Carbon Capture Journal

CCS in Europe

A decadal staircase to 2°C: time to step up - implementing Paris

ZEP: CCS vital for clean growth and competitiveness

European Parliamentary Hearing on CCS

May / June 2017 Issue 57

New carbon capture and exchange technology: CO2 to chemicals for £47 per tonne

- UK Public Accounts Committee: act now on CCS to save billions
- What will it take to secure civil society and public support for CCS?
- Molecular 'leaf' collects and stores solar power, captures CO2
- ADM begins second Illinois CO2 storage project

GHGT-13 closing panel

The aim of the closing session at the 13th Conference on Greenhouse Gas Control Technologies was to look at initiatives that are underway but also ask the critical questions: are we doing enough and what more needs to be done to deploy CCS more rapidly?

The Closing Panel Members were:

• Jean-Francois Gagne, Head of the Energy Technology Policy Division, International Energy Agency

• Jonas Helseth, representing the EU Zero Emissions Platform

• Tim Bertels, representing the Oil and Gas Climate Initiative

• Jarad Daniels, Office of Fossil Energy, Director of Planning and Environmental Analysis, US DOE

• Niall Mac Dowell, Head of the Clean Fossil and Bioenergy Research Group, Imperial College, UK

Questions posed to the panel

Jean Francois Gagne - "Has Policy failed CCS to date and what more work in this area is needed?"

CCS is a climate technology but pre-Paris climate ambitions were not high enough. As a result, Policy support has fluctuated, leading to CCS not being on track for 2 degrees or for Paris ambitions. The start-stop policy cycle for CCS has impacted on investment, but the Paris Agreement can change that. In the last 20 years we have learnt a lot and the technology has advanced significantly.

Going forward we need targeted support to advance CCS. We will need both Capital and operational incentives. Such incentives can be in the form of grants, tax incentives, feed-in tariffs, CO2 purchase contracts etc. Whatever best suits the appropriate market situation.

Jonas Helseth - "CCS has not taken off in Europe what new efforts/initiatives are needed?"

Europe needs an Executable Plan for CCS at scale. Such a plan would involve 3 phases:

1. Deliver existing / planned single source / sink CCS projects in prime locations which can be expanded into strategic European CO2 hubs;

2. Source CO2 from nearby emitters to create the CCS hubs and ensure that the storage capacity identified and is appraised well in advance of its need, driven by hub expansion;

3. Expand the hubs over a wider region and across neighbouring countries. This could be coordinated and financed by regional CO2 Market Makers like Norway capitalised by EU / national funds such as Horizon 2020 and the Innovation Fund (NER400)

Tim Bertels – "What more can the oil and gas industry do to stimulate the deployment of CCS?"

The Oil and Gas Climate Initiative was launched at COP21 by 10 oil and gas companies who committed to spending $1billion over the next 10 years on innovative greenhouse gas reduction technologies that includes CCS. The Oil and Gas Industry has the skills and expertise to help develop a CO2 transport and storage framework for the future.

They can play a key role by sharing the information they have gained from existing CCS projects as well as advising stakeholders on what it takes to deliver CCS projects. Also, they can contribute to storage mapping activities in regions where CCS will need to be deployed in the future but first steps are needed to assess and then develop the storage resource. The industry should take a lead on the deployment of gas fired CCS projects, which is a critical technology to achieve the below 2°C target.

Jarad Daniels - "How can technology Innovation contribute to the deployment of CCS?"

We need technology deployment and innovation of current CCS technology now. In addition, we need accelerated deployment of new generation CCS technology going forward. Innovation is needed on both capture and storage components of CCS. It is needed to drive down the costs of CCS components and the plants themselves to make them competitive in the market place with other low carbon technologies.

Developments like Mission Innovation, launched at COP21, where 20 countries have committed to double their R&D budgets on low carbon technology developments show that governments are taking low carbon technology innovation seriously.

R&D efforts need to be guided by and help inform techno-economic and Integrated Assessment Models. There is work that needs to be done to inform the modelling and policy discussions of the value of CCS.

Niall Mac Dowell – "Is CCU a game changer or distraction for CCS?"

Meeting the 2°C temperature target involves the mitigation of > 800 GtCO2, estimates based on the projected technological growth rates suggest that the contribution of CO2 conversion/utilisation accounts for only 0.49 – 0.6% of the CO2 that needs to be mitigated under the 2°C target. The reason for this low contribution is that most CCU options do not correspond to permanent storage removal of CO2 and therefore do not contribute to offsetting climate change.

A key bottleneck to industrial scale deployment of many CO2 conversion technologies is likely to be cost effective availability of low carbon/renewable H2. The argument that CO2 and electricity will be available at no cost is flawed.

With CCU you also need to be aware of the unintended consequences for example converting CO2 to methanol and using as a transport fuel results in 115% of the CO2 emissions associated with gasoline. Also, you are taking a concentrated point source of CO2 and converting it to a diffuse source making it more difficult and expensive to capture in the future.

More information

The presentations given by each panel member can be found at:

www.ghgt.info

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Front cover:

The carbon capture and exchange technology is modular by design, and can capture and convert CO2 to valuable chemicals for £47 per tonne of CO2 abated.

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A decadal staircase to 2°C: time to step up

Climate change has a long and prolific track record when it comes to talks. Yet talking the talk turned out to be far from walking the walk: almost 3 decades after first World Climate Conference in 1979, coordinated international action is still an idle and listless attempt at solving the greatest problem of mankind. However, if the current goals of the Paris Agreement are re-calibrated into a comprehensive set of action steps, we just might stand a fighting chance.

By Bellona Europa

If the current goals of the Paris Agreement are re-calibrated into a comprehensive set of action steps, we just might stand a fighting chance

A recently published article from one of the worlds' leading journals of scientific research, Science, gives a clear breakdown on the steps for how to get to the 2°C goal by 2050. In their step-by-step narrative, they present a decadal decarbonisation plan to effectively and affordably curb climate change. The key to the future of decarbonisation are, among other climate change mitigation tools, technologies that remove carbon dioxide (CO_2) from the atmosphere, also known as Carbon Capture and Storage (CCS). Ever since its foundation three decades ago, Bellona has been vocal in advocating the large scale deployment of this indispensable technology.

So what do the authors envision for the decades to come?

Step 1 (2017-2020): Paving the way

By the end of this decade, the already existing policy instruments are expanded and improved. Steering climate mitigation on a new pathway will also mean getting rid of fossil fuel subsidies entirely. In the industrialised world, cities and major corporations have elaborate decarbonisation strategies.

Here, reshaping industrial policies will be vital to reach the next step on the stairway to 2°C. Without fertile political ground and much needed preparation, taking CO_2 out of the atmosphere will remain a far-fetched concept. Clarity on the long term direction and support for the deployment of CCS in the next decades is crucial in order to incentivise investment, mitigate risk and gain public support.

In its latest report on industrial CCS, Bellona defines the nuts and bolts of the steps needed to set the stage for large-scale decarbonisation. Laying the regulatory groundwork for a successful CCS scale-up will include:

• Developing a game plan for creating CO_2 hubs and clusters that can drive costs down significantly

• Pick up the check on first large scale CO_2 storage projects

• Vouch for CCS to reassure investors

• Win the crowd over

Once this regulatory blueprint is set, the real challenge begins.

Step 2 (2020-2030): Walking the walk

From 2020, efforts need to be scaled up dramatically. Going carbon-negative will be imperative in order to ensure that the climate goals are met: CCS should, by this point, be well under way. Research efforts are directed at driving the costs of the technology down and removal of CO_2 is coupled with second- and third-generation bioenergy in order to go carbon negative.

Efforts are amped up in the transport sector as well: by the end of this period, leading countries phase out the production of internal combustion engines. Additionally, research is increasingly focused on the development of battery life extensions, which can offer significant benefits both for energy storage and electric mobility.

Bellona considers electric vehicles to be a cost effective mitigation measure that addresses multiple problems when it comes to climate change. Apart from decarbonising the transport sector, electrifying transport on a larger scale will clear out air pollution and boost energy security by providing energy storage to variable renewable power.

2030-2040: Picking up pace

In this decade, all of the inputs to society should be either carbon-neutral or carbon-negative. The cities of tomorrow need to use emissions-free concrete and steel or replace those materials with other materials, such as wood, stone or carbon fibre. Not only will our cities have to be built with neutral materials, but also the renewables powering them. Unless we find a different way to make them, wind turbines, electric cars and solar panels will all require CCS to remain emission-neutral.

Manufacturing our future will certainly require an extensive application of CCS in cement, steel and other carbon-intensive industries in order to remain on the 2°C pathway. For this decade, the scenario envisions a roll out of large-scale BECCS (the combination of CCS with sustainable bioenergy) schemes and an overall doubling the annual rate of CO2 removal.

2040-2050: Revising progress

By this time, the planned CCS projects will be full-scale and will ensure that the remaining backup energy from natural gas has a limited carbon footprint. At the end of this decade, the world reaches net zero CO2 emissions, with "a global economy powered by carbon-free energy and fed from carbon-sequestering sustainable agriculture". The CCS projects coupled with biofuels are either scaled up or re-evaluated in order to ensure their sustainability in the future.

The forecast for a 2050 world might be a hard prediction to make.

Yet, setting boundaries might drive us away from just wishful thinking and help us make zero-emissions future a reality.

Rockström J, Gaffney O, Rogelj J, Meinshausen M, Nakicenovic N, & Schellnhuber HJ (2017). A roadmap for rapid decarbonization. Science 355 (6331): 1269-1271. DOI:10.1126/science.aah3443.

More information

www.bellona.org

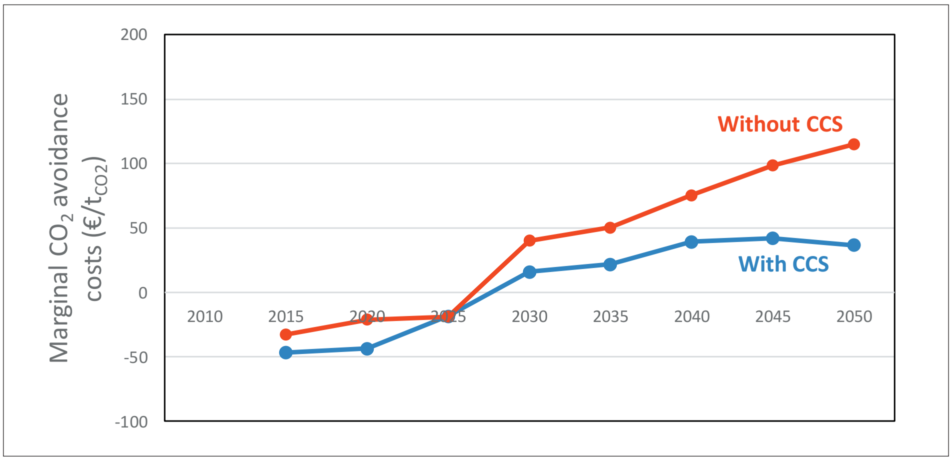
ZEP report: CCS vital for clean growth and industrial competitiveness

The Zero Emissions Platform has published its 5th annual Market Economics report: CCS and Europe's Contribution to the Paris agreement – Modelling least-cost CO2 reduction pathways. The report reiterates that the lowest cost pathway to meet Europe's climate change targets requires CCS deployment from the 2020s onwards.

The report models 10 countries and concludes that in all countries, CCS will be essential to achieving the 80-95% emissions reduction target set out in the EU 2050 Energy Roadmap.

The report also highlights the tremendous importance of CCS to the future competitiveness of key European industries such as steel, cement, chemicals and refining – these industries can achieve a step-change in emissions reductions in scenarios where CCS is available.

ZEP's modelling shows that to achieve the least-cost pathway for meeting Europe's climate change targets, CCS must be deployed from the early 2020s onwards. This will unlock negative emissions from 2025 and lower emissions in 2050. Enabling commercial-scale CCS by the early 2020s requires the urgent development of CO2 transport and storage infrastructure – this needs to start now.



Marginal CO2 avoidance costs with and without CCS

Dr. Graeme Sweeney, ZEP Chairman, said, "The Paris agreement has set the bar high with the aim of keeping the global temperature increase to well below 2 degrees. CCS is absolutely critical to ensuring that Europe can play its part in meeting this goal. Not only CCS is ready for commercial deployment, but our new modelling shows that its value to the EU could exceed €1 trillion between now and 2050. It also confirms that Europe has sufficient storage resources to meet the CCS industry's needs until 2050. The time to translate talk into action is now - the industry and the European Commission must work together to bring CCS forward."

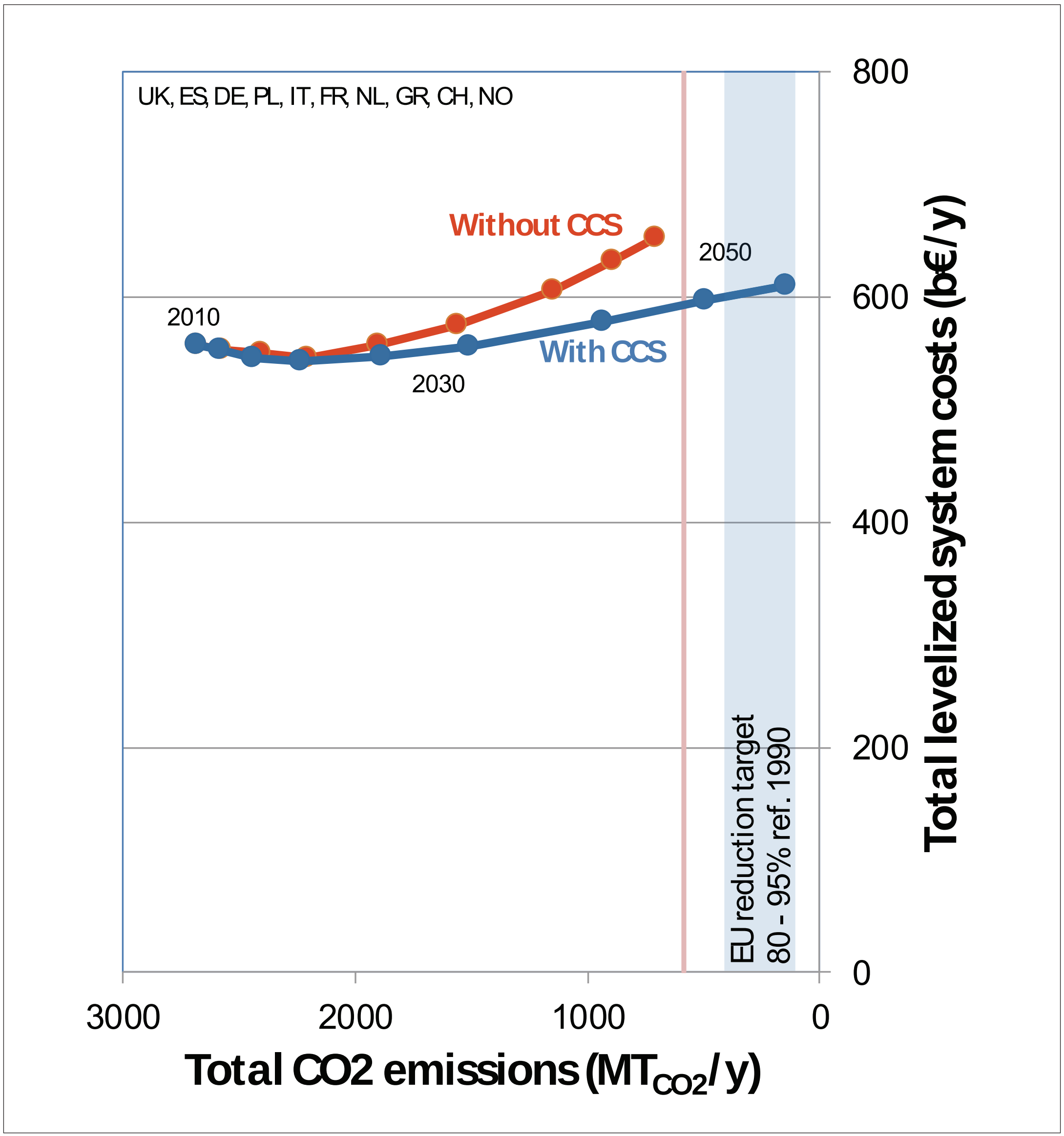
Costs vs. CO2 emissions

The Figure shows the total system costs versus the CO2 emission reduction. The end point of the two curves corresponds to the 95% and 74% emission reduction, with and without CCS, respectively.

A number of conclusions can be drawn:

• The cumulative CO2 emissions for the 10 countries are 74 Gt with CCS and 80 GT without CCS. Having CCS available saves 6 Gt within the timeframe from 2010 to 2050.

• The cumulated energy system costs (capital, operation and fuels) for the 10 countries are €25.5 trillion with CCS and €26.2 trillion without CCS but it should be emphasized that the latter scenario does not deliver on energy and climate objectives. Having CCS available saves approximately €700 billion within the timeframe from 2010 to 2050.



Costs vs. CO2 emissions for the sum of the considered countries

• The model can allow readers to deduce an implied social cost of CO2 that is emitted to account for the damage of climate change. Estimates are in the order to 50 to 100 €/tCO2 27. Taking 60 €/tCO2 leads to additional savings of 6 Gt x 60 €/tCO2 = €360 billion if CCS is available.

• Considering that the selected countries represent approximately 70-75% of the EU28 emissions it can be concluded that the availability of CCS has a value in excess of €1 trillion for the time period of 2010 to 2050.

• Following the same logic and assuming that the emission intensity and costs stay constant after 2050, one can derive a yearly value of CCS in excess of €60 billion per annum for the second half of the century. This corresponds roughly to 0.5% of the GDP.

Conclusions

Building on ZEP's previous Market Economics reports, the results here show that the business case for CCS in the European energy system to meet energy and climate objectives is even stronger when the heating, cooling and transport sectors are added to energy intensive industries and electricity generation.

CCS has a vital role in the energy mix if many Member States and other European countries are to meet their proposed own national plans. Not only does the absence of CCS appear to preclude the achievement of emissions reductions targets, the analysis has shown a value of CCS to the EU as a whole of approximately €1 trillion by 2050 alone, with the expectation that CCS has an even-greater value post-2050 as the EU moves towards a net zero economy and the importance of negative emissions technologies (such as BECCS) increases. The modeling estimates the post-2050 value of CCS in excess of €50 billion per annum.

A key conclusion from the modelling exercise is that Europe needs to shift the balance of its expenditure away from fuel imports towards infrastructure development. Not only does help to achieve energy and climate objectives in terms of costs and emissions reductions, it could also help to create and retain sustainable jobs, increase security of supply and unlock opportunities for innovation and technology exports.

The report once again reinforces the essential role that CCS is expected to play in reducing CO2 emissions from the energy intensive industries across Europe, unlocking a long-term, low emission future for cornerstone industries such as steel, cement and chemicals. The analysis demonstrates the underlying economic rationale for investment in CCS to support these industries in their transition to a low-carbon economy; highlighting the important role for EU institutions and Member States in providing the framework to enable investment in the CO2 transport and storage infrastructure that can, in turn, unlock investment and innovation in CO2 capture and CO2 utilisation.

The report highlights the large growth in electricity demand that can be expected to come with electrification of heat and transport, but shows that this can be accommodated with a portfolio mix of renewables, nuclear and indigenous fuels with CCS. Furthermore, the availability of CCS can greatly reduce the total installed capacity required to meet future demand, both directly and indirectly.

The tighter CO2 limits discussed at the Paris COP require not just strong reductions in CO2 emissions; they necessitate negative emissions from the use of Biomass with CCS to remove CO2 from the atmosphere. ZEP's analysis here shows the value of negative CO2 emissions to achieving the EU's 2050 energy and climate goals; a role expected to increase in importance over time, both environmentally and economically. But any application of CCS – be it to power, industry, transport or heat sectors; be it direct or indirect; whether it is for negative emissions or not – first requires the availability of CO2 transport and storage infrastructure.

Following on from this report, ZEP recommends that polices and incentives should be designed at the nation state level to suit the local situation, and effectively facilitate regulated infrastructure for transport and storage of CO2.

A collaborative approach to infrastructure development – as suggested in ZEP's business case for storage report and further elaborated upon in its work on an Executable Plan for CCS for Europe – can help to unlock industrial investment decisions to reduce the emissions of CO2 from existing industrial sources and help to encourage inward investment in flagship, low-carbon regions.

More information

www.zeroemissionsplatform.eu

Key conclusions

For the fifth iteration of ZEP's Market Economics analysis, a new energy systems model was developed to encompass the whole energy system, including the heat, power, industrial and transport sectors. A total of 10 countries were modelled and results were drawn for both the individual countries and the 10 countries combined. The conclusion are:

• Across the European energy system, ZEP's modeling shows that the value CCS to the EU could be in excess of €1 trillion by 2050 alone.

• In the longer term, and as European countries move towards net zero emissions, the value of CCS is expected to further increase to more than €50 billion per annum.

• When CCS was not available to the model, total emissions in 2050 from the 10 countries modelled were found to be 3 to 4 times higher.

• Combined Heat and Power/District Heating is a low hanging fruit is the first and fastest way to increase supply side energy efficiency in Europe. It is selected most in northern and eastern countries where the climate and social traditions make CHP appropriate. In the longer term, there is economic and climatic value in combining CHP with CCS to yield further emissions reductions.

• Increased electrification can avoid distributed emissions and plays a vital role in emissions reduction from transport and heating and cooling. In certain circumstances, hydrogen also has the potential to be a key low carbon energy vector for reducing emissions in these sectors. In either scenario, CCS has been shown to have an important role to play.

• The future of energy intensive industries including cement, steel and oil and gas is highly dependent on CCS. For these sectors and many more, CCS is critical to retaining high-skilled jobs and boosting economic activity across EU Member States in an increasingly carbon-constrained world.

• The modelling demonstrates the high value add that can be achieved by shifting spending on energy away from imported fuels to investments in infrastructure, renewables and local indigenous fuels. This can have important co-benefits for energy security objectives, employment and sustainable industrial activity.

• Infrastructure investments are needed now to achieve the lowest emissions and lowest costs out to 2050. CCS infrastructure can unlock emissions reductions across the whole energy system with significant potential for cost reductions through cross-border initiatives and sharing of infrastructure.

• The countries studied are different and the model shows that local solutions and indigenous fuels, as well as weather patterns, should be taken into account when countries develop their Integrated National Energy and Climate Plans under the proposed EU Energy Union governance arrangements.

• CCS facilitates the integration of renewables with near zero CO2 backup power. Across the various scenarios, EU targets for renewables deployment (20% in 2020 and 27% by 2030) are expected to be achieved and, by 2050, renewables are expected to represent more than 50% of the energy system on an energy usage basis for cases both with and without CCS.

• Biomass is shown to be an important component of the future European system because of its potential role in reducing CO2 emissions from the heating sector. Biomass as a renewable energy is modelled to contribute the largest energy content of the total energy system, approximately equal to ambient heat. Sustainable use of Biomass/Biofuels combined with CCS is needed for negative CO2 emissions, which are essential to realise the "well below 2 degrees" vision of the Paris Agreement.

ZEP report on European Parliamentary Hearing on CCS

Through a series of three panel discussions, the event on 23rd March examined the urgent and important role of CCS in reducing CO2 emissions from Europe's energy intensive industries in line with deep decarbonisation targets, safeguarding jobs in these industries, and the existing barriers, and potential opportunities to CCS deployment.

By the Zero Emissions Platform

MEP Lambert Van Nistelrooij (EPP, NL) hosted the European Parliamentary Hearing on CCS: Unlocking Clean Growth through Carbon Capture and Storage, in partnership with the Zero Emissions Technology and Innovation Platform (ZEP), Gassnova, the Norwegian Ministry for Petroleum and Energy, and the International Energy Agency (IEA).

In her opening remarks, moderator Sandrine Dixson-Declève noted the increasing profile of CCS in Europe, particularly in light of developments in Norway and the Netherlands, remarking that Europe is now paying close attention to CCS. This was followed by a welcome from MEP Van Nistelrooij, who reaffirmed his commitment to pushing the CCS agenda in Parliament, and noted his previous activities in this area, including a visit to Canada's Boundary Dam project in 2016.

He reiterated that further innovation alone will not deliver CCS, which requires greater ambition at the political level. When asked about the level of CCS awareness within Parliament, considering the last debate took place four years ago, Lambert Van Nistelrooij responded that the delivery of powerful examples, such as the ROAD project, are now needed to raise the profile of CCS.

The first panel discussion examined the topic: 'Reducing CO2 emissions in Europe: what is the role for CCS?' Sandrine Dixson-Declève introduced the discussion, commenting on the importance of adopting technology-neutral policies and asking speakers where they believed CCS featured in the overall picture of reducing Europe's CO2 emissions.

Trude Sundset, Chief Executive of Gassnova, responded that in Norway attitudes have changed post-Paris Agreement, with renewed interest and a sense of urgency in dealing with

On the 23rd March, ZEP held a European Parliamentary Hearing on CCS "Unlocking Clean Growth through Carbon Capture and Storage"

CO2 emissions reduction, adding that there is now understanding amongst politicians and the public that addressing this issue will require 'all the tools in the toolbox'. She remarked that everything was in place to deliver the Norwegian CCS projects by 2022, leaving only the spending of allocated funding.

Kamel Ben Naceur, Director at the International Energy Agency (IEA), stated that the IEA has been developing 2 °C scenarios for a decade, always maintaining technological neutrality, and concluding that "about 15% of emissions could be abated with CCS between now and 2050 in a 2 degrees scenario … without it the whole system would be extremely expensive." He added that there was already the political will, but for this to be achieved the development of CO2 transport infrastructure must now be progressed.

Leading on from this point Charles Soothill, Vice Chair of ZEP, introduced ZEP's flagship report: CCS and Europe's Contribution to the Paris Agreement. The report was launched that day and estimates that the cost of meeting the Paris Agreement could be up to €1 trillion cheaper for Europe with CCS by 2050, with a further saving of €50 billion for each following year.

The report demonstrates that to achieve the ambitions of the Paris Agreement, CCS must be part of the picture, and could also facilitate greater integration of renewables by allowing for the best-use of wind and solar. Jonas

Helseth, Director of Bellona Europa, commented that this work clearly demonstrates the business case for CCS, adding that conversations around CCS need to move away from cost and start talking about finance, utilising a large infrastructure approach and allowing costs to be reduced through sharing.

The second panel examined the question: Can CCS help to unlock clean growth and sustainable jobs? Rob van der Meer, Director at HeidelbergCement, opened the discussions by noting the current economic importance of energy intensive industries, with 1 million European jobs associated with the cement industry alone. He stated that the retention of these jobs will be closely tied to investment in emissions reduction options for European industries.

Allard Castelein, President and Chief Executive of the Port of Rotterdam Authority, followed on from this point, noting that as Europe's largest port, and employer of over 100,000 people, it was vital that industries be supported to reduce emissions, allowing them to focus on core activities and growth. To achieve this, the Port is progressing a number of initiatives, which aim to establish a coalition of the willing for industrial decarbonisation and create the backbones of the infrastructure needed to capture both heat and CO_2.

The event was hosted by MEP Lambert Van Nistelrooij (EPP, NL), and was co-hosted by Gassnova, the Norwegian Ministry for Petroleum and Energy, and the International Energy Agency (IEA)

Sarah Tennison, Technology and Innovation Manager at Tees Valley Combined Authority, built on the idea of 'industrial green zones', adding that CCS is seen as the only solution for the industries in the Tees Valley region, where much of the emissions produced are inherent to industrial processes, and referring to a recent study estimating this could be achieved at a cost of €67 per tonne of CO_2 abated.

When later asked if she believed the CCS narrative had been too technology focused in the past, Sarah Tennison responded that although important to reinforce the point that the technology is viable, jobs should also form part of the discussion, and that perhaps in the past this had not been heard loudly enough.

Benjamin Denis, Senior Advisor for the European Trade Union Congress followed this point by stating that the jobs narrative now needed to extend beyond the short to medium term; stressing that CCS could both maintain existing jobs in Europe and also create new ones, through attracting inward investment. He noted that for the European industry to remain competitive in the future progress on CCS needs to be accelerated now.

In introducing the final panel, MEP Lambert Van Nistelrooij commented that discussions around CCS 'should not stick to the old story', and should focus on a regional and local approach, adding that there will be no progress without local commitment.

This panel examined the question: What can the EU and Member States do to accelerate progress? Ingvil Tybring-Gjedde, State Secretary for the Norwegian Ministry of Petroleum and Energy, began discussions by emphasising the importance of learning from both past failures and operational experience, such as that of the Norwegian petroleum industry in the North Sea Basin.

When asked if she believed CCS could be progressed in other countries with state-owned enterprises, she responded that it will be important that governments do not interfere in the business models. Later the Secretary of State stressed that the Norwegian Government wishes to share what they have learnt in order to progress CCS deployment in the rest of Europe.

Mechthild Wörsdörfer, Director Energy Policy in DG Energy at the European Commission, stated that although the EU executive has 'always been positive and friendly towards CCS', 'so far our EU efforts have not been matched as much as we would have wished by member states'. She added that further EU engagement would focus on clusters of carbon emissions and Europe's energy-intensive industries.

Graeme Sweeney, Chairman of the ZEP Advisory Council, concluded the event's discussions by stating that he was 'cautiously optimistic' about the progress of CCS in Europe, with the narrative now making sense at a local level, as was demonstrated by the Rotterdam and Tees Valley regions.

He noted the importance of ongoing projects, such as the European Commission's Strategic Energy Technology Plan for CCUS and the current application process for Projects of Common Interest, in progressing CCS in Europe, adding that for this to be successful a regional focus must be adopted and be driven from the 'bottom-up'. He concluded that the CCS technology is ready but infrastructure development is crucial and must be progressed now.

More information

www.zeroemissionsplatform.eu

setis.ec.europa.eu

New technology holds key to reaching carbon emissions targets

A new carbon capture and exchange technology offers the potential to convert CO2 from flue gas into valuable chemicals at a cost of £47 per tonne of CO2 abated.

By Mark Stacey, MD of Crown International

The Climate Change Act (2008) set out ambitious plans to reduce carbon emissions in the UK by at least 80% from 1990 levels by 2050.

With five-yearly carbon budgets in place to support this transition, the Government recently (June 2016) set out ambitious new targets for the fifth budget period to reduce emissions by 57% compared to 1990 levels by 2030.

So, with figures from the London School of Economics suggesting that electricity generation currently accounts for over 25% of the UK's carbon emissions, it's clear that achieving such targets will require a step change across the energy industry to deliver.

Most recently, the industry has looked towards renewable energy production to replace traditional electricity production but, what if the carbon produced by the existing generation processes could be captured and neutralised or, better still, turned into useful by-products that could generate new value streams or potential alternative sources of energy?

Of course, carbon capture and exchange technologies already exist but, to date, these have proven to be too expensive to develop, build and operate to deliver a viable solution for the industry.

Four years ago, we were approached by a fellow Bristol-based company that was looking to develop an exciting new technology to overcome these challenges.

They had the technology, we had the manufacturing expertise, and a partnership was born that today, following two successful pilot projects for the Department of Energy & Climate Change (DECC), has demonstrated not only that the technology works, but also that it delivers in both environmental and financial terms sufficiently to make it an attractive option for the industry.

This new carbon capture and exchange technology uses flue gas carbon dioxide as a feedstock for conversion into a range of valuable commodities, including formates and industrial alcohols.

Figures from the two DECC trials suggest that it not only captures 90% of CO2 at 99% purity, but at a net present value (NPV - the present value of a sum of money, in contrast to some future value it will have when it has been invested at compound interest) of just £47 per tonne of CO2 abated. This compares to up to £75 per tonne for existing technologies.

Inside the carbon capture and exchange cell: the technology is modular by design, allowing it to be easily retrofitted onto existing power stations and scaled up or down

So how does the process work?

As you'd expect from the name, it's a two-stage carbon capture and exchange process.

In stage one, the flue gas is captured from the power plant's flue stack at temperatures up to 270 degrees C. It is then cooled via a bespoke Condensing Economiser (CE), which recovers heat and water and also acts as the input gas monitoring point. From here, the gas moves into a wash column, where a continually circulating metal ion solution acts as the gas capture and carrying medium, removing and converting or destroying any Nitrous Oxide (NOx) and Sulphur Oxide (SOx) present.

Once this process is complete, the conversion process can get underway.

The remaining carbon dioxide gas flows into a second stage wash column where the gas is captured and separated. It then undergoes further processing via a patented methodology to be converted into High Grade Hydro-Carbon gas and/or by-products for on-site reuse or sale. Opportunities exist to convert the output to harmless carbonates and bi-carbonates for direct safe deposit into the sea or into a diverse set of products including but not limited to formic acid, ethylene, methanol, syngas and, with additional feed materials – sulphuric acid. The remaining remediated cooled flue gas is then emitted from the wash column stack (which also acts as the output gas monitoring point). The process does not require elevated temperatures and pressures, nor does it produce any waste products that require disposal.

Where the technology really scores is that it uses a modular design, allowing it to be easily retrofitted onto existing power stations and scaled up or down. It was originally developed to suit industrial locations generating anywhere between five and 100 Ktonnes of CO2 a year, where other technologies are not economically viable.

From design to production, it takes only one to two years to install, meaning operators can begin to see a return on the their investment within just one year. Combine this with the fact that independent consultants have assessed the technology as offering operating cost reductions of between £840,000 (v. Advanced Amine Processes) and £1,470,000 (v. Monoethanolamine); Capex savings of £855,000 NPV; and likely upward carbon levy pressures creating a pressing need for savings, and the financial incentives for adoption are clear. That's even before a projected value stream of around £22 million per year for the carbon captured and converted is taken into account.

DECC case studies that created and proved the concept

Carbon capture

The first DECC project was a three-year Carbon Capture project, to deliver a cost/tonne of CO2 abated significantly lower than current carbon remediation technologies – principally Carbon Capture & Storage (CCS)/Amine-based processes. The project was hosted and developed on a COHMA Tier 1 site in South Wales. The new technology successfully abated 95% of the CO2 captured from a natural gas boiler-generated flue gas stream using the approximate 10KtCO2 per annum capture capacity equipment.

Another essential component of this project was the need to prove the long-term performance characteristics of the electrochemical cells in removing near 100% of the CO2 from fossil fuel flue gas emissions. This is important as fouling and mineral deposition in the electrochemical cells have traditionally been a stumbling block to developing the technology - an issue we needed to prove could be overcome using this new proprietary technology.

Carbon conversion

The second DECC project was a nine-month R&D project to convert carbon dioxide into high grade formic acid, using a process and at a cost that would make the technology commercially viable. Our goal was to develop, build and demonstrate a complete system that could utilise captured CO2 and, rather than consider it a waste product, create a viable revenue stream while maintaining a low carbon footprint for the capture and utilisation of CO2. In the DECC project, the system took a CO2 feed from pressurised cylinders but, in a deployment situation, it would interface directly with the carbon capture system to utilise the captured flue gas CO2.

The pilot plant demonstrated the ability to convert 100% of CO2 into formic acid. It also demonstrated a production capacity with a product value stream of over £8m per annum (for this single site), at significantly lower cost than current methods of production.

By combining these two projects, we developed the complete carbon capture and exchange technology, using flue gas carbon dioxide as a feedstock for conversion into a range of valuable commodity products, such as formates and industrial alcohols.

Creating value streams - the formic acid market

As part of the second DECC project, we carried out a detailed review of the global formic acid market to evaluate the potential value of this bi-product revenue stream (just one of many possible bi-products).

Our findings suggested that, while concentration within the industry is relatively high (the industry's top 15 producers account for 88% of industry production), production is forecast to grow at a compound annual growth rate of 1.34% from 2017 to 2022, in order to keep pace with increasing demand.

Margins in the industry (based on factory gate prices and input costs) are typically tight at around 14%, reflecting the high cost base of existing methods of production, but a significant component of this is the reliance on feedstock chemicals as part of the process.

There is therefore a real opportunity for disruptive technologies that can deliver relatively low set-up and operating costs while meeting the relevant compliance regulations, creating a valuable potential revenue stream for anyone using our new technology.

Next steps

Most importantly, the role adopting such technology could play in helping the UK reach its carbon emission targets should not be underestimated.

The DECC projects demonstrated that the process could simultaneously capture in excess of 95% of CO2 and 85% of the NOx in the pilot sites' flue gas emissions.

By treating carbon as a raw material feedstock for the production of valuable formates, rather than as an expensive waste material to be disposed of at high financial and environmental cost, the process creates a value stream from the by-products that makes taking this more environmentally-friendly approach commercially appealing.

Re-using by-products, rather than releasing them into the atmosphere, has the potential to significantly reduce CO2 emissions across the energy generation sector. It's a promising and versatile process that produces a variety of commercial organic compounds, depending on the individual set-up of the conversion cell.

If, as the LSE report states, the electricity sector is responsible for 25% of current emissions, that would be a significant step forward on its own. But, with the energy generation and industrial sectors combined being responsible for 42% of UK CO2 emissions, adopting this technology across both sectors could represent the step-change we are looking for.

The key to success of any carbon capture technology lies in making sure it is commercially attractive enough for energy companies to invest time and resources in adopting. The results of the DECC trials suggest the benefits of this new technology are clear.

More information

www.crown-international.co.uk

UK Public Accounts Committee says act now on CCS to save billions

The UK Public Accounts Committee report warns that halting CCS deployment means taxpayers will have to pay billions more to meet targets.

Despite spending £168 million, the Department for Business, Energy and Industrial Strategy has failed to support the construction of the UK's first large-scale carbon capture and storage (CCS) projects, says the report.

After its first competition for support ended in 2011, the Department launched its second competition without being clear with HM Treasury on the support that would be available to successful CCS projects through bill payer-funded contracts for difference once they were up and running, or ensuring that its proposed risk allocation was viable for developers.

These design weaknesses contributed to the Treasury's decision, as part of the 2015 Spending Review, to bring the competition to an early end by withdrawing the £1 billion capital grant it had previously made available to contribute to the projects' construction costs.

The Peterhead project was in the running for the UK's CCS competition before it was cancelled

This was the latest in a series of decisions that indicate the Treasury is having undue influence on the government's energy policy.

Halting CCS's deployment means that the UK will have to pay billions of pounds more to meet its decarbonisation targets, has missed opportunities to be at the forefront of a growing global industry, and has damaged investors' confidence in working with the government on CCS in the future.

"There is now a major gap in the government's decarbonisation plans, and we urge the Department to set out as soon as possible how this gap will be filled."

Conclusions and recommendations

1. After two competitions costing taxpayers £168 million, the UK is no closer to establishing CCS. The UK has now missed opportunities to be at the forefront of a growing global industry.

In 2012 the government launched a second competition for supporting CCS projects. The competition was cancelled in 2015 after Treasury decided, as part of the Spending Review, to withdraw the £1 billion of capital funding it had previously committed to the programme. The Department had spent £100 million of this on the second competition before it ended, having already spent £68 million on the first competition that was cancelled in 2011.

As part of the competition process, developers and government gained some technical and commercial knowledge. But much of this knowledge is project-specific and will be lost, unless the same projects are resurrected. Since 2007 when the first competition was launched, other countries have been developing CCS projects successfully, and more projects are due to come online in 2017. There is a risk the UK will now miss out on the chance to lead the way in this technology, much as it did with wind power in the 1980s.

Recommendation: The Department should set out in its Industrial Strategy the role that CCS can play, recognising the potential economic value of being a world leader in a globally expanding technology.

2. It is now highly likely the UK will have to pay billions of pounds more to meet its decarbonisation targets.

In 2015, the Department's own calculations showed that it would cost the UK £30 billion more to meet the 2050 emissions target without CCS in the power sector. The Committee on Climate Change recently reported that the total costs to the UK of inaction on CCS in power, industry, heat and transport would be higher still: £1 billion to £2 billion per year in the 2020s, rising to between £4 billion and £5 billion per year in the 2040s, if the UK is to achieve its carbon emissions targets.

However, neither the Department nor the Treasury quantified the impact of the delays to deploying CCS that would inevitably result from cancelling the second competition.

Recommendation: By the end of 2017, the Department should quantify and publish the impact across the whole economy of delays to getting CCS up and running, and of it not being established at all.

3. Without CCS, there is a gap in the government's plans for achieving decarbonisation at least cost while ensuring a secure supply of electricity.

CCS was a key part of the government's Electricity Market Reform programme, along with renewables and nuclear power, for establishing a low-carbon power sector. The Department expected its competition to lead to the deployment of CCS technology at scale. This would allow low-carbon, flexible gas power to complement intermittent renewables and inflexible nuclear power in a diversified generating mix.

It also expected the competition to establish the infrastructure and commercial arrangements that would support decarbonisation of heavy industry, heat and transport in future decades. The Department has not yet set out its next set of detailed plans for decarbonising the economy and the role it expects CCS to play, saying it will do this in its delayed Emissions Reduction Plan by the end of this year.

Recommendation: The Department's Emissions Reduction Plan should set out a clear, joined-up strategy for deploying CCS in the sectors where it is needed to achieve decarbonisation at least cost.

4. Once again, the Department did not allocate the risks appropriately between the government and developers, meaning at least one of the two projects was likely to have been unviable.

The Department made good progress compared to its first competition in understanding the risks in deploying the first CCS projects. However, it is unclear whether the Department tested at the outset of the competition which risks the private sector could feasibly bear. Instead, the Department opted for its prevailing approach to energy policy, of shifting risks as far as possible to the private sector, without properly considering the merits of alternative approaches.

In particular, it asked developers to bear the 'full-chain' risk, which created problems for sharing risks between investors in different parts of a CCS project, making one of the competition projects unviable. It remains to be seen whether the Department will have sufficient commercial skills to avoid this problem repeating in the future, particularly following the recent machinery of government changes.

Recommendation: When designing future energy policies, the Department should assess and explain the viability of different options for allocating risks between the government and developers.

5. Establishing CCS is now likely to cost taxpayers or billpayers more in the future because of the damage to investors' confidence caused by aborting two competitions.

In the most recent competition, matters were made worse by the timing of the cancellation: the Treasury withdrew the funding just before developers were due to submit their final bids for government support. The Department expected at least one of the bids would have met its criteria for support and been a viable project.

Throughout this Parliament, several energy policy decisions have similarly damaged investors' confidence. These include cuts to demand-led green tariffs and sudden changes to low carbon support prompted by the failure to forecast an overspend on the Levy Control Framework. Investors are now likely to require greater incentives to engage with the government again on CCS and other low-carbon projects, which will mean higher costs.

Recommendation: HM Treasury and the Department should ensure they fully agree on the Emissions Reduction Plan from the outset, and quantify the negative impact on investors' confidence before making any sudden changes.

6. The Treasury seems to be determining energy policy, often with detrimental impacts on the government's long-term energy objectives.

The Treasury did not appear committed to CCS from the outset, as demonstrated by the fact it did not make clear the total funding available to the projects, through consumer-funded contracts for difference. The Treasury's decision to withdraw funding was based in part on it expecting the projects to require a 'strike price' of £170 per megawatt hour, which it considered to be too expensive compared to other low-carbon power generation technologies.

But this measure neglects the potential long-term benefits of the projects, such as building infrastructure for subsequent facilities to share and the value of CCS to other sectors of the economy, or the additional costs that would result from any delay to CCS deployment. This is reminiscent of other energy policies which HM Treasury has cut across in recent years, driven by short-term considerations. We are concerned that the Treasury has had undue influence on energy policy in recent years.

Recommendation: Given our concerns about HM Treasury's undue influence on energy policy, the Department and HM Treasury, as part of their work on the replacement for the Levy Control Framework, should agree a way of appraising the costs and benefits of energy policies, which reflects the potential impact across sectors and over the long term, rather than relying on the strike price

The Carbon Capture and Storage Association (CCSA) welcomed the report, saying that it made a number of recommendations; in particular emphasising the need for the Department to set out a "clear, joined-up strategy for deploying CCS in the sectors where it is needed to achieve decarbonisation at least cost".

Dr. Luke Warren, Chief Executive of the CCSA, commented, "The report out today represents yet another voice highlighting the incredible importance of CCS for the UK. Critically the Committee found that developing CCS could save the UK many 10s of billions of pounds, making the UK economy more competitive whilst supporting the low-carbon industrial regions of the future."

"It is clear that developing CCS is in the national interest, and whichever party is in power after the 8th June has a key early opportunity to act on the Committee's findings and release the Emissions Reduction Plan, setting out a fresh, ambitious approach to CCS that learns the lessons of the past."

"The Committee has highlighted the benefits of CCS to multiple sectors of the UK's economy, including heavy industry, heat, transport and power, demonstrating that CCS is integral to a new sustainable Industrial Strategy."

"We are ready to work with the new Government to develop this Strategy and ensure the UK can play its role in the significant global CCS market that is already emerging".

More information

www.parliament.uk

Scottish Economy could benefit from CO2 re-use

A report published by the University of Sheffield outlines how the re-use of carbon dioxide could help Scotland shift to a more sustainable and circular economy.

The report titled 'Actions required to develop a roadmap towards a Carbon Dioxide Utilisation Strategy for Scotland (2016)', was commissioned by Scottish Enterprise to provide an overview of whether the re-use of CO2 could hold potential for Scotland and to recommend a number of actions to develop the sector.

The CO2 emissions from Scotland are predominantly from the use of fossil fuels from industrial sectors such as Oil and Gas, Paper and Wood and energy from waste, says the report. In previous years these large emitters produced 10 million tonnes per year, of which 4.3 million tonnes were identified in the report as having potential for capture.

Type of CO_2 resource	Tonnage of CO_2 per annum	Could connect to CCS CO_2-EOR infrastructure?	Suggested target use for CO_2
The top 12 largest emitters within 50 road miles of Grangemouth	3.1 million (0.5 million is biomass)	YES	CCS, CO_2-EOR, CO_2 derived fuels, chemical feedstocks, specialist chemicals
Seven bioenergy locations greater than 50 road miles away from Grangemouth	0.7 million	NO (Tanker option)	CO_2 derived fuels, inorganic fertiliser
Biogenic fermentation CO_2 from distillery sector	0.5 million	NO (Tanker option)	Inorganic fertiliser
Smaller point sources in island, rural and agricultural communities	?	NO	CO_2 derived fuels, inorganic fertiliser
Smaller industrial point sources	?	NO	Mineralised wastes
Total	4.3 million		

Scotland's CO2 resources in tonnes per annum and suggested target uses (from "Actions required to develop a roadmap towards a Carbon Dioxide Utilisation Strategy for Scotland (2016)")

Interest also lies with significant levels of biogenic CO2 which is released as a by-product of the fermentation of malted barley in the Scotch Whisky sector - estimated to be in the region of 500,000 tonnes each year.

The study suggests that the Grangemouth region is the location most suited to create a CO2 utilisation hub on a large industrial scale. It is the largest manufacturing region in Scotland and host to ten of the largest CO2 emitters. However, the report makes clear that the development of the CO2 re-use sector should not be seen as a substitute for the development of a Carbon Capture and Storage sector.

The principal author of the study Dr Grant Wilson from the Department of Chemical and Biological Engineering at the University of Sheffield commented, "For most countries and policy makers around the world, carbon dioxide is viewed only as a problem that needs to be controlled. However, with the ongoing development of novel technologies and processes for the re-use of CO2 it is also starting to be viewed as a potential resource that could be exploited."

"This report identifies that Scotland has a unique combination of key advantages and a real opportunity to explore and develop its carbon dioxide resources. It is also important to note that it is one of the first countries in the world to even consider the creation of a roadmap for the re-use of its carbon dioxide, in essence to view CO2 as a resource."

"This provides a very powerful message in terms of Scotland's belief in considering all available options to decouple its future economic activity from emissions."

The report presented a case study with a potential to be scaled up to a £500m market, sustaining 600 new jobs and a new Scottish export by utilising innovative UK technology to convert the estimated 500,000 tonnes of distillery sector (biogenic CO2) into inorganic fertiliser.

The development of this technology could be of interest to Scotland as a way to help decarbonise part of the agricultural sector through the introduction of inorganic fertiliser that is not derived from fossil fuels. The Scottish Government recently published their latest Climate Change Plan and Energy Strategy for consultation, which mentions carbon dioxide re-use and carbon capture and storage as areas of potential development.

Although the University of Sheffield report found that Scotland holds a number of key advantages to develop a carbon dioxide re-use sector, there are several areas of uncertainty that would benefit from more detailed analysis.

Key findings

• Scotland has:

- a significant source of high quality biogenic CO2 from the distillery and bioenergy sectors
- vibrant CO2 utilisation, hydrogen and CCS academic communities
- a significant renewable energy resource

• There are near-term opportunities for Scotland to consider for CO2 utilisation, the two of greatest interest are the production of inorganic fertiliser using CO2 as a feedstock, and the mineralisation of certain industrial waste streams using CO2. Both of these have UK based technology providers that have already built pilot and demonstration scale facilities, and are looking for further opportunities.

• Based on DECC's emission projections for IPCC reporting purposes, it can be assumed that the CO2 resource in Scotland will remain relatively stable (or even grow) over the next 20 years.

• Data for larger scale CO2 emitters is readily accessible through the Scottish Pollution Release Inventory database, but there are at present only limited publicly available data for the current market demand for CO2 in Scotland or the UK as a whole

• Scottish demand for CO2 is estimated at 200,000 tonnes per annum (a tenth of the estimated 2 million tonnes per annum UK-wide), although this is subject to significant uncertainty.

• Current CO2 demands in the UK are varied and include: Food & Beverage, Chemicals, Pharmaceuticals & Petroleum Industry, Metals Industry, Manufacturing & Construction,

Rubber and Plastics Industry, Health Care, and the Nuclear Sector.

• Innovation in technology and market changes that lead to the development of new cost effective carbon based products may in time result in a closer match between emissions and the demand from CO2 utilisation.

• Appreciating more about the subjective factors likely to shape perceptions of risk relating to new industrial technologies, like CO2 utilisation, is important to their successful promotion; as is the selection of trusted communicators to convey information about proposed projects and plans.

Overall recommendations

The overall recommendation of the report is that Scottish Enterprise should prioritise the development of a roadmap for CO2 utilisation in Scotland to help accelerate its development and deployment.

The creation of a roadmap to develop a strategy for CO2 utilisation in Scotland requires the preparation of a greater depth of evidence than this report was able to undertake. Many of the recommended actions therefore are aimed at commissioning further studies to provide this underpinning evidence in greater detail to allow policy options to be better understood.

Near-term actions to develop a roadmap are:

• Facilitate a medium-term field study of the use of cellulosic carbonate fertilisers on microbial activity on a range of soils in Scotland, how this impacts the nitrogen use efficiency and release of N2O and how this impacts the retention of organic matter in soils under a range of differing conditions. This should have a particular focus on the soils typically used to grow spring barley for the Whisky industry.

• A demonstration scale CO2 utilisation project competition should be promoted with Innovate UK and DECC to provide significant levels of investment to accelerate CO2 utilisation in the food and drink and agricultural sector.

• Commission further research (with the CCS sector) to identify in greater detail the medium and long-term opportunities for Grangemouth in CO2 utilisation including EOR, Industrial Biotechnology, low carbon manufacturing and as a hydrogen hub.

In order to build a better evidence base, the report also recommends a number of additional, more detailed projects. The information developed from these will enable Scottish Enterprise to take a more evidenced based approach to the formation of a CO2 Utilisation Roadmap.

More information

Download the report from:

www.evaluationsonline.org.uk
www.sheffield.ac.uk

Best ways to remove greenhouse gases to be investigated

An Imperial-led study will focus on how the world can meet climate change targets by removing greenhouse gases from the atmosphere.
By Hayley Dunning, Imperial College

The project is part of a new £8.6m UK research programme on greenhouse gas removal announced this week.

The UK has committed to the 2015 Paris Agreement, which seeks to keep global temperature rise below 2°C pre-industrial levels. As well as reducing the amount of greenhouse gases being emitted, actively removing them from the atmosphere could help reach this target.

There is intensive research into methods for greenhouse gas removal, but questions remain around their feasibility, as well impacts on society and public attitudes. To help answer these questions, the £8.6 million research programme will evaluate the potential and wider implications of a variety of options.

The programme is jointly funded by NERC, the Economic and Social Research Council (ESRC), the Engineering and Physical Sciences Research Council (EPSRC) and the Department for Business, Energy & Industrial Strategy (BEIS). The Met Office and the Science and Technology Facilities Council (STFC) are providing in-kind support.

Dr Niall Mac Dowell, from the Centre for Environmental Policy at Imperial, will lead a £2 million project that will investigate the options for greenhouse gas removal in different regions, and how these regions can work together to meet global climate goals. Hayley Dunning talked to him about his vision for the project.

What are the current options for removing greenhouse gases?

One of the most discussed option is bio-energy with carbon capture and storage (BECCS). This involves burning plants for fuel and then capturing the carbon emissions from this process and permanently storing them underground.

Plants draw carbon dioxide (CO2) from the atmosphere as they grow, so by burning them and storing the carbon that is emitted underground, we are removing greenhouse gasses from the atmosphere – creating negative emissions.

Alongside these technologies, removal of greenhouse gases from the atmosphere can be increased, for example by the direct capture of CO2 from the atmosphere, by planting trees as part of the process of reforestation.

Another option is increasing the natural process of weathering, where carbon dioxide in the atmosphere reacts with certain rocks on the surface. However, the available evidence prioritises BECCS as a key option.

What are some of the issues around using these technologies effectively?

BECCS is being demonstrated in the USA, most notably at the Illinois Industrial Carbon Capture and Storage Project which has recently started and is expected to remove one million tonnes of CO2 from the atmosphere per year. However, this is still small scale compared to what is required to achieve our climate change targets.

One thing that that is vital to accelerate large-scale adoption by countries would be for policy makers to explicitly value this service of atmospheric carbon dioxide removal. This would create a market incentive to develop the technology and its capacity.

What will you be doing in your project?

We will work to determine how BECCS can be used in sustainable ways tailored to each regional situation. For example, it is important where the biomass comes from – if biomass burned in the UK is grown on the other side of the planet, it won't be nearly as sustainable as if it were grown locally. Other factors which affect the sustainability, or otherwise, of biomass include the way in which it is cultivated, harvested and transported. Each of these elements is core to our study.

Different options will also work better in different places. Installation of BECCS plants might work well in the UK as we have ample space to store CO2 in the North Sea, but large-scale reforestation might be a better option where CO2 storage resources are limited, but there are good conditions for afforestation.

This feeds into questions about how international co-operation can reduce the cost of reaching global climate goals. At the moment, there are global climate goals and then each country works out an individual plan for their own targets. A better solution might be to exploit the technological options best suited for each region, so that the overall global goal is reached collaboratively.

We want to produce papers on regional options, roadmaps and opportunities for collaboration, but also to establish the UK as thought leaders in this area. Our work is intended to feed into the next Intergovernmental Panel on Climate Change (IPCC) reports, and be available to world leaders debating at the next COP climate conference.

Who are you working with?

Our project is in collaboration with organisations such as the International Institute for Applied Systems Analysis (IIASA) in Vienna and the International Energy Agency, universities such as MIT and Colorado School of Mines, industry partners, and the government Department for Business, Energy & Industrial Strategy.

More information

www.imperial.ac.uk/people/niall

ZEP - clean hydrogen with CCS for European energy transition

There is significant future potential for hydrogen, both clean and electrolysis-derived from renewable energy according to a report from the European Zero Emission Technology and Innovation Platform (ZEP). Clean hydrogen production with CCS is a proven technology with plants operating globally.

The European Zero Emissions Technology & Innovation Platform (ZEP) has launched a new report on the "Commercial Scale Feasibility of Clean Hydrogen".

The report concludes that clean hydrogen, produced from natural gas and fitted with CO2 capture and storage (CCS), can help decarbonise different sectors within the energy system and enable the shift to a low-carbon economy. Additionally, by locating hydrogen production and CCS facilities in sustainable industrial zones, the development of industrial CCS clusters that share CO2 transport and storage infrastructure can be boosted.

MEPs will exchange views on the newly-proposed Electricity Market Design in the European Parliament's Committee on Industry, Research and Energy (ITRE). One area for reform is the rising share of variable renewable energy in the electricity system. ZEP's report demonstrates the key role clean hydrogen equipped with CCS can play in providing reliable and clean base load power to realise Europe's renewable energy demand.

Commenting on the report, Dr. Graeme Sweeney, Chairman of ZEP, said, "More and more countries are recognising the potential for low-cost clean hydrogen to contribute to the decarbonisation of the energy system, including in the heat, power and transport sectors. Our analysis shows that hydrogen production fitted with CCS has lower costs today than electrolysis-derived hydrogen and could play a major role in kick-starting a European hydrogen economy."

"The technologies required to produce clean hydrogen from natural gas with CCS are available today and a number of projects are already operating at a commercial scale. To enable the wider deployment of this technology, Europe needs to invest in CO2 transport and storage infrastructure, as well as developing the necessary hydrogen infrastructure and adaptations at points of use."

"CCS is vital to achieving Europe's climate goals, providing the only decarbonisation option for most energy intensive industries and delivering significant benefits to society. We now need to move forward in building the cross-border CO2 infrastructure necessary to realise sustainable industrial zones and generate jobs across the European economy."

Recommendations

The report makes the following key recommendations:

• Identify policies and stable support mechanisms that could promote the production of clean hydrogen, for example EU RFD, and to create economically viable clean hydrogen projects.

• Encourage collaboration along the clean hydrogen value chain to promote new projects.

• Identify local clusters where synergies could be established between hydrogen production, hydrogen consumption, and CCS. First targets are intensive industrial areas like the industrial clusters of Antwerp, Rotterdam and Teesside, especially where hydrogen or CO2 networks exist.

• Investigate the role clean hydrogen could play in decarbonising the EU power sector, including assessment of the ability to balance intermittent renewable energy with hydrogen combustion in Combined Cycle Gas Turbines (CCGTs).

• Maximize cross-cutting opportunities with other world initiatives around low-carbon hydrogen (Japan, China), and other EU hydrogen initiatives.

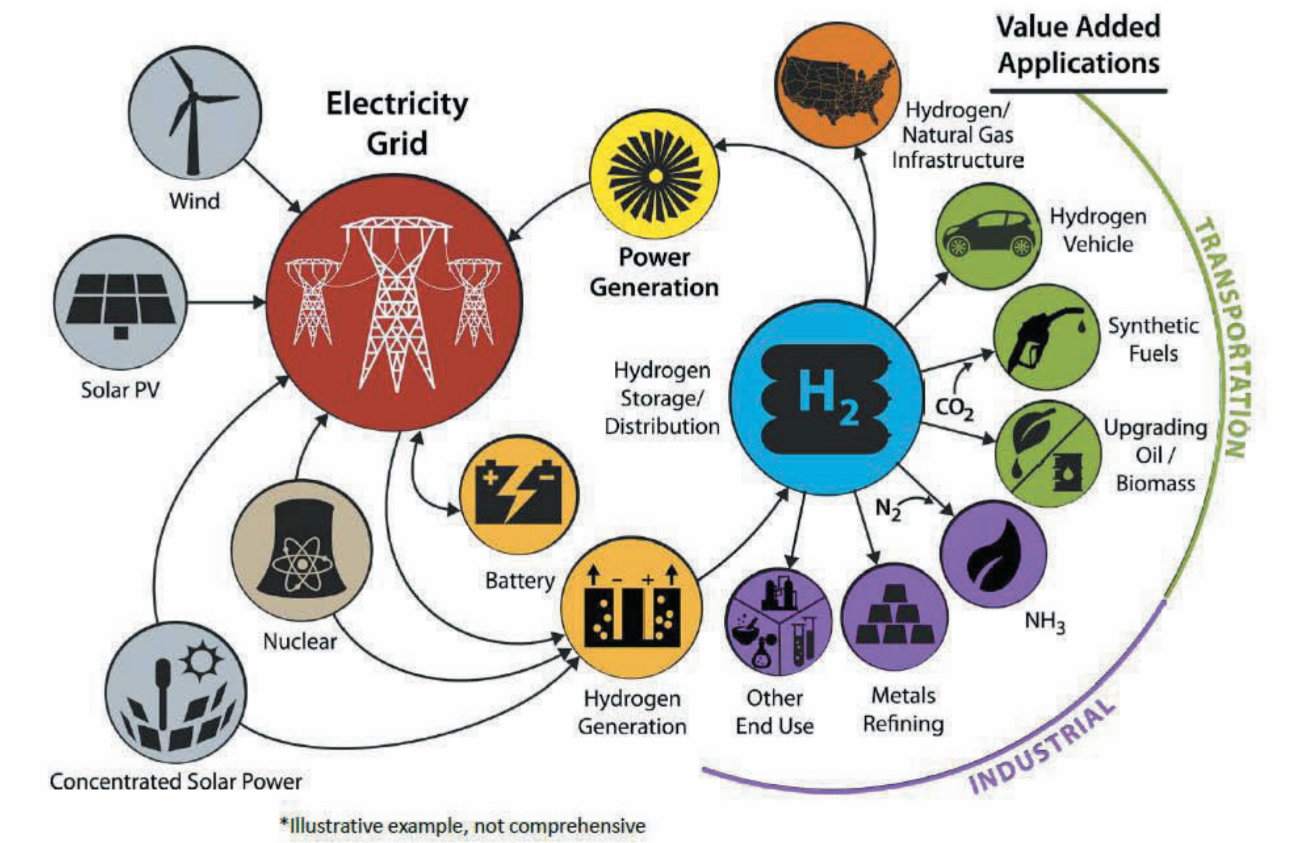
• Develop Least Cost Analysis (LCA) for clean and electrolysis-derived hydrogen from renewable energy value chains to assess the CO2 abatement potential.

• Support Research Development and Innovation (RD&I) for emerging clean hydrogen production technologies, with the potential to significantly reduce energy consumption and/or cost.

• Initiate the establishment of CO2 transport and storage infrastructure as soon as possible, recognising that the production of clean hydrogen can be one of the early suppliers of CO2 for geological storage, or for other uses, such as Enhanced Oil Recovery (EOR).

Summary

It is widely recognised that hydrogen has the potential to decarbonise a number of different industries and play a key role in the energy transition, says the report. Decarbonised hydrogen can be produced through the application of CCS on established natural gas to hy-



Conceptual H2 at scale energy system illustrating value added applications

drogen production units ("clean"/"low GHG emissions" hydrogen), or electrolysis using renewable energy sources. The report addresses the role of clean hydrogen and provides recommendations for its promotion.

Clean hydrogen currently has lower production costs than that of electrolysis-derived hydrogen from renewable energy (3-4 €/kg ex-works at 30-40 bar) and could be a key accelerator of the hydrogen economy. The report shows that, depending on location specifics, clean hydrogen production is currently achievable at the same cost as that projected for the renewables route for around 10 to 25 years.

Furthermore, hydrogen production equipped with CCS in industrial clusters - where several large users for hydrogen can co-exist - could also trigger the initiation of a CO2 transport and storage network.

There are multiple country roadmaps and studies that discuss the ability of hydrogen to decarbonise different industries. Current and future uses for decarbonised hydrogen range from mobility and synthetic fuels production, to power generation and fuel switching for domestic or industrial heating.

A recent study by CertifHy[1] predicts a potential hydrogen demand of up to 300 Million Tonnes Per Annum (mtpa) in 2050, increasing from the current demand of 65 mtpa (2% of primary energy). A US study[2] estimates that up to 10% of primary energy could come from hydrogen by 2050, and a study for Japan[3] predicts an increase up to 20% of primary energy from hydrogen, with significant volumes of hydrogen for mobility and power generation.

The UK Leeds City Gate H21 Project[4] assesses the feasibility to decarbonise the city of Leeds in Northern England through end use fuel switching and the replacement of natural gas used for domestic heating/use with hydrogen. The results show a peak hydrogen demand of 6.4 TWh per annum (corresponding to 0.2 mtpa H2) and a decarbonisation potential of approximately 1 mtpa CO2, using predominantly centralised hydrogen production from natural gas with CCS.

The technologies required to produce clean hydrogen from natural gas are available, with multiple projects already capturing CO2 from the hydrogen production process. Today the limiting factors are the availability of CO2 transport and storage infrastructure, demand for hydrogen as a clean fuel, and the requirement for substantial hydrogen infrastructure and adaptations at points of use.

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More information

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Projects and policy news

£8.6 million UK research programme on greenhouse gas removal

www.nerc.ac.uk

New research will investigate ways to remove greenhouse gases from the atmosphere to counteract global warming.

The UK is committed to the 2015 Paris Agreement to keep global temperature rise well below 2°C and pursue efforts to limit the temperature increase to 1·5°C above pre-industrial levels. Alongside significant emission reductions, large-scale removal of greenhouse gases from the atmosphere could considerably increase the likelihood of achieving this goal. Researchers know there are ways to approach this challenge but they have yet to be demonstrated on scales that are climatically-significant. Major questions remain around their feasibility, as well as impacts on society and public attitudes.

To help answer these questions, the £8·6 million Greenhouse Gas Removal Research Programme will evaluate the potential and wider implications of a variety of options. For example, researchers will investigate the potential for increasing carbon storage in agricultural soil and forests, and new ways to remove methane gas from the air on a local scale.

Other researchers will look into using waste materials from mining as a greenhouse gas removal technique, and explore how bioenergy crops could be used in power stations in combination with carbon capture and storage methods. Recognising that the UK alone cannot solve these problems, the research will address the political, socio-economic, technological and environmental issues concerning the potential for greenhouse gas removal on a global scale.

The programme is jointly funded by NERC, the Economic & Social Research Council (ESRC), the Engineering & Physical Sciences Research Council (EPSRC) and the Department for Business, Energy & Industrial Strategy (BEIS). The Met Office and the Science & Technology Facilities Council (STFC) are providing in-kind support.

Professor Tim Wheeler, Director for Science & Innovation at NERC, said, "The UK research community is addressing the challenges of climate change by providing world-leading, independent research to inform decision-making that will ensure future wellbeing and prosperity for the UK and internationally.

This new Greenhouse Gas Removal programme will shed light on how new approaches could be used to prevent the effects of climate change, alongside reducing emissions, aligning with the UK's commitment to the 2015 Paris Agreement. This multi-disciplinary research embodies the research councils' shared commitment to working together to provide vital answers to society's most pressing questions."

Four interdisciplinary, multi-institute consortium and seven topic-specific projects have been awarded funding. Around 100 researchers from 40 UK universities and partner organisations will be involved, and seven research studentships providing PhD training will also be supported.

UKCCSRC awarded funding until 2022

www.ukccsrc.ac.uk

The UK Carbon Capture and Storage Research Centre (UKCCSRC) has been awarded £6.1M by the Engineering and Physical Sciences Research Council (EPSRC) to continue its work for the next five years.

The goal for this next phase of the UKCCSRC is to ensure that Carbon Capture and Storage (CCS) will play an effective role in reducing net CO2 emissions while securing affordable and controllable electricity supplies, low carbon heat and competitive industries for the UK.

"Celia Yeung, of the EPSRC, said "The Research Councils UK (RCUK) Energy Programme recognises the significance of carbon capture and storage research within the energy landscape. The previous Centre has taken great strides over the last few years and has done well strengthening relationships within the carbon capture and storage community, engaging with industrial stakeholders and policy makers, and has pursued high quality, novel research within the research area.

The Engineering and Physical Sciences Research Council are fully supportive of carbon capture and storage research and has high hopes for the new Centre to continue developing and delivering an effective, high impact strategy for the UK."

The Centre's core activities are delivered by six of the UK's leading CCS institutions with complementary expertise: the British Geological Survey, the University of Cambridge, the University of Edinburgh, Imperial College London, the University of Nottingham, and the University of Sheffield. Investigators from other partner institutions bring specialist knowledge to the team: Cardiff University, Cranfield University, the University of Manchester, the University of Strathclyde and University College London.

Jon Gibbins, UKCCSRC Director, welcomed the Research Council's continued funding for carbon capture and storage, "CCS is an area where the UK has a long-term, strategic advantage and the new support will help make sure that our industries and consumers are able to see the benefits of this in the 2020s".

Stuart Haszeldine, UKCCSRC Deputy Director for Storage, said, "Strategic research investment by the EPSRC in direct reduction of carbon emissions, is welcome and essential. This will continue the development of geological carbon storage for the UK, where uniquely accessible natural assets are low in cost and high in reliability.

Removing carbon emissions from industry, heat, and transport will future-proof the UK economy against clean air taxes, will improve near-term health, and long-term competitiveness. Carbon management is an essential component of the sustainable energy transition, which cannot be achieved by renewables alone."

The UKCCSRC will continue to provide a focal point for coordinating national and international CCS research and to help give academic researchers access to the world-leading UKCCSRC Pilot-Scale Advanced CO2-Capture Technology (PACT) experimental facilities. In addition to its core research programme the centre will make £1.5M of funding available through open calls over the course of the grant for emerging research topics.

Over 250 early career researchers actively participate in the UKCCSRC's research and wider activities.

Gassnova awards contracts for CO2 studies

www.gassnova.no/en/ccs-projects

Norcem, Yara and the Klemetsrud facility have all been awarded financial support to continue their studies on carbon capture.

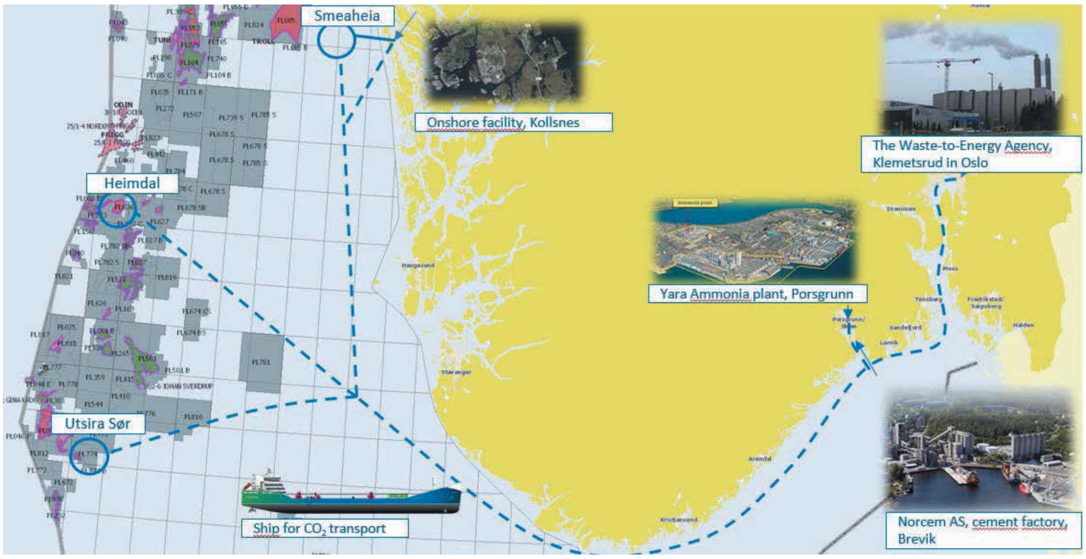

Illustration of CO2 chains assessed in the feasibility study

Feasibility studies from July 2016 show that carbon capture is technically possible at Norcem's cement factory in Brevik, at Yara's ammonia factory on Herøya and at the energy recovery plant at Klemetsrud. Going forward, the carbon capture facilities will planned in greater detail and with more accurate cost estimates. The basis for decisions should be complete by the autumn of 2018 so that any investment decisions can be taken by the Storting in the spring of 2019.

The plan is that carbon from one or more of these facilities will be transported by ship to intermediate storage. The carbon will subsequently be carried by pipeline to a store under the seabed in the North Sea. The Smeaheia area, to the east of the Troll gas field, and around 50 km offshore, has been chosen as the storage site. According to the schedule, a contract will be signed with an operator of the store before the summer. Statoil conducted the feasibility study that identified the Smeaheia area as an optimal storage site.

?'We are delighted that all three providers are going to remain on board. They represent three industries that will all need carbon capture and storage in future. This climate solution must be applied on a large scale globally if we are to achieve the targets set in the Paris agreement,' said Trude Sundset, CEO of Gassnova.

In addition, Gassnova is in negotiation with industrial actors regarding concept studies on storage. Contracts for carbon storage will be awarded later this spring. In 2017, 360 million NOK was awarded to work on full scale CCS projects.

"CCS is an important part of the Norwegian Government's climate policy," said the Norwegian Minister of Petroleum and Energy, Mr. Terje Søviknes (Progress Party). "The Government's ambition is to realize at least one full scale demonstration project for carbon capture and storage. The substantial interest from industry partners in the project is vital, and we are pleased that contracts are awarded to three industrial actors."

Comments from the project operators:

'The world is being overwhelmed by poor waste management. In future, we can see the potential for up to 140 million tonnes of carbon being generated from burning waste in Europe. Waste is second only to power generation in terms of being the most important area to get to grips with. At Klemetsrud, we will be able to remove around 90 per cent of carbon using CCS, and we have a lot of biological waste. This means that we are carbon negative. This is completely unique to our project,' says Pål Mikkelsen, CEO of Klemetsrudanlegget.

'Norcem has a vision that our concrete products will be carbon neutral by 2030. CCS is absolutely vital if we are ever going to achieve this. Taking this seriously is also important to us as an industry too. We have an opportunity to be at the top of the game at our factory in Brevik,' says Per Brevik of Norcem.

'Carbon capture can become an important part of the solution for cutting industrial emissions, and through this project we have been granted a unique opportunity to contribute to developing a full scale chain for carbon capture and storage. Now that the award has been made, we are looking forward to the continued dialogue with the authorities, and as an industrial operator in a global market, it will be crucial that we put in place a good incentive scheme for construction and operation,' says Petter Østbø, Executive Vice President Production at Yara.

Mongstad signs partnership deal for operations until 2020

www.tcmda.com

Gassnova, Statoil, Shell and Total today announce that they want to participate in the continuation of the test operations at TCM until 2020.

The prolonged operations, and the fact that Total has signed a MoU to join the partnership, confirms that TCM has become an international competence center for development of carbon capture (CCS) as a climate solution, said TCM.

The Norwegian Minister of Petroleum and Energy Terje Søviknes participated in a TCM event where the three owners signed an agreement on the continuation of the operation of TCM for another three years, and Total signed the MoU to enter into the partnership.

"TCM is a cornerstone in the government's strategy for CO2 management. We have now laid down a good foundation for further operations. I would like to congratulate Shell, Statoil and Gassnova with a job well done and wish Total welcome as a new owner," says MPE Terje Søviknes.

IPCC highlights carbon capture and storage (CCS), as a key tool in climate mitigation and their reports indicate that it is very difficult to achieve the climate targets adopted in Paris Agreement in 2015 without adopting CCS. TCM is working to make CCS a more efficient and more affordable climate solution.

TCM has since its inauguration in 2012 paved the way for full-scale CCS projects by delivering important results that can provide safer and cheaper development of CO2 capture in Norway and the rest of the world. We are pleased that Statoil and Shell want to continue their involvement so that thisimportant work can continue, says CEO of Gassnova Trude Sundset.

The test activities on an industrial scale at TCM has qualified several companies to participate in full-scale CCS projects in Norway and internationally. Alstom (now GE), Aker Solutions, Cansolv and Carbon Clean Solutions (CCSL) have carried out extensive test campaigns at TCM. TCM has also established a close cooperation with the US Department of Energy (DOE) and in 2016, the American company ION Engineering started testing its technology at TCM with the support of DOE.

Statoil currently has ongoing activities within CCS and in general, we want a close collaboration with government and industry partners to qualify CCS as an important climate tools. Further operation of TCM is an important place where we contribute with our expertise and broad experience, says Executive Director Irene Rummelhoff in Statoil.

Shell emphasizes that the construction and test operations of TCM has played a very important role in uncovering areas for technology improvements that have helped to drive the cost of CCS down, and we see that such learning takes place in every test campaign. We believe that this will also be the case in the coming years and the continuation is therefore an important contribution to achieving the objectives of Shell's strategy within CCS. Shell wishes to play a key role in the continued operations of TCM, says Tor Arnesen, Managing Director of A / S Norwegian Shell.

Total is taking steps to support the IEA's 2°C scenario, in particular via CCUS*. We're a pioneer in CCUS and we want to take it even farther. It's a strategic investment for Total, because it meets our commitment to fight climate change in two ways: by building our expertise in CCUS* technologies and by reducing the carbon emissions of production facilities. We therefore feel it's important to be involved in the project, the only industrial-scale one in Europe," explains Philippe Baptiste, Total's Chief Technology Officer.

Later this year, TCM will collaborate with SINTEF and other industry players on test campaigns to develop better solutions associated with CO2 capture using amine technology.

TCM continues its efforts to test new and potentially more effective capture technologies to prepare them for future developments of CCS projects. TCM can also offer unique lessons learned in terms of measurements of emissions, the approval processes for environmental authorities, as well as training of operations personnel who will work at full-scale plants.

The existing participant's agreement is valid until August this year. The continuation to 2020, as it has been agreed upon now, depends among other things on the Norwegian Parliament's and the EFTA Surveillance Authority's (ESA) consent to the Norwegian State's continues participation

Public finance of Norway CCS project approved

www.eftasurv.int

The EFTA Surveillance Authority (ESA) has approved Norwegian public financing of studies for full-scale Carbon Capture and Storage (CCS) demonstration projects that aim to reduce CO2 emissions.

In 2014, the Norwegian Government presented its CCS strategy. The goal is to realise at least one full-scale CCS demonstration project by 2020 and Norway has allocated up to NOK 360 million (approx. EUR 40 million) to CCS studies in 2017.

"Norway has been at the forefront of CCS technology development and ESA is happy to approve well-designed measures with clear environment objectives", says ESA president Sven Erik Svedman.

To be able to continue the development of CCS technology and reach the goal of realising at least one concrete CCS project, Concept and FEED studies will play an important role. They reduce the uncertainties inherent in the delivery of the CCS projects through mapping of the potential risks and issues affecting the project.

Depending on the results from the Concept and FEED studies, the Norwegian authorities will decide whether to proceed with a full-scale project. The Concept and FEED studies are managed by Gassnova SF, a Norwegian state enterprise that has been tasked with finding solutions to ensure that technology for capture and storage of CO2 can be implemented and become an effective climate measure.

Aker Solutions wins study contracts from Yara and Norcem

akersolutions.com

Aker Solutions will conduct concept studies for carbon capture at Yara's ammonia plant on Herøya and Norcem's cement production facility in Brevik, Norway.

Norcem and Yara are among three companies in the running to receive funding from the Norwegian government to build and operate a full-scale carbon capture plant at their respective facilities. The government aims to fund at least one of the plants, which would be operational by 2022.

"Perfecting carbon capture will be key to meeting global climate goals," said Luis Araujo, chief executive officer at Aker Solutions. "The confidence placed in us by both Yara and Norcem shows we are taking a leading role in this crucial technological push."

Aker Solutions has previously carried out extensive testing with a pilot capture plant at the factory in Brevik. The results were so promising that Norcem selected Aker Solutions' technology to be used for a potential facility at the cement factory in Southeast Norway.

The study for Norcem will design a carbon capture plant that's integrated with the cement factory, including a process to turn the CO2 into liquid and storage facilities that can be used before shipping. The plant will have a capacity of about 400,000 tons of CO2 a year. The Yara study will design and develop a capture plant for the reformer flue gas and will also include liquefaction.

Both concept studies are set to be completed in September this year.

ENOS - Enabling onshore CO2 capture and storage

www.enos-project.eu

Research institutes across Europe join forces through a new scientific project named ENOS (ENabling ONshore CO2 storage in Europe).

The project was launched in September 2016, and the main objectives of the European Horizon 2020 project are to increase field experience relevant to geological storage of CO2, refine techniques and tools used for site selection and monitoring and to advance communication between science and society on the geological storage of CO2. The project will run until August 2020.

ENOS strives to enhance the development of CO2 storage onshore, close to CO2 emission points. Several field pilots in various geological settings will be studied in detail and best practices that stakeholders can rely on will be produced. In this way, ENOS will help demonstrate that CO2 storage is safe and environmentally sound and increase the confidence of stakeholders and the public in CCS as a viable mitigation option.

Several onshore research sites will serve to test CO2 injection. At the storage pilot of Hontomin in Spain, 10,000 tonnes of CO2 will be injected into a limestone rock layer at a depth of 1,500 m. Key parameters will be studied in order to monitor the evolution of the geological reservoir and to demonstrate that the storage operations have no negative impact on the environment. Innovative injection strategies, designed to optimise storage whilst guaranteeing site safety in the short and long term, will also be tested.

Tests at two other sites will allow project partners to improve techniques to detect CO2 in the subsurface so that, in the unlikely case that CO2 leakage were to occur, smaller amounts of CO2 could be identified more quickly. Such in-situ experiments will also help provide ground truthing for leakage simulations in two different geological settings, one in a shallow aquifer and the other along a fault plane. The first site, an initiative of the University of Nottingham and the British Geological Survey, is a field laboratory near Nottingham, UK, called the 'GeoEnergy Testbed', and the second is the 'Sulcis Fault Lab', located in Sardinia, Italy.

An additional two proposed pilot storage sites, LBr-1 in the Czech Republic and Q16 Maas in the Netherlands, complete the ENOS test site portfolio.

Carbon Clean Solutions joins Veolia for large scale CO2 re-use

carboncleansolutions.com

The partnership will lead to the large-scale de-carbonisation of a number of industrial processes and reduce their greenhouse effect under an Open Innovation approach.

Veolia has signed a partnership agreement with Carbon Clean Solutions Limited (CCSL), a global leader in low-cost carbon capture technology, for the large-scale rollout of CCSL's patented carbon dioxide (CO2) separation technology. The agreement provides the two partners with an opportunity to reduce the impact of the greenhouse effect of industrial activities.

CCSL recently announced the successful commissioning of its flagship project in Tamil Nadu, India, where a coal-fired power plant has become the site of the first industrial installation to re-use all its CO2 emissions. The project capture 60,000 metric tons of CO2 each year which is then converted into soda ash, a chemical compound that is commonly used in glassmaking. Privately financed, the site captures all the CO2 at a cost of US$30 per metric ton, half the cost of existing technology.

"This partnership is a fantastic illustration of Veolia's Open Innovation strategy to partner with the most promising industries to stay one step ahead with solutions and technology," says Laurent Auguste, Executive Vice President Innovation & Markets at Veolia. "With CCSL, we will mitigate CO2 emissions and enhance the prospects for the circular economy around carbon capture and its use by industry. It demonstrates Veolia's commitment to co-create solutions to fight climate change."

CEO of CCSL, Aniruddha Sharma added, "The partnership with Veolia will further boost our mission to help companies lower their carbon footprint in a cost-effective and sustainable manner. Our cuttingedge technology and Veolia's extensive service offering in water, energy and waste represents an ideal alliance".

What will it take to secure civil society and public support for CCS?

Speaking at the UKCCSRC Biannual in London in April 2017, Phil Macdonald from Sandbag, a climate thinktank, argues that in order to win support for CCS among the wider public we need to forget about coal, throw our suport behind industrial CCS, and focus on the jobs and climate benefits that CCS will bring.

CCS is essential to tackle climate change. A bible of the environmental movement, the IPCC's Fifth Assessment Report (AR5), is explicit in its climate model's reliance on CCS to stay below 2 degrees. Other models focused on the UK show dramatically reducing emissions is nigh-on impossible without carbon capture.

And yet, CCS is not widely supported by green groups, and is publicly invisible. A concept used for decades as a fig-leaf for continued unabated fossil fuel burn, CCS has been renewables' poor and ugly cousin, hiding in the shadows whilst wind and solar became the darling of the decarbonisers. Is there any hope that CCS be rehabilitated?

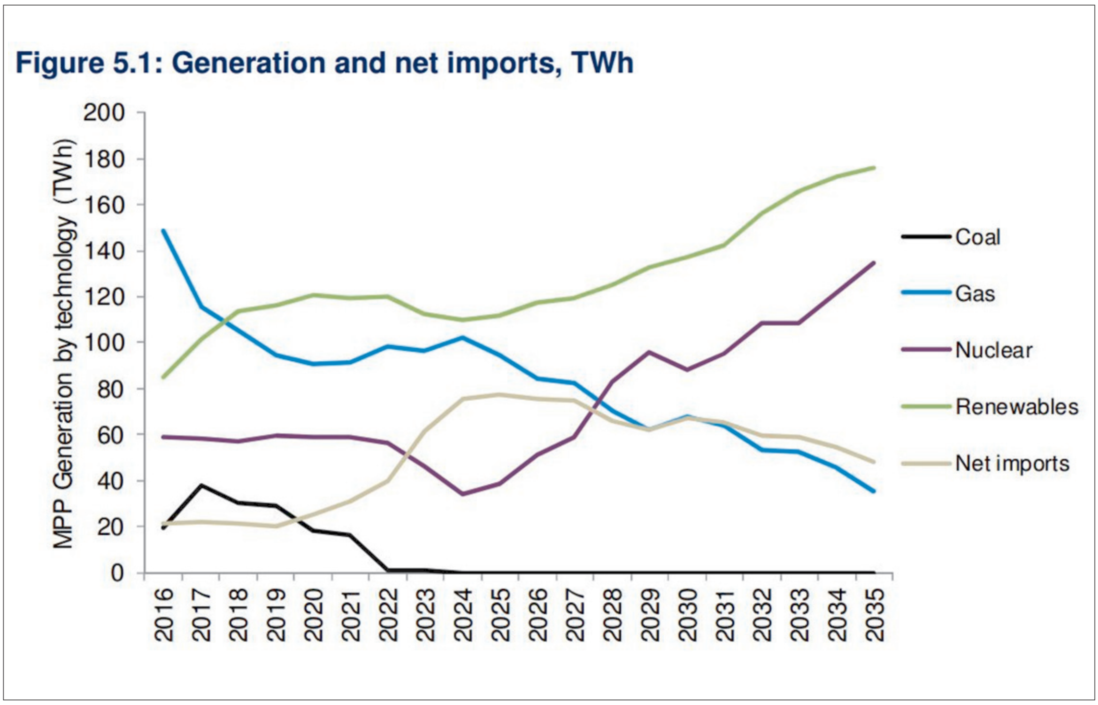

Figure from the March 2017 BEIS Energy & Emissions projections

Earlier in April I spoke at the UK CCS Research Council's conference at Imperial College, London to discuss how with a new focus on industrial CCS, jobs in the North Sea, and the inevitability of BECCS to avoid two degrees of warming, Carbon Capture and Storage can become a technology and industry with wide public support.

An unpopular technology

Unlike CCS the other main climate-fighting technologies, solar and wind, have extremely wide public support. Polling in 2017 by Bright Blue, the Conservative think tank, found that over 80% of Conservative voters wanted to maintain or strengthen EU renewable energy targets after Brexit. Meanwhile polling in 2013 by the UKCCSRC found that 40% of people don't know if CCS is useful for tackling climate change or not.

Clearly CCS has a publicity problem, one that mainly comes about because it is restricted to a handful of commercial projects around the world. But where it is known about, it is often unpopular, and that is down to its continued association with coal, the most unpopular energy source. A YouGov poll in 2015 spells it out; just 2% of the UK public support coal the most for Britain's future energy needs. Indeed, CCS in the UK is still tarred by the Kingsnorth debacle.

In 2006, E.ON announced plans to replace Kingsnorth coal power station in Kent. The new 800MW station would be "capture-ready" and would bid into the government's CCS competition. This motivated an almost unprecedented coalition of civil society, with opposition from organisations as diverse as the Campaign to Protect Rural England, the Royal Society, and Christian Aid. Alongside these institutions, E.ON faced a rolling campaign of direct action hampering its operations. In 2010, E.ON announced the station would permanently close. The association of Carbon Capture and Storage as a veil for continued unabated coal generation was complete.

Of course, public opposition does not always hold the current government back, as with the continuing battle over shale gas. But widespread dislike, even in Conservative constituencies, has held up the fracking industry in the UK. The road to commercial CCS will be far smoother if it can genuinely lay claim to the 'green' technology mantle.

If not coal, then gas?

Gas has long been regarded as a transition fuel from coal to clean, and so until recently appeared a natural home for CCS in the UK. Indeed, Sandbag has shown that coal-to-gas switching has been responsible for some of the 58% fall in UK coal emissions in 2016, alongside reduced electricity demand and growth in renewable capacity.

However, new projections from the Department for Business, Energy and Industrial Strategy (BEIS) in March show a new picture for CCGT gas, based on the unsuccessful build rate in the Capacity Market auctions, and current government policy. Gas is now projected to represent a dwindling part of UK generation, supplanted by increasing use of interconnectors, growth in renewables, and the nuclear programme. In the last Capacity Market auction, 500MW of lithium-ion batteries were contracted. Sandbag has proposed that the remaining 6GW of coal capacity uncontracted for can be replaced by battery capacity, a growth rate which ties with the National Grid's new projections for energy storage. Expensive, foreign gas may be required even less than expected.

Is there space here for CCS on gas? Possibly yes; a large, permanent supply of CO2 is useful for demonstrating the long-term need for a transport and storage system. But polling shows gas is also an unpopular energy source, if not as hated as coal. BEIS stated unambiguously that power CCS "is not assumed to come on in any significant capacity over the period of this modelling" [to 2035].

Highlighting industrial CCS

The only sector where CCS has made progress in Europe is industrial CCS. Norway is the jewel in the carbon capture crown, with three commercial industrial projects due for completion by 2022 (a cement plant, a waste incinerator, and a fertiliser plant). Shipped CO2 storage in Norwegian undersea fields is now an option for all countries in the North Sea basin.

Hopes in the UK have been buoyed by the government's new, interventionist approach to industrial strategy, with Theresa May quoted: "Underpinning this [industrial] strategy is a new approach to government, not just stepping back and leaving business to get on with the job, but stepping up to a new, active role".

The manufacturing hub at Teesside is the UK's most advanced CCS proposal. Chemical and process industries there bring £2.5bn in gross-value added each year, and the businesses have collected together, recognising the need to remove their emissions presents an existential threat and opportunity.

Industry isn't perfect. It produces small, intermittent streams of CO2, which may not last more than a few years if the companies involved go bankrupt, as SSI steel did at Redcar. Different industries will require different capture tech, and have different impurities and individual problems. However, industrial CCS offers plenty of jobs to save for (or bring to) Britain, compared to the dwindling fossil fuel power sector (BEIS says there are less than 2,000 jobs left in the UK associated with coal). There are strategic benefits to supporting UK manufacturing and expertise for the future. Carbon-neutral industrial hubs offer a strong possibility of green growth in the future.

Hydrogen and CCS

How to cut emissions from heat is perhaps the hardest decarbonisation problem, with the Climate Change Committee's Progress Report showing some of the slowest progress to date. Two options have come to the forefront: electrifying heat production; or replacing natural (methane) gas with hydrogen gas, produced by steam methane reformers with CCS.

Sandbag has proposed blending small amounts of hydrogen into the current gas grid. At each of the east coast's four gas terminals, capture plants fitted to steam methane reformers could initially place their CO2 directly onto Norwegian ships. This could be a chance to demonstrate carbon capture, demonstrate hydrogen in the grid, and immediately begin to decarbonise the heat network.

CCUS already happening

It may be that for CCS to ever begin to reach scale, it may have to grow incrementally rather than through initial large projects, just as the wind industry did not begin with the Thames Array, but with singular turbines. The building aggregates company Carbon8 have just opened their third plant in Leeds, and are storing CO2 and landfill wastes safely and permanently in their aggregates. It's small scale compared to the size of the problem, but represents the only storage actually happening currently. Sandbag has proposed that such CCU with permanent storage, and indeed all CCS, is rewarded with a new form of CO2 certification, opening up the potential for a market and new funding for CCS.

The growing cost of North Sea decommissioning

It's not just an industrial issue, but as the North Sea dries up, 350,000 jobs are on the line in the UK, and a £24 billion decommissioning bill for the UK taxpayer. A new Carbon Capture industry could transition these jobs and UK expertise. In last years Energy Act, Sandbag and a cross-party group of Lords argued for the Oil and Gas Authority to consider CCS before beginning infrastructure decommissioning, but the amendment fell in the Commons. The decommissioning bill has not gone away, so we will continue to push the government to take action.

So...How do we secure broad support for CCS?

To win public and civil society support for CCS in the UK, we need to forget about coal.

We may need to start small, as politicians find it difficult to back expensive proof-of-concept megaprojects with unclear rewards. We need to link CCS to jobs it will bring outside of power, and link it much more explicitly to tackling climate change. The world can't meet the Paris Agreement net-zero emissions target without CCS. It's essential the UK gets moving, and the next government must throw their support behind industrial CCS.

More information

Full conference slides available on the UKCCSRC website:

www.ukccsrc.ac.uk

www.sandbag.org.uk

Permeability and sealing characteristics of reservoir caprock

Structural trapping of CO2 by the reservoir cap rock is the most important initial factor for the success of a CO2 storage project. Predicting how much CO2 can be stored before the seal breaks, and how much CO2 will leak if it does, are key to planning storage operations.

Dr. Nathan Welch, Dr. John Crawshaw, Imperial College London

Laboratory measurements of geologic reservoir seal fluid flow properties are important in providing evidence of a reservoir's geologic carbon storage capabilities as well as providing representative data for use in reservoir simulations used to plan carbon storage operations.

Although not a new field of study, research aimed at understanding and measuring the sealing characteristics of reservoir seals, or cap rocks, has acquired a renewed interest from the on-going research of the geologic storage of carbon dioxide. With this renewed interest, there has been recent development of novel techniques for the measurement of the unique extreme properties associated with reservoir seal samples.

The permeability and capillary forces present in reservoir seals approach experimental extremes beyond time-effective measurement using traditional methods. The work presented in this poster provides a summary of the work Dr. Nathan Welch completed during his PhD at Imperial College London in studying the fluid flow properties of reservoir cap rocks.

An apparatus was constructed to measure the capillary threshold pressure and permeability of reservoir seal plug samples using traditional and experimental techniques. The measurement of capillary threshold pressure is important to carbon storage operations and planning as it determines the maximum pressure difference that can be applied across a given reservoir seal before a non-wetting fluid, i.e. CO2, begins to flow through the water/brine saturated sample pore space.

This measurement can be used in determining important injection operation parameters, as well as an estimate of the ultimate maximum storage capacity of a given reservoir. The use of the dynamic method developed by Egermann et al. to measure the capillary threshold pressure of geologic samples was verified using a ceramic reservoir seal analogue [1], and was later used to determine the change in a samples capillary threshold pressure with varying applied stresses.

The ability to measure the extremely low permeability of cap rock samples was achieved using the same fluid flow apparatus modified using specially machined pore fluid reservoirs to increase measurement accuracy and simplify the apparatus design. Permeability measurements are important in determining how quickly and how much carbon dioxide would be able to flow through a cap rock if the previously noted capillary threshold pressure were to be exceeded.

Permeability measurements were recorded for several geologic samples using water/brine with the pressure decay technique originally developed by Brace et al. in the 1960s for determining the permeability of granite [2]. One important characteristics of the apparatus developed compared to other common techniques to measure the permeability of cap rocks is the use of water/brine as a working fluid. Often inert gases are used to perform these measurements in favour of water to take advantage of the lower working fluid viscosity, but important steps in sample preparation to use such techniques may cause significant deviations from representative subsurface properties.

Many cap rock samples contain clays that are highly responsive to changes in water saturation and ion concentration, and the use of gas to measure sample permeability requires prior drying of analysed samples to avoid capillary effects. This drying can have a significant impact on the nanometre-scale pore structure from changes in these clays that then causes deviations in measured sample properties from representative subsurface properties.

These measurements have then been completed over a wide range of experiment conditions observing important trends in sample behaviour with changing fluid/fluid interactions, applied sample stresses, and to support the development of digital rock physics techniques. The dynamic technique for the determination of capillary threshold pressure has been shown to provide results in agreement with the traditional method for measuring sample capillary threshold pressure, as well as accurate scaling of different fluid pair measurement results to build confidence in future comparisons in systems with different experiment conditions.

Important trends in sample permeability and capillary threshold pressure have been observed to show critical stress conditions after which important changes in sample pore structure can occur to greatly reduce the predicted carbon dioxide sealing capacity of the reservoir seal. Image analysis and fluid flow simulations have also been completed on direct images of the sample pore using the results from focused ion beam – scanning electron microscopy imaging to build confidence in the use of the imaging technique in the continued development of predictive computational techniques.

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More information

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Qatar Carbonates and Carbon Storage Research Centre

Improving reservoir recovery and carbon storage potential

Imperial College London

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Permeability and Sealing Characteristics of Reservoir Caprock

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Introduction

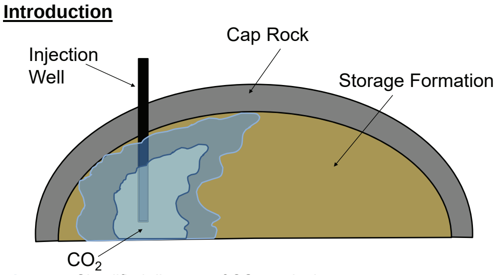

Figure 1: Simplified diagram of CO_2 geologic storage

- Structural trapping of CO_2 by the reservoir cap rock is the most important initial characteristic for the success of a sequestration project[1].

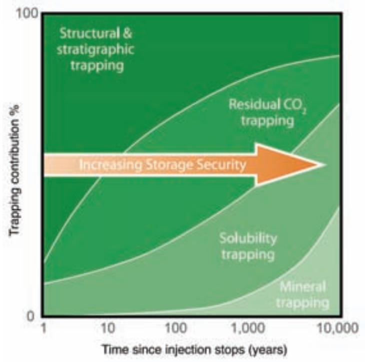

Figure 2: The trapping contribution percentage of the four main trapping mechanisms of carbon dioxide within a sequestration reservoir during the maturation of a selected site[1].

Major Questions to Answer:

- **How much CO_2 can be stored in a given reservoir before it begins to flow through the reservoir seal?**
- **In a worst-case scenario, how fast will CO_2 leak through a intact cap rock?**
- **What can be done to predict these properties?**

Methods

Q: How much CO_2 can be stored in a given reservoir before it begins to flow through the reservoir seal?

A: Capillary Threshold Pressure (CO_2/Water System)

- The capillary threshold pressure of a reservoir's sealing formation determines how much carbon dioxide can be stored in the reservoir before CO_2 begins to flow through the cap rock.

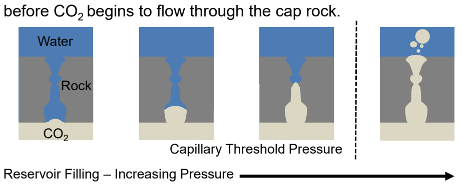

Figure 3: Simplified diagram of the flow of CO_2 through the core rock pore space as a reservoir is filled, raising the pressure of the non-wetting phase until the capillary threshold pressure is exceeded.

- The capillary threshold pressure can be determined from the change in the water flow rate when the non-wetting phase (CO_2) begins to flow through the sample as[2]:

$$P_c^{entry} = \Delta P_t - \Delta P_w = \Delta P_t - \frac{\mu_w L}{kA} q_w^{effective}$$

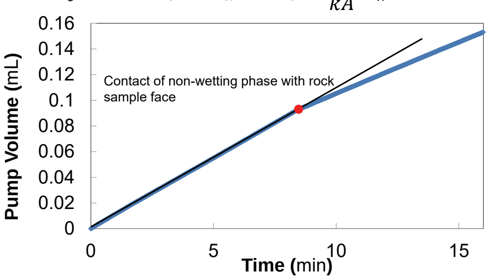

Figure 4: The produced wetting phase flow rate change as the non-wetting phase begins to enter the cap rock sample This slope change corresponds to a capillary entry pressure of 5.79 bar.

Q:In a worst-case scenario, how fast will CO_2 leak through a intact cap rock?

A: Reservoir Seal Permeability

- The permeability of a reservoir cap rock is used in determining the maximum flow rate that can occur from a reservoir if the capillary entry pressure of the sealing formation is exceeded during the injection of CO_2.
- Fluid flow in cap rocks is extremely low as opposed to the reservoir rocks out of which a majority of hydrocarbons are produced
- Originally proposed by Brace et al., the pressure response of a pressure pulse applied to two reservoirs across the rock sample could be shown to follow [3]:

$$(P_{up} - P_f) = \Delta P_{int}\left(\frac{V_{up}V_{dn}}{(V_{up}+V_{dn})^2}\right)e^{-\alpha t}$$

$$\alpha = \left(\frac{kA}{\mu\beta L}\right)\left(\frac{1}{V_{up}}+\frac{1}{V_{dn}}\right)$$

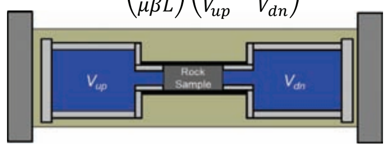

Figure 5: Diagram showing two fluid reservoirs connected via a reservoir cap rock sample contained inside of a hydrostatic core holder.

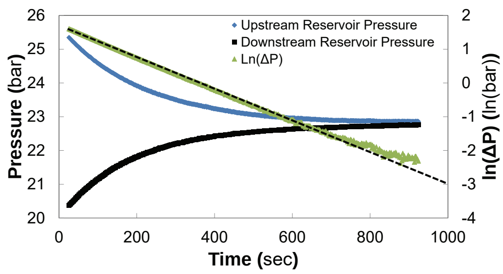

Figure 6: The pressure response of the two fluid reservoirs separated within the core holder by a anhydrite cap rock analogue. A linear regression of the logarithm of the pressure difference is used to determine the sample's permeability to be 2.618±0.070 μDarcy.

Q:What can be done to predict these properties?

A:Sample Imaging and Digital Rock Physics

- Focused Ion Beam – Scanning Electron Microscopy (FIB-SEM) can be used to directly image the pores found in reservoir seals, that can then be used in fluid flow simulations to predict sample properties.

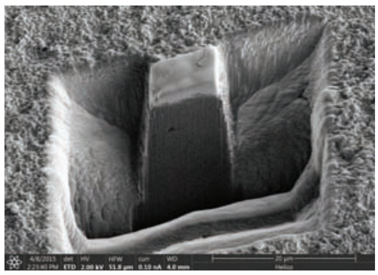

Figure 7: FIB-SEM Extraction Site. Examined cube is about the size of a single blood cell.

- Computerized Microtomography (Micro-CT) can be used to image samples during fluid flow experiments, but can only image larger samples features such as fractures.

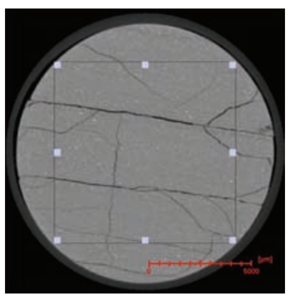

Figure 8: Micro-CT slice of 1/2" dia. fractured reservoir seal sample.

Results and Discussion

Capillary Threshold Pressure (CO_2/Water System)

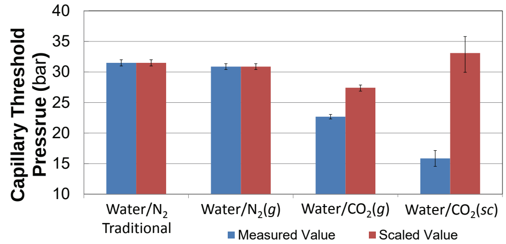

Figure 9: Verification of dynamic capillary threshold pressure method and comparison of N_2 and CO_2 systems.

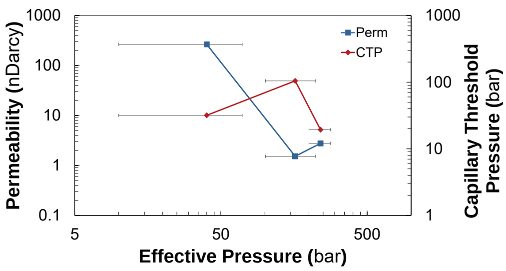

Figure 10: Effect of effective pressure on Hontomin reservoir seal capillary threshold pressure.

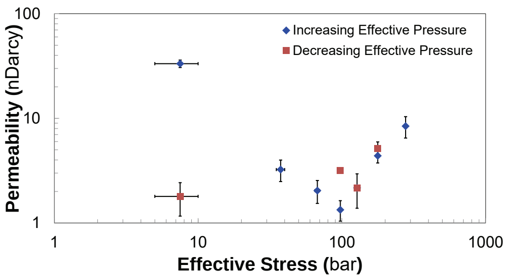

Figure 11: Effect of effective pressure on Hontomin reservoir seal permeability.

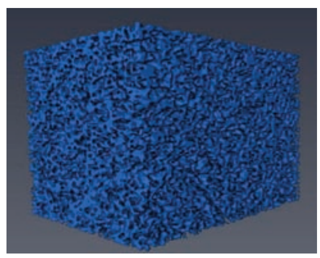

Figure 12: Extracted pore space from FIB-SEM imaging of reservoir seal analogue ceramic.

Table 1: Comparison of measured permeability to predicted sample permeability from fluid flow simulations run on FIB-SEM extracted pore space from two mesoporous ceramics.

Sample Pore Size	Measured Permeability (μDarcy)	LB Predicted permeability (μDarcy)
50 nm	7.9±0.2	5.6±0.3
150 nm	15.8±4.0	14.5±0.8

Conclusions

- We successfully developed a fluid flow apparatus capable of recording cap rock permeability and capillary threshold pressures.
- We have verified the dynamic method for capillary threshold pressure determination compared to the traditional technique.
- We have measured the effect of effective pressure on capillary threshold pressure and permeability of reservoir seals to provide more accurate results for reservoir modelling.
- We have developed reservoir seal imaging techniques for direct pore space imaging of the nanometre scale pore space, along with sample imaging techniques during fluid flow experiments.
- We have shown that it is possible to predict the permeability of homogeneous samples from FIB-SEM collected images for the advancement of digital rock physics.

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Thermodynamic evaluation of carbon negative power generation: bio-energy CCS (BECCS)

Understanding the effect of process enhancements on the efficiency of BECCS systems and how this impacts on CO2 capture rates is key to the commercial viability of the technology.

Mai Bui, Mathilde Fajardy, Niall Mac Dowell, Imperial College London

Carbon capture and storage (CCS) and "negative emissions" technologies are expected to play an essential role in limiting global warming (IPCC, 2014). Bio-energy with CCS (BECCS) is a promising negative emissions technology which can achieve an overall negative CO2 balance when carefully deployed (Azar et al., 2010; Fajardy and Mac Dowell, 2017; Mac Dowell and Fajardy, 2017). During biomass growth, there is a net transfer of CO2 from the atmosphere into the biomass.

The subsequent capture of the CO2 arising from biomass combustion and geological storage enables permanent removal of CO2 from the atmosphere (Kraxner et al., 2003; Fuss et al., 2014). Hence, the 5th assessment report by IPCC has emphasised the importance of having BECCS as a CO2 mitigation option (IPCC, 2014).

Efficiency improvement of BECCS can enhance commercial viability of the technology, thereby encouraging full scale deployment. Compared to conventional monoethanolamine (MEA), using advanced novel solvents can reduce heating requirements of the post-combustion CO2 capture process by over 30%, subsequently decreasing the efficiency penalty imposed by the capture technology on the power plant (Ye et al., 2015).

In terms of heat integration, one promising opportunity for efficiency enhancement is waste heat recovery from the exhaust gas exiting the power plant boiler to supply energy for the CO2 capture process (Harkin et al., 2009, 2010). The recoverable heat from the flue gas is a function of the adiabatic flame temperature (AFT), which depends on the fuel properties, e.g., moisture content (Flagan and Seinfeld, 2012). Biomass typically has lower heating value, less ash and higher moisture content in comparison to high quality coal (Veijonen et al., 2003).

The selection of biomass with favourable properties (e.g. low ash and low moisture content) can improve combustion efficiency, leading to an increase in AFT (Sami et al., 2001), which in turn, enhances heat recovery and power generation efficiency (Bui et al., 2017a; Bui et al., 2017b). Furthermore, co-firing biomass can reduce SOX and NOX emissions, due to biomass having lower sulphur and nitrogen content compared to coal (Spliethoff and Hein, 1998; Spliethoff et al., 2000).

This study assesses the power generation efficiency, recoverable heat and carbon intensity of a 500 MW pulverised fuel BECCS system (using ultra-supercritical technology) for different biomass co-firing proportions and capture solvents. The evaluation procedure is as follows:

1) Selection of coal type (high and medium sulphur content), biomass type (wheat straw and clean wood chips), and CO2 capture solvents (MEA, Cansolv, "new solvent").

2) Model of a 500 MW ultra-supercritical pulverised fuel power plant: Calculate the fuel firing flow rate and net power output for different biomass co-firing proportions.

3) Thermo-chemical model of biomass and coal co-combustion: Determine the flue gas composition, flow rate, gas thermodynamic properties and adiabatic flame temperature (AFT).

4) Heat recovery model: Determine the effect of flue gas heat recovery on the overall plant efficiency and carbon intensity.

It was found that the power generation efficiency of a BECCS system can be significantly improved through the use of high performance CO2 capture solvents and higher flue gas heat recovery. BECCS using the conventional MEA system achieves an efficiency of 31%HHV, which increases to 38%HHV through the use of a new solvent (e.g., biphasic system) and heat recovery.

Increasing the biomass co-firing proportion or using coal with low sulphur content provides substantial reductions in SOX emissions. The emissions of NOX are predominantly dependent on combustion conditions. Thus, control of the combustion temperature, also air and fuel staging is necessary to minimise NOX formation. The low efficiency MEA system was more carbon negative on a per MWh basis compared to the high efficiency system, which is due to the greater rate of fuel consumption per MWh generated.

Therefore, lower efficiency BECCS systems can capture more CO2 from the atmosphere on a per MWh basis. However, the load factor of the system is a function of the power plant efficiency. The dispatch of higher efficiency systems is typically favoured due to their lower marginal cost of electricity generation (Mac Dowell and Shah, 2015; Mac Dowell and Staffell, 2016).

Subsequently, the annual CO2 removal rate of a BECCS system (tCO2/year basis) is a function of the generation efficiency and annual capacity of the power plant (i.e. load factor). Hence, it is important to consider the trade-off between efficiency and carbon intensity when evaluating the CO2 mitigation potential of BECCS.

More information

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Thermodynamic evaluation of carbon negative power generation: Bio-energy CCS (BECCS)

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Approach and Aim of research

Bio-energy with carbon capture and storage (BECCS) has been identified as a key technology in reducing atmospheric CO_2 concentration with power generation. The power generation efficiency of BECCS can be improved through: (i) flue gas heat recovery to supply energy for solvent regeneration, (ii) selection of efficient capture solvents, or (iii) use of high quality fuels. To understand the effect of process enhancements on the performance of a 500MW BECCS system, this study will:

- Assess the influence of solvent selection and biomass co-firing proportion on recoverable heat, energy efficiency and carbon intensity,
- Evaluate the effect of coal type (high and medium sulphur content), biomass type (wheat straw and clean wood chips), variable moisture content (MC), and biomass co-firing % on the adiabatic flame temperature (AFT) and emissions of SO_X and NO_X,
- Develop a performance matrix to summarise the effects of key process parameters.

Methodology

1) Select the **biomass**, **coal** and **solvent,** and calculate the fuel flowrate and net power output in IECM for different biomass co-firing proportions based on a **500 MW ultra-supercritical power plant.**

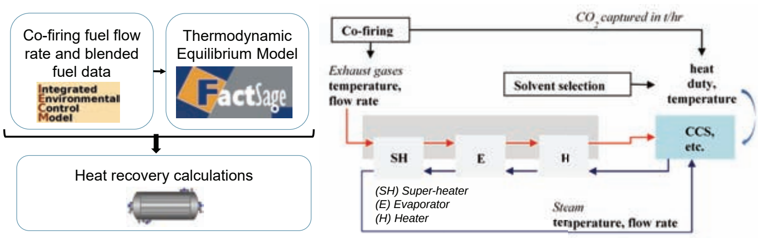
Scenario	Coal type	Biomass type
A	Medium sulphur coal	Wheat straw 5% MC
B	Medium sulphur coal	Wheat straw 16% MC
C	Medium sulphur coal	Wood chip 5% MC
D	Medium sulphur coal	Wood chip 50% MC
E	High sulphur coal	Wheat straw 5% MC
F	High sulphur coal	Wheat straw 16% MC
G	High sulphur coal	Wood chip 5% MC
H	High sulphur coal	Wood chip 50% MC

CO_2 Capture Solvent	Heat duty (MJ/tons CO_2)	Reboiler temperature (°C)
MEA (base case)	3600(1)	120
Cansolv	2300	120
"New solvent"	2000(2)	80(2)

(1) IECM
(2) Ye et al. 2015, Rochelle et al. 2011

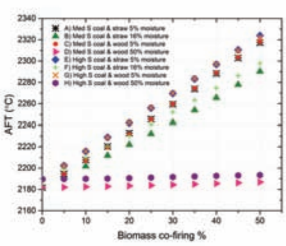
2) Model the combustion of biomass with coal in the power plant. Determine the composition, fuel flow rate, adiabatic flame temperature (AFT) and thermodynamic properties of the exhaust gas.

3) Carry out heat recovery calculations and determine the influence of exhaust gas heat recovery on overall power plant efficiency and carbon intensity.



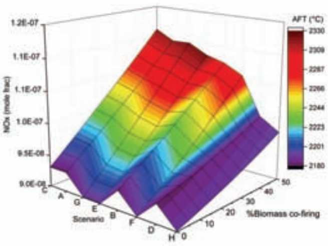
Results & Discussion

Adiabatic flame temperature (AFT)



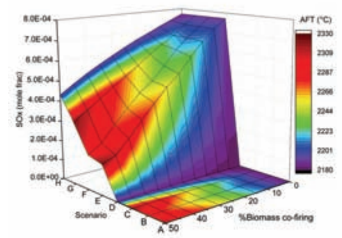
- Increasing biomass co-firing % increases AFT,
- The degree of increase for AFT is greatest when co-firing with low 5% moisture biomass,
- High sulphur coal generates higher AFT than medium sulphur coal because of its lower ash content,
- Combustion is enhanced with low moisture & low ash fuels.

NO_X emissions



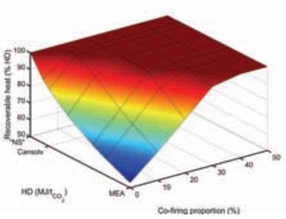
- NO_X emissions increase with AFT (strongly dependent on combustion conditions).

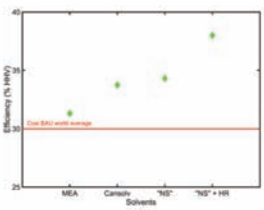
SO_X emissions



- Increased biomass co-firing % decreases SO_X emissions due to:
  (i) reduction in fuel sulphur content,
  (ii) ash compounds (e.g. CaO, MgO, N_2O and K_2O) that absorb SO_2.
- SO_X emissions for medium sulphur coal scenarios (A to D) also decrease.

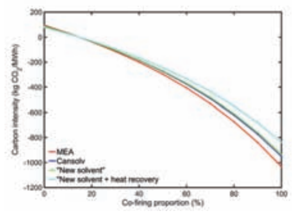
Effect of heat recovery and solvent selection on efficiency





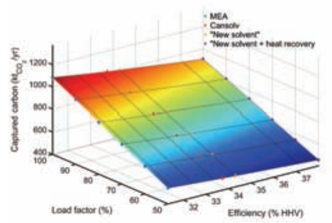
- Heat recovery increased with increased biomass co-firing,
- For all 3 solvents, flue gas heat recovery can supply 100% of the energy requirements when biomass co-firing is ≥40%,
- At 50% co-firing, an efficiency of 38% is reached in the scenario of "new solvent" with heat recovery.

Carbon intensity



- Carbon intensity decreases with co-firing proportion and capture rate,
- At 90% CO_2 capture and 50% biomass co-firing, carbon intensity ranges from -295 (MEA) to -245 ("new solvent" + HR) kg CO_2/MWh.

Annual captured CO_2



- For an MEA system at 60% load factor, annual capture capacity is 0.65 Mt CO_2.
- For a new solvent system working at 90% load factor, 0.8 Mt CO_2 is capture annually.
- Captured carbon increases with higher load factor and lower efficiency.

BECCS Performance matrix

Performance parameter	Ash content	Sulphur content	Moisture content	HHV	Biomass co-firing proportion	Solvent heat duty
NO_x ↓	*dependent on combustion conditions*					
SO_x ↓	↑	↓	↓		↑	
AFT ↑	↓		↓		↑	
Heat recovery ↑	↓		↓	↓	↑	↓
Exhaust gas flowrate ↑				↓	↑	
Efficiency ↑	↓		↓	↓↑	↓	↓
CO_2 negativity ↑	↑		↑	↑	↑	↑

- Performance can be optimised in terms of efficiency, CO_2 intensity or pollutant reduction,
- Efficiency is maximized when low ash coal is co-fired with minimal proportions of low moisture biomass while using flue gas heat recovery with a high performance CO_2 capture solvent (low heat duty),
- CO_2 negativity is maximized when co-firing low quality biomass (high moisture and ash) with the least efficient CO_2 capture system (e.g. high heat duty MEA solvent),
- SO_X and NO_X are reduced when biomass co-firing proportion are increased while controlling combustion conditions and using coal that is low in sulphur.

Conclusion

- There are different measures of power plant performance depending on whether the objective is to optimize: (i) efficiency, (ii) CO_2 negativity, (iii) pollutant reduction.
- Factors that enhance efficiency included the use of high performance solvents (low heat duty) and higher heat recovery (higher AFT and flue gas flow rate).
- Greater carbon negativity in achieved with low efficiency systems; as more biomass fuel is burned per MWh, more CO_2 is captured and permanently stored.
- SO_X emissions are minimized by increasing biomass co-firing, whereas control of combustion conditions is required to regulate NO_X emissions.

References

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- Rochelle, G., Chen, E., Freeman, S., Van Wagener, D., Xu, Q., & Voice, A. (2011). Aqueous piperazine as the new standard for CO2 capture technology. *Chemical Engineering Journal*, *171*(3), 725–733. http://doi.org/10.1016/j.cej.2011.02.011

Go now or wait and see? - optimal investment timing in national power systems

What if a "super technology" became available in the future? Is it better to wait or continue investing in CCS?

Clara F. Heuberger, I. Staffell, N. Shah, and N. Mac Dowell, Imperial College London

The reluctant deployment of low-carbon and zero-carbon power generation and energy storage technologies, perhaps besides wind and solar power technologies, are impeding the transition to power system decarbonisation. We put to test the notion that a strategy of waiting for a ``unicorn technology'' to become available could be more effective than deploying technologies which are commercial and viable today.

Especially in the context of Carbon Capture and Storage (CCS) equipped power plants, we are facing the question if it is economically and environmentally more sensible to "go now" or to "wait and see".

To answer such a question, we have expanded on previous work [1], in developing a mixed-integer linear formulation of a hybrid power generation capacity expansion and unit commitment model with a high level of technical detail. We apply a novel time clustering and profiling technique to compress hourly time-dependent data sets achieving an average error in system-level results of -1.7% to 2.5% compared to the full hourly time series over the planning horizon from 2015 to 2050. The national-scale model is implemented in different facets of temporal and spatial (dis-)aggregation; it considers up to 2000 units of 16 different power generation and storage technologies, including international interconnectors for electricity import and export, and grid-level energy storage. The Electricity System Optimisation framework (ESO-XEL) includes the consideration of endogenous learning for technology capital cost in a piecewise linear fashion.

We compare a baseline scenario on the power system expansion of the United Kingdom (UK) with a scenario where a "unicorn technology" becomes available for deployment in 2035. This technology is parametrised as a zero-carbon emission, dispatchable, highly flexible power generation option at low capital and operational cost.

We observe that the effect of such a technology becoming available reduces the deployment for nuclear, unabated gas-fired power generation, as well as intermittent renewables. Also, CCS-equipped power generation would reduce by 36 %, however, it remains a vital part of the least-cost capacity mix in 2050. Furthermore, its optimal investment timing remains unaffected by the availability of the future disruptive technology. Total system cost are reduced by 2% by the deployment of the unicorn technology. More significantly however, without the deployment of CCS-equipped gas and coal-fired power plants total system cost by 2050 could be 44% greater compared to the baseline scenario.

References

[1] C. F. Heuberger, I. Staffell, N. Shah, and N. Mac Dowell. Levelised Value of Electricity - A Systemic Approach to Technology Valuation. In 26th European Symposium on Computer Aided Process Engineering, volume 38, pages 721-726, 2016.

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"Go now or wait and see?" – Optimal Investment Planning for CCS

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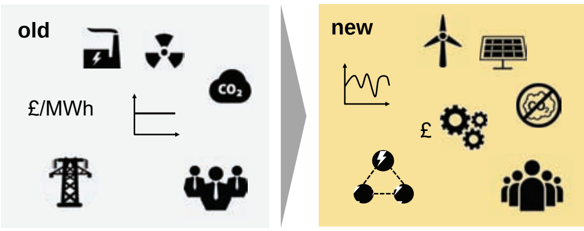
[a] Centre for Environmental Policy, [b] Centre for Process Systems Engineering, [c] Department of Chemical Engineering, Imperial College London

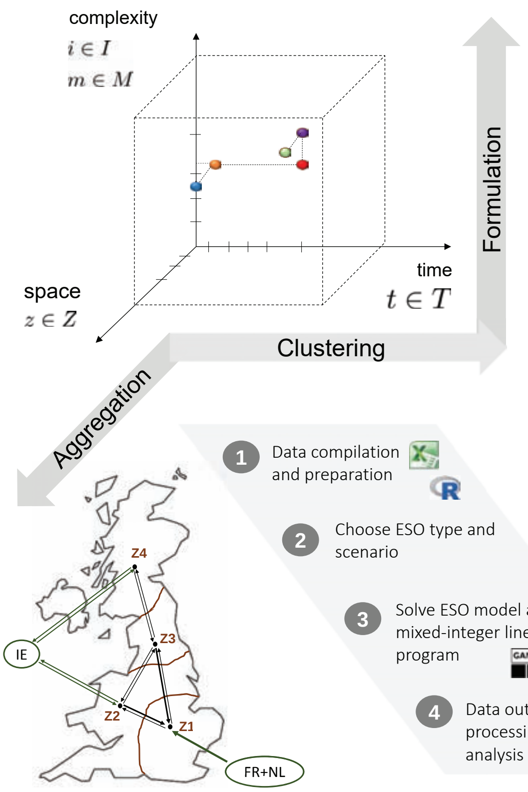
Motivation

- CCS in power generation is widely recognised as being vital to least cost decarbonisation
- Today however, it is generally referred to as being too costly
- Consequently, relatively small sums are spend on research & development, in the hope that a future "super technology" will bring prices down



- Additionally, power systems are in a transition w.r.t. supply, demand, markets, transmission & distribution, environmental constraints
- Power technologies cannot be compared in isolation but require assessment within the systemic context

The Electricity System Optimisation Framework



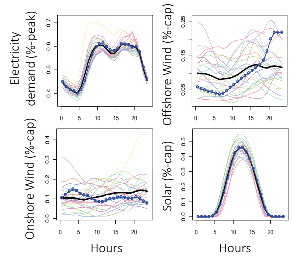


Fig. 1: Example of a cluster of time dependent input data [1-2].

Results from the ESO-XEL model

Should we wait with investment in CCS **today** if a "super technology" becomes available in the **future**?

— No, CCS remains a vital part of the least cost solution. Total system cost by 2050 without CCS deployment could be 44 % greater.

Carbon Price –no ST | Zero-CO_2 Target –no ST | Carbon Price –ST

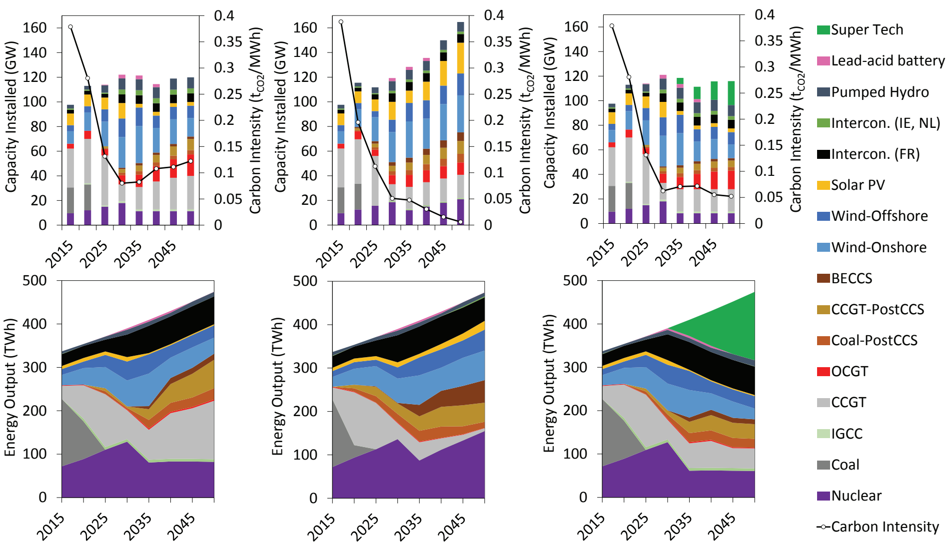
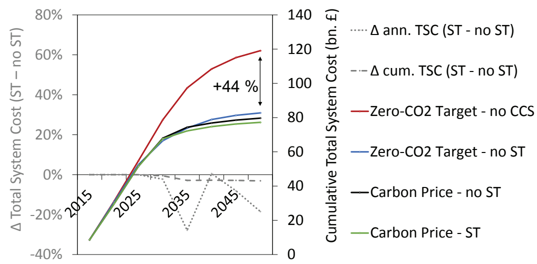


Fig. 2: Study of decarbonisation via carbon price, and an enforced zero CO_2 emission target by 2050 without the availability of a "super technology" (ST), and with a ST available from 2035 onwards.

Conclusions

- Optimal investment timing for CCS remains unaffected by a future disruptive technology.
- However, optimal CCS capacity deployment by 2050 reduces by 30 %, energy output by 36 %.
- It is unlikely that a carbon price alone will lead to a complete decarbonisation of the power sector.



A potential "super technology" — Chemical Looping Combustion (CLC)

Tab. 1: Parameterisation of a 500 MW unit NGCC-CLC as "super technology" in the ESO-XEL model.

Characteristic	Unit	CCGT-CCS	NGCC-CLC [3]
Efficiency	$\%_{HHV}$	45.5	46.8
CAPEX	$£_{2016}$/kW	2,368	1,066
OPEX (fixed)	$£_{2016}$/MWh	2.8	2.46
OPEX (fuel, CO_2 tax, CO_2 T&S)	$£_{2016}$/MWh	42.1	37.8
Carbon Intensity (emit./cap.)	t_{CO2}/MWh	0.041 / 0.369	0 / 0.386
Economic Lifetime	Years	30	30
Minimum Stable Generation	%	70	40

References

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Acknowledgements

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Molecular 'leaf' collects and stores solar power without solar panels

A new molecule developed at Indiana University harvests sunlight to create useable materials from carbon dioxide in the atmosphere.

An international team of scientists led by Liang-shi Li at Indiana University has achieved a new milestone in the quest to recycle carbon dioxide in the Earth's atmosphere into carbon-neutral fuels and other materials.

The chemists have engineered a molecule that uses light or electricity to convert the greenhouse gas carbon dioxide into carbon monoxide, a carbon-neutral fuel source, more efficiently than any other method of "carbon reduction."

The process is reported in the Journal of the American Chemical Society.

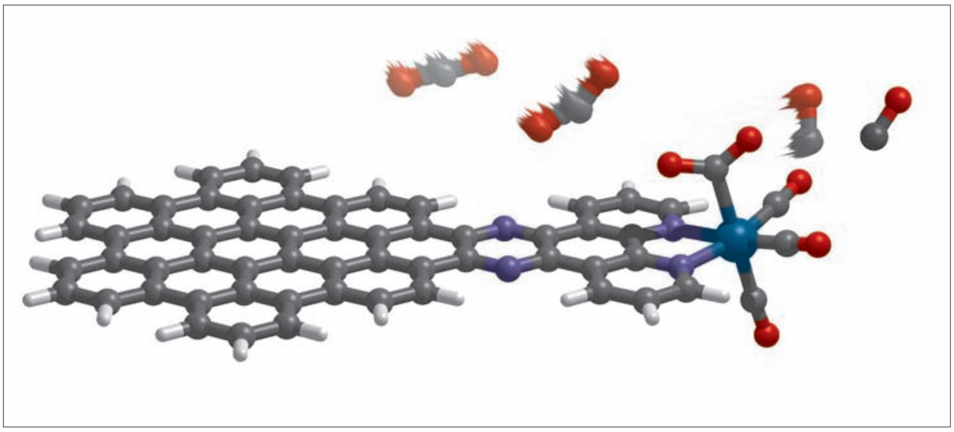
"If you can create an efficient enough molecule for this reaction, it will produce energy that is free and storable in the form of fuels," said Li, associate professor in the IU Bloomington College of Arts and Sciences' Department of Chemistry. "This study is a major leap in that direction."

Burning fuel -- such as carbon monoxide -- produces carbon dioxide and releases energy. Turning carbon dioxide back into fuel requires at least the same amount of energy. A major goal among scientists has been decreasing the excess energy needed.

This is exactly what Li's molecule achieves: requiring the least amount of energy reported thus far to drive the formation of carbon monoxide. The molecule -- a nanographene-rhenium complex connected via an organic compound known as bipyridine -- triggers a highly efficient reaction that converts carbon dioxide to carbon monoxide.

The ability to efficiently and exclusively create carbon monoxide is significant due to the molecule's versatility.

"Carbon monoxide is an important raw material in a lot of industrial processes," Li said. "It's also a way to store energy as a carbon-neutral fuel since you're not putting any more carbon back into the atmosphere than you already removed. You're simply re-releasing the solar power you used to make it."



The new molecule employs a nanographene complex (on left) to absorb light and drive the conversion of carbon dioxide (upper center) to carbon monoxide (on right). Photo by Ben Noffke and Richard Schaugaard

The secret to the molecule's efficiency is nanographene -- a nanometer-scale piece of graphite, a common form of carbon (i.e. the black "lead" in pencils) -- because the material's dark color absorbs a large amount of sunlight.

Li said that bipyridine-metal complexes have long been studied to reduce carbon dioxide to carbon monoxide with sunlight. But these molecules can use only a tiny sliver of the light in sunlight, primarily in the ultraviolet range, which is invisible to the naked eye. In contrast, the molecule developed at IU takes advantage of the light-absorbing power of nanographene to create a reaction that uses sunlight in the wavelength up to 600 nanometers -- a large portion of the visible light spectrum.

Essentially, Li said, the molecule acts as a two-part system: a nanographene "energy collector" that absorbs energy from sunlight and an atomic rhenium "engine" that produces carbon monoxide. The energy collector drives a flow of electrons to the rhenium atom, which repeatedly binds and converts the normally stable carbon dioxide to carbon monoxide.

The idea to link nanographene to the metal arose from Li's earlier efforts to create a more efficient solar cell with the carbon-based material. "We asked ourselves: Could we cut out the middle man -- solar cells -- and use the light-absorbing quality of nanographene alone to drive the reaction?" he said.

Next, Li plans to make the molecule more powerful, including making it last longer and survive in a non-liquid form, since solid catalysts are easier to use in the real world. He is also working to replace the rhenium atom in the molecule -- a rare element -- with manganese, a more common and less expensive metal.

All of the research on the study was conducted at IU. The first authors on the paper are Xiaoxiao Qiao and Qiqi Li, former graduate students at IU. Additional authors are professor Krishnan Raghavachari and graduate students Richard N. Schaugaard, Benjamin W. Noffke and Yijun Liu, all of the Department of Chemistry; Dongping Li, a visiting professor from Nanchang University; and Lu Liu, a visiting undergraduate from the University of Science and Technology of China.

More information

www.indiana.edu

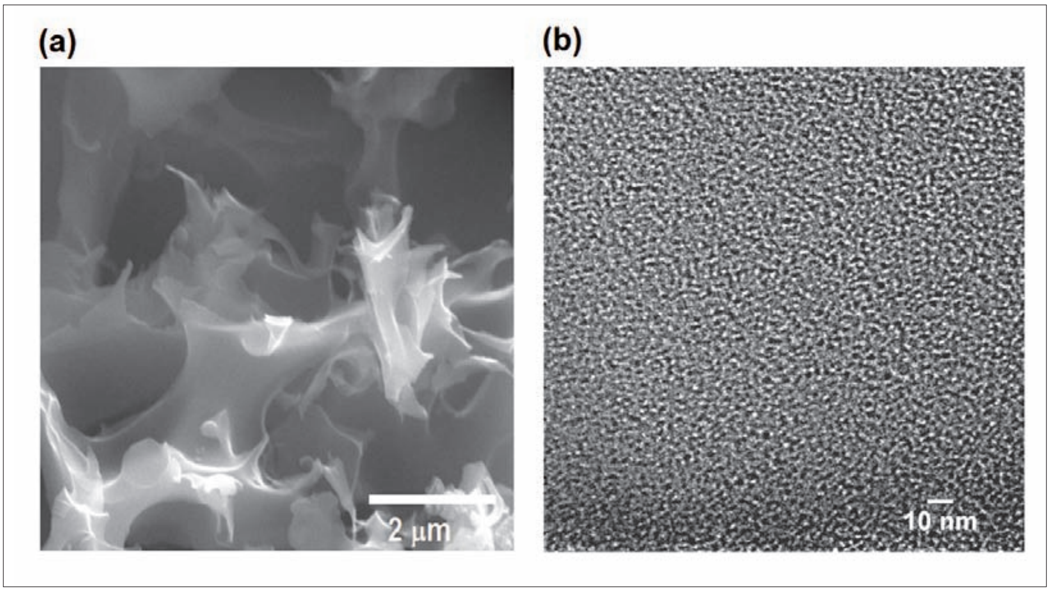
Rice University refines filters for CO2 capture

Study defines best materials for carbon capture or methane selectivity.

Natural gas producers want to draw all the methane they can from a well while sequestering as much carbon dioxide as possible, and could use filters that optimize either carbon capture or methane flow. No single filter will do both, but thanks to Rice University scientists, they now know how to fine-tune sorbents for their needs.

Subtle adjustments in the manufacture of a polymer-based carbon sorbent make it the best-known material either for capturing the greenhouse gas or balancing carbon capture with methane selectivity, according to Rice chemist Andrew Barron.

The specifics are in a paper this month by Barron and Rice research scientist Saunab Ghosh in the Royal Society of Chemistry journal Sustainable Energy and Fuels.



A scanning electron microscope image, left, and a high-resolution transmission electron microscope image show an activated, sulfur-containing porous carbon sample. The material created at Rice University can be tuned to balance carbon dioxide sequestration and methane selectivity. Courtesy of the Barron Research Group

"The challenge is to capture as much carbon as possible while allowing methane to flow through at typical wellhead pressures," Barron said. "We've defined the parameters in a map that gives industry the best set of options to date."

Previous work by the lab determined that carbon filters maxed out their capture ability with a surface area of 2,800 square meters per gram and a pore volume of 1.35 cubic centimeters per gram. They also discovered the best carbon capture material didn't achieve the best trade-off between carbon and methane selectivity. With the new work, they know how to tune the material for one or the other, Barron said.

"The traditional approach has been to make materials with ever-increasing pore volume and relate this to a better adsorbent; however, it appears to be a little more subtle," he said.

The lab made its latest filters by heating a polymer precursor and then treating it with a chemical activation reagent of potassium, oxygen and hydrogen, aka KOH. When the polymer is baked with KOH at temperatures over 500 degrees Celsius (932 degrees Fahrenheit), it becomes a highly porous filter, full of nanoscale channels that can trap carbon.

The ratio of KOH to polymer during processing turned out to be the critical factor in determining the final filter's characteristics. Making filters with a 3-to-1 ratio of KOH to polymer gave it a surface area of 2,700 square meters per gram and maximized carbon dioxide uptake under pressures of 5 to 30 bar. (One bar is slightly less than the average atmospheric pressure at sea level.)

Filters made with a 2-to-1 ratio of KOH to polymer had less surface area - 2,200 square meters per gram - and a lower pore volume. That resulted in the optimum combination of carbon dioxide uptake and methane selectivity.

The size of the pores was critical as well. Filters with maximum carbon uptake had the largest fraction of pores smaller than 2 nanometers. Bigger pores were better for methane selectivity.

"It appears that total pore volume is less important than the relative quantity of pores at specific sizes," Barron said. "Our goal was to create a guide for researchers and industry to design better materials.

"Not only can these materials be used for carbon dioxide separation from natural gas, but they are also models for carbon dioxide sequestration in a natural resource. This is the future direction of our research."

More information

www.rice.edu

Capture and utilisation news

CO2 Solutions announces collaboration agreement with Hatch

www.co2solutions.com

Companies collaborate on Valorisation Carbone Québec project and industrial projects integrating CO2 Solutions' proprietary technology.

Under the terms of the agreement, CO2 Solutions and Hatch will collaborate on delivering carbon capture systems integrating CO2 Solutions' low-cost, environmentally benign, enzymatic technology in large industrial environments. Within these projects, CO2 Solutions will license its proprietary technology and Hatch will provide its globally renowned engineering and project delivery expertise.

In conjunction with this agreement, Hatch announced that it is the provider of engineering services to the previously announced $15 million Valorisation Carbone Québec (VCQ) project. The objective of the VCQ project, which is being led by CO2 Solutions, is to demonstrate CO2 capture and beneficial reuse at large scale in an industrial facility, and to support the development of second generation reuse applications.

This project will centre on CO2 Solutions enzymatic capture technology and draw on the most promising reuse applications and development efforts worldwide. Hatch will play a key role in enabling CO2 Solutions to reach the objectives of the VCQ project and in jointly delivering demonstrated capture and reuse solutions.

From CO2 to fuel at Delaware

www.udel.edu

University of Delaware researcher wins DOE funding to produce alcohols from CO2 flue gas.

University of Delaware's Feng Jiao recently received a $1 million grant from the U.S. Department of Energy to investigate this alternative.

The grant, "Electrochemical Conversion of Carbon Dioxide to Alcohols," was awarded through the National Energy Technology Laboratory.

Jiao explains that the proposed technology is an integrated electrolyzer system that takes flue gas from the power plant and produces multi-carbon alcohols through a two-stage electrolysis process.

"This is the first integrated electrolysis system that can produce high-concentration alcohols using the CO2 from flue gas," he says. "Successful completion of this project will offer society a new approach to utilize greenhouse gas CO2 from coal-fired power plants as a chemical stock to produce valuable chemicals, such as ethanol and propanol. This is an approach that offers numerous benefits in terms of environmental and economic impacts."

The three-year effort involves electrocatalyst development, system design and evaluation, and investigation of compatibility with simulated flue gas from coal-fired power plants.

Feng Jiao joined UD in 2010. In addition to his faculty role as an assistant professor in the Department of Chemical and Biomolecular Engineering, he is affiliated with the Center for Catalytic Science and Technology.

His research interests include developing clean, sustainable and environmental friendly energy supplies by combining catalysis, materials science and electrochemistry to address current energy conversion and storage challenges.

In January 2014, he and his team reported the development of a nanoporous silver catalyst capable of electrochemically converting carbon dioxide to carbon monoxide with 92 percent efficiency. Silver offers high selectivity, costs much less than other precious metal catalysts, and remains stable under harsh catalytic environments. The breakthrough was documented in a paper published in Nature Communications.

Industrial collaboration to solve aerosol emission from CO2 capture

www.sintef.no

SINTEF, NTNU, Engie, Road, Uniper, TNO and TCM are collaborating on a solution to emissions from amine CO2 capture.

One of the most important research topics in post combustion CO2 capture is to control the emissions of amine and amine degradation products to the atmosphere. Aerosol-related emissions to air from amine absorbers for CO2 capture is a topic of increasing interest and concern.

Aerosolve is part of a larger scientific test campaign starting at Technology Centre Mongstad this summer, and is a good example of how several companies and organizations can collaborate with test activity at TCM, says Roy Vardheim, Managing Director of TCM.

The current project proposal is for 12 months, with startup at Technology Centre Mongstad in mid-2017. This serves the purposes of providing results pertaining to urgent issues in full-scale CO2 capture projects. The project receives 50% funding from Climit Demo.

It is commonly known that flue gas pre-treatment, absorber configuration, operating conditions and solvent selection are factors that can minimize these emissions, but there is currently limited theoretical and experimental understanding of the physical/chemical mechanisms involved in the process and certainly insufficient knowledge to allow the techno-economic optimization of aerosol control at industrial scale.

There are also contradictory results reported in literature as to e.g. effect of various pre-treatment options. Establishment of reliable continuous measurement methodology for absorber aerosols and online process monitoring is needed in order to increase the availability of high quality data, underpin model validation, assess the effectiveness of abatement options, such as the use of wet electrostatic precipitators and Brownian diffusion filter techniques, and ultimately deliver reliable process monitoring and control.

Validated theoretical models and generic tools for flue gas pre-treatment design will be important tools for future process optimization of design. Therefore, it is of importance to demonstrate suitable treatment options under real and relevant conditions. This work will lead to the insights how to develop and operate CO2 capture plants with emission levels within the given emission permits.

Transport and storage news

ADM begins operations for second Carbon Capture and Storage Project

www.adm.com

The Illinois Industrial Carbon Capture and Storage (ICCS) project, a partnership to safely and permanently store more than 1 million tons of carbon dioxide a year, has begun operations.

The project captures carbon dioxide, which is created as a byproduct at ADM's Decatur corn processing facility, and stores it safely almost a mile and a half underground in the Mt. Simon Sandstone. With the capability to store 1.1 million tons of carbon annually, ICCS is designed to demonstrate the commercial-scale applicability of carbon capture and storage technology in a saline reservoir. The project is currently permitted to operate for five years and has the potential to store up to 5.5 million tons of carbon dioxide.

This is the second carbon capture and storage project that ADM has helped to lead. Previously, the company removed and stored approximately a million tons of carbon over three years as part of the smaller-scale Illinois Basin – Decatur Project, led by the Midwest Geological Sequestration Consortium at the University of Illinois.

"We are extremely proud to be part of this important program," said Todd Werpy, ADM chief technology officer. "The technology that we are using in Decatur can be a model for reducing industrial carbon emissions around the world. We're pleased to be working with great partners in the U.S. Department of Energy, Richland Community College and the University of Illinois – Illinois State Geological Survey, and we're excited to move forward as we not only reduce our carbon emissions in Decatur, but also contribute to important research that will help other companies do the same."

"2017 is a watershed year for carbon capture in the United States. On the heels of the successful opening of Petra Nova in Texas, the Illinois Industrial facility serves as another example that large-scale CCS deployment works, is safe, and serves as a key component of a low carbon future," said Jeff Erikson, general manager of the Americas region with the Global CCS Institute.

Gassco awards study jobs for CO2 transport

www.gassco.no

Gassco has been commissioned by the Norwegian Ministry of Petroleum and Energy to clarify the basis for ship transport of CO2 from capture sites to the storage point.

Plans envisage CO2 being shipped by sea from capture facilities in eastern Norway to intermediate storage on the west coast. The greenhouse gas would then be piped to a subterranean store.

"We're very pleased to award contracts to Larvik Shipping and Brevik Engineering covering conceptual studies for transporting CO2 by ship," says Gassco CEO Frode Leversund.

"These companies provided the best tenders out of the five submitted. Further assessments of CO2 transport will make an important contribution to realising a full-scale Norwegian solution for carbon capture and storage (CCS)."

The Smeaheia area of the North Sea, located east of the Troll field and about 50 kilometres from land, has been chosen as the final storage site.

"Larvik Shipping and Brevik Engineering will now plan such transport in greater detail and with more exact cost estimates," Leversund explains.

"Both companies submitted good tenders, and we're now looking forward to developing a detailed decision base for the government.

"CCS, including a transport leg, could be an important part of the solution for cutting industry emissions, and will help to meet the goals of the Paris agreement."

Work done at the idea stage in 2015 and in last year's feasibility study shows that ship transfer will be flexible and appropriate in a start-up phase, with long transport distances and limited CO2 volumes.

If desirable, the vessels would be able to fetch the gas from other ports and the system can be scaled up with additional ships if the transport requirement increases.

The conceptual study is due to be completed in the autumn, with the decision base for the whole full-scale project scheduled for the autumn of 2018. That would allow the Storting (parliament) to take a possible investment decision in the spring of 2019.

Gassnova, the state-owned company for CCS projects, is responsible for incorporating this work into a complete CCS chain together with studies of capture and storage facilities. It recently awarded contracts for further studies of full-scale carbon capture to Oslo's Klemetsrud incineration plant, Norcem and Yara. The company is also due to enter into a contract with the storage operator before the summer.

IEA CLEAN COAL CENTRE

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