Carbon Capture Journal

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New and old CCS projects in Europe: What's different this time?

In comparison to previous waves of projects, the design and focus of new projects as well as the policy environment has changed, making the case for CCS as a key component in reaching the EUs climate objectives, says a paper from the International Association of Oil & Gas Producers.

In Europe, several new CCS projects aim to address clusters of industrial emissions, decarbonise hydrogen production and transport of CO2 for storage across borders. They will take place in hubs and clusters where different industries may share transport and storage infrastructure allowing for a cross-sectorial and cross-border industrial system. Coupled with hydrogen infrastructure, CCS can also deliver low-carbon hydrogen across sectors of the European economy.

CCS failed to live up to its potential during the previous investment cycle (2009-2015). The paper outlines the key changes in CCS projects and highlights what is different this time in terms of regulatory context and the development of new business models for CCS, making the case for CCS as a key component in reaching the EU's long-term climate objectives.

What's different this time?

The paper highlights several key differences that make the case for CCS in Europe:

• Innovation in CCS business models has shifted the focus away from single emission sources on to industrial clusters linked with CCS hubs, allowing for a better spread of risk and investment across the value chain and achieving economies of scale.

• Improved design of EU funding instruments, such as the Innovation Fund, may now help supporting CCS projects through improved risk-sharing, simple selection processes, stronger synergies between different programmes and streamlined governance and decision-making processes.

• Low-carbon hydrogen production with CCS allows for extending the climate benefits of CCS beyond the power sector, as hydrogen can support the decarbonisation of EU industrial, transport, power and heating sectors while revenues may underpin and finance the integrated CCS component.

• Finally, a higher CO2 ETS price will no doubt favour the economics of investments in new projects

Single industrial emitter vs. hub and cluster-based projects

The business model of CCS projects promoted in 2009-2015 was considerably different in comparison with that of projects promoted today. In earlier development phases, CCS projects were linked to a single industrial emitter, whereas today we see the development of CCS hubs linked with industrial clusters where emissions are captured from different installations which can benefit from a shared infrastructure.

Under this approach, risks, investments and support mechanisms can be better spread across the CCS value chain, as industrial installations, gas infrastructure companies, upstream E&P companies, and/or new state owned or regulated storage entities can have clear and coordinated roles for delivering and being compensated for capture, transport and storage activities. The shared approach to the transport and storage infrastructure also creates economies of scale, driving down unit costs for the CCS value chain.

Well-designed EU funding instruments

EU funding instruments have been revised to better support innovative, large-scale decarbonisation projects. In 2018, the European Court of Auditors published a special report where the lack of success in reaching the ambitious goals of the NER300, a funding instrument established in 2009 based on ETS allowances, was subject to an audit. It emerged that at the time of the NER300, a lack of certainty around policies, regulations and public financial support affected the financial viability and progress of innovative low-carbon energy demonstration projects.

Moreover, the low price of the ETS negatively impacted the firepower of the NER300, bringing the expected largest possible size of a grant from €675 million to €337 million, thus representing a major setback for capital-intensive CCS projects that required greater support.

Compared to the past, there is stronger coordination between the Commission and Member States. As an example, in 2015, the Commission implemented the SET-Plan, where a dedicated working group on CCS and CCU now provides the Commission, Member States and stakeholders an opportunity to update on the progress of projects and address policy and economical barriers.

Extending the climate benefits of CCS beyond the power sector

Natural gas can be reformed to hydrogen with CCS to support the decarbonisation of the EU industrial, transport and heating sectors in addition to power generation. The versatility of hydrogen as an energy carrier is shown by its potential to tackle difficult emissions across various sectors of the economy.

In 2018, six new large-scale CCS projects were listed in the Global CCS Institute database - all are in Europe, and all are related to the production of hydrogen from natural gas with CCS. The hydrogen revenue from such projects can help underpin and finance the integrated CCS component

More information

The full report is free to download:
www.oilandgaseurope.org

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Front cover: Researchers from Curtin University and Lawrence Berkeley National Laboratory inspecting the Surface Orbital Vibroseis (SOV) installed at the Otway National Research Facility

Back: INOVA vibroseis truck providing the seismic source to baseline the new monitoring technology being deployed and tested at the Otway National Research Facility (pg. 15)

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Aker Solutions' carbon capture tech approved by DNV GL

Aker Solutions is working together with Norcem HeidelbergCement to realise the world's first commercial-scale carbon capture facility for use in cement production.

Aker Solutions' mobile test unit in operation at the Norcem cement plant in Brevik, Norway

Globally, the cement industry accounts for 5-7 percent of total CO2 emissions – from all industries and sectors. Aker Solutions' post-combustion technology is intended to capture and liquefy 400,000 tons per year of the released carbon dioxide at the Norcem plant in Brevik, south of Oslo.

The captured volume is equivalent with the removal of about 200,000 fossil cars from Norwegian roads. Once the technology is applied this will contribute to Norway's target of becoming a low-emission society by 2050.

The project is one of two contenders for funding in the Norwegian government's demonstration project programme. Gassnova, the country's state agency for implementation of carbon capture and storage projects, initiated the projects which will apply carbon capture technology at scale.

The projects are now mature to the point that the Norwegian parliament could make a decision on whether to go forward with one or both projects later in 2020.

The Norcem plant is a good candidate for industrial-scale CCS. Cement flue gas contains about 18 percent CO2 by volume. Initial studies have demonstrated that the carbon capture plant will be compact and cost-efficient. Heat integration studies have concluded that about half of the CO2 emission from the cement plant in Brevik can be captured by utilisation of waste heat, by heat recovery from the cement production and the planned capture facilities.

Cost of heat supply is normally one of the highest operating cost factors for the capture plant, but for the Norcem plant the operating cost of heat will be almost zero.

The cement plant location is also ideal for further intermediate storage and ship transportation of liquefied CO2.

Qualified Technology

Last week, the project received a further boost as DNV GL announced it had approved as qualified the technology for a full-scale demonstration project.

"We have now completed all necessary studies, tests and preparations and are ready to take the next step towards realizing a full-scale industrial plant," says Oscar Graff, head of Aker Solutions' CCUS business.

Aker Solutions is a Norwegian engineering and technology company with strong roots in the oil and gas industry – where it started working on CCS solutions offshore in the mid-1990s. In the past 15 years, it also developed its patented amine-based CCS solutions, which have been applied at the Technology Centre Mongstad in Norway.

The company started carbon capture tests with its mobile test unit (MTU) at the cement plant in Brevik back in 2014. The capture process performance was carefully monitored during various operating condition of the plant for 18 months, using the same robust solvent. The test runs helped reduce the risk and cost estimates for the project. Norcem then selected Aker Solutions as technology provider for the Norcem CCS Demonstration Project.

DNV GL engaged with Norcem and Aker Solutions to verify the application of DNV GL's recommended practices Technology Qualification and Qualification procedures for carbon dioxide capture technology at the plant.

Novel elements of Aker Solutions' carbon capture technology and potential technological risks were evaluated and mitigation identified, DNV GL said. Documentation was reviewed to provide a better understanding of the technology and the specific application and conditions at Norcem's plant.

"The extensive experience and systematic qualification procedures from DNV GL have been a great support for our engineers in our technology development," said Graff. "The procedure is an excellent tool to identify risk elements and to propose how to solve them."

More information

By Oscar Graff, Head of CCUS at Aker Solutions

www.akersolutions.com

From greenhouse gas to a high-tech resource

Within the NECOC Research Project, a test facility for conversion of CO2 from the air into solid carbon is being built at Karlsruhe Institute of Technology in Germany.

At Karlsruhe Institute of Technology (KIT), the NECOC research project is aimed at building a unique test facility for active reduction of atmospheric carbon dioxide (CO2). The world's first container-scale facility of this type is to convert CO2 contained in ambient air into highly pure carbon black powder that can be used as a resource in industry.

Project partners are INERATEC GmbH, a spinoff of KIT, and Climeworks, a spinoff of ETH Zurich. The research project, scheduled for a duration of three years, is funded with a total of EUR 1.5 million by the Federal Ministry for Economic Affairs and Energy (BMWi).

With the Paris climate agreement of 2015, the global community has committed itself to limit global warming to below 2°C by the end of the century. To reach this goal, however, global efforts to reduce greenhouse gas emissions will have to be complemented by solutions for removing already emitted CO2 from the atmosphere.

"Our project approach consists of removing CO2 from the atmosphere and converting it into carbon black, i.e. highly pure carbon in powder form," says Professor Thomas Wetzel of the Institute of Thermal Process Engineering (TVT) and Head of the KALLA Karlsruhe Liquid Metal Laboratory of the Institute for Thermal Energy Technology and Safety.

"In this way, a hazardous greenhouse gas will be converted into a raw material for high-tech applications. Carbon black can be used in electronics, printing, or construction."

Test Facility combines several process steps

The test facility to be set up within the NECOC research project will combine the following process steps: By means of an adsorber, CO2 is first captured from ambient air (direct air capture, DAC). Together with renewable hydrogen, it is then converted into methane and water in a microstructured reactor.

The methane produced serves as a carbon carrier in the downstream process and is passed into a bubble reactor filled with liquid tin. In the ascending methane bubbles, a pyrolysis reaction takes place, by means of which methane is decomposed into its constituents. These are, on the one hand, hydrogen, that is directly fed back to methanation and, on the other hand, solid carbon in the form of microgranular powder, i.e. carbon black.

All process steps have already been studied and developed up to the laboratory scale by the researchers involved. "We know the individual modules well," says Dr. Benjamin Dietrich (TVT), project coordinator of NECOC.

"However, they have never been realized together in an integrated facility so far. This is the first time worldwide. Skillful integration

In the NECOC research project, an integrated pilot plant is being built to test a new process for reducing the greenhouse gas CO2 in the atmosphere. The process will produce carbon black – a high-quality, solid carbon. (Photo: Moritz Leg)

of the process modules and correct process conduct will be decisive for the energy efficiency of the process and the quality of the carbon black product.“

The major advantage over previously proposed concepts to reduce atmospheric CO2, such as carbon capture and storage methods (CCS) to store CO2 in deep rock layers, con

sists in this end product. “Solid carbon is far less difficult to handle than CO2 and can even be used as a resource. So far, carbon black has been produced mainly from fossil petroleum. That is why our process represents a technological approach for a sustainable future in several respects. It combines the direct contribution to solving the climate problem with a process for post-fossil resource supply.”

The test facility will be built on the premises of KIT. It is aimed at demonstrating operation over a longer term. Future extensions of the facility are planned to increase the performance per container and to enable parallel operation of many facilities.

The KIT partners of the NECOC research project (NECOC stands for NEgative Carbon diOxide to Carbon) are the Karlsruhe Liquid Metal Laboratory (KALLA), a facility of the Institute for Thermal Energy Technology and Safety (ITES), and the Institute of Thermal Process Engineering (TVT). KIT will not only coordinate the project and operate the facility, it will also contribute pyrolysis technology. NECOC is funded with a total of EUR 1.5 million for a duration of three years by the Federal Ministry for Economic Affairs and Energy.

Industry partners contribute innovative technologies

Setup of this new kind of test facility is the result of close cooperation with two industry partners responsible for specific modules of the container facility. Climeworks Germany GmbH concentrates on the DAC process. “Our know-how lies in capturing CO2 from ambient air. This process, however, is always associated with the question of what happens with the CO2 after it’s captured,” says Dr. Dirk Nuber, Director of Climeworks Germany GmbH. “Conversion of CO2 into a storable resource is very close to an ideal solution.”

INERATEC GmbH has specialized in innovative, microstructured reactors to convert regeneratively produced synthesis gases into climate-neutral liquid fuels or chemical products. ”NECOC is aimed at removing CO2 from the atmosphere on a permanent basis,” says Dr. Tim Böltken, one of the founders of the startup. “With our reactor technology, we contribute to enabling this new process pathway for negative emissions,” Böltken adds.

More information

www.tvt.kit.edu/21_3547.php


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Integrating the climate challenge with the circular carbon economy

On 25 - 26 February 2020, 600+ government officials and leading private sector professionals working on CCUS project development and climate change initiatives from over 16 countries came together for Saudi Arabia's inaugural International Carbon Capture, Utilization and Storage Conference. By Janet Pinheiro, Saudi Aramco.

At a gathering of energy leaders Saudi Arabia called on global cooperation for the rapid scale up of carbon capture utilization and storage (CCUS) to address climate change, and urged the adoption of the "circular carbon economy" concept as an inclusive path for addressing the dual challenge of meeting the world's growing energy needs while delivering on climate commitments.

Ahead of a ministerial panel, which included ministers from Bahrain, the UAE, Singapore, and the secretary general of OPEC, Saudi Arabia Minister of Energy HRH Prince Abdulaziz bin Salman bin Abdulaziz Al-Saud, reaffirmed the need to move faster on greenhouse gas emission reduction efforts globally.

He said it was vital for the world to undertake CCUS, and appealed for the removal of investment barriers, describing CCUS as a "tried and tested technology," which can have a positive impact on emissions reduction, and ripe for large-scale deployment.

Saudi Aramco president and CEO Amin Nasser participated in a "Thought Leaders Views on the Climate" panel discussion moderated by CNN, which included the CEOs of ADNOC and Schlumberger, and the deputy secretary general of the United Nations Framework Convention on Climate Change.

Nasser echoed the call for global cooperation saying, "We need to work together and collaborate to find solutions to reduce emissions."

Energy leaders met to discuss cooperation on scaling up CCUS and the 'circular carbon economy' at Saudi Arabia's inaugural International Carbon Capture, Utilization and Storage Conference

Numbers speak for Saudi Aramco

Referring to Saudi Aramco's emissions mitigation efforts, Nasser explained that years of implementing best-in-class technology and reservoir management practices was behind the company's leadership in low carbon intensity, pointing to efficient management of produced water through inflow control devices as an example.

"You have to look at it from a full cycle basis, otherwise you cannot achieve the results that we have in terms of low methane and CO2 emissions," he said.

Hydrocarbon research support

Nasser said that currently most government support globally was directed toward renewables, whereas hydrocarbons will remain a part of the energy mix for a long time, therefore, regulators should incentivize investments into CCUS technologies to help reduce emissions from hydrocarbon sources.

Adding that Saudi Aramco has been working with the auto industry to design more efficient engines, and to enable carbon capture on trucks, he said, "We have the responsibility to provide cost-effective energy in a world where nearly 3 billion people do not have access to clean cooking, a third of vaccines in Africa are wasted due to a lack of cooling, and half the people have never traveled on an airplane."

Circular carbon economy

In a world needing to decrease its greenhouse gases, there is a dual challenge globally to deliver more energy with fewer emissions

More energy is needed for the nearly 1 billion people with no electricity access, plus growing energy demand from the world's increasing population.

The conference emphasized the concept of the circular carbon economy, an approach designed to reduce, reuse, recycle, and remove carbon.

Conference chairman and Saudi Aramco chief technology officer Ahmad O. Al-Khowaiter explained a circular carbon economy model was a sustainable, pragmatic and cost-effective approach to achieve ambitious climate goals.

"We must adopt the principles of a circular carbon economy, emulating the balance of nature in its production, use and reuse of energy and materials," said Al-Khowaiter. "This is in contrast to the linear economy concept, which results in a lot of waste and requires significantly greater resources."

Technology is a key enabler to all four elements — reduce, reuse, recycle, and remove — of the circular carbon economy, with CCUS being the most mature and impactful technology.

CCUS $2.5 billion market

The United Nations Intergovernmental Panel on Climate Change has advised that the global climate goals will not be achieved without CCUS playing a central role.

Great strides have been made with the cost and efficiency of CCUS, and the technology can also be applied to industries other than oil and gas.

CCUS is a proven technology with a $2.5 billion market, resulting in the capture of 32 million tons of CO2 per year.

More than 2,000 carbon capture plants are needed by 2040 to meet global emission reduction targets.

"The concept of the circular economy offers a new way of approaching climate goals that implicitly values all options and encourages all efforts to mitigate carbon accumulation in the atmosphere," said Al-Khowaiter, adding that truly closing the emissions loop requires CCUS in addition to other technologies.

"To achieve the desired impact CCUS will need a 40% to 50% annual growth rate until 2030 to get to 1 billion tons of CO2 captured per year," he said.

"We have done this before, with solar and wind energy. We can do it again, if we work together to create an environment of collaboration, cooperation, and a level playing field for all energy sources."

Added benefit of hydrogen

Bashir M. Dabbousi, Saudi Aramco's director of Technology Strategy and Planning, chaired a "Hydrogen and CCUS" panel, discussing how CCUS enables production of low carbon hydrogen at industrial scale.

"Hydrogen is the fuel of today, not the fuel of the future," said Dabbousi, adding people easily understood that hydrogen is a clean fuel, "because when it burns it only produces water."

Hydrogen is considered an ideal energy carrier for deep emissions reductions in hard-to-decarbonize sectors such as heavy-duty transport, heating, and industrial applications

Also participating from Saudi Aramco on the conference stage was EXPEC ARC manager Ashraf M. Al-Tahini on a "Lessons from Large-Scale Demonstration Projects" panel, which was chaired by Environment Protection Department manager Omar Abdulhamid, Technology Strategy and Planning Department CCUS lead Tidjani Niass on a "CCUS Value for the Low Carbon Economy" panel, and Research and Development Center chief technologist for carbon management Aqil Jamal on a "Carbon Removal from Air" panel.

Circular carbon economy concept explained

Continual use of resources rather than disposal as waste.

The "Circular Carbon Economy" model is a key enabler for achieving deep greenhouse gas emissions reductions in hard to decarbonize sectors such as heavy-duty transport, aviation, and industry.

Inspired by how our planet's circle of life works — nature's balanced and ongoing system of taking and giving back to the Earth — the circular carbon economy approach moves away from a linear economic model where materials are used then disposed, to a more circular model through the reduction, reuse, recycling, and removal of carbon dioxide, and other greenhouse gas emissions.

Reduce - amount of carbon entering the system

Reuse - utilizing CO2 in gaseous form

Recycle - putting CO2 in chemicals and materials

Remove - storing CO2 permanently underground, including nature based solutions

More information

www.saudiaramco.com

www.iccusksa.com

LEILAC project moves to Phase 2

After very good results from the first phase of the project, HeidelbergCement is starting the further development and scale-up of the LEILAC technology (Low Emissions Intensity Lime And Cement) together with the Australian technology company Calix and a European consortium.

The patented LEILAC process makes it possible to capture high-purity CO2 from cement production via a separate exhaust gas stream and to utilize it for other purposes. Two-thirds of the CO2 emissions of a cement plant are process-related emissions generated during the heating of limestone and are therefore unavoidable.

The LEILAC-2 demonstration plant will be a four-fold scale-up of the LEILAC-1 pilot plant, currently undergoing operational testing at HeidelbergCement's Lixhe cement production facility in Belgium. Early results from the pilot have proven the technology concept, and work continues on the gradual increase in operational throughputs, temperatures and durability testing in a test program that will run until the end of 2020.

Central aspects of the LEILAC 2 project are the further scale-up of the technology to an industrial level, the full process integration into an existing cement plant, and the heat supply of the plant from renewable energies for climate-neutral CO2 separation. LEILAC-2 will be officially launched on April 7, 2020 and will run to the end of 2024 at a working HeidelbergCement cement plant in Europe.

Like its predecessor LEILAC 1, the LEILAC 2 project is based on Calix's innovative calcination technology and is supported with 16 million euros from the EU research funding programme Horizon 2020. As part of LEILAC 1, a CO2 separation pilot plant with a capacity of 25,000 tonnes per year was constructed at the HeidelbergCement plant in Lixhe, Belgium.

Calix's commercialisation strategy for its LEILAC technology involves proof of demonstration at the LEILAC-2 scale by 2025, after which licence or royalty arrangements will be sought from those wishing to use the technology, delivered via engineering and technology partners. If fully proven at demonstration scale, LEILAC should have significant cost and operating advantages over competing technologies such as amine CO2 capture and oxyfuel.

In Phase 1 a CO2 separation pilot plant with a capacity of 25,000 tonnes per year was constructed at the HeidelbergCement plant in Lixhe, Belgium

Key objectives of LEILAC-2 are:

• Construction of a demonstration plant that will aim to capture around 20 per cent of a full-scale cement plant's process CO2 emissions (100,000 TPA of CO2), equivalent to 100 per cent of a large lime kiln's process emissions, for minimal energy penalty other than compressing the CO2.

• Successful demonstration of up to a four-times scale-up of the technology for around twice the capital cost of the LEILAC-1 facility, confirming cost-efficient CO2 capture for the lime and cement industries.

• Prove the effective retrofit and full integration of the technology into a cement plant's operations.

• Demonstrate the efficiency and stability of the complete cement-kiln process and high-quality clinker output when integrating Calix's CO2 separation technology.

• Showcase a modular, replicable, retrofit design for accelerated commercial deployment that delivers flexible scalability for varying operation size and configurations, agility to adopt the technology and decrease emissions progressively, and a broad range of options for captured CO2 utilisation and sequestration. These factors can eliminate the need for large capital expenditure and significant asset write-downs.

• Demonstrate the operation of direct separation kilns for lime and cement using renewable sources of energy such biomass and renewable sources of electricity, bringing the running of the plant to net zero CO2 emissions and enabling a move away from high carbon-emitting gas or coal-fired plants.

• Enable lime and cement kiln processing plants with a cost-efficient solution to effectively use intermittent renewable energy sources, with rapid ramp up/down rates leveraging electricity and load balancing techniques for grid stability.

More information

www.project-leilac.eu

Operation at Technology Centre Mongstad to continue until 2023

The Government of Norway has proposed a continuation of the financial support for the Technology Centre for CO2 capture at Mongstad (TCM) until end of 2023.

The Technology Centre for CO2 capture at Mongstad (TCM) in Lindås municipality in the Vestland county has for several years been an important arena for the development of the CO2 capture technology. The technology centre is operated by the state enterprise Gassnova and the private companies Equinor, Shell and Total.

The state and the industrial companies have now agreed to continue the operation of TCM from the expiration date of the current agreement until the end of 2023.

"The technology centre at Mongstad is an important part of the Norwegian carbon capture and storage (CCS) efforts, making significant contributions to the development of a necessary tool to mitigate climate change," said Norwegian Minister of Petroleum and Energy, Tina Bru.

"I appreciate that we have reached an agreement with the partners Equinor, Shell and Total to continue the operation of the facilities. The industrial commitment to TCM is very important for the government. The new agreement provides a good foundation to continue the positive development at TCM."

The agreement provides a framework to diminish the reliance on both state aid and contributions from the industrial owners to finance the future operations of the TCM facilities. This is to be achieved through several measures, including contributions from additional future owners of TCM DA, reduced operational cost, cost sharing contribution from the users of the TCM facilities, third parties paying for specific services from TCM and sponsors of certain campaigns.

"We believe that we might be able to bring in new industrial owners as early as in August, at the start of the new operational period," added Bru.

"We see an increasing interest from international actors to test their technology at TCM.

Technology Centre Mongsaatd will receive further financial support from the Norwegian Government allowing it to continue operations until 2023

With the new agreement in place, TCM can continue the dialogue and cooperation with these actors to push forward the development of cost-effective capture technology."

Since 2012, TCM has played an important role in testing, verifying and demonstrating a number of CO2 capture technologies on an industrial scale, and has garnered considerable recognition from companies and partners worldwide.

Contract with OGCI Climate Investments

Technology Center Mongstad (TCM) has signed a contract with OGCI Climate Investments – the $1B+ investment fund of the Oil and Gas Climate Initiative (OGCI) – to test carbon capture technology at TCM's facilities in Norway in March 2020

TCM has provided advisory services to OGCI Climate Investments on the assessment of carbon dioxide capture technologies since 2019.

On 28th February, OGCI Climate Investments announced the formation of a consortium of OGCI members – BP, Eni, Equinor, Shell and Total, with BP as operator – to develop the Net Zero Teesside project to deliver the UK's first zero carbon cluster. From the mid-2020s, the project plans to capture up to 6 million tonnes of carbon dioxide emissions each year, equivalent to the annual energy use of up to 2 million homes in the UK.

The CO2 capture test being conducted by TCM this month will be an important step to enabling the project to achieve these goals.

More information

tcmda.com

www.oilandgasclimateinitiative.com

Will our future world be NICE?

Philippe Fonta, Founder and CEO of SCRUM-consult, argues that we should build an international multi-stakeholder collaboration to scale up the research, development and commercialization of opportunities related to CCUS under a common platform, the New International Carbon Economy (NICE), that rebrands CO2 as a fuel rather than a waste product.

In the middle of the current Covid-19 crisis, a lot of voices have become louder, promoting a systemic change in our globalized organization, claiming that the world of tomorrow cannot and should not be the world of yesterday. Evaluating the unattended reduction in CO2 emissions caused by the imposed sanitary lock down in most countries and the subsequent economic downturn, environmentalists point out that if we want to avoid consequences of climate change, that would be much more dramatic than the ones of Covid-19, we would need to adopt a new organization that would reduce the global CO2 emissions by at least the same amount, at least, year after year.

The diagnostic – CO2 atmospheric concentration hits record levels

Since the first industrial revolution, our economy is based on carbon-related products and services, where carbon comes exclusively from fossil resources (coal, oil and gas). Initially considered as abundant, these resources are available in finite quantities in the Earth underground and some experts consider that the peak oil has already been reached, threatening the future of some industries.

In addition, the use of carbon-based materials (as a fuel or a raw material) emits CO2 into the atmosphere, in quantities that keep increasing, thus contributing to climate change. Furthermore, the long life and residence time of CO2 generates a tremendous inertia in the concentration of atmospheric CO2, so that the natural sinks (forest and oceans) cannot absorb in enough quantities to create an equilibrium with regards to the natural greenhouse effect.

Scientist estimate that to hold the rise in global temperature to 1.5 degrees Celsius over the preindustrial baselines (the ambitious objective of the Paris Agreement), humanity should stabilize the atmospheric concentration of CO2 to about 350 parts per million (ppm). The latest estimations (in February 2020) indicated that this concentration reached a record level of 416 ppm and if the current crisis will reduce the overall CO2 emissions in 2020, it is very unlikely that the concentration will drop, because of the above-explained inertia. As a consequence, if we are serious about climate change mitigation, we don't just have to reduce CO2 emissions, but we have to pull some CO2 out of the atmosphere and create so-called "negative emissions". Carbon Capture and Storage (CCS) by which some of the CO2 produced by the economic activity would be captured and permanently stored comes into play in this long-term scenario.

Some commonly shared solutions

As fossil resources are mainly used to produce energy, the obvious immediate solution one could think of is to replace the source of energy from fossil fuels to more electricity and hydrogen. Electricity could be produced from nuclear of renewable energies, thus being CO2-free, even if it is not fully the case when we consider the full life cycle of manufacturing photovoltaic panels, wind turbine or nuclear plants.

This electricity, produced with no CO2 emitted, could then be used for heating and cooling buildings and individual housings, for ground mobility and for applications where electricity provides enough power for manufacturing and services. Similarly, hydrogen could come from solar-powered electrolysis (pulling hydrogen directly out of water) and be CO2-free, contrary to the most common way of making it today (from steam reforming of natural gas). However, the electrolysis process requires a lot of energy and is very costly, so that solar-powered energy is today preferably used for other applications.

Even if these new sources of CO2-free energy could be increasingly developed, that radical shift may not be done fast enough and at scale to meet the Paris agreement. For instance, even if several European countries have decided to ban the production and sale of thermal cars in the next decades and replace them with electric, hybrid or hydrogen-driven cars, the time to have these news vehicles representative of the average fleet will take time and the fate of the retired thermal cars will have to be regulated.

If they are sold to developing countries, the CO2 emissions will be simply displaced and will keep contributing to the overall atmospheric concentration. In addition, the higher cost to produce CO2-free energy means that it might not be affordable for all countries in the world, especially if these countries have available and cheap fossil fuels in their underground. Countries like China and India, for instance will continue using these resources to grow and develop their economy.

Finally, some sectors will have extreme difficulties to exist in a completely decarbonized world. They are called "hard-to-abate" sectors by the Energy Transitions Commission, as they are difficult-to-decarbonize parts of the economy: this is the case for:

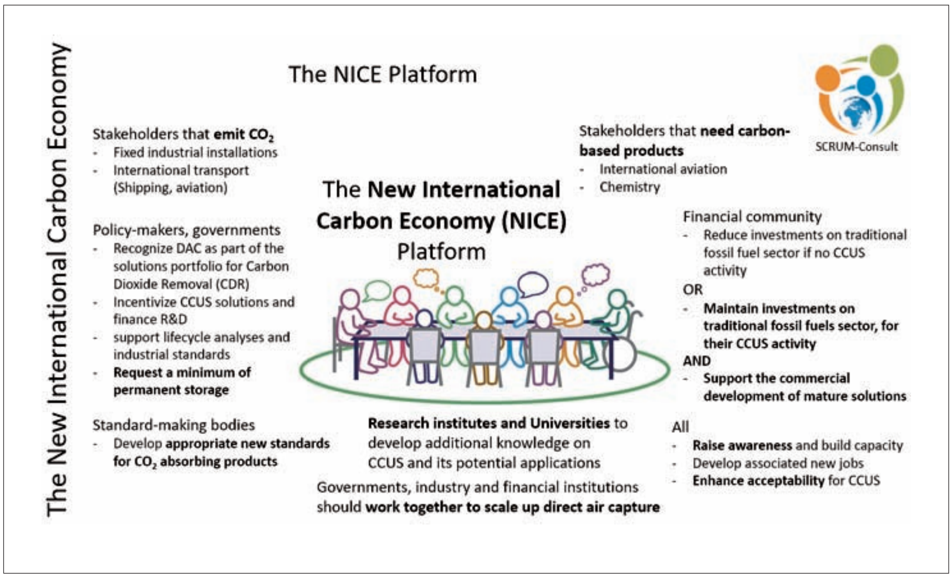
• aviation (for which synthetic fuels will be necessary – and hydrogen is also indispensable), an essential tool for our modern economy (as the Covid crisis also emphasized) ;

• industry sectors (cement, steel) that are emitting CO2 from their manufacturing process itself and are suppling products that will still play a major role in the future for cites and infrastructure development ; and

• organic chemistry and plastics sector, or which decarbonizing seems impossible by essence.

Using carbon from captured CO2

Of course, decarbonizing the whole economy



must remain the ultimate objective but this should not be considered as creating a completely new economy where carbon would be fully absent. For some sectors that currently need carbon and will most probably need it in the future (organic chemistry and its derived products, synthetic fuels…), rather than finding substitutes to carbon-based processes, it would be relevant to find substitute for the carbon used in them (carbon in the air rather than carbon on the ground).

In that context, industrial carbon capture should be further developed to remove CO2 from atmosphere at a speed and scale that are much higher than with natural sequestration (forest, oceans). CO2 can either be pulled out of flue gases (from heavy industry plants) or of the ambient air through Direct Air Capture (DAC). This technology is fully achievable but is costly (a few hundreds of $US per tonne of captured CO2) and energy intensive too.

The CO2 could then be permanently stored (in the ground), making negative emissions or being used for enhanced oil recovery (EOR), which is the only industrial use of CO2 that has reached appreciable scale. However, burying permanently CO2 in the ground does not bring economic revenue: in the absence of a global price on carbon (that would be established to mitigate climate change) or of financial incentives, the extra cost of capturing CO2 is not economically compensated, thus leaving this solution to some niche markets.

An additional opportunity would be to use the captured CO2 (CCU) and bring it back into the economy, in a sort of circular economy of carbon. According to a recent stud made by the Center for Climate and Energy Solutions (C2ES), the biggest CO2 usage potential lies in building materials (cement and aggregates) and fuels (synthetic and algal).

Aggregates could be made by converting CO2 into solid mineral carbonates like calcium carbonate (CaCO3), through a process called CO2 mineralization and then incorporated in concrete for instance, and CO2 could also be substituted for water in “curing” concrete during its mixing, resulting in a similar mineralization. This “curing” process, already used by companies like Solidia and CarbonCure makes the resulting concrete even stronger, in addition to saving lots of water.

According to some estimates, carbon capture and utilization (CCU) is a potentially $1 trillion market by 2030 and could provide a push for carbon capture. It could reduce emissions (if CO2 is stored in durable products like concrete for a very long time) and substitute for carbon-intensive processes (fossil fuels), thus avoiding emissions that would otherwise have occurred if using carbon from underground.

The New International Carbon Economy (NICE)

The current Covid-19 crisis illustrated that although the tremendous reductions in CO2 emissions are to be appreciated, the living conditions imposed to achieve them are certainly not the ones we strive for and not the ones we want to leave to the future generations. At the same time, environmental stakeholders claim that this is a good opportunity to change paradigm and develop a new world in which carbonated industries would be reduced, if not stopped, because of climate change imperatives.

The alternative option is clearly to speed up and scale up the use of captured carbon. But we need to move from niche opportunities towards a mainstream activity by gathering all relevant stakeholders in a common platform: the New International Carbon Economy (NICE).

The graph above indicates how and why every stakeholder should be involved and how it could contribute to enhancing the full potential of this new source of carbon.

On average, $400 Billion is invested by the financial community in supporting fossil fuels companies. A strong pressure develops to lobby this community for divesting their money from this sector but an alternative would be that this money be channeled in new CCUS projects within these sectors and in cooperation between sectors. That would enable some of them to transition to a new type of business, progressively dropping their activity with traditional fossil fuels.

Policymakers and governments should elaborate regulatory frameworks to support the development of CCUS. For instance:

• for each amount of captured CO2, part of it should be permanently stored (geological storage in saline aquifers, EOR, mineralization…) to create negative emissions ;

• Research and Development (R&D) should be financially supported as it was the case in initial times for photovoltaic solutions for instance. This can be through finance mechanisms or fiscal measures like the 45Q in the USA ;

• Life cycle analyses and industrial standards will have to be developed for the use of products (concrete, fuels) based on captured CO2 ;

• Government procurement should be used to create substantial markets for these alternative products ;

• Direct Air Capture (DAC) should be recognized as part of the solutions portfolio for Carbon Dioxide Removal (CDR).

Should DAC be developed to become a mainstream activity (some companies like ClimeWorks expect to remove 1% of atmospheric CO2 every year in 2025), a real NICE system could be put in place, with carbon capture from DAC being the new fuel of the carbon-based economy. It has a lot of advantages:

• It is geographically agnostic: wherever a CO2 molecule is emitted, due its long residence time in atmosphere, this molecule can be found in another part of the atmosphere. As a consequence, CO2 could be potentially captured, through DAC, everywhere in the world: its availability would not depend on any country's price or production policy, and it could be captured close to where it would be used, reducing the transportation costs and logistics. It could then provide energy in remote or hardly accessible parts of the world, including to support the development of these regions

• Atmospheric CO2 would be the only fuel for which the resource is increasing while the economy is growing, thus providing an infinite source of fuel to feed the current and future economy

Conclusion

If we want our future economic system to be NICE, it will be crucial to convince all stakeholders and enhance acceptability for these technologies by forging public opinion and policymakers' interest.

Words are essential in this communication and capacity building exercise and positive thinking words will be more helpful than conservative or acronymic ones (with no direct meaning). CCUS should be abandoned as it conveys some negative thinking through the world "capture" (as our brain is used to seeing "capture" associated to something negative or violent, definitely against us).

"Carbon" is consequently considered as a waste product and everyone knows that the most efficient way to manage waste is to avoid its production, thus maintain our spirit in reducing CO2 emissions only, that prove to be insufficient to solve the Climate Change problem.

With NICE, carbon is no longer a waste but a fuel (renewable, with resources infinite and equally shared), full integrated in a circular economy approach.

Our future, indeed, can and should be NICE.

More information

www.scrum-consult.com

Global CCS Institute – how to scale up the CCS market

The Global CCS Institute has been evaluating what factors are proving most helpful getting projects into operation, and how to increase the survival rate of planned projects. By Karl Jeffery

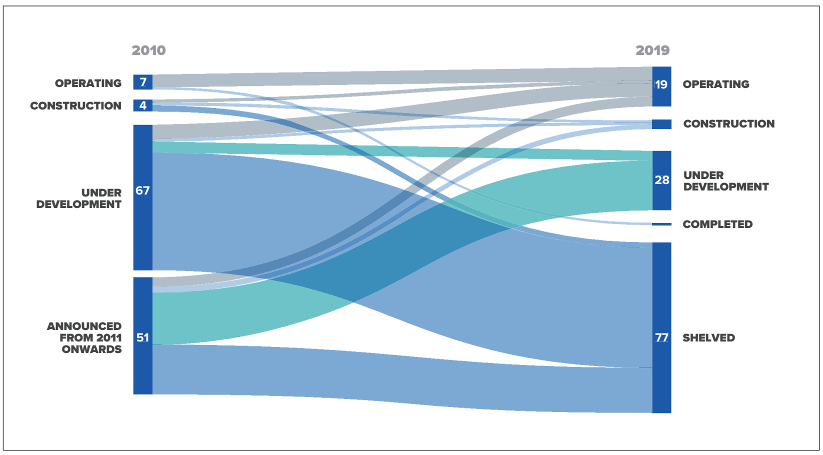
The Global CCS Institute (GCCSI) has produced a study on the best way to get more CCS projects in operation, and the best way to increase the survival rate of planned projects.

As of the end 2019, GCCSI calculates that there were 51 large scale projects altogether, of which 19 were in operation, 4 in construction, 10 in advanced development, 18 in early development. There are a further 39 projects in the "pilot" stage".

Most projects already in operation are in North America, particularly the US – which GCCSI attributes to a mix of industry knowhow, revenue from EOR, a supportive CCS policy and established CCS regulation.

Out of the 19 facilities in operation, the majority of these are in applications which have lower capture costs than power generation. 10 of the 19 are in gas processing, 2 in fertiliser, and 1 in ethanol, where typical capture costs are $25 / tonne, GCCSI says.

They all use pipelines for transporting CO2 (rather than shipping), and 14 of the 19 use the captured CO2 for enhanced oil recovery. So only 5 of the 19 are pure storage.



Changes in the large-scale CCS facility pipeline 2010-19 from Scaling up the CCS Market report

The CCS projects which are under development and close to being in operation have a broader range of characteristics, such as cement, waste to energy and chemicals. They don't rely on pipelines for CO2 transport, some use ships and barges.

In the projects which are in the early stage, and which "haven't even entered the funnel", we see a broader range of ideas for sourcing CO2, and different options for transport, such as rail and road. This diversification is "very healthy when looking to maximise the feed rate," says Angus Gillespie, manager, European affairs with GCCSI, and a former manager of special CO_2 projects with Shell.

The biggest factors in growing the feed rate are probably having a supportive CCS and regulatory framework, and availability of storage, GCCSI says. It has started scoring 50 countries for 70 different criteria for how well they provide such an enabling environment, as a "Readiness Index".

The 5 highest scoring countries account for 70 per cent of all of the projects in the pipeline today - US , Australia, Canada, UK and Norway, says Alex Townsend, senior consultant, economics with the Global CCS Institute.

The US scores particularly well with its 45Q tax credit and changes to carbon regulation in California.

The scheme currently has a condition that projects must enter the construction phase by 2024, and projects typically take 2-3 years to get to that stage, which implies only a year to get any further projects started. But "That 2024 construction start requirement is subject to a House of Representatives bill so may be relaxed," Mr Gillespie says.

In Europe, Australia, Canada and the US, there is a growing interest in hubs and clusters. It "provides a good opportunity for more projects to come into the pipeline," he says. "It gives a central storage network, you can connect to quickly."

Survival rate

Looking back to the end of 2010, we see at that time there were 7 large scale CCS facilities in operation, 4 in construction and 67 under development. So 71 projects in construction or under development in 2010. Of these, only 37 per cent remain in operations or in the pipeline today.

Since 2010, a further 51 projects have been announced. Of these, 50-60 per cent are still surviving, GCCSI calculates.

"As projects move through development phases , the survival rate improves," Mr Gillespie says. "Once they reach construction stage, survival rate is relatively robust. So we need to help projects through that early stage of development."

It is interesting to compare the survival rate with other industrial sectors. GCCSI looked at LNG liquefaction plant projects, where it found a survival rate of 56 per cent. Although if you model LNG projects starting in 2012, the survival rate drops to 44 per cent.

Offshore wind projects showed a much better survival rate – 90 per cent for the UK.

"It shows there are still learnings for us in CCS – maybe by reaching out to other capital project developers to try to improve the survival rate," Mr Gillespie says.

Of the projects which did not make it through the pipeline, about three quarters were for power generation.

And 3 countries accounted for three quarters of the projects which failed – UK, US and China.

The period 2012 to 2014 was particularly bad for projects which "fell out" – which probably reflects the external market conditions. "That period was when gas became competitive to coal for generation," Mr Gillespie said.

"A lot of these projects were originally on coal. When gas generation became competitive – the economics became more challenging."

"2015 was also the year that the UK competition was cancelled at a late moment."

On the other hand, natural gas processing projects, and other lower cost projects, showed a much higher success rate, and that hints to the importance of looking for projects with a strong business case, Mr Townsend said.

Overall goal

We need to have 2000 projects in operation by 2050, GCCSI calculates, based on the IEA Sustainable Development Scenario stating a need to have 2.8 GT CO_2 captured and stored each year by 2050, and the average capture facility today having capture capacity of 1m tonnes CO_2 per year.

GCCSI estimates we need to have 70 to 100 large scale projects making it through to operations a year, taking into account the time which projects take. It classifies "large scale" as capturing 400,000 tonnes CO_2 a year, or 800,000 tonnes a year if it is a coal power plant. This also means about 200,000km of CO_2 pipeline by 2050 and 400 storage sites by 2050.

As the analysis shows, with high project dropout levels, you need to start much more than 70 projects a year in order to have 70 projects a year in operation.

Many people might be sceptical about whether 2000 projects is achievable at all. "You have to remain optimistic if you work in CCS," Mr Gillespie said. "But you can't get away from the fact that it's a massive challenge."

"The energy industry has stepped up to the challenge on several occasions [before]. I remain optimistic it can be done. It is not immediately foreseeable. The longer we delay, the longer it takes to get ourselves going."

Using bioenergy carbon capture and storage (BECCS), where CO_2 is also absorbed from the atmosphere when energy plants are growing, would make it easier to reach the target, Mr Gillespie said.

GCCSI recently published a report looking at policy priorities, which highlighted the importance of policymakers putting a value on CO_2 emission or tightening climate emission reduction targets, supporting the building of a transport and storage network, and ensuring finance is available.

GCCSI hopes that developers will be encouraged to have projects "trigger ready" – planned and ready for investment as soon as there is a supportive policy, rather than wait until the market conditions are right before starting to plan projects.

Having more projects brought into operation would give suppliers and technology companies more confidence to enter the market, including looking for ways to develop projects at lower costs.

"One of the benefits of a technology that is quite young, there's a lot of scope for cost reduction."

"After some major projects dropped there was a question about how committed [people] are to this technology," Mr Townsend said. "You always felt that companies' commitment was still a bit fragile."

The report "Scaling up the CCS Market" is available for free download on the www.globalccsinstitute.com website under resources / publications.

More information

www.globalccsinstitute.com

Projects and policy news

CCUS projects gain funding from UKRI

www.ukri.org

A range of decarbonisation projects have attracted seed funding from UK Research and Innovation to conduct further work on CO2 reduction programmes.

UK Research and Innovation (UKRI) have announced funding projects for the first phases of the Deployment and Roadmap programme for decarbonisation strategies, run on behalf of the UK government. The projects awarded funding are focused on helping the UK achieve net zero emissions by 2050 as part of the Industrial Decarbonisation Challenge, a key component of the government's Clean Growth Strategy.

The first phases of the two competitions are as follows:

Deployment – In the first phase of this programme, UK businesses applied for a share of £1 million to develop plans for decarbonising an industrial cluster.

Roadmaps – Six businesses have been awarded shares of £1 million to prepare plans for their journey to achieving low carbon and net zero industrial clusters.

Bryony Livesey, Challenge Director, Industrial Decarbonisation, said, "As the UK goes through trying times we nonetheless must plan for the future. We can announce today the funded projects of the first phases of the Industrial Decarbonisation Challenge. These projects are the first stride towards the government's plans to develop cost-effective decarbonisation in Industrial hubs that tackle the emissions challenge that UK industry faces. We look forward to the development of these plans and their contribution to meeting the 2050 net-zero target."

Full list of Deployment competition winners:

- Scotland's Net Zero Infrastructure
- Net Zero Teesside Project
- Humber Industrial Decarbonisation Deployment Project (Humber-DP)
- HyNet Carbon Capture Utilisation and Storage (CCUS)
- South Wales Industrial Cluster (SWIC)
- Green Hydrogen for Humber

The six winners of phase one will now be able to compete for a total of up to £131m in phase two of the competition, for projects that will deliver, or support delivery of, significant emissions reductions in a UK industrial cluster by 2030.

Full list of Roadmaps competition winners:

- Net Zero Tees Valley - Decarbonising the Full Cluster: Roadmap Pathfinder
- Scotland's Net Zero Roadmap (SNZR)
- Humber Industrial Decarbonisation Roadmap
- North West Hydrogen and Energy Cluster: Route to Net Zero
- South Wales Industrial Cluster (SWIC)
- Repowering the Black Country

These winners will now be able to compete for a total of up to £8 million in phase two of the competition to develop decarbonisation roadmaps for major UK industrial clusters.

Starwood Energy, OGCI Climate Investments and Elysian Ventures launch new Carbon Capture Project

www.starwoodenergygroup.com

Large-scale commercial project will be one of the world's first to capture CO2 from a natural gas power plant and seeks Section 45Q tax credits.

Starwood and OGCI CI will co-invest in the initial development of the project, which will use commercially available CO2 capture technology and is expected to capture 90% of the CO2 emissions from an existing power facility. The captured CO2 will then be used in enhanced oil recovery and permanently sequestered in an existing oil field. The project will be jointly developed by Starwood and Elysian Ventures.

The project will seek to use Section 45Q tax credits for the deployment of carbon capture projects once final regulations are implemented, including potential upcoming legislative enhancements. The project will be non-recourse financed, with construction of the facility expected to commence in early 2021.

"We believe that the deployment of large-scale carbon capture for enhanced oil recovery is a unique opportunity to further enhance the value of critical power infrastructure, enabled by historically low natural gas prices and incentives for carbon sequestration," said Himanshu Saxena, CEO of Starwood. "We are excited to partner with OGCI CI in their mission to catalyze industry response to climate change, and to work with our partners at Elysian in developing this important project. Once constructed, this will become a premium asset and showcase for the deployment of this technology. We look forward to this project, and to exploring further carbon capture opportunities across multiple sectors, consistent with our ESG goals."

Study on using CCS to develop high CO2 gas fields in Malaysia

www.jogmec.go.jp

JOGMEC, JX Nippon Oil & Gas Exploration and PETRONAS have signed an agreement for a joint study looking at separating, capturing and storing the CO2.

There are a large number of gas fields containing high CO2 concentration in Malaysia which have been discovered but left undeveloped due to technical and economic reasons. Separation, capture and proper storage of CO2 from the produced gas is required to develop such gas fields.

In view of future commercialization, JOGMEC and JX will conduct the study by fully utilizing their knowledge and experiences to explore the feasibility of development of such gas fields.

In the study, CO2 produced from the fields is to be separated, captured and injected into suitable storage reservoirs such as mature and depleted gas reservoirs. JOGMEC intends to establish an environmentally friendly gas development concept by applying CCS technology.

The study also plans to look into the future possibility of exporting hydrogen produced from natural gas to Japan. JX and JOGMEC will work together to seek the possibility of establishing new energy value chains.

JOGMEC considers CO2-EOR as one of its core technologies, and relating technologies such as CCUS including CCS to be the key technology for an environmentally friendly

CO2CRC: reliably validating CO2 plume migration models in the subsurface

The Otway Stage 2C project enabled detection of a 15,000 tonne plume of injected CO2 as it grew and stabilised deep in the subsurface using a range of seismic technologies.

CO2 storage sites require ongoing monitoring and verification (M&V) so we can understand the behaviour of the CO2 plume and provide assurance of storage integrity. Injection of CO2 into rock formations alters their rock-fluid equilibrium.

Seismic data can detect variations in the elastic properties of rocks, caused by changes in fluid saturations and pore pressure. Repetitive seismic (also known as time lapse seismic) is a powerful technology to monitor such variations.

This project set out to demonstrate field-scale storage of CO2 in a saline aquifer. The objectives were:

1. Detect injected CO2 in the subsurface, ascertain minimum seismic detection limit

2. Observe the gas plume development using time-lapse seismic

3. Verify stabilisation of the plume in the saline formation using time-lapse seismic.

CO2CRC injected 15,000 tonnes of Butress-1 gas (~79% CO2 and ~21% CH4) into the Paaratte Formation, a saline aquifer at 1,500m depth. The injection occurred between December 2015 and April 2016.

The injection and evolution of the plume was monitored by a comprehensive time-lapse seismic program. It used a 1 km2 array of 908 geophones buried at 4m in lines spaced at 100m with 15m between each receiver and 40km of fibre optic cable deployed belowground at 80cm (Figure 1), together with well-based Distributed Acoustic Sensing (DAS) fibre optics and 4D Vertical Seismic Profiling (VSP) to monitor the injected CO2.

Mini vibroseis trucks were used as the source for each survey with approximately 3000 shot points in conjunction with two permanently deployed Surface Orbital Vibrators (SOV) for continuous monitoring.

Figure 1: Installing the geophone to a depth of 4m and the buried fibre optic cable into the 80cm deep trench

Seismic surveys were undertaken before injection in February 2015 (base line), then after 5,000, 10,000 and 15,000 tonnes. Two post injection surveys were also performed in 2017 and 2018. A joint analysis of the seismic images for original and monitoring surveys demonstrates that the plume images from post-injection surveys are very similar (Figure 2).

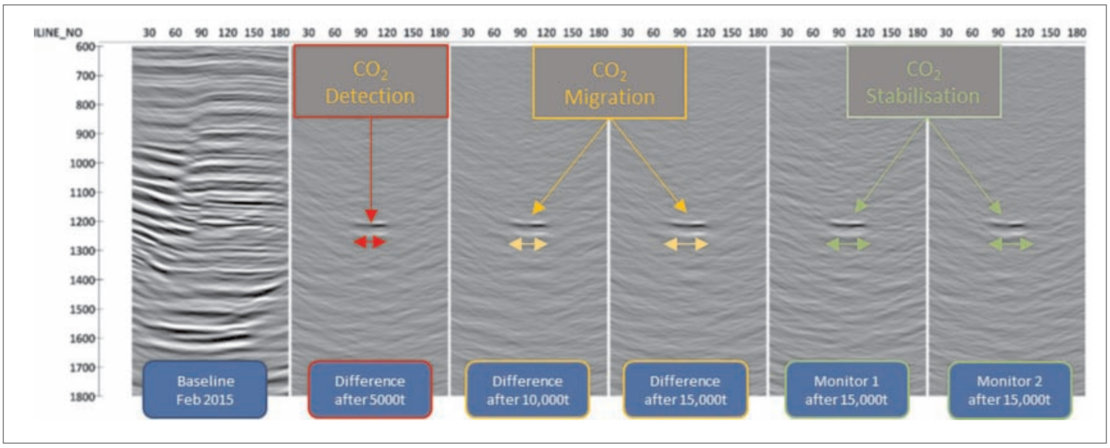


Figure 2. Injection of CO2 in the saline aquifer and monitoring the plume development

The plume signature is also clearly visible on the 4D VSP images and agrees with the results of the 3D surface seismic. An evidence-based conclusion therefore points to the stabilisation of the CO2 plume.

The research, led by Curtin University and supported by CSIRO and Lawrence Berkley National Laboratory, USA, demonstrated that a small amount of CO2 (as little as 5,000 tonnes), can be detected using seismic monitoring tools and its movement underground successfully mapped.

The Otway Stage 2C project enabled detection of a 15,000 tonne plume of injected CO2 as it grew and stabilised deep in the subsurface using a range of seismic technologies. In addition to delivering a broadly applicable procedure to predict, monitor, verify and assure CO2 migration and trapping in deep saline aquifers, the project produced the following findings:

• Using the buried geophone arrays in acquiring 4D data, greatly enhances quality and repeatability enabling detection of as little as 5,000 tonnes of CO2.

• Despite the limited spatial resolution compared to 3D seismic, Offset VSP can be used to monitor the injection along the planned transects.

• Burying geophones and cable underground can reduce seismic acquisition time and decrease the impact of a survey upon landowners. Higher data quality and 10% repeatable acquisition geometry also reduces the time for fast track processing.

• Data obtained using SOV is of similar quality to that obtained by conventional vibroseis trucks, has higher repeatability and significantly lower costs, while minimising impact on landholders.

The project demonstrates that even small amounts of the injected volume of CO2 can be detected if the relevant technologies are being deployed over regions of interest. The project also trialled at field scale, a variety of new seismic monitoring techniques including emerging technologies such as the Distributed Acoustic Sensing array and Surface Orbital Vibrators to image the plume.

"The ability to reliably predict the movement of CO2 and optimise the use of seismic monitoring to validate the plume migration path will be invaluable to CCS project operators and regulators around the world," said David Byers, CEO of CO2CRC.

"Our hope is that the applied scientific and technological research conducted at CO2CRC's Otway National Research Facility will lead to more CCS projects around the world, allowing CCS to play a vital role in meeting the dual challenge of reducing emissions across all major industry sectors while meeting the growing global demand for affordable and reliable energy," Mr Byers said.

A workflow for verifying the stabilisation of the CO2 plume using seismic data and dynamic modelling has been developed under Stage 2C and will be tested in the next phase of the project, expected to be completed by June 2020.

Being able to demonstrate the predictability of plume migration and stabilisation provides additional confidence in site selection, greenhouse gas permitting and supports investment decisions for geological CO2 storage projects.

CO2CRC Limited is one of the world's leading CCUS research organisations, having invested more than A$125 million to develop and deliver better and more cost-effective technologies for CCUS. As owner and operator of the Otway National Research Facility CO2CRC commissions and undertakes research projects with partners worldwide.

The CO2CRC Otway Stage 2C project is jointly funded through its industry members and research partners, the Australian Government, the Victorian State Government and COAL21 through ANLEC R&D.

Publications

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More information

www.co2crc.com.au

Aquistore demonstrates safe and cost-effective CO2 storage

Aquistore is an on-going CO2 measurement, monitoring and verification project to demonstrate that storing carbon dioxide 3.4km deep underground in a brine and sandstone water formation is a safe, workable solution to reduce greenhouse gases.

Located in southeastern Saskatchewan, Canada, the Aquistore project is Canada's first deep saline aquifer carbon dioxide (CO2) storage project. It began injection in February of 2015, and has safely stored over 300,000 tonnes of CO2 from SaskPower's Boundary Dam Carbon Capture Facility. At the time of its commissioning in 2014, Boundary Dam represented the world's first commercial post-combustion CO2 capture from a coal-fired power plant.

The Aquistore project began its development in 2009, well before construction on the Boundary Dam Capture Facility began. Initial plans for deep geological storage were devised by the Petroleum Technology Research Centre (PTRC) – a not-for-profit research company based in Regina, Saskatchewan – and early planning considered different industrial CO2 sources. The capture scenarios from different industrial sources in Saskatchewan were initially driven by new provincial and federal emissions regulations being developed with the aim of reducing Saskatchewan's greenhouse gas emissions to 2005 levels by 2030.

The province is blessed with just the right geology for deep geological storage of CO2, and has a perfect reservoir in the Deadwood Formation that ranges from3400 metres deep in the province's southeast to 2200 metres in the Regina area. It was this formation that was chosen as the proposed target formation in the early stages of the project.

In 2009 PTRC established Aquistore's Scientific and Engineering Research Committee (SERC) to identify and characterize a target storage formation, conduct a risk assessment, develop the research program, and define a public outreach/consultation plan. PTRC had a significant knowledge base for CO2 geological storage research, having managed the Weyburn-Midale CO2 Monitoring and Storage Project beginning in 2000. The SERC for Aquistore utilized many of the lead researchers from the Weyburn-Midale project in the design and management of its program.

Value	Health & Safety	Environment	Financial	Schedule	Reservoir Suitability	Storage Security	Capacity Building	Societal Acceptance
Goal	No lost days due to health or safety incidents.	No adverse environmental impacts.	Execute the project within budget (financial).	Maintain project schedule	Demonstrate CO_2 injection into a deep saline formation, at rates and in volumes sufficient for a large industrial CO_2 source.	Demonstrate containment of injected CO_2.	Build industrial ability to conduct CCS by conducting and disseminating industry-leading research.	Public education and consultation leading to project support.

Table 1. Aquistore project values

Funding was secured from different sources, including cash and in-kind support from levels of government and private sector partners.

In 2011, PTRC settled on the source of CO2 for Aquistore when the government-owned power utility, SaskPower, went forward with carbon capture on a 150MW coal-fired turbine at Boundary Dam Power Station. The company received over 250 million dollars (CND) from the Government of Canada to offset some of the eventual 1.5 billion dollar cost to retrofit the plant (the cost represented the combination of a new turbine -- $600 MM – and post-combustion capture ($900 MM). Construction lasted from 2011 to 2014.

Risk assessment

After determining Boundary Dam as the source, PTRC worked with SaskPower to establish a location for the CO2 injection and observation wells, which were proposed for SaskPower's land just 3 km from the capture facility. In 2011, the SERC developed a risk assessment plan that was enacted prior to the start of drilling and the implementation of appropriate monitoring and measurement technologies.

Analyzing risk reduces the likelihood of a project's failure – both from technical issues and public perception – and helps mitigate the severity of any possible challenges. A proper risk assessment is critical ahead of project execution, instills confidence from external stakeholders and allows for an efficient application of project resources.

Effective risk management includes proper geologic characterization of the injection location and surrounding area, deciding on an effective monitoring program, and creating an interactive communications and public outreach plan.

At Aquistore, a "Feature, Event and Process (FEP)" risk evaluation was performed, based on the severity and likelihood of specifically identified events, and then scaled on a risk matrix. The following were the four stages of the risk assessment conducted:

• Stage one built a project value matrix, identified project relevant FEPs, and identified key experts to contribute to the risk assessment.

• Stage two was a workshop to discuss and evaluate the likelihood and severity of selected FEPs.

• Stage three involved FEP ranking – concrete risk scenarios were identified, and the likelihood and severity of risks were evaluated.

Finally, actions were identified to reduce or eliminate the impact of FEPs, which in turn resulted in a comprehensive measurement, monitoring and verification program and an effective public outreach plan. Table 1 shows the values that emerged from the risk assessment process.

Public consultation and engagement

Aquistore held its first public open house in the community of Estevan, Saskatchewan –

near the Boundary Dam facility and proposed well locations – in May of 2012. The public consultation was ahead of the commencement of the drilling of the observation and injection wells, allowing residents to offer feedback and voice concerns about project risks and well locations. The open house was well advertised – including flyers delivered door-to-door – and over 100 residents attended.

Additional feedback was provided before the open house via one-on-one meetings with local landowners most directly affected by the wells near their properties. An additional feature of the outreach and engagement plan was informational presentations to local chambers of commerce, Estevan city council and other community/political leaders.

injection well.

The injection well was completed first with casing to the bottom of the well and tubing to allow for CO2 injection, then perforated in the target Deadwood porous zones. Pressure gauges and fibre optic lines to carry pressure and temperature data were installed on the tubing and casing.

Figure 1. The first Aquistore public open house occurred in Estevan in May, 2012, with information stations about the project's wells, proposed MMV, and capture source

The observation well saw only casing to total depth, but also included fibre optic and fluid sampling lines run on the outside of casing. The observation well itself has never been perforated and remains isolated from the reservoir. This allows for various logging and other measurement tools to be run in the well to monitor injection performance.

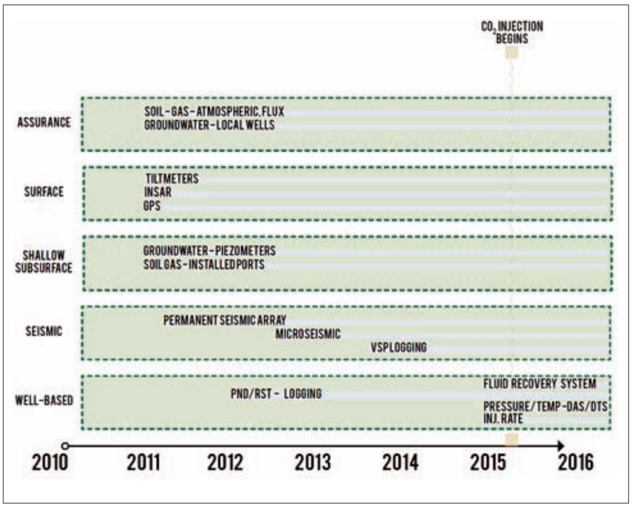


Table 2. Aquistore monitoring, measurement and verification program as developed before injection of CO2 began in 2015

Drilling and completion of the wells

In the summer of 2012, the wells were drilled for the Aquistore program. The target zone for injection was the Deadwood Formation, the deepest and oldest sedimentary unit throughout the province. It is Cambrian in age, and is an interbedded mix of high porosity sandstone/shale filled with a dense, hot salty brine. First, the injection well was drilled to a depth of 3396m, making it, at the time, the deepest well drilled in the Province of Saskatchewan. Cores were taken from the caprock zone, called the "Icebox Shale" and from further down in the Deadwood reservoir.

The "deepest well in the province" record was broken later that summer, when the observation well was drilled to 3400m. The observation well is located 150m to the north of the

Measurement, monitoring and verification program

As a result of the risk assessment, Aquistore undertook the development of a rigorous measurement, monitoring and verification (MMV) program ahead of CO2 injection to assure the safety and effectiveness of operations (see list of MMV in Table 2). The Aquistore site constitutes the largest field laboratory in the world for the study of CO2 injection and storage at an industrial scale. What follows is a description of the scientific measurement procedures and equipment in place that is assuring the safety and security of long term storage.

Surface Monitoring

Aquistore's surface monitoring equipment includes ground water well and soil-gas sampling wells, piezometers to measure well water pressures, and three surface deformation measurement technologies:

• GPS

• Interferometric Synthetic Aperture Radar (InSAR) reflectors;

• Tiltmeters to measure shifts due to CO2 fluid injection or natural land deformation as compared to the earth's seasons, tides, or rainfall.

InSAR and GPS collect data by satellite to monitor earth surface deformation with a precision of a few mm/year and also to assess whether there are changes attributable to CO2 injection and storage. Eight dedicated GPS stations provide a stationary reference location for tiltmeter and InSAR systems. Tiltmeters monitor extremely small changes in inclination of the ground surface resulting from subsurface activities such as CO2 injection.

The tiltmeter array consists of six high-resolu-

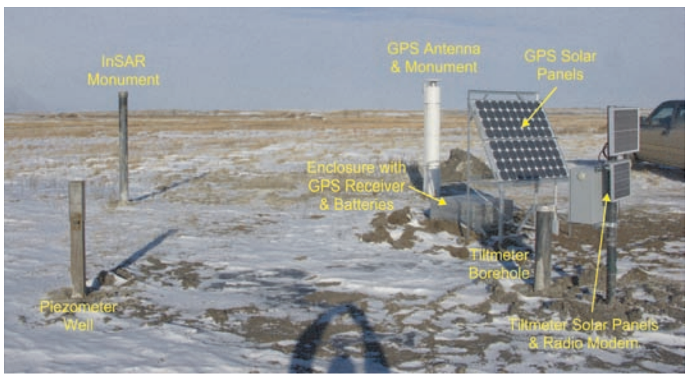


Figure 2. An Aquistore superstation showing surface instruments from different surveillance systems

tion surface meters with 15 m cables, 5-Watt solar panels and rechargeable batteries. See Figure 2 for the arrangement of these surface MMV in one of several locations at Aquistore.

Baselines of all these technologies' measurements were undertaken prior to the start of CO2 injection. Physical and chemical data have continued to be collected from 21 groundwater wells and 49 soil gas monitoring wells at the site.

The sampling program is intended to monitor any potential changes in the baseline groundwater and soil gas chemistry since the start of CO2 injection. The soil gas sampling is a biannual practice and groundwater samples are collected annually from both domestic and project water wells.

Permanent Geophone Array and Passive Seismic Monitoring

A permanent array of 645 geophones was installed to collect seismic data and assist in monitoring the injected CO2 plume (See Figure 3). There are two sets of geophones within the array. Most of the 645 are charged up only during seismic shoots and measure the returning waves coming back up from the Deadwood formation as set off by vibroseis vehicles or dynamite charges. These seismic imaging shoots occur only when CO2 totals injected into the Deadwood formation reach certain milestones.

The data from the geophones helps create deep subsurface images and help locate the plume in the reservoir to show how it has changed shape and location (See Figure 4). These images are also compared to simulations done by researchers to makes sure the CO2 is acting in conformance with the expectations from those models.

A further number of these geophones have been placed 20 meters deep in the ground (in a north, south, east, and west cross shape) and are collecting data for continuous passive seismic monitoring.

Passive seismic allows Aquistore to differentiate sources of subsurface seismic activity, whether they are naturally occurring, induced by the project, or sourced from other industrial processes nearby. Passive seismic data is collected not just from the geophones, but via fibre optic technologies downhole.

Five broadband stations that consist of seismometers and recorders integrate the data from the geophones and fibre optic lines. To date the passive seismic monitoring at Aquistore has not recorded any induced seismicity due to the injection of CO2 although local and farther afield events (natural earthquakes) have been detected

Figure 3. Aquistore's permanent seismic array of 645 geophone locations (blue dots), within a 2.5 km square zone indicated in orange. Theinjection and observation wells are indicated in the centre of the blue dots

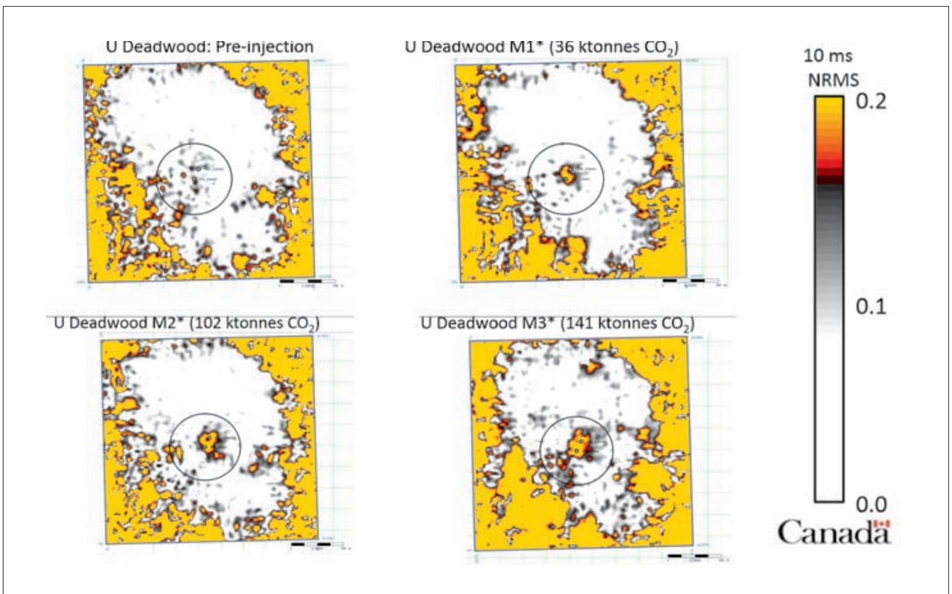


Figure 4. Seismic images of Aquistore's injected CO2 in the Deadwood formation, taken prior to injection, at 36 kt, 102 kt, and 141 kt. The injection and observation wells are indicated with dots inside the circled area. Image from Geological Survey of Canada

Fibre Optics for Seismic Imaging and Other Monitoring

At Aquistore, fibre optics are being used for seismic sensing. There are two kilometres of distributed acoustic sensing fibre optic cables trenched about a meter deep in the ground and one fibre optic cable cemented behind the casing down the observation well to a depth of 2800 meters (see Figure 5). Distributed acoustic sensing (DAS) as a method of data collection is a routine practice at Aquistore, and DAS data and geophone-based seismic data complement one another and provide more in-depth analysis of the CO2 location in the subsurface.

Observation Well MMV Tools

Aquistore's observation well is used to monitor different aspects of the CO2 injection activity, and aside from a downhole DAS fibre optic cable there are other downhole gauges, such as a fluid sampling. The fluid recovery system (FRS) developed at the University of Alberta was commissioned at Aquistore prior to first injection of CO2. This system was permanently installed to a depth of 3200m.

The FRS had been designed to allow reservoir fluids to be sampled at depth and brought to the surface preserved under "in-situ" conditions. The samples provided valuable insight into the conditions of the reservoir as it was impacted by the injected CO2, giving a better understanding of subsurface fluid phase behaviour and predicting plume migration and behavior.

For the first three years of the Aquistore project, the FRS performed satisfactorily and was valuable in assessing and confirming the presence of CO2 at the observation well. Over time, as the plume inundated the Deadwood with CO2, the FRS was less useful since the presence and concentration of CO2 in the vicinity of the observation well was well-known.

Since pressure sensors in the observation well were damaged and had become inoperable, it was felt the project needed to regain measurement of formation pressure away from the injector. The decision was made to convert the FRS into a bubble tube pressure monitoring system. This has allowed for the measurement of pressures in the observation well, and the stream of data from this new unit has been useful in seeing the pressure transients between the two wells as CO2 injection ramps up and down. The data obtained helps numerical simulation, and prediction of the position of the CO2 plume.

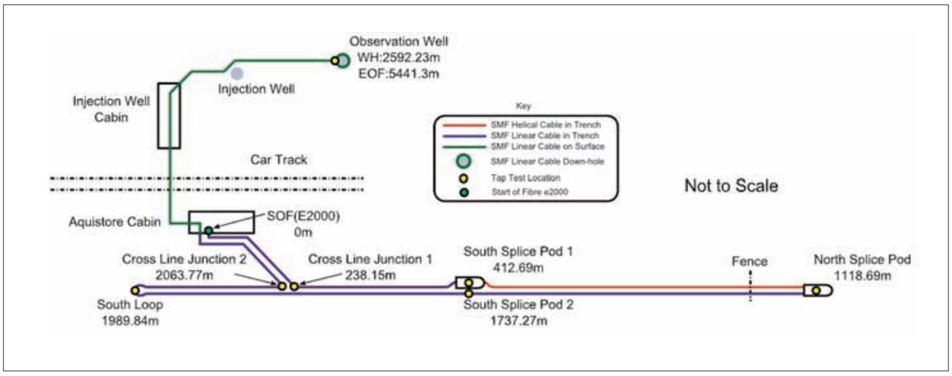


Figure 5. Aquistore fibre optic cable layout

Additional Plume Monitoring Technologies

Utilizing both wells' downhole instrumentation, borehole gravity (BHG) technology has been integrated to detect changes in the gravity field near the injection and observation wells throughout the life of the project. The changes in density, which are caused by changes in mass surrounding a well, vary according to shape and size of the CO2 plume. The changes in the gravity field are detected by time-lapse borehole gravity surveys run as the CO2 injection progresses.

Aquistore has also deployed time-lapse pulsed neutron decay (PND) technology in the observation well to track CO2 saturation changes in the reservoir and to monitor the cemented casing-borehole annulus for evidence of vertical migration of CO2. For mechanical integrity monitoring, PND is most effective when used as a time-lapse measurement comparing a base pass to subsequent monitoring passes. Since the commencement of the project 17 PND surveys have been conducted at Aquistore.

Electromagnetic data has also been collected at Aquistore to provide information about regions within the reservoir with different resistivity. Resistivity data is collected utilizing a downhole casing source (a deep electrode at storage formation depth), a top casing source (a clamp on the wellhead), and surface electrodes – all are then compared to baseline resistivity measurements. The goal of electromagnetic studies is to use the data, along with information obtained from other technologies (e.g. gravity, seismic, PND), to feed sophisticated models that generate two-dimensional maps showing the location of the CO2 plume.

Discussion of Results and Learnings Thus Far

While lessons were learned early on about bringing a project of this type to reality, the more important findings now are from its operations. Specific challenges, such as the intermittent CO2 supply (both because of capture plant maintenance and the reality that most of the CO2 is sold for enhanced oil recovery to Weyburn) affected well operations early on. The intermittent supply led to strange and interesting transient pressure changes, changes that detected a leak in the tubing string long before it became impactful. It was readily mitigated.

Operational activities have also given rise to the impact of geochemical phenomena that have been traced, imaged, and modelled. The brine in the Deadwood is 300,000 ppm chlorides, which have interesting effects when subjected to pressure and temperature changes due to injection.

In monitoring, the conversation has turned from doing everything possible that the budget and imaginations allow, to paring measurement and monitoring down to the minimum. The minimum represents what would allow for safe operation of the well, monitoring of the plume, and detecting any leaks, while maintaining public confidence.

This may lead the project more towards fibre optic seismic imaging over the cost and maintenance of the permanent array, and may lead away from soil gas/ground water monitoring, opting instead for earlier leak detection. The goal is to decrease costs incurred by future CCS storage projects, while at the same time maintaining security of storage and public confidence in the process.

All of the monitoring systems, along with the well itself, generate massive streams of data, as granular or as general as is desired. Second-by-second data, or monthly averages, can be gleaned from all of the systems on site. This allows for a steady stream of data to be incorporated into models and simulations of on-site processes to help determine best courses of action, or to predict CO2 behaviour under certain conditions. This type of data analyses is only available to working projects that have actual injection, but can be applied more broadly to CCS projects elsewhere that are more conceptual.

Future of Aquistore

The PTRC, along with the SERC and partners in the Aquistore program, are excited for what is coming for Aquistore:

- Continued investigation in cheaper and better methods of seismic plume imaging is ongoing. Minimizing the monitoring datasets is important work in demonstrating reduced costs for CCS worldwide.

- A manual of "regular industrial operations" of a CCS site, due in 2022.

- New modelling that includes more reservoir properties and processes, with an emphasis on geochemical reactions in the near-wellbore.

- Temperature effects on the geomechanics of the reservoir, arising from cooler CO2 hitting the warmer reservoir, is important work to explain some interesting injection phenomena related to intermittency.

• Linking the Aquistore well to a nearby deep circulation geothermal project to attain more reservoir attribute data.

• Investigating the use of deeply circulated CO2 as a geothermal carrier.

• Looking into the placement and design of a 3rd well in the Aquistore program. A well that will begin life as a monitoring station, but be converted to an injector later. This will speak to the ultimate capacity of the Deadwood reservoir in the region, and what magnitude of CCS we can reasonable expect to install.

Ultimately, the future of CCS in Canada, and internationally, will need to be driven by proper policy and regulatory development. Aquistore and the Weyburn oilfield – which also receives CO2 from Boundary Dam for enhanced oil recovery – are located very close to the United States, and the Weyburn field also receives CO2 via pipeline from the Dakota Gasification Company's facility in Beulah, North Dakota.

This raises interesting questions for both the United States and Canada related to carbon credits and tax incentives that have already been put in place in the US (45Q) but which do not have direct application as a motivating factor for creating more capture facilities for its northern neighbor.

With the possibility of trans-border transport of CO2 already a reality in the case of DGC and Weyburn, questions about credits for storing CO2 in a foreign jurisdiction raises interesting possibilities for development of policies and incentives on both sides of the border that will further advance CCS projects. If Aquistore and its success at demonstrating the safety of storage advances the CCS cause by bringing down storage costs and demonstrating minimum monitoring requirements, the project will have attained many of its goals.

More information

For more information on becoming a partner in the research at Aquistore, contact the PTRC at **info@ptrc.ca**. Follow the latest research results by following the company on twitter **@ptrc_sk**

TÜV SÜD - the need to measure carbon dioxide flows accurately

How much went downhole? The ability to accurately measure the amount of carbon dioxide sequestered will be a fundamental foundation of large-scale CCS. By Martin Hanton, Technical Director at TÜV SÜD National Engineering Laboratory

After several previous false starts, the dawn of large-scale carbon capture and storage (CCS) is now breaking. Whilst there is still uncertainty about the energy system of the future, all of the various scenarios envisaged by organisations such as the IPCC and the UK's Committee on Climate Change recognise that fossil fuels will still be part of the energy mix in 2050.

Hence with the legislative adoption of 'net zero' targets by the UK and other countries, the need for CCS is now beyond doubt. Furthermore, apart from off-setting the direct end use of fossil fuels, it is generally agreed that a need for CCS will arise through the production of 'blue-hydrogen' which is when hydrogen is produced from fossil fuels sources through reforming and the carbon produced (both directly and indirectly) sequestered.

Crucial to the implementation of large-scale CCS is the method by which it will be monetised, with numerous different approaches being considered from taxation through to credit-based systems. However, the purpose of this article is not to consider the precise mechanism of monetisation, but rather the underpinning measurements of carbon dioxide that will be required, regardless of the mechanisms that eventually prevail.

In short, monetisation requires accurately knowing how much carbon dioxide has been sequestered, much the same as custody transfer metering in the oil and gas industry today. In addition to the pecuniary aspects, the ability to accurately measure the flow rate of process streams at various points and reconcile this data to provide a holistic mass-balance across the whole system will be important for two other reasons.

First is reservoir management, which will require knowledge of the amount of carbon dioxide and other process stream components fed into the geological formation. Second is safety; carbon dioxide is a heavy, asphyxiant gas that can readily pool upon leakage if conditions are correct, and so any breach of system integrity will need to be detected and located quickly.

Accurately measuring the amount of carbon dioxide sequestered requires two pieces of primary information: the flow rate through the pipeline and the composition of the mixture. Starting with composition, in practice carbon dioxide streams will never be pure, but have varying degrees of contaminants in the form of post-combustion gases and entrainment of air. Hence, it will be necessary to measure the composition of the process stream in real-time, especially where carbon dioxide from multiple sources is fed into shared infrastructure.

When combined with the bulk flow rate through the pipeline, the actual flow rate of carbon dioxide specifically, can then be determined for custody transfer (monetisation) purposes. It is worth highlighting that for custody transfer metering in the oil and gas sector, single phase meters prevail due to the requirement for uncertainties of less than ±1%.

Whilst multiphase meters are used for reservoir management, in practice their uncertainties are typically an order of magnitude greater (or more) than single phase meters,

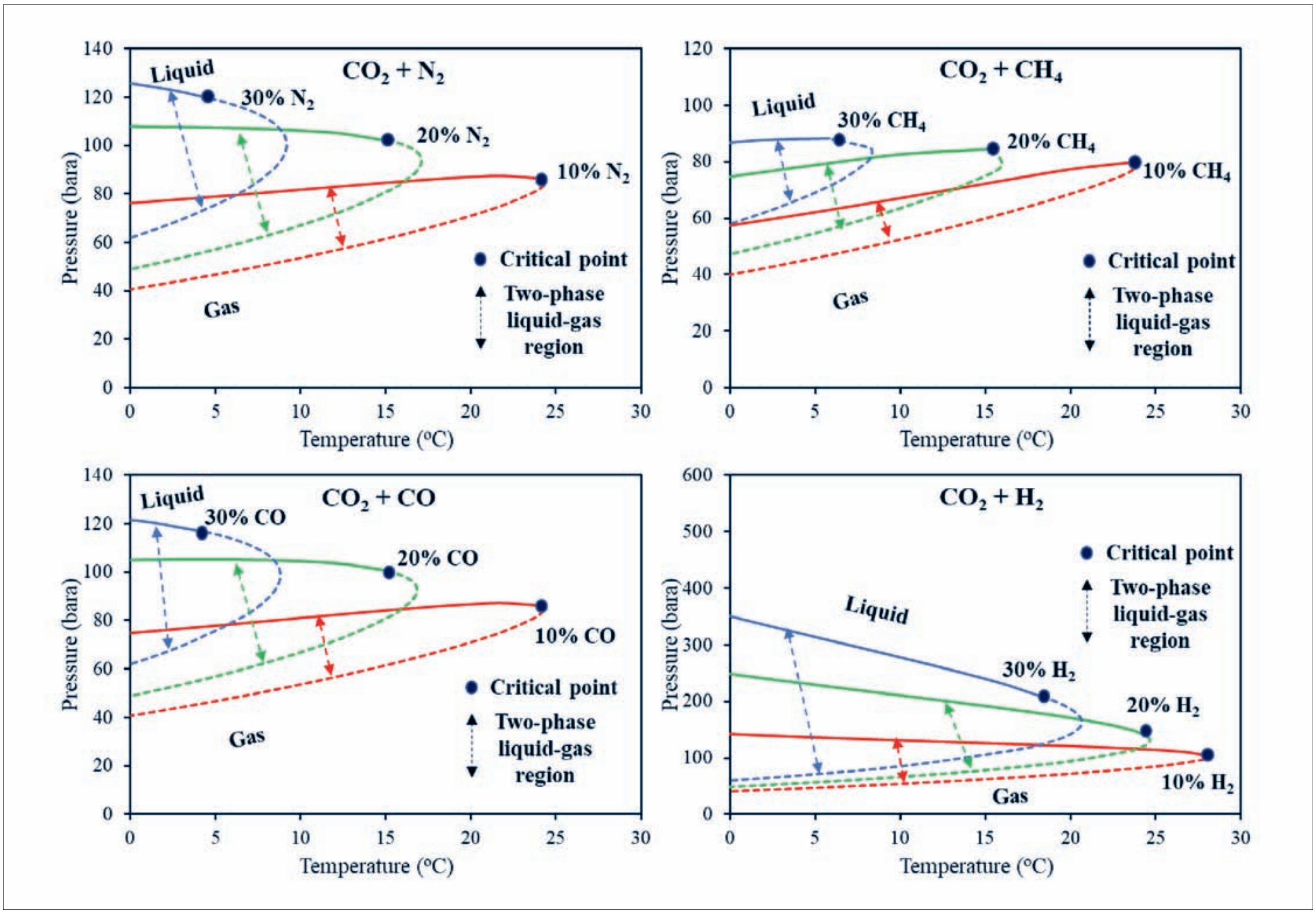


Figure 1 - Phase diagrams of CO_2 rich streams in presence of some common industrial impurities: N_2, CH_4, CO, and H_2 at various concentrations from 10 to 30 mol%. Solid lines are bubble lines, and square dot lines are dew lines

making them too crude a tool for custody transfer. For comparison, under the EU Emissions Trading System there is a requirement for uncertainties of ±1.5% or less on mass flow measurements of carbon dioxide. Thus, it may be concluded that single phase flow meters will be required for CCS applications.

Having discussed the primary measurements, there is also a need to consider a crucial suite of secondary pieces of information, most importantly the fluid properties of the process stream. The phase diagram of carbon dioxide has several phase transition boundaries close to the temperature and pressure regions relevant for pipeline transport, for example the critical point is 31˚C and 74 bar. Furthermore, even low levels of impurities significantly perturb the fluid properties and open up two-phase region boundaries.

These factors impact on flow measurement in several ways. Firstly, given the use of single-phase flow meters, it is important to understand the fluid properties of the process stream in real-time to ensure that the stream stays in the intended phase, be that gaseous, supercritical or liquid. If the prevailing phase changes from that for which the meter is intended, or if multiphase flow develops, the accuracy of the flow meter will deteriorate significantly to the point where fiscal measurements would not be possible.

Secondly, unless a Coriolis flowmeter is used, a conversion from volume to mass flow rate is required which relies upon detailed knowledge of fluid properties, and pressure and temperature conditions, to determine the instantaneous density of the process stream. Therefore, at a high-level, the composition of the process stream (one of the primary measurements) will feed into determination of the fluid properties, which in turn will then feed back into the primary flow rate measurement.

To conclude, the ability to accurately measure the amount of carbon dioxide sequestered will be a fundamental foundation of large-scale CCS but presents some interesting technical challenges that require an integrated approach to real-time determination of process stream composition, bulk flow rate and fluid properties. The essential technologies exist, but the challenge of integrating these and making them economically viable, should not be underestimated.

TÜV SÜD National Engineering Laboratory is a world-class provider of technical consultancy, research, testing and programme management services. Part of the TÜV SÜD Group, TÜV SÜD National Engineering Laboratory is also a global centre of excellence for flow measurement and fluid flow systems and is the UK's National Measurement Institute for Flow Measurement.

More information

www.tuvsud.com

On Mars or Earth, biohybrid can turn CO2 into useful products

Scientists at University of California, Berkeley have developed a device to capture carbon dioxide from the air and convert it to useful organic products.

If humans ever hope to colonize Mars, the settlers will need to manufacture on-planet a huge range of organic compounds, from fuels to drugs, that are too expensive to ship from Earth.

For the past eight years, researchers have been working on a hybrid system combining bacteria and nanowires that can capture the energy of sunlight to convert carbon dioxide and water into building blocks for organic molecules. Nanowires are thin silicon wires about one-hundredth the width of a human hair, used as electronic components, and also as sensors and solar cells.

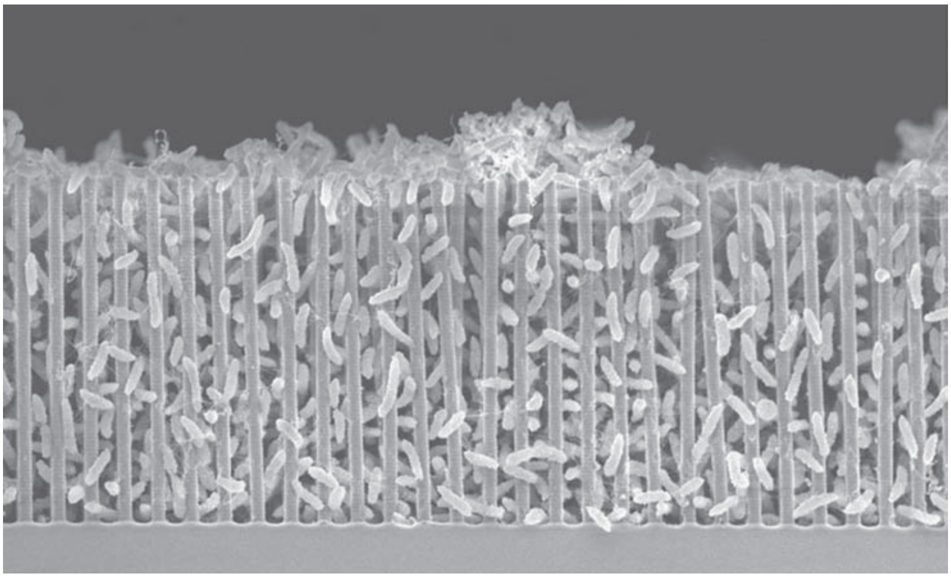
"On Mars, about 96% of the atmosphere is CO2. Basically, all you need is these silicon semiconductor nanowires to take in the solar energy and pass it on to these bugs to do the chemistry for you," said project leader Peidong Yang, professor of chemistry and the S. K. and Angela Chan Distinguished Chair in Energy at UC Berkeley.

"For a deep space mission, you care about the payload weight, and biological systems have the advantage that they self-reproduce: You don't need to send a lot. That's why our biohybrid version is highly attractive."

The only other requirement, besides sunlight, is water, which on Mars is relatively abundant in the polar ice caps and likely lies frozen underground over most of the planet, said Yang, who is a senior faculty scientist at Berkeley Lab and director of the Kavli Energy Nanoscience Institute.

The biohybrid can also pull carbon dioxide from the air on Earth to make organic compounds and simultaneously address climate change, which is caused by an excess of human-produced CO2 in the atmosphere.

In a new paper to be published March 31 in the journal Joule, the researchers report a milestone in packing these bacteria (Sporomusa ovata) into a "forest of nanowires" to achieve a record efficiency: 3.6% of the incoming solar energy is converted and stored in carbon bonds, in the form of a two-carbon molecule called acetate: essentially acetic acid, or vinegar.



A scanning electron micrograph of a nanowire-bacteria hybrid operating at the optimal acidity, or pH, for bacteria to pack tightly around the nanowires. Close packing gives more efficient conversion of solar energy to carbon bonds. The scale bar is 1/100 millimeter, or 10 microns. (UC Berkeley image by Peidong Yang)

Acetate molecules can serve as building blocks for a range of organic molecules, from fuels and plastics to drugs. Many other organic products could be made from acetate inside genetically engineered organisms, such as bacteria or yeast.

The system works like photosynthesis, which plants naturally employ to convert carbon dioxide and water to carbon compounds, mostly sugar and carbohydrates. Plants, however, have a fairly low efficiency, typically converting less than one-half percent of solar energy to carbon compounds. Yang's system is comparable to the plant that best converts CO2 to sugar: sugar cane, which is 4-5% efficient.

Yang is also working on systems to efficiently produce sugars and carbohydrates from sunlight and CO2, potentially providing food for Mars colonists.

Watch the pH

When Yang and his colleagues first demonstrated their nanowire-bacteria hybrid reactor five years ago, the solar conversion efficiency was only about 0.4% — comparable to plants, but still low compared to typical efficiencies of 20% or more for silicon solar panels that convert light to electricity. Yang was one of the first to turn nanowires into solar panels, some 15 years ago.

The researchers initially tried to increase the efficiency by packing more bacteria onto the nanowires, which transfer electrons directly to the bacteria for the chemical reaction. But the bacteria separated from the nanowires, breaking the circuit.

The researchers eventually discovered that the bugs, as they produced acetate, decreased the acidity of the surrounding water — that is, increased a measurement called pH — and made them detach from the nanowires. He and his students eventually found a way to keep the water slightly more acidic to counteract the effect of rising pH as a result of continuous acetate production.

This allowed them to pack many more bacteria into the nanowire forest, upping the efficiency nearly by a factor of 10. They were able to operate the reactor, a forest of parallel nanowires, for a week without the bacteria peeling off.

In this particular experiment, the nanowires were used only as conductive wires, not as solar absorbers. An external solar panel provided the energy.

In a real-world system, however, the nanowires would absorb light, generate electrons and transport them to the bacteria glommed onto the nanowires. The bacteria take in the electrons and, similar to the way plants make sugars, convert two carbon dioxide molecules and water into acetate and oxygen.

“These silicon nanowires are essentially like an antenna: They capture the solar photon just like a solar panel,” Yang said. “Within these silicon nanowires, they will generate electrons and feed them to these bacteria. Then the bacteria absorb CO2, do the chemistry and spit out acetate.”

Yang has tweaked the system in other ways — for example, to embed quantum dots in the bacteria’s own membrane that act as solar panels, absorbing sunlight and obviating the need for silicon nanowires. These cyborg bacteria also make acetic acid.

His lab continues to search for ways to up the efficiency of the biohybrid, and is also exploring techniques for genetically engineering the bacteria to make them more versatile and capable of producing a variety of organic compounds.

The research is supported by a grant from NASA to the Center for the Utilization of Biological Engineering in Space (CUBES), a multi-university effort to develop techniques for biomanufacturing in space.

UC Berkeley co-authors of the paper are current or former graduate students Yude Su, Stefano Cestellos-Blanco and Ji Min Kim, who contributed equally to the work; and graduate students Yue-xiao Shen, Qiao Kong, Dylan Lu, Chong Liu, Hao Zhang and Yuhong Cao.

More information

nanowires.berkeley.edu

New self-forming membrane to separate CO2 from other gases

Newcastle University researchers have developed a new class of self-forming membrane to separate carbon dioxide from a mixture of gases at low cost.

Operating like a coffee filter, it lets harmless gases, such as nitrogen, exit into the atmosphere and then the carbon dioxide can be processed.

The team believe that the system may be applicable for use in carbon dioxide separation processes, either to protect the environment or in reaction engineering.

By growing the expensive part of the membrane - made from silver - during membrane operation, they dramatically reduced the demand for silver and the cost of the membrane.

The work is published in Energy and Environmental Science and Dr Greg Mutch, NUAcT Fellow from the School of Engineering, Newcastle University, UK explains, “We didn’t build the entire membrane from silver, instead we added a small amount of silver and grew it within the membrane adding the functionality we desired."

“Most importantly, the performance of the membrane is at the level required to be competitive with existing carbon capture processes – in fact, it would likely reduce the size of the equipment required significantly and potentially lower operating costs.”

The self-forming membrane

In a method never tried before, aluminium oxide supports in pellet and tubular form were used to grow the silver membrane. Silver was added to the membrane, and the conditions experienced during operation forced the silver to grow within the membrane, bestowing higher performance.

Using X-ray micro-computed tomography, the team were able to look inside the membrane and confirm that the permeation of CO2 and O2 stimulated self-assembly of silver dendrites.

Importantly, the performance of the membrane was shown through permeation measurements to be at the level required to be competitive with existing carbon capture processes. The permeability of the membrane was one order of magnitude higher than that required, and the flux of CO2 was the highest reported for this class of membrane.

Dr Mutch added, “These savings are important – the cost of carbon capture is one of the key factors limiting uptake of the technology. There is a common metric for membrane performance – the “upper bound”. As our membrane relies on a unique transport mechanism, we avoid the limitations of most membrane materials and go far beyond the upper bound!

“We hope that this study inspires new ways to form membranes, that lower costs, as well as drives interest in this new class of membrane for future application to protect our environment.”

More information

www.ncl.ac.uk

Report highlights twenty years of DOE's carbon storage program

The U.S. Department of Energy has tested, monitored and safely stored more than 11 million tonnes of CO2 in subsurface geological formations. netl.gov.uk

The recently released report, "Safe Geologic Storage of Captured Carbon Dioxide: Two Decades of DOE's Carbon Storage R&D Program in Review" dives into how the department and NETL and other national laboratories, research organizations, and industry stakeholders have worked collaboratively to meet the challenge of addressing the emission of greenhouse gases while ensuring the continued use of fossil fuels that underpin our nation's economic prosperity.

One of the most successful pillars of DOE's Carbon Storage Program is the NETL-managed Regional Carbon Sequestration Partnership (RCSP) Initiative, which began in 2003 with a characterization phase that focused on collecting and analyzing data on potential reservoirs and assembling resources to test CO2 storage.

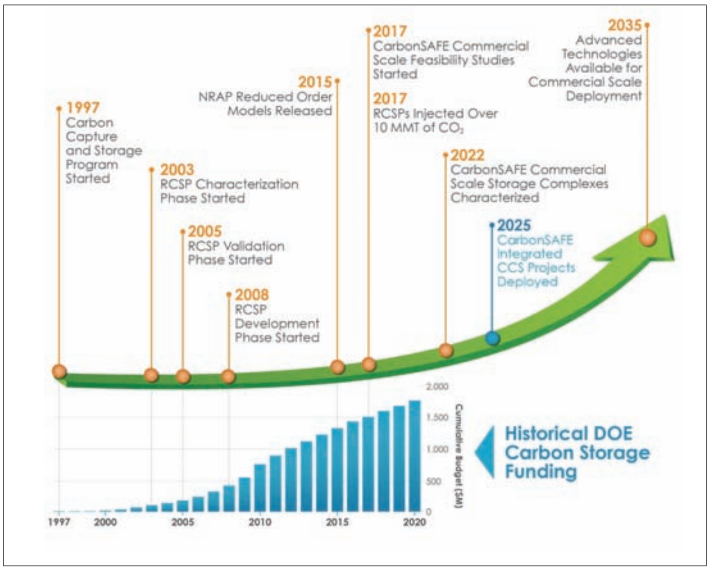
This effort culminated in the development of a standard, consistent methodology for assessing geologic reservoirs and estimating the volumes of CO2 that could be stored, an effort led by NETL. The methodology has since been applied in a series of Carbon Storage Atlases for the U.S. and portions of Canada.

Following the development of a suitable methodology was the second phase of the RCSP Initiative, which included 19 small-scale field projects during which more than one million metric tons of CO2 were safely injected. The projects were performed across numerous potential storage settings including eight projects in depleted oil and gas fields, five in coal seams unsuitable for mining, five in clastic and carbonate saline formations, and one in basalt.

These small-scale tests provided the foundation for the development phase field projects, which commenced in 2008. Results provided a more thorough understanding of permanent CO2 storage in a variety of geologic formations. The experience gained from these projects helped support regulatory development and commercial deployment of geologic storage. The formations tested are expected to have the potential to store centuries of CO2 emissions from stationary sources.

More than 11 million metric tons of CO2 were stored in geologic formations via RCSP large-scale field projects with no indications of negative impacts to either human health or the environment.

The success of RCSPs in validating secure storage at their respective sites was largely based on the deployment of new or improved monitoring technologies. Technology research by the RCSPs and NETL targeted demonstration of robust and reliable monitoring systems.



Cumulative investment and milestones toward achieving technology readiness for widespread commercial-scale deployment

Another example of NETL's support is the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Initiative. These projects focus on development of geologic storage sites for the storage of 50+ million metric tons (MMT) of CO2 from industrial sources. CarbonSAFE projects aim to improve understanding of project screening, site selection, characterization, and baseline monitoring, verification, accounting, and assessment procedures. These efforts will contribute to the development of 50+ MMT storage sites in anticipation of injection by 2026.

CCUS can also have significant economic potential. For more than 40 years, the U.S. has used CO2 for enhanced oil recovery from fields depleted following primary production and subsequent water flooding. Over this time, more than 600 million metric tons of purchased CO2 have been used in the southwest U.S. Permian Basin alone.

According to the report, 85 percent of the CO2 used for enhanced oil recovery in the U.S. is extracted from natural geologic sources where CO2 generated from thermogenic and biogenic processes has accumulated for thousands if not millions of years.

However, the mass of CO2 used for enhanced oil recovery is small compared to the 5.2 billion metric tons emitted in the U.S. each year from industrial processes, electricity generation, vehicles, home heating, and all the other forms of energy production or conversion, thus demonstrating the need for safe geologic storage capabilities

The challenge going forward for NETL and its partners in industry and academia is lowering costs of the CCUS processes to incentivize widespread adoption and commercialization on a large scale. By reducing financial risks via more advanced technology, NETL and DOE continue their mission to ensure the nation's energy security.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