_2$.market**

ACKNOWLEDGEMENTS

The author(s) would like to acknowledge the financial support of the UK CCS Research Centre (http://www.ukccsrc.ac.uk) in carrying out this work. The UKCCSRC is funded by the EPSRC as part of the RCUK Energy Programme.

REFERENCES

[1] British Geological Survey; Industrial Carbon Dioxide Emissions and Carbon Dioxide Storage Potential in the UK Report, 2006

[2] Mac Dowell & Staffell, The role of flexible CCS in the UK's future energy system, IJGGC, 2016

[3] Petroleum Engineering: Principles and practice, J.S. Archer & C.G. Wall, Graham & Trotman, 1986

Science and Solutions for a Changing Planet sired rates of CO2 injection and this delay was smallest for the second scenario.

We then use the injectivity index to describe this phenomenon. The injectivity index is the fraction of the injection rate over the pressure difference of the bottom-hole pressure at the injection point and the average reservoir pressure, demonstrating the ability to inject CO2 at a given rate and safe injection pressure (Bacci, Korre and Sevket).

The injectivity index is unique at every injection site and therefore is sensitive to reservoir permeability, depth of the injection site and the bottom-hole pressure limit at the injection point. From these calculations we find that initially, the injectivity at a given site is the same for all three scenarios as the CO2 injection is pressure limited.

As the pressure dissipates in the reservoir and a CO2 plume is formed pushing back the brine in the aquifer, the CO2 injection is no longer pressure limited and instead becomes rate limited. As this switch occurs, the injectivity at each site for the three scenarios then starts to differ as the desired injection rates of CO2 in each scenario are reached.

The key outcome of this work is demonstrating the ability to use reservoir simulation to reflect prospective consequences and responses to realistic CCS deployment and reaction to CO2 supply. Hence, the reservoir generates a feedback to the CO2 transport network system - controlling the injection rates delivered to the storage site - the capture system - feeding into the network - and the market demand for fossil fuel products that in turn controls the CO2 supply.

Understanding this link between CO2 supply and reservoir behavior allows us to inform decision makers on how best to develop CO2 storage in line with capture and transport system deployment.

## Bibliography

Bacci, Giacomo, Anna Korre and Durukan Sevket. "An experimental and numerical investigation into the impact of dissolution/precipitation mechanisms on CO2 injectivity in the wellbore and far field regions." International Journal of Greenhouse Gas Control 5.3 (2011): 579-588.

MacDowell, Niall and Ian Staffell. "The role of flexible CCS in the UK's future energy system." International Journal of Greenhouse Gas Control 48.2 (2016): 327-344.

Survey, British Geological. "Industrial Carbon Dioxide Emissions and Carbon Dioxide Storage Potential in the UK Report." 2006.

### More information

The poster opposite summarises the research.

**www.imperial.ac.uk**

# CCS power stations at the interface of CO2 transport and electricity transmission networks: How to deal with the dual set of requirements?

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Many studies have been performed which examine and optimise operation and integration of carbon capture units at coal and natural gas-fired power plants. Boundary conditions concerning the interface to CO2 transport and electricity networks have been considered, however, only in a very simplified form, and never simultaneously at the short timescale required for effective operation of both networks.

This might be a reasonable starting point for an initial evaluation of the potential and the economic viability of carbon capture technologies. Nevertheless, the large scale deployment of the technology requires a profound understanding of the interfaces to related systems in the process chain.

This work will show that close interaction of different system requirements, particularly the CO2 transport and electricity network, can have immediate effects on the operating behaviour of CCS equipped fossil power plants.

The project aims to contribute to an identified lack in the literature by investigating the implications of likely future CO2 transport and electricity networks on the optimal design and operating behaviour of coal and natural gas-fired power plants equipped with CCS. It aims to inform policy makers as well as researchers about the options, challenges and problems arising from the integration of the systems.

### More information

The poster on the next page summarises the research.

**www.eng.ed.ac.uk**

# CCS power stations at the interface of CO2 transport and electricity transmission networks: How to deal with the dual set of requirements?

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## Aims & Objectives

- This research project aims at contributing to an identified gap in the literature by examining and ***optimizing a fossil fuel power plant with CO2 capture*** capability ***for operation at the interface of future electricity transmission and CO2 transport networks***.
- The optimisation will be performed ***in terms of design and operating behaviour*** and it will be ***based on the economic viability*** of the plant.
- By taking a wider approach towards the carbon capture and storage system and the electricity market, the project further aims to ***analyse potential scope for optimisation***, as well as bottlenecks, ***of the integrated system***.
- In this way the project intends to ***identify options for cost reduction through an optimized CCS power plant in an efficiently integrated overall system***.

## Methodology

- Establish a set of technical requirements (hard and soft) for the interface of the power plant and the CO2 transport network.
- Establish illustrative operating profiles of natural gas fired power plants with CCS in future energy networks.
- Develop configurations of natural gas-fired power and CO2 capture plants that deal efficiently with the requirements and constraints of both networks.
- Establish market framework and payment structures for both networks in future energy scenarios.
- Perform technical simulations of the different plant configurations with given boundary conditions and constraints using software such as gPROMS and gCCS.
- Perform techno-economic simulation of the plants in different future energy market scenarios.
- Communicate results and give recommendations regarding the scope for further optimisation of the plant within the CCS system, and the integration of the system as whole.

## Schematic Presentation

**ELECTRICITY TRANSMISSION NETWORK**

### Technical Requirements

Requirements of current electricity network are well established, however, they might change in the transition towards a low-carbon economy.

Relevant topics include:

- Load pattern
- Flexibility required
- Frequency and voltage support required

### Market / Regulation

Markets and regulatory framework of current electricity networks are well established, however, conditions might change in the transition towards a low-carbon economy.

Relevant topics include:

- Dispatch of electricity producing generators
- Trading/dispatch intervals (e.g. 5 min, 30 min, 60 min)
- Government support schemes for different power generating technologies
- Time between scheduling and actual dispatch
- Ancillary services
- Payment structures

**POWER PLANT**
**with carbon capture**

$ Optimal Design and Operating Behaviour of Power and Carbon Capture Plant Integrated in the CCS System (based on economic cost-effectiveness) $

**CO2 TRANSPORTATION NETWORK**

### Technical Requirements

Requirements of prospective CO2 networks are not yet established, they are only being developed.

Relevant topics include:

- Ability of CO2 transport network to accommodate variable flows (in the short, medium & long term)
- Levels of impurities allowed
- Entry conditions of CO2 (pressure, temperature)
- Design of networks in the future (pipelines/ships/single source to sink / network)

### Market / Regulation

Markets and regulatory framework of CO2 transport networks are not yet established, they are still to be designed.

Relevant topics include:

- Market design/Nature of interaction between CO2 producer and off-taker and how tariffs on CO2 transport and storage are set (fixed, fluctuating)
- Ancillary services
- Payment structures
- Can we anticipate market and regulatory framework from similar industries (e.g.: natural gas, electricity, water industry)?

***Corresponding author: T.Spitz@ed.ac.uk +44 (0)131 6507444**

# Capture and utilisation news

## Cement consortium awarded €12m to demonstrate CO2 capture

**www.leilac.org.uk**

**The Low Emissions Intensity Lime And Cement (LEILAC) consortium has secured funding to test Calix's direct separation process to capture CO2 emissions from cement and lime production.**

The funding is from  from the European Commission Horizon 2020 Grant programme. The consortium comprises HeidelbergCement, Cemex, Tarmac, Lhoist, Amec Foster Wheeler, ECN, Imperial College, PSE, Quantis and the Carbon Trust. The consortium will also contribute a further €9m towards the project.

During the first three years, the project will focus on finalising the design of the demonstration plant, to be constructed at the HeidelbergCement plant in Lixhe, Belgium once the necessary permits have been secured. The high temperature Direct Separation Calciner pilot unit will then undergo two years of testing in a standard operational environment, at a feed rate capacity of 240t/day of cement raw meal and 200t/day ground limestone respectively, on a continuous basis for several weeks.

Fundamental research on the process demands and performance will be carried out to demonstrate that the technology works sufficiently and robustly enough to be scaled up to full operational use. The project results will be shared widely with industry at key intervals during the testing.

Calix's direct separation technology is achieved by re-engineering the process flows used in the best available technology for lime and cement calcination. Carbonate calcination occurs by indirect counterflow heating, and consequentially the flue gases are not mixed with the CO2emitted from the carbonate minerals. This technology is already operating at a commercial scale for magnesite calcination. It does not require any separation technologies, new materials or processes. The technology is complementary with other carbon capture methods already developed in the power and cement sector, such as oxy-fuel, and can make use of alternative fuels.

*HeidelbergCement's plant in Lixhe, Belgium, location of the demonstration plant*

## MHI receives order for CO2 Capture Unit for Nippon Ekitan's Mizushima Plant

**www.mhi-global.com**

**The CO2 capture unit is for a new liquefied carbonic acid gas production facilities under construction at the company's Mizushima Plant in Japan.**

The plant's recovery capacity will be 283 metric tons per day (mtpd), with installation slated for completion in October 2017.

MHI will license its CO2 capture technology to Mitsubishi Chemical Engineering Corporation, which is to handle engineering, procurement and construction (EPC) of the new liquefied carbonic acid gas production facilities. In addition, MHI will be responsible for the basic design of the CO2 capture unit and supply its core components.

Nippon Ekitan is a group company of Taiyo Nippon Sanso Corporation that undertakes business in Japan relating to carbonic acid gas. The company primarily purchases high-density carbonic acid gas from petrochemical firms, ammonia manufacturers, etc. and, after liquefying and refining it, markets it as liquefied carbonic acid gas and dry ice.

The Taiyo Nippon Sanso group became a member of the Mitsubishi Chemical Holdings Corporation group in November 2014, and today it is promoting collaboration with Taiyo Nippon Sanso's various business enterprises. The liquefied carbonic acid gas production facilities being newly constructed will use an absorption solvent to separate and capture CO2 from low-density carbonic acid gas generated by Mitsubishi Chemical's Mizushima Plant, where Nippon Ekitan's Mizushima Plant is located, to enable the production of high-quality liquefied carbonic acid gas.

MHI's CO2 capture technology, known as the "KM CDR Process™," uses a high-performance absorption solvent (KS-1™) jointly developed with The Kansai Electric Power

Co., Inc. This technology achieves significant reductions in energy consumption compared with earlier methods, and since 1999 it has been adopted in 11 plants to capture CO2 from the flue gas of boilers fired by natural gas or fuel oil at chemical plants worldwide. This track record has made MHI a global leader in commercial applications of CO2 capture units.

Besides the production of liquefied carbonic acid gas and dry ice, MHI's CO2 capture technology can be employed in a wide array of applications. These include: chemical applications such as production of urea, methanol and dimethyl ether (DME); capture and storage of CO2 generated by thermal power plants, etc.; and enhanced oil recovery (EOR).

MHI CO2 capture process wins Okochi Memorial Technology Prize

## C-Capture receives £150,000 as Shell Springboard National Winner

**www.c-capture.co.uk**

C-Capture, a spin out company from the University of Leeds, received £150,000 as the Shell Springboard National Winner for its innovation which removes CO2 from industrial gas streams.

The company aims to introduce new amine-free solvent materials for CO2 capture with low cost to ensure commercial viability. It has so far conducted tests at a pre-pilot scale solvent assessment facility in Leeds.

Shell Springboard supports breakthrough low-carbon enterprises in the UK. C-Capture, whose clean energy technology captures carbon dioxide (CO2) emissions from different industrial gas streams – from large scale point sources such as power stations to smaller scale applications such as biogas upgrading – saw off competition from a shortlist of six finalists and a total of 140 other entries from across the country.

The company has been chosen by an independent panel of judges, comprising of some of the leading experts in the low-carbon and enterprise sectors.

Professor Chris Rayner of C-Capture, said, "Winning Shell Springboard is a fantastic achievement and comes at a critical time for our business as we look to bring C-Capture technology to market."

Shell Springboard is one of two Enterprise Development programmes run by Shell to support and inspire UK entrepreneurs to innovate for a lower-carbon future.

## NETL capture tech used in commercial biomass conversion

**www.cognitek.com**

The National Energy Technology Laboratory (NETL) has granted a license for two patented sorbent technologies that capture CO2 from streams of mixed gases.

The license was granted to renewable energy systems developer CogniTek Management Systems through the company's MG Fuels.

Sorbents are materials that can absorb gases, like CO2, and CogniTek plans to incorporate these sorbent technologies into its integrated biomass-to-biofuels conversion process with power generation. This innovative process includes carbon capture and represents a sustainable solution for distributed power. The liquid biofuels produced by the process can also be used as transportation fuels.

Biofuels are usually derived from corn, but CogniTek plans to use a wide range of plant matter for feedstock, including quick-growing grasses and trees, nuisance crops, and agricultural and commercial waste. Biomass is an abundant domestic resource and may significantly contribute to the renewable fuel market within the next decade.

The CogniTek process will have naturally low carbon emissions because the plants used as feedstock consume CO2 from the atmosphere as part of their growth process. Incorporating the NETL technologies, which employ a regenerable magnesium hydroxide to capture CO2, makes an inherently green process even greener and will result in a near 100 percent "carbon negative" process.

Biomass conversion technologies, such as the CogniTek process, can help produce affordable power using more environmentally friendly methods. That's why the Energy Department is committed to supporting research focused on making use of biomass resources. And at NETL, researchers like Ranjani Siriwardane, Robert Stevens Jr., and James Fisher II—who invented the sorbent technologies to be used by CogniTek—work every day to develop solutions to the nation's energy and environmental challenges.

But these new technologies will make a difference only if they're deployed commercially. To accomplish that goal, NETL is dedicated to transferring newly developed processes and products, like this sorbent technology, from laboratory to the marketplace.

## Quebec Government to invest $15m in CO2 Solutions

**www.co2solutions.com**

CO2 Solutions will be part of a consortium developing CO2 capture technology.

The company's technology has been selected by the government of Quebec in the framework of its Stratégie gouvernementale de développement durable 2015-2020 (2015-2020 Government Strategy for Sustainable Development).

In its 2016-2017 Budget, released yesterday afternoon, March 17, 2016, the provincial government announced that it has allocated a budget of $15 million over the next three years to support the creation of a consortium to promote adoption of CO2 Solutions' patented enzyme-enabled carbon capture technology.

Effectiveness and robustness of this technology were recently successfully confirmed during an extensive demonstration project at Valleyfield in Quebec. The project's results, validated through an independent third party engineering firm, were conclusive and the process is now ready for commercialization.

The consortium "Valorisation carbone Québec" will be composed of CO2 Solutions, Laval University and other organizations from the private and public sectors. Its mandate will be to develop and implement concrete solutions that will make a positive contribution to the Quebec economy through the creation of a new value-add carbon life cycle. This life cycle is envisaged to include the capture of CO2 and its subsequent conversion into value-added goods, such as biofuels.

Quebec recently established a goal to reduce its GHG emissions by 20% below 1990 levels by 2020, and 37.5% below this same level by 2030. The government sees its contribution to the new consortium as a strategic contribution towards helping industry reduce GHG emissions without damaging its ability to compete on economic terms.

# Berkeley lab develops CO2 capture membrane

**A new highly permeable carbon capture membrane has been developed by scientists from the U.S. Department of Energy's Lawrence Berkeley National Laboratory.**

The researchers focused on a hybrid membrane that is part polymer and part metal-organic framework, which is a porous three-dimensional crystal with a large internal surface area that can absorb enormous quantities of molecules.

In a first, the scientists engineered the membrane so that carbon dioxide molecules can travel through it via two distinct channels. Molecules can travel through the polymer component of the membrane, like they do in conventional gas-separation membranes. Or molecules can flow through "carbon dioxide highways" created by adjacent metal-organic frameworks.

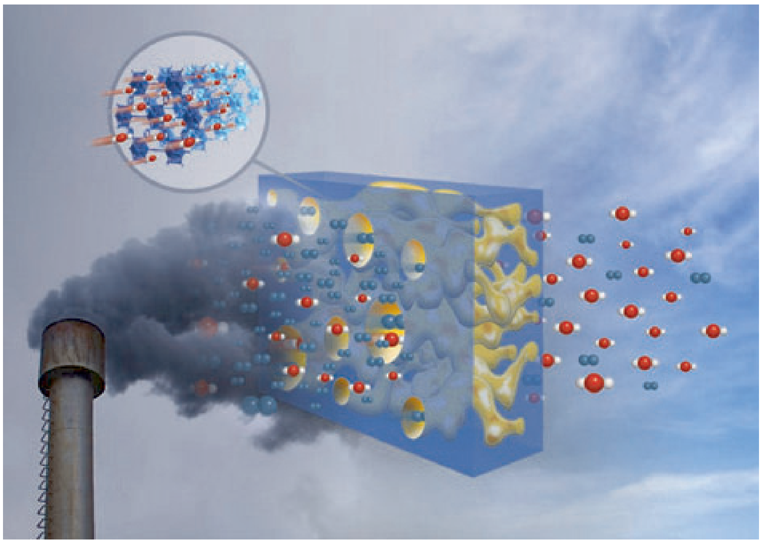
Initial tests show this two-route approach makes the hybrid membrane eight times more carbon dioxide permeable than membranes composed only of the polymer. Boosting carbon dioxide permeability is a big goal in efforts to develop carbon capture materials that are energy efficient and cost competitive.

The research is the cover article of the March issue of the journal Energy & Environmental Science.

"In our membrane, some CO2 molecules get an express ride through the highways formed by metal-organic frameworks, while others take the polymer pathway. This new approach will enable the design of higher performing gas separation membranes," says Norman Su, a graduate student in the Chemical and Biomolecular Engineering Department at UC Berkeley and a user at the Molecular Foundry.

He conducted the research with Jeff Urban, Facility Director of the Inorganic Nanostructures Facility at the Molecular Foundry, and a team of scientists that included staff at the Advanced Light Source.

Capturing carbon emissions from electric power plants and other sources is a hot research topic because there's a lot of room for improvement. The conventional way of separating carbon dioxide from flue gas is amine adsorption, which isn't economical at scale because it adds significant capital cost and reduces the electrical output of power plants.



*Exhaust from a power plant contacts a hybrid membrane recently developed at Berkeley Lab. The membrane's carbon dioxide highways (yellow) enable the rapid flow of carbon dioxide (red and white molecules) while maintaining selectivity over nitrogen (blue molecules). The membrane is eight times more carbon dioxide permeable than a polymer-only membrane. (Image: Berkeley Lab)*

Scientists are exploring polymer membranes as a more energy efficient alternative to amine adsorption. These membranes are relatively inexpensive and easy to work with, but current commercial membranes have low carbon dioxide permeability. To overcome this, scientists have developed hybrid membranes that are part polymer and part metal-organic framework. These hybrids harness the carbon dioxide selectivity of metal-organic frameworks while maintaining the processability of polymers.

But, until now, scientists have not been able to engineer hybrid membranes with enough metal-organic frameworks to form continuous channels through the membrane. This means that, somewhere in a carbon dioxide molecule's journey through the membrane, the molecule must contact the polymer. This constrains the molecule's transport to the polymer.

In this latest research, Berkeley Lab scientists have developed a hybrid membrane in which metal-organic frameworks account for 50 percent of its weight, which is about 20 percent more than other hybrid membranes. Previously, the mechanical stability of a hybrid membrane limited the amount of metal-organic frameworks that could be packed in it.

"But we got our membrane to 50 weight percent without compromising its structural integrity," says Su.

And 50 weight percent appears to be the magic number. At that threshold, there are so many metal organic frameworks in the membrane that they form a continuous network of highways through the membrane. When that happens, the hybrid membrane switches from having a single channel to transport carbon dioxide, in which the molecules must go through the polymer, to two channels, in which the molecules can either move through the polymer or through the metal-organic framework highways.

"This is the first hybrid polymer-MOF membrane to have these dual transport pathways, and it could be a big step toward more competitive carbon capture processes," says Su.

## More information

**www.lbl.gov**

# Transport and storage news

## 15,000 tonnes of CO2 stored at Otway

**www.co2crc.com.au**

The Australian project has reached another carbon dioxide storage milestone.

After four years, CO2CRC and its Australian and international research partners have safely injected 15,000 tonnes of CO2 at the Otway research facility in Nirranda South West Victoria.

Tania Constable CEO, CO2CRC said “This experiment proves that field operations can be safely carried out and shows with certainty that CO2 storage is low risk.”

CO2 has been injected into a saline formation over the last four months with the aim to accurately predict the movement of CO2, giving confidence to the users of carbon capture and storage technologies and regulators how CO2 will behave when permanently stored, and the technical capabilities of seismic monitoring to validate this plume movement.

Cost effective fibre optic cables and a high resolution buried receiver, have been fitted with automated communications facilities to allow researchers to remotely access and operate this advanced surface and subsurface monitoring system. The equipment tested provides several options to reduce the surface monitoring activities required to verify the CO2 plume movement. CO2CRC’s research partners Curtin University, Western Australia, Lawrence Berkley National Laboratory, US, and CSIRO continue to work collaboratively on the analysis of this data.

Key to success has been the involvement and support received from local landowners and the Nirranda community who have been consulted and kept informed about this experiment over the last four years. “Without the continuing support of our local community, this world leading innovation would not be possible” said Constable.


*Aerial view of the Otway site where 15,000 tonnes of CO2 have been permanently stored*

## Western Australia project releases well data

**www.dmp.wa.gov.au/CCS**

New well data from the South West Hub Carbon Capture and Storage project has been released.

The data will aid research into the feasibility of permanently storing carbon dioxide in deep underground formations in the Harvey-Waroona area and determine if another well is required.

Mines and Petroleum Minister Bill Marmion said the results of data studies would help determine the project's potential.

"The aim of the drilling program was to evaluate the containment properties of the strata immediately above the potential CO2 reservoir within the Lesueur Sandstone," Mr Marmion said.

"The data includes drilling reports and wireline logs from three stratigraphic wells drilled into the three distinct fault blocks around Harvey between December 2014 and June 2015. It also includes photographs of drill core and geological analysis reports."

The well drilling program, funded by the Australian Government and managed by the Department of Mines and Petroleum (DMP), successfully reached target depths of between 1,350 metres and 1,800m.

Geological laboratories and South West Hub research partners at the National Geosequestration Laboratory, The University of Western Australia, Curtin University and CSIRO are continuing to work on the core samples and well data.

A total of 24 gigabytes of information about the drilling program is available on the DMP website, in the Western Australian Petroleum and Geothermal Information Management System.

"Further analysis and 3D modelling will continue for another year before a decision can be made on drilling a further deep stratigraphic well," the Minister said.

## Simulating CO2 saturation in rocks

**i2cner.kyushu-u.ac.jp/en/about**

A more detailed model of rocks used to store CO2 could help understanding of storage capacity and leakage risk.

A detailed understanding of the passage of fluid within the rocks of target locations is imperative for ensuring that CO2 is stored effectively and leakage risk is minimized.

This level of detail naturally requires state-of-the-art techniques, and one such method is under development at Kyushu University's International Institute for Carbon-Neutral Energy Research (I2CNER) and Department of Earth Resources Engineering.

"The idea is that if we can generate a detailed and realistic model of the target reservoir rock, we can precisely determine how the

$CO_2$ will displace water," lead and corresponding author Takeshi Tsuji of I2CNER explains. "We can then use the model to help us to estimate the storage capacity and leakage risk for $CO_2$ capture below ground."

There have been many studies of the passage of $CO_2$ through porous rocks, but these rely on relatively simple computer models that typically assume the pores are the same size and shape and are spread uniformly through the rock. "These techniques, and simple laboratory simulations, limit our ability to understand a broad range of potential $CO_2$ storage reservoirs below ground," study coauthor Fei Jiang says.

The researchers scanned the rocks using X-ray microcomputed tomography, a similar technology to that used in hospitals to see inside the human body, and combined the results with detailed mathematical simulations. Using this "digital rock model," they were able to generate a picture of the real displacement of water by $CO_2$ below ground and identify the optimal conditions for $CO_2$ storage in real rocks.

The application of this approach to a sandstone sample allowed the researchers to examine the movement of fluids inside the rock at an unprecedented level of detail. This enhances understanding of the processes that occur at the micro-scale inside the rock as $CO_2$ is injected. "We were able to identify the main regime for fluid displacement inside our sandstone sample," Tsuji explains, "and because of the properties of our sandstone, we can determine which processes are most dominant in natural rocks that could be used for $CO_2$ storage." In the future, if rock samples are available from a potential reservoir, the method could be used to analyze rock's storage potential and contribute to advancement of CCS as a viable technique for $CO_2$ removal.

The article "Characterization of immiscible fluid displacement processes with various capillary numbers and viscosity ratios in 3D natural sandstone" was published in Advances in Water Resources.

## Researchers assess attitudes to North Sea energy future

**www.sccs.org.uk**

**New research in Scotland has stressed the need for a clear government policy which positions Enhanced Oil Recovery (EOR) in the North Sea as part of a managed transition towards a low-carbon economy in the UK.**

The findings from a joint research project between Robert Gordon University (RGU) in Aberdeen and Scottish Carbon Capture & Storage (SCCS) highlight differing attitudes when people consider how current government priorities on maximising oil recovery relate to climate change objectives.

The use of carbon dioxide ($CO_2$) captured from the power and industry sectors could boost oil production from mature oil fields and providing long-term storage of the greenhouse gas as a means of addressing climate change.

Findings from the research, conducted by Dr Leslie Mabon from RGU's School of Applied Social Studies, and Chris Littlecott from SCCS, have been published in the International Journal of Greenhouse Gas Control.

Their paper is entitled Stakeholder and public perceptions of carbon dioxide enhanced oil recovery ($CO_2$-EOR) in the context of Carbon Capture and Storage (CCS) – results from UK focus groups and implications for policy.

It assesses the views of citizens and expert stakeholders regarding the government's policy push to maximise oil recovery in the North Sea against the need to combat climate change and the UK's transition towards a low-carbon economy.

Based on focus group data from Aberdeen, Edinburgh and London, the research assessed how stakeholders and members of the public responded to four varying scenarios for CCS with $CO_2$-EOR in the North Sea, and drew implications for deployment in other mature fossil fuel basins around the world.

Dr Mabon said, "Interest is growing in carbon dioxide enhanced oil recovery as an additional economic incentive for $CO_2$ injection and the acceleration of $CO_2$ storage as a means of addressing climate change. However, given increasing concerns and campaigns against the continued extraction of fossil fuels, it is possible that $CO_2$-EOR may unintentionally hinder CCS by reducing support from neutral or cautiously supportive voices from Non-Governmental Organisations."

Dr Mabon and Mr Littlecott found that scenarios which emphasised maximising oil recovery were met with scepticism or even opposition, and that there is an expectation for national governments to lead and ensure $CO_2$-EOR and CCS are developed in the public interest.

Mr Littlecott said, "Through our research we found that all stakeholder groups wanted to look beyond scenarios that focus purely on maximising economic recovery of North Sea oil. Citizens and experts alike recognise that action must be taken to reduce $CO_2$ emissions, and want to see coherence between these different government objectives."

"We also found that the public recognises that fossil fuels are currently deeply embedded in society, with Scotland particularly dependent on the offshore oil and gas sector. There was therefore significant interest in seeing a fair transition pathway put in place for workers."

"Within this context, we found that there may be qualified support for CCS with $CO_2$-EOR to make best use of existing fields whilst decarbonising the power and industrial sectors at the same time. However, for this support to emerge there is a need for a joined-up government policy that positions $CO_2$-EOR firmly within a managed transition towards a low-carbon economy."

Development and deployment of conventional CCS has been slower than expected, with the UK government withdrawing support for its £1 billion Commercialisation Competition in autumn 2015.

Dr Mabon said, "There is an increasing awareness of the need to imagine a future for the North Sea that balances our oil and gas needs with our obligations to climate change mitigation and the need to develop a sustainable economic base for the north-east of Scotland. The idea of a 'managed transition' for the North Sea from existing oil and gas operations has started to appear a lot more widely in the political sphere, with the recent decline in oil prices bringing the future of the North Sea and the north-east of Scotland into even sharper focus."

"$CO_2$-EOR might offer one way of enacting this, by capturing emissions from industrial sources on land and using this to extract remaining required oil in a more sensitive manner. This could make a contribution towards mitigating the effects of climate change that also gives the North Sea, and the communities that depend on it for income and employment, a gentler transition away from oil and gas."

# Use it or lose it: door closing on UK CCS

**A new report from Scottish Carbon Capture & Storage (SCCS) says the UK must use its offshore assets now or risk losing the opportunity.**

The UK Government is planning tighter climate laws to deliver net zero carbon emissions – but how? A new report shows how the UK's unique assets can be used to support this ambition cost-effectively through carbon capture and storage (CCS) but warns that this opportunity must be grasped now, with strategic policy to regain lost momentum.

As MPs and external stakeholders meet today [Wednesday] at Westminster to discuss the potential for industrial CCS in the UK – and in light of the Government's development of its 2050 industrial decarbonisation roadmaps – the report presents the expertise and opportunities that can create a viable route to a zero carbon economy. These include:

• Retaining skilled jobs and creating new industries at clusters of industrial emitters around the UK coastline, with plans already developed for shared-cost CCS "hubs"

• A globally significant and exceptional North Sea geological asset for CO2 storage

• An oil and gas workforce that routinely delivers high-quality infrastructure and could build a new offshore CCS industry serving the UK and Europe

• An enviable research & development community with its amassed knowledge and strategic international collaborations

• Large-scale CCS projects poised to decarbonise industry and power generation

The report also highlights the potential cost to taxpayers of delaying CCS deployment, the loss of crucial infrastructure through North Sea decommissioning and the risk of a "brain drain" of expertise to countries where CCS is already being delivered.

The Scottish Carbon Capture & Storage (SCCS) report derives from its 2015 annual conference, which brought together policy-makers, industry, academia and representatives from Scottish, UK and European governments. It shows how low-carbon, competitive economies can be rapidly and uniquely assisted by CCS.

The authors have called for a reset of objectives and ambition in the UK, and recommend a concerted effort by industry, government and academia in four key areas:

**Delivering industrial CCS:** Many industries can decarbonise at a low capture cost, but that still outweighs the current carbon price. If the UK Government wants to retain industry, it should develop funding mechanisms for CCS as a top-up to the carbon price. An East Scotland Low Carbon Zone, potentially in partnership with Teesside, could provide industrial emitters with access to CO2 transport and storage facilities and support the creation of production hubs future-proofed against the rising cost of emitting carbon.

*"The progress and potential of CCS in the UK is much more than a government competition. Our report describes why we need to get one of the most obvious and effective climate change tools back on track and highlights the strengths and opportunities that the UK – and Scotland, in particular – possesses." – Professor Stuart Haszeldine, SCCS Director*

**Genuinely CCS-ready power**: If gas-fired power generation forms a sizeable proportion of UK demand, in line with government policy, then future plants must be genuinely CCS-ready, unlike the simplistic assessments made now, and their siting assessed alongside the viability and cost of pipeline and/or shipping connections to suitable CO2 storage sites. The decommissioning of North Sea infrastructure means the door is closing fast on reusing equipment to access storage sites.

**Clarity on cost**: A correct statement of the cost of CCS occurs only when capture costs are separated from transport and storage. At present, the first CCS projects are expected to bear the full cost of infrastructure despite the fact that follow-on projects would benefit from this development. This creates an uneven playing field against other forms of low-carbon power, such as offshore wind or nuclear.

**A Scottish CO2 Hub**: The development of a CO2 collection and storage hub in Scotland could unlock a CCS industry serving both the UK and Europe, providing access to extensive storage in the Central North Sea at low financial risk. By using cost-effective shipping, this can support the collection-and-dispatch hubs envisaged for mainland Europe and Scandinavia, and could be expanded sequentially on a project-by-project basis.

Professor Stuart Haszeldine, SCCS Director, said: "We must never lose sight of our ultimate goal – a zero carbon future for the UK as part of international efforts to contain global warming. We welcome the UK Energy Secretary's recent commitment to tightening climate law to enable this ambition, but these good intentions will hit a significant problem if we delay the deployment of CCS any further. The stark reality is that net zero carbon is unachievable without CCS."

"In the UK, we have an enviable set of unique offshore assets that, if used now rather than decommissioned, will deliver a least-cost pathway to a competitive, low-carbon economy. Any delay risks creating a considerable burden for UK taxpayers further down the line, as well missing the opportunity to build a homegrown CCS industry that can support the climate actions of other countries."

## More information

The full report is available from Scottish Carbon Capture and Storage:

**www.sccs.org.uk**

# NIST could help keep sequestered carbon from blowin' in the wind

**Scientists at the National Institute of Standards and Technology (NIST) have taken an important first step in validating a technique for monitoring CO2 emissions from sequestration sites.**

The NIST team members, who collaborated on the study with Harris Corporation and Atmospheric and Environmental Research (AER), said the findings could permit far more effective monitoring of sequestration sites under real-world conditions, which ordinarily make it difficult to determine whether the carbon dioxide is escaping storage.

Carbon sequestration involves removing carbon dioxide gas from power plant smokestack streams and other large emission sources that release greenhouse gases into the atmosphere. Once captured, the carbon dioxide can be pumped deep into the earth, effectively removing it from the atmosphere.

*This laser scanner monitors a field near Ft. Wayne, Indiana for carbon dioxide leaking from underground. The data, needed to measure carbon sequestration success, helped NIST improve monitoring efforts. (Image ©Harris Corporation)*

A sticking point is that the carbon dioxide must remain underground for centuries. If more than 0.1 percent of the gas leaks out per year, it's all for nothing. So scientists from around the world have been trying to develop an effective way to monitor sites for potential gas leaks.

One approach places a system of laser reflectors above the ground directly over a carbon storage site to scan for escaping gas. Traditional methods of scanning the region with a laser can reveal leaks. Collecting useful data, however, requires a half-hour period when the wind does not shift and the sampled atmosphere does not change. This isn't a common situation, and if the wind shifts, the data is ruined.

Enter the NIST-Harris-AER team. Harris and AER built the laser-based measurement system under a cooperative agreement with the Department of Energy's National Energy Technology Laboratory. The system collected data over a mock storage site in Ft. Wayne, Indiana. The data went to NIST for analysis. NIST developed a mathematical model that considers the change in shape of a gas leakage plume in the wind. In this way, the model factors out other carbon dioxide sources in the sequestration area. The practical upshot is that wind variables and other outdoor field conditions are no longer a constraint.

The results from their analysis surprised them, and not just because of the pleasing findings: They could now, according to their simulations, pinpoint a gas leak from the ground to within about 5 meters, or ten times more accurately than other approaches, and regardless of the wind conditions.

"What surprised us is that even though one of these experiments was meant to be one with no carbon source present, we found one anyway," said NIST physicist Zachary Levine. "This was supposed to be the 'null set' that we were going to compare with data from another field that has an artificial carbon dioxide source buried beneath it. Instead, we found something none of us had expected."

Levine described the results as a proof of concept for carbon sequestration monitoring.

"The approach means far fewer demands placed on the laser sensors, and much reduced worries about unrealistic wind conditions," he said. "It also means we can detect less intense leaks with far better spatial resolution. We're looking forward to testing it further on additional field campaigns."

## More information

Z.H. Levine, A.L. Pintar, J.T. Dobler, N. Blume, M. Braun, T.S. Zaccheo and T.G. Pernini. The detection of carbon dioxide leaks using quasi-tomographic laser absorption spectroscopy measurements in variable wind. Atmospheric Measurement Techniques:

**www.atmos-meas-tech.net/9/1627/2016**

**www.nist.gov**


$CO_2$ Concentration evolution in atmosphere

# TOGETHER, WE CAN HELP FLATTEN THE $CO_2$ CURVE

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