Carbon Capture Journal

CCUS in Canada

Canada's Clean Energy Plan

Viability of CCS projects in Alberta's oilsands

First full-scale cement CCUS solution advances in Edmonton

Sept / Oct 2023

Issue 95

Occidental acquires Carbon Engineering for $1.1 billion

Image: Occidental

CCS in Europe: challenges and opportunities

Carbon capture for hard to abate industries with membranes

The Storing '20s: can the UK realise its offshore CCS ambitions?

Transporting frozen CO2 by box container - seeking research partners

Governments should invest now to cut the cost of air carbon capture

Capturing carbon from the air could cost six times more than hoped, according to a new report published in the journal One Earth. rccs.hw.ac.uk

Dr Mijndert Van der Spek and colleagues from Heriot-Watt University in Edinburgh compiled the new report with colleagues from the University of Pennsylvania, Philadelphia. They have developed a new way of projecting the cost of direct air capture. Van der Spek says the higher-than-expected cost can be mitigated, if governments invest now.

Globally there is just one commercial-scale plant in operation in Iceland. Two more are under construction - one in Iceland and one in Texas.

"The US government's Carbon Negative Shot is working towards a cost of 100USD per tonne of carbon dioxide removed, as are other organisations like the market maker Frontier Climate Fund," said Van der Spek.

"Our model, based on scenarios of four different direct air capture technologies in seven different countries, shows that the future cost is likely to range from 100-600USD per tonne of carbon dioxide removed from the atmosphere.That's if we reach deployment of a gigatonne of carbon removal every year - anything below that and the cost will be higher."

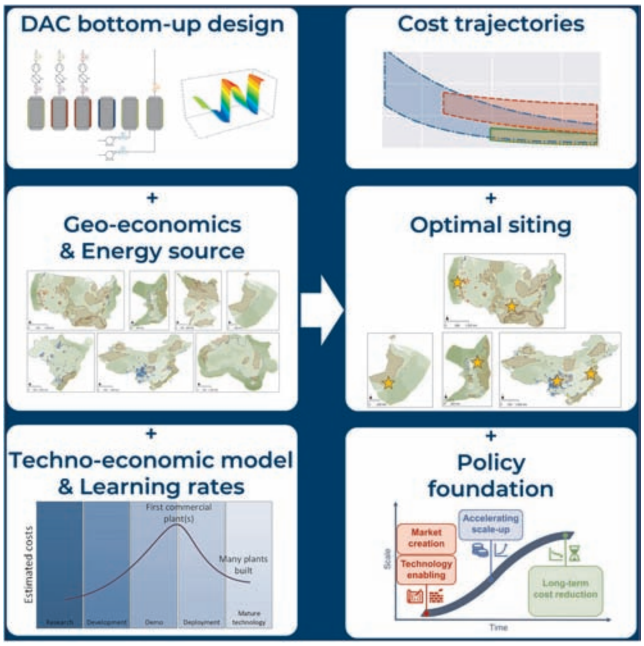
"It's a little unclear why the rate of 100USD per tonne was adopted; it seems some earlier scientific studies, as well as some direct air capture entrepreneurs, have pushed this or even lower values into the public domain."

Van der Spek says the new price tag doesn't make the technology unviable.

"There is no 1.5 degree scenario that doesn't involve removing carbon from the atmosphere. We can cut our greenhouse gas emissions to zero and we'll still need to deal with the carbon that's already there."

"The best way to get direct air capture technologies down the cost curve and make a planet-wide impact is for governments to invest now in direct air capture technology to deploy it at scale more quickly. That's the only way to bring down the cost. We can act now or pay even more later."

Calculating the cost of direct air capture



Instead of estimating the cost of direct air capture using common costing methods for existing technologies, Van der Spek and his colleagues used a new approach specifically for technologies that are not commercial yet.

Their method accounts for the costs rising at first when scaling the technology from the lab to the first commercial plant, and then slowly going down due to large-scale production. Other studies had overlooked or disregarded the rising costs incurred until the first commercial deployment, leading to low-cost estimates.

The Heriot-Watt team also included the performance and capital costs of using solid absorbents, which are used by the commercial-scale plant in Iceland, which previous projections haven't.

It's the same as what has been observed with wind turbines and solar panels. They also use ranges for each model input, and only present ranges as outputs, rather than point estimates.

Catered policy support for direct air capture

Van Der Spek points out that governments have historically invested in new technologies to advance them quickly and create a market. He says the same is now required for direct air capture.

"This technology is of global importance; it really can't be overstated. Wind energy and solar energy received governments' subsidies to get them off the ground and look at how successful that has been in countries like the UK."

"The UK government launched the direct air capture and other greenhouse gas removal technologies competition, which is a good starting point, and the USA has launched regional DAC hubs, applications for which are currently under review."

"The UK could consider Contracts for Difference to create a market and potentially lower the cost of financing direct air capture projects, or provide grants or state loans. These have been used successfully for renewable technologies like onshore and offshore wind. Tesla benefitted greatly from cheap state loans in the USA in its early years."

"Different countries will have different mechanisms available to them, the policy is up for them to decide. But they must do it quickly."

They are now investigating the performance and costs of different materials for direct air capture, and feeding this into fully-fledged environmental and energy systems models. This will lead to more granularity on the technology and a better understanding of how direct air capture can be integrated into the wider economy.

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United House, North Road, London N7 9DP
www.carboncapturejournal.com
Tel +44 (0)208 150 5295

Editor

Keith Forward
editor@carboncapturejournal.com

Publisher

Future Energy Publishing
Karl Jeffery
jeffery@d-e-j.com

Subscriptions

subs@carboncapturejournal.com

Advertising & Sponsorship

David Jeffries
Tel +44 (0)208 150 5293
djeffries@onlymedia.co.uk

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Front cover: Occidental and Carbon Engineering recently broke ground on the STRATOS facility in Texas which is expected to capture 500,000 tonnes of carbon dioxide per year when fully operational (pg. 6)

Back cover: ANDRITZ carbon capture plant is now operating successfully at voestalpine's steel mill in Linz (pg. 24)

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Leaders - CCUS in Canada

Projects and policy

Capture and utilisation

Transport and storage

Canada's Clean Economy Plan - welcome but industry must not wait

Canadian businesses should not be idle while the Canadian Government sets out a timeline for its legislative policy to incentivise CCUS investment through the tax system.

The Government of Canada has announced the start of public consultation on draft legislation for the Carbon Capture, Utilization and Storage (CCUS) Investment Tax Credit (ITC).

The investment tax credit for CCUS projects is the government's centrepiece for incentivizing heavy industries to build CCS infrastructure and will cover 50 per cent of the capital cost of CO2 capture projects between 2022 and 2030.

The tax credit is higher (60 per cent) for projects that capture CO2 directly from the atmosphere (direct air capture) and it also covers 37.5 per cent of the cost for facilities required to transport, utilization and permanent storage of CO2.

James Millar, President and CEO of the International CCS Knowledge Centre, issued the following statement in response.

"We are very pleased the Government of Canada has followed through on its commitment to implement the investment tax credit for CCUS and other legislation supporting the development of large-scale CCS/CCUS projects in a timely fashion."

"Providing opportunity for public input is an important step towards putting important policy tools in place before the end of this year, which will provide much-needed clarity for heavy industries across Canada to move forward with multi-billion-dollar projects that will be critical to achieving Canada's ambitious goals for cutting greenhouse gas emissions and reaching net-zero emissions by 2050."

"We look forward to reviewing the draft legislation on the CCUS ITC to determine what costs will be eligible, labour requirements, the obligation of companies to share knowledge about their CCS projects and report on climate risks, and other technical issues that will impact the value of the tax credit for project developers."

Investment Tax Credit for CCUS at a glance

In Budget 2022, the federal government announced design details of the Investment Tax Credit for Carbon Capture, Utilization, and Storage.

In August 2022, a consultation on draft legislation and additional design features was launched, which provided the Department of Finance with submissions that have informed additional design elements of the investment tax credit.

Budget 2023 proposes that the ITC:

- Include dual use heat and/or power equipment and water use equipment, with tax support prorated in proportion to the use of energy or material in the carbon capture, utilization, and storage process, subject to certain conditions;
- In addition to Saskatchewan and Alberta, be available to projects that would store CO2 using dedicated geological storage in British Columbia;
- Require projects storing CO2 in concrete to have their concrete storage process validated by a third-party based on an ISO standard prior to claiming the investment tax credit; and,
- Include a recovery calculation for the investment tax credit in respect of refurbishment property.

The proposed changes are expected to cost about $520 million over five years, beginning in 2023-24.

"The Knowledge Centre will release a detailed analysis of the draft policies in the near future."

Earlier this year, the Knowledge Centre delivered a comprehensive primer on the federal budget released March 28, 2023, providing a detailed break-down of the proposed CCUS ITC and an aggregation of government policies related since the ITC was first proposed in April 2021.

That was followed by the release of a consultation document regarding the proposed requirements for public knowledge sharing to be included in the CCUS ITC legislation, which were released for stakeholder feedback before May 31 this year.

Canada has been a leader in the first generation of global CCS development, with five of the 30 commercial CCS projects in the world today, including the Quest CCS project operated by Shell at the Scotford oil sands upgrader near Edmonton, the largest CO2 pipeline on the planet - the Alberta Carbon Trunk Line, and SaskPower's Boundary Dam Unit 3 CCS Facility — the world's first fully integrated CCS facility on a coal-fired power plant.

Building on this world-leading experience, dozens of projects to develop carbon capture, pipeline and storage technology are moving forward in a wide range of industries, including cement, steel, mining and fertilizer, petrochemical, oil and gas and hydrogen fuel production.

"Business leaders understand the window is closing fast for firms to capture a competitive advantage by providing low-carbon products the world continues to need," said MillarOn behalf of many of the world's leading environmental scientists, academics and experts on CCS the letter states the importance of large-scale CCS as a safe, proven and economically viable tool for addressing climate change and achieving the world's ambitious targets for reducing greenhouse gas emissions.

More information

www.ccsknowledge.com

CCS is needed and ready to address climate change - open letter to leaders

The International CCS Knowledge Centre sent the letter to government leaders in the United Kingdom, United States and Canada stressing the importance of CCS.

While the letter is specifically addressed to national leaders, the intent of the co-authors is to encourage all levels of government and industry to recognize the value of CCS and to collaborate on finding realistic and sustainable solutions that will bring new CCS projects to life across heavy-emitting industries worldwide.

The letter states the following:

Re: Carbon capture and storage is needed and ready to address climate change

The significant support for carbon capture and storage (CCS) projects adopted by the United States, Canada and the United Kingdom in recent months has highlighted the importance of CCS in meeting international climate goals. Indeed, achieving net-zero emissions will rely heavily on implementing CCS in industries across the world — power generation, cement, steel and fertilizer manufacturing and mining, in particular — as well as for hydrogen fuel production from natural gas and addressing emissions from the production and consumption of fossil fuels as the world undertakes an orderly transition towards decarbonization.

While much attention is on the hefty upfront price tag for building large-scale CCS infrastructure, what is often lost in the discussion about investment in CCS are the costs to our society if we do not proceed at pace with the massive build-out of CCS that is required to meet Paris Agreement commitments.

At the highest level, the world can't afford to ignore CCS as a key tool in fighting climate change, along with energy efficiency and greater electrification based on the expansion of renewable and nuclear power. The International Energy Agency estimates that CCS will be required for 15 to 25 per cent of the GHG reductions necessary by 2050, while the United Nations' Intergovernmental Panel on Climate Change forecasts that the cost of climate mitigation could more than double without the application of CCS technologies.

It is also important to look beyond the direct cost of building a CCS facility and consider how the cost of CCS impacts end users of the products and services we all rely on for daily life. Several studies have concluded that implementing CCS on large-scale industrial projects yields significant CO2 reductions at minimal cost to the public over the long term.

As seen in a recent study examining CO2 emissions from the construction of a major U.S. bridge project, CCS is a relatively cheap emissions reduction solution for the end users of the commodities that heavy-emitting industries provide. After all, the average person does not tend to directly buy a lot of steel, cement, fertilizer or crude oil, but we do rely on these inputs for our homes, buildings, roads, clothing, food, pharmaceuticals and electronic devices. It turns out the overall cost for mitigating CO2 emissions with CCS is marginal and well within the normal range of variation we see in market prices for many goods and services.

To be clear, reaching a net-zero world requires using all the tools we have at our disposal. However, CCS is the only proven solution we have today that can drastically cut CO2 emissions from hard-to-decarbonize industries that are the pillars of our economy. It is worth pointing out that investment in this emissions reduction pathway has been virtually non-existent compared to what has been spent on wind turbines, solar panels and electric vehicles so far this century – during which time greenhouse gas emissions have continued to climb, absolute fossil fuel consumption has grown by more than one-third, and the share of fossil fuels in the world's energy mix has only budged marginally from 87 per cent in 2000 to 84 per cent by 2020.

The argument against CCS, that it is unproven — aside from being incorrect — is circular. Far from unproven, this group of technologies is being applied on many tens of industrial CO2 capture projects, including two offshore operations in the North Sea (Sleipner and Snohvit), which have been capturing a million tonnes of CO2 a year for 27 years and 15 years respectively. Meanwhile, Canada is home to the world's first CCS facility on a commercial power plant – SaskPower's Boundary Dam Unit 3 CCS facility, which has captured more than 5 million tonnes of CO2 so far, while the Quest CCS facility operated by Shell has captured and safely sequestered more than 7 million tonnes from the Scotford Refinery near Edmonton since 2015.

Like any evolving technology, the rapid scale-up of CCS comes with uncertainties and unexpected challenges, which is why applying the knowledge and lessons learned from the first generation of CCS projects is critical to reducing the risk, lowering costs and improving the performance of the hundreds of new projects being planned around the world.

Building the new CO2 capture facilities, pipelines and storage systems on the massive scale and aggressive timelines needed to meet international climate obligations requires significant collaboration between industry, governments, financial institutions and other partners. As governments continue to work on implementing the necessary policies and efficient regulatory processes to support private-sector investment in CCS, the industries that depend on the successful development of CCS for their long-term survival must also set out realistic business models that are not overly reliant on public subsidies to ensure their existence in a net-zero world.

It's time to get on with proving the enormous potential of CCS to fight climate change in a just and sustainable manner — transitioning our CO2-intensive industries that employ millions of people, provide major contributions to national GDP and government revenues — while driving up efficiency, reducing hydrocarbon consumption and paving the way for the necessary removal of historic CO2 emissions from the atmosphere.

Our children are counting on us to realize this once-in-a-generation opportunity.

Cash flow modeling shows CCS can help meet climate goals

In collaboration with the Canadian Climate Institute, analysts at the Pembina Institute developed a cash flow model to assess the economic viability of CCS projects under existing and announced policies and incentives in Alberta's oilsands.

Getting Canada's oilsands on a net-zero pathway requires companies to make timely, transformative investments. Companies representing 95% of oilsands production have committed to achieving net-zero (upstream) emissions by mid-century – efforts that will be essential for complying with the federal government's forthcoming cap on oil and gas emissions. CCS could be a significant technology to achieve these ambitious targets.

Yet the economic viability of CCS has been questioned. On one hand, industry claims that more public support is necessary to make these projects economic. This is despite significant financial incentives through existing and proposed government policy.

On the other hand, providing any level of public support to the oil and gas sector could "lock in" carbon emissions and make it harder and more expensive to reduce emissions in the future. And with record profits in the oilsands, there is a bigger question about whether companies should pay their own way, treating CCS as a cost of doing business in a global context focused on tackling the climate crisis.

The report examines installing CCS on two typical oilsands facilities: an in situ facility and a mine with an upgrader. The analysis shows that these projects are financially feasible under a range of potential costs and incentives, assuming a consistent carbon price that reached $170 per tonne in 2030.

In the oilsands context, CCS is not only an investment in competitiveness and regulatory compliance, but it can also offer positive returns for what is the cost of doing business in the low-carbon economy.

Key findings of the report

The report gives more details on the analysis discussed in a recent article in Policy Options and builds on a previous report analyzing the policy landscape for CCS in Canada's oilsands. It found that existing and announced incentives bolstered the expected strong price signal from planned carbon pricing increases to incentivise carbon capture in the oilsands.

The report accounted for incentives from the CCS investment tax credit, offsets/compliance credits from carbon pricing, contract for difference, and Clean Fuel Regulations.

Installing CCS on two typical oilsands facilities was examined: an in situ facility and a mine with an upgrader. The analysis showed that these projects are financially feasible under a range of potential costs and incentives, assuming a consistent carbon price that reaches $170 per tonne in 2030.

In the model, both projects would break even below the headline carbon price in 2030, and with expected incentives:

• A 1-megatonne (Mt) CCS project at the in situ facility reduces emissions by 63% and achieves internal rates of return of 11-33%

• A 1-Mt CCS project at a hydrogen plant at an oilsands mine reduces emissions by 12% and achieves internal rates of return of 8-16%

The analysis included the cost of capturing the CO2, the cost of transporting it using Pathways' proposed pipeline from Fort McMurray to Cold Lake, and the cost of storing the CO2.

In the oilsands context, CCS is not only an investment in competitiveness and regulatory compliance, but it can also offer positive returns for what is the cost of doing business in the low-carbon economy.

For private operators, the results signal that substantial CCS build-out in the oilsands is cost effective. For policymakers, the results signal the importance of solidifying keystone policies, while also ensuring that oilsands CCS is not over-incentivised by public funds.

Conclusions

Cash flow results suggest that investments in CCS by the oilsands sector are cost-effective and generate a positive (private) return of up to $2 per barrel. They could also help the sector become more competitive as demand for oil declines in the global low-carbon transition, potentially reducing their emissions intensity by 40%. In fact, in the context of the federal government's forthcoming cap on oil and gas emissions, investments in CCS will become a cost of doing business and a form of regulatory compliance.

These positive returns are based on carbon price certainty for the life of the project, which can be achieved by tools like contracts for difference — which are not yet available. Policies like CfDs and the announced investment tax credit are critical for providing certainty for the sector to make what will amount to billion-dollar investments in CCS technology.

The results also suggest that public supports for CCS adoption could be too high in certain cases, potentially resulting in high private returns for what arguably should be a cost of compliance with Canada's proposed oil and gas emissions cap. The research suggests that despite calls for further subsidies by industry, announced incentives and public support is likely sufficient in many cases.

However, governments need a clearer framework for evaluating the costs and benefits of public support for individual projects to ensure efficient use of public funds for transition investments. For example, CfDs could be awarded through a competitive process to projects that request the lowest guaranteed carbon price.

More information

www.pembina.org

policyoptions.irpp.org

Heidelberg Materials and MHI cement CO2 capture demo in Alberta advances

Through a partnership between Heidelberg Materials, the Government of Canada and the Government of Alberta, the facility is expected to become the first full-scale CCUS solution for the cement industry.

Mitsubishi Heavy Industries, Ltd. (MHI) has delivered and installed a compact CO2 pilot capture system "CO2MPACT™" at Heidelberg's cement plant in Edmonton, Alberta, Canada.

The new facility, which Heidelberg Materials anticipates being operational by late 2026, will capture more than 1 million tonnes of CO2 annually from its Edmonton cement plant and the combined heat and power facility that is integrated with the capture process.

Alberta Minister of Environment and Protected Areas, Rebecca Schulz, joined the Heidelberg Materials and MHI teams at the Edmonton cement plant to formally initiate operations of the pilot CO2 capture system.

"Alberta is widely recognized as a leader in developing CCUS technology thanks in large part to industry trailblazers like Heidelberg Materials," said Minister Rebecca Schulz.

With Alberta Environment Minister in front of MHI's newly installed carbon capture system at Heidelberg Materials' cement plant in Canada, Aug. 15, 2023 (photo courtesy of Heidelberg Materials.)

"Our province has invested billions of dollars to help industry cut emissions and will continue to support practical innovations that create jobs and grow the economy. We look forward to seeing this exciting Alberta success story continue in the years ahead."

This project supports Heidelberg Materials' vision of leading the decarbonization of the cement industry. Actively contributing to the development of the new 1.5°C framework, Heidelberg Materials was the first company in the cement sector to have its targets endorsed by the Science Based Targets Initiative (SBTi) in 2019.

The pilot plant will enable Heidelberg Materials to validate the effectiveness of MHI's technology on its specific flue gas as part of a two-stage competitive process that is currently underway to inform the final design.

"Today is substantial milestone in our journey to building the world's first full-scale carbon capture project in the cement industry," said Joerg Nixdorf, Vice President Cement Operations, Northwest Region for Heidelberg Materials North America.

"This initiative focuses the cement industry's decarbonization efforts on the Province of Alberta, and we are encouraged by this significant step to lead the sector in CCUS."

The Edmonton cement plant will use MHI's proprietary Advanced KM CDR Process™ using the KS-21™ solvent (jointly developed with The Kansai Electric Power Co., Inc.) and will initially pilot the technology by testing different fuel sources and various plant operating modes.

At full operation, captured CO2 will be transported via pipeline and permanently sequestered. MHI's involvement also includes providing remote support services for the facility, using its proprietary remote monitoring system.

"MHI Group is proud to collaborate with Heidelberg Materials as an innovative solution provider for decarbonization of the cement sector, which is still a new frontier for CCUS and excited to contribute to the effort on carbon neutrality in the Province of Alberta." said Kenji Terasawa, CEO and Head of Engineering Solutions.

More information

www.heidelbergmaterials.us

www.mhi.com

Oxy acquires British Colombia based Carbon Engineering for $1.1 billion

Occidental has been working with Carbon Engineering on direct air capture (DAC) deployment since 2019. They recently broke ground on the STRATOS facility in Texas which is expected to capture 500,000 tonnes of carbon dioxide from the atmosphere annually when fully operational.

The company said acquiring Carbon Engineering aligns with its net-zero strategy and provides Occidental, through its 1PointFive subsidiary, the opportunity to rapidly advance DAC technology breakthroughs and accelerate deployment of DAC as a large-scale, cost effective, global carbon removal solution.

Carbon Engineering Process Engineer, Alex Goulet, provides a walkthrough presentation for guests at the 3D model of STRATOS

“We expect the acquisition of Carbon Engineering to deliver our shareholders value through an improved drive for technology innovation and accelerated DAC cost reductions. The technology partnership also adds new revenue streams in the form of technology licensing and royalties. Importantly, the acquisition enables Occidental to catalyze broader development partnerships for DAC deployment in the most capital efficient and valuable way,” said Occidental President and CEO Vicki Hollub.

“We look forward to continuing our collaboration with the Carbon Engineering team, which has been a leader in pioneering and advancing DAC technology. Together, Occidental and Carbon Engineering can accelerate plans to globally deploy DAC technology at a climate-relevant scale and make DAC the preferred solution for businesses seeking to remove their hard-to-abate emissions.”

Upon closing, Carbon Engineering would become a wholly owned subsidiary of Oxy Low Carbon Ventures. Carbon Engineering’s personnel will continue to pursue ongoing DAC technology development efforts and work closely with the Occidental and 1PointFive teams to bring DAC solutions to market. Carbon Engineering’s research and development activities and Innovation Center will remain in Squamish, British Columbia.

“We have always believed that global partnerships and cross-industry collaboration would be required to deploy DAC infrastructure at the scale required to make a climate-relevant impact. Carbon Engineering and Occidental have been working increasingly close together for the past five years to address the CO2 problem, making Occidental a trusted and committed partner for this next chapter in Carbon Engineering’s journey,” said Carbon Engineering CEO Daniel Friedmann.

“At the core of this deeper relationship is the commitment to invest in the development of our technology here in Canada, and the global reach to accelerate implementation of DAC-based climate solutions in the U.S. and around the world.”

Construction on STRATOS began in the third quarter of 2022 and start-up is expected in late 2024. Upon completion, the first DAC plant will be the world’s largest of its kind and would be an important step in advancing Oxy’s low-carbon strategy to deliver large-scale carbon management solutions that accelerate a net-zero economy.

Once operational, the plant is expected to capture up to 500,000 metric tons of carbon dioxide per year with the capability to scale up to 1 million metric tons per year. Captured CO2 can be stored underground in saline formations or used in the production of hydrocarbons to enable lower-carbon or net-zero transportation fuels, and in products like chemicals and building materials.

1PointFive has announced a plan to deploy 70 DAC facilities worldwide by 2035 under current compliance and market scenarios.

More information

www.carbonengineering.com

www.oxy.com

CCS in Europe: challenges and opportunities

The message is simple: there will be no net-zero without CCS, but policymakers need to be reminded that CCS is critically important if we want the potential to be realised in time. By Chris Davies, Director of CCS Europe.

Some of the best words ever written about CCS were made public on 15 June 2023. Aker Carbon Capture announced in a press release that it had signed a contract with Ørsted to develop the Kalundborg Hub in Denmark. This was confirmation that the first Final Investment Decision for a CCS project within the European Union had finally been taken.

The project ticks a lot of boxes. Ørsted will build capture plants at its wood chip-fired Asnæs Power Station in Kalundborg in western Zealand and at the Avedøre Power Station's straw-fired boiler in the Greater Copenhagen area. Some 430,000 tonnes of biogenic CO2 annually will be shipped for permanent storage at the Northern Lights site.

As a BECCS initiative, the project will help to reduce the amount of CO2 already within the atmosphere, which is why Microsoft has contracted to buy negative-emission credits to help it achieve its own net-zero ambitions. The Danish Government is providing substantial support, offering an example of leadership on CCS for governments across Europe.

Ørsted will capture CO2 from its Avedøre Power Station in a first for Europe

All of this is good news for the CCS community. If the celebrations are a touch muted it is because this first FID is at least ten years later than was needed. By some estimates it will be necessary over the next 20 years to approve up to 1,000 more CCS projects the size of Kalundborg if the 2050 net-zero target is to be achieved. Given progress to date it needs a strong dose of optimism to have confidence that this will be realised.

The European Union has never embraced CCS with enthusiasm. At best, it has been considered as an unfortunate but probably necessary technology. At worst, individual countries have turned their back on it completely, introducing legal prohibitions on the sequestration of CO2.

In March 2007, heads of government meeting in the European Council approved a recommendation that the EU should have up to 12 CCS demonstration projects by 2015, but the words were only secured on the understanding that no Member State would be forced to support CCS on its own territory. No provision was made for financial support.

An EU Directive laying down requirements to provide for the safe and permanent storage of CO2 was approved by EU policymakers at the end of 2008, but again it applies only if CO2 storage is endorsed nationally. Politicians in most countries have until recently avoided the subject altogether, and for understandable electoral reasons.

Although one environmental NGO, Norway's Bellona, has been a vocal supporter of CCS for more than 30 years, many other environmentalists have been critical. Promotion of a technology that might have the sole purpose of helping to curb climate change came to be portrayed as a cynical public relations exercise by fossil fuel companies with a business-as-usual agenda. CCS was (and often still is) described as an expensive and immature technology that would never live up to its promise and would divert public funds from support for renewable energy.

CO2 storage was condemned as unsafe, and even compared with the burial of radioactive waste. The debacle in 2011, when Shell proposed CO2 storage beneath the Rotterdam suburb of Bahrendrecht and aroused strident local opposition, warned politicians that CCS was a subject to be treated with extreme caution.

In any case, there was an insurmountable reason for investment in CCS not taking place: there was no business case to justify it.

The European Commission used to claim that a desire to avoid the cost of buying CO2 allowances from the Emissions Trading System would provide the financial incentive needed, at least for operators of coal and gas power stations. The financial crash of 2008 put paid to that. Instead of increasing above their €30/tonne price the cost of allowances sunk, eventually to less than €4, a negligible amount.

A proposal I tabled in the European Parliament to provide financial support for CCS from a fund created out of the sale of 500 million 'surplus' ETS allowances gained the support of EU leaders in December 2008, albeit reduced to 300 million allowances. But the NER300, as it came to be known, failed to deliver. Inextricably linked to the price of ETS allowances its value could not match its potential, and caveats imposed on its use restricted even that.

Back in 2008, CCS thinking was closely linked to coal. The fuel was cheap and provided many European countries with a substantial proportion of their baseload electricity. As the years passed, coal ceased to be seen as having a future, at least by governments in western Europe. Renewable energy, initially supported by large public subsidies, had become credible and attracted the lion's share of investment. But electricity, however green and plentiful, cannot deal with every source of CO_2 emissions.

Cembureau, the cement industry association, published in 2011 a roadmap that pointed to alternative sources of energy and transport enabling a reduction in emissions from cement production of more than 30%, but it made clear that achievement of an 80% reduction would require CCS.

The cement roadmap spelt out to policymakers what technology was needed but not how it could be delivered. There was no carrot of financial support available, and the ETS stick could inflict no pain when the price was low and allowances were in any case free to key industrial sectors.

Enthusiasts for CCS within the European Commission disappeared. Support units of staff were wound down; work on CCS was not regarded as the best way to secure career advancement! One European Commissioner after another paid lip service to the need for CCS but none used up political capital in promoting it.

With the departure from Brussels last month of climate policy supremo Frans Timmermans, who has returned to Dutch politics, yet another Commissioner has left office without having gained any sort of reputation as a champion for CCS.

Yet this is hardly surprising, because in Brussels, let alone in national capitals, there has been little by way of CCS political advocacy. Compared to the lobbies in support of wind and solar and hydrogen the supporters of CCS have made little impact.

Since 2005, the Zero Emissions Platform (ZEP) has provided technical support for the Commission, publishing fine reports but with a restrained advocacy role. As a recipient of financial support from the EU budget it has not been in a position to publicly challenge the failures of EU policymakers.

The Global Carbon Capture and Storage Institute (GCSSI) is an invaluable source of information but describes itself as a thinktank not as a lobbyist. Britain's Carbon Capture and Storage Association (CCSA) is just starting to play a role in Brussels that may develop.

If CCS advocates fail to bang the drum we can hardly complain when policymakers say they hear no noise. What is surely most surprising is that companies that stand to gain very significantly from CCS investment have not come together and invested time and money in persuading EU policymakers of the need for the technology that they will provide.

The press release from Aker Carbon Capture demonstrated the potential that is being missed. It went on to say that the supply of equipment for the Kalundborg Hub has "an expected total contract value above EUR 200 million". Here was proof that CCS deployment can bring very significant commercial opportunities for European business.

As the former lead advocate for CCS in the European Parliament I have found the lack of CCS promotion in Brussels hugely frustrating. I am pleased now to be trying to make a difference by having helped to establish Carbon Capture & Storage Europe, an advocacy and communications body dedicated to presenting the case for CCS to policymakers.

Launched in April, with start-up funding from the European Climate Foundation, our membership brings together industrial companies, business associations and environmentalists. Our focus is on hard-to-abate sectors – cement, lime, steel, waste-to-energy, chemicals and other energy-intensive industries – and our aim is to ensure that CCS deployment becomes very much part of the EU climate policy agenda.

The best time to try pushing open a door is when someone has unlocked it. For CCS, this is that time.

The price of ETS allowances hovers around €90/tonne and is expected to rise, with free allowances coming to an end in a decade. The costs for unabated CCS emitters will be huge. A business case for CCS investment is starting to appear but first-movers will require public funding support. At a European level, the Innovation Fund, itself the successor to the NER300, now has a seriously large amount of money to distribute, albeit not all for CCS.

Thanks to the efforts of some dedicated Commission officials, attitudes have started to change and there is a new can-do, must-do, approach towards CCS within the EU executive. Nothing demonstrates this more than the requirement in the Net-Zero Industry Act now being debated for oil and gas companies to be obliged to provide sites with 50Mt of CO_2 storage capacity by 2030. In the words of one Commission official, it is an "unprecedented" requirement.

Hurdles remain in the path of developing full chain CCS projects. The Commission thinking is that any company even considering CO_2 capture will back away in the absence of there being anywhere to store it, so one part of the Gordian Knot needs to be cut by providing storage space on an open and competitive basis.

The oil and gas companies have often said that CCS creates commercial opportunities for them so they should surely endorse the Commission proposal. To be fair, many of their calls for change to its details are based on practical considerations rather than on outright opposition. Still, there is a battle to be had in the weeks ahead to persuade both MEPs and EU governments to back the Commission.

An EU Industrial Carbon Management Strategy to due be published towards the end of the year or early next. It is expected to focus on the provision of CCS transport infrastructure, as well as addressing concerns raised during months of discussion within the CCUS Forum of interested parties initiated by the Commission.

Brussels matters, but national capitals matter more. CCS will only be deployed if projects have strong support from the governments where they are located. Every EU Member State was legally required to present a draft

National Energy and Climate Plan (NECP) by June. Some have still to do so, but those so far published suggest that not a few governments are paying only lip service to the need for the technology.

Yet there are other European governments providing inspiration and example for others. The Dutch were the first to agree targets and to put in place a financial support mechanism for CCS, only for progress to be delayed by the country's legal disputes over nitrogen emissions. Denmark, having disregarded CCS for a good while, has within the past three years emerged as the front runner by adopting an ambitious strategy for CCS deployment.

The recent Court decision in the Netherlands has aroused hopes that a FID will be taken to support Rotterdam's Porthos project. Given its scale and location this could have a transformational impact on thinking about CCS across the continent.

The French government is consulting on plans to capture CO2 from major industrial plants, with much of it proposed for permanent storage in onshore sites. Germany is consulting on a change in the law to permit CCS, with the economy ministry having suggested that annual capture of up to 73Mt of CO2 will be needed by 2045. Sweden is increasingly active on CCS, and even Austria is contemplating lifting its prohibition on CO2 storage.

The final versions of the NECPs are due to be published in June 2024, so this is the time to press for them to be strengthened. Industry needs to speak up, and CCS Europe wants the support of project developers and equipment suppliers to remind policymakers that CCS is critically important. The message is simple: there will be no net-zero without CCS.

My involvement with CCS dates back 17 years. I know we are not where we should be.

The optimists can point at the scores of projects now being developed across Europe, and they can claim with justification that CCS is back on the climate policy agenda. But we are not yet at a tipping point.

The potential exists to bring about positive change. One government after another may adopt CCS deployment targets and provide the support needed to attain them. But the potential will only be realised if policymakers are persuaded of its necessity. This is the time for the industries that have most to gain to recognise the opportunity and invest in the advocacy needed to make it happen.

More information

Chris Davies

chris.davies@ccs-europe.eu

www.ccs-europe.com

Saipem and Stockholm Exergi working on a large-scale CO2 project in Sweden

The companies have signed a Letter of Intent for a CO2 capture plant to be installed at Stockholm Exergi's existing bio-cogeneration plant located in the Swedish capital.

Saipem's scope of work covers the engineering, procurement and construction activities for the carbon capture unit, the CO2 storage as well as the ship loading systems for CO2 transportation.

"We are pleased to be selected for this large-scale carbon capture project in Stockholm, and fully committed to support our client sustainability goals. This project will enable Saipem to further consolidate its position in the decarbonization sector and expand its portfolio in the CCS segment, providing a fundamental contribution to the energy transition of Sweden and Europe," said Fabrizio Botta, Chief Commercial Officer at Saipem.

In the meantime, the agreement allows the start of limited, engineering-related activities, while finalising the main terms of the EPC Contract expected to be signed in Q3 2023.

When completed, the plant will be able to capture 800,000 tonnes of biogenic carbon dioxide every year from the biomass-fuelled Värtaverket power plant in Stockholm, thus enabling a net removal of CO2 from the atmosphere, otherwise known as "negative emissions".

The Värtaverket biomass power plant in Stockholm

Stockholm Exergi's project, which received financial support from the European Innovation Fund, will be one of Europe's first large-scale plants to generate "negative emissions", leading to the issuing of Carbon Removal Certificates which can then be traded on the market.

"The cooperation between us and Saipem is an important step towards the development of our large-scale plant for the separation and permanent storage of Bioenergy with Carbon Capture and Storage (BECCS)," said Per Ytterberg, Director of business development at Stockholm Exergi and Head of its BECCS business project.

"Stockholm Exergi is at the forefront of establishing BECCS and the goal is to construct one of Europe's first and largest value chains for bio-energy carbon capture and storage."

More information

www.stockholmexergi.se

Moving towards Net Zero: convergence of CCS, H2, renewables and digitalisation

Effective use of digitalisation will be strategic for the winning entrants in the low-carbon economy. For companies to achieve Net Zero goals at the speed and scale required, a "born digital" approach will be essential. By Ron Beck, Senior Director, AspenTech.

Asset-intensive companies such as refining, petrochemicals, fertilisers, mineral processing, and steel are major energy users and face challenges in progressing towards net-zero. Energy efficiency is the obvious low-hanging fruit, able to reduce asset emissions by 20%. What are other strategies these companies can embrace?

Surveys conducted by AspenTech globally in 2022 suggest that the "crowd-sourced" answer, evidenced by revealed capital plans, is a basket containing green hydrogen, carbon capture and storage, and electrification via renewables, in that order. For all three of these to scale fast enough to move the needle for these companies, digitalisation; or an approach we call "born digital" will be a required part of the strategy.

The particular challenge that asset-intensive companies face, and the reason they are termed "hard to decarbonise," is their energy intensity (constrained by the basic laws of chemistry and physics), and their corresponding dependency on very high temperature energy in particular, to successfully operate. Heat transfer and high temperatures involved in key refining units, ethylene crackers, iron smelters, and high electricity consumption by aluminium refining and electric-arc steel processes exemplify the challenge.

These are all high volume, low margin processes, so the requirements for carbon requirement present a challenging "green-premium," which must be overcome. Approaches which are energy inefficient, no matter how green the energy, will not be an ultimate answer (although they may work short term due to government incentives). Scale-up and improved operating economics of carbon abatement and carbon avoidance processes will be crucial.

Green Hydrogen

Green hydrogen is attractive from a zero-carbon viewpoint, since it can be produced from water and renewable power, with no carbon emissions. The further production of green ammonia as an option of this strategy can have an important and sizeable decarbonisation impact on fertiliser production, and indirectly on food production (the CO2 cost of fertiliser manufacture is often skipped from the lifecycle analysis of food production today).

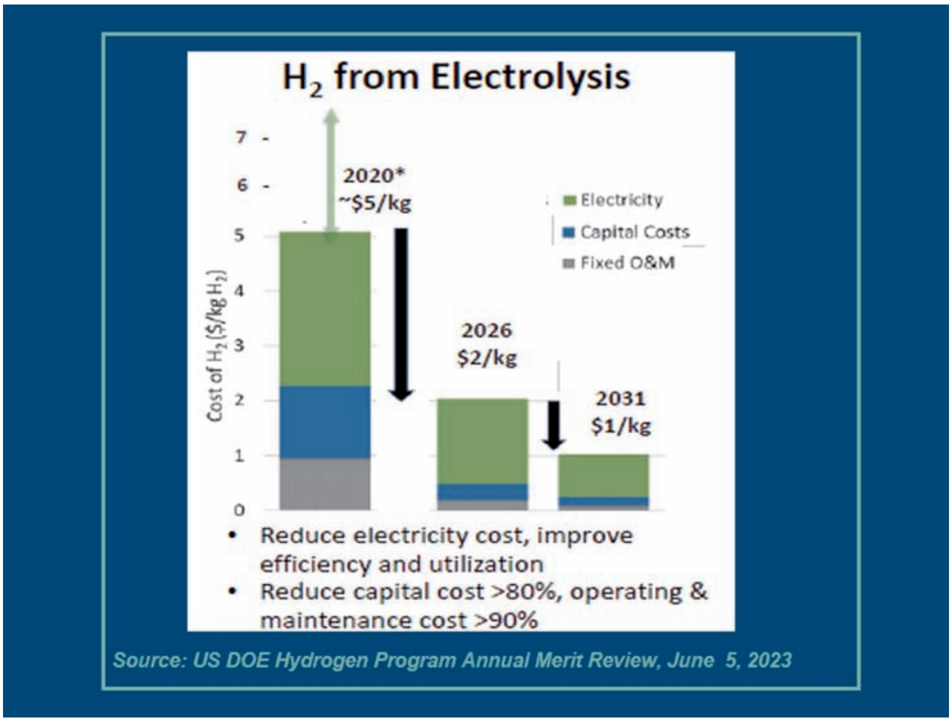


Figure 1: US DOE "Moonshot" goals for improvement of green hydrogen economics through grants

The challenge is the capital and operating cost of hydrogen electrolysers, and also the capital cost penalties of adding significant battery storage into the green hydrogen system. Operating cost challenges are driven by the stochastic and variable nature of solar and wind production which lead to low "load factors," i.e. low average utilisation of the electrolyser and ammonia conversion process units.

The accompanying chart (recently published by the US DOE) shows the targeted improvement in green hydrogen economics that the US DOE's hydrogen program hopes that its industry project grants will help achieve (see figure 1).

Digitalisation will have a crucial and strategic role to play in scaling up the hydrogen economy. Systems-level, probability-based models are helping project sponsors sort through the dizzying array of options for designing the desired hydrogen systems, ensuring investor confidence and certainty.

Accurate electro-chemical models are crucial in improving and optimising designs for renewables tied to the electrolysis process and so-called "balance-of plant" (the systems that surround the electrolysis system and make it work at an industrial scale).

Optimisation systems (known as adaptive

process control), assisted by predictive AI, will maximise load factors and minimise the operating impacts of variability of the incoming renewable power.

According to one of our customers following this strategy, it will reduce the cost of production of hydrogen from \$6 per KG to \$2.50 per KG. And industrial microgrids can be expected to increase the efficiency of tying renewables to the hydrogen process, increasing power yields by up to 10%.

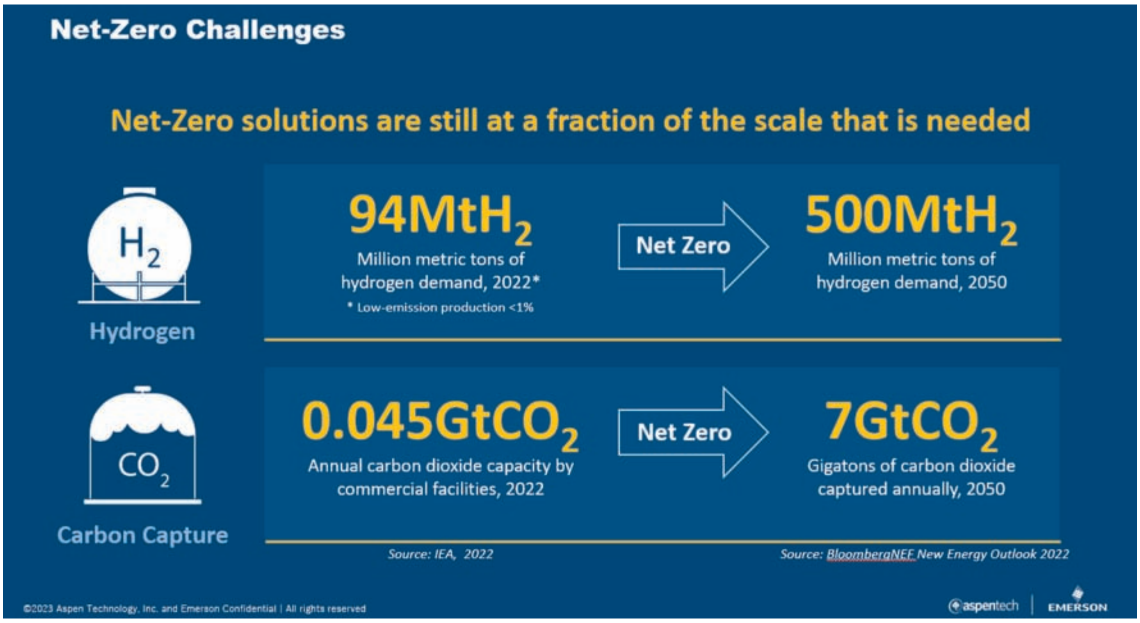


Figure 2: The formidable scale-up of hydrogen and CCS projects required by 2050

Blue Hydrogen

Blue hydrogen involves the conversion of natural gas to hydrogen. Due to the recent European energy-security requirements, LNG has been playing a crucial and growing bridge-strategy in the European and global energy picture.

To make the high level of LNG buildout sustainable in the long term, conversion of at least some of the projected natural gas supply to blue hydrogen will make sense for some uses and in some geographies.

A by-product of this hydrogen route is CO2, so carbon capture is integral to this approach. We will discuss the economics of CCS next. What is essential, though, in making blue hydrogen viable is the close coupling of CCS with the reforming process which converts natural gas to hydrogen or ammonia, and the carbon capture process.

This is a process optimisation problem, for which accurate first principle digital models are crucial in achieving maximum possible efficiency and economics, both in the process itself and in energy use (or what is called in design, heat integration).

Combining AI with first principal models, an approach we call hybrid models, is crucial in using plant data to achieve accurate digital twins for understanding of carbon and energy intensity, and maximising results. One customer, Nissan Chemicals, has used this hybrid model approach resulting in reduce energy requirements, with published savings of over 1% energy in the ammonia process.

Carbon Capture Utilisation and Storage

Carbon capture is recognised by the UN, IEA and industry as a crucial element of the pathway to net zero emissions. Carbon capture (CCS) and carbon removal via direct air capture (DAC) both face a key techno-economic challenge. Namely, these technologies have been proven technologically, and in fact work well, however they remain challenging in terms of long-term economic viability.

Ultimately, the lifecycle cost of CCS and DAC must be driven below \$100 per metric ton of CO2 removed, to make sense. In the short term, subsidies are spurring projects to proceed. Political uncertainties around these subsidies are creating risk, while financial market penalties of not acting, are creating a risk in the other direction for companies.

The key challenges surrounding carbon capture include increasing the process efficiency of both capture and solvent (catalyst) recharge must be increased. This will happen through continued and high-paced innovation and scaling up of technology. For carbon removal through direct air capture, a key challenge is optimising the integration of renewable power sources with the mechanical (fans to blow air through the system) and chemical capture process.

As mentioned above with green hydrogen, digital twin models that combine highly accurate first principal models with AI based analytics, to achieve hybrid models, have been the key tools on the ongoing economic improvement. Carbon Capture Inc, for example, is heavily using our first principal models and AI approaches to optimise solar power with direct air capture.

Carbon Engineering, whose technology is driving the world's largest announced project from OnePoint5, also has used our rigorous digital twin models to move from experiment to demonstration plant, to scaling to the world's largest implementation. Technology Centre Mongstad, the Norway-based consortium, uses similar comprehensive modelling approaches to rapidly test and establish economics for new materials and processes for carbon capture.

Another challenge for CCS and DAC, is permitting geological carbon storage and monitoring stored CO2 over the long term. The same subsurface modelling systems that help the oil and gas industry optimised their production from hydrocarbon reserves, helps characterise target reservoirs and saline aquifers for CO2 sequestration.

Here, AI applied to the interpretation of subsurface data is also a key resource in predicting the best and most stable subsurface target zones. The net result is the crucial role of digital models in accelerating the permit process, and assuring, companies investing in carbon offsets that sequestered carbon is being securely stored in place.

The biggest challenge at an industrywide level is the speed at which carbon capture and hydrogen projects must proceed. Figure 2 gives a picture of the size of the challenge:

The only way to accomplish this is to use automated engineering workflows to achieve design and project certainty, through repeatable and accelerated project designs. One company, ENI Progetti, the research and project arm of ENI, has fully captured their invested CO2 capture process in our automated front end design system (Aspen Basic Engineering).

This enables new CO2 capture projects to proceed through the front end design (FEED) phase of projects from 30 to 90% faster. Project sponsors and engineering contractors will need to adopt such “born digital” approaches to project execution to meet company and industry-wide goals for net zero. Today’s approach to project-by-project engineering simply is an approach that will not meet the requirement.

Renewable Electricity: achieving a Resilient, Optimised and Distributed Grid

The move towards electrification is an opportunistic one for organisations across sectors including chemicals, mining, conventional and green energy, plus power generation and distribution. However, there are challenges standing in the way. Grids must be not only expanded, but modernised, enabled to rapidly evolve to support distributed (renewable) power and power storage, and more resilient in the face of cyber threats.

More organisations are now decarbonising assets to achieve carbon abatement pledges, and utilising electrification as part of that strategy. Microgrids are enabling control of critical power needs to ensure vital assets do not suffer sudden shutdowns.

Organisations with their finger on the pulse are already exploring renewable solutions, such as energy storage technology, direct air carbon capture, wind and solar farm optimisation, hydrogen fuel cells and distributed generation and distribution. With the proliferation of distributed renewable power sources, grids need to be more digitally enabled, to dynamically manage the variability of both supply and demand, and ensure 100% availability as grids begin operating increasingly in a bidirectional mode. The primary objective is to ensure complete network reliability.

It's crucial that the data being incorporated in both generation and storage solutions should be part of an intelligent to predict load and demand and route power efficiently. Also, digital upgrades are essential to support new pricing and revenue models for electricity, to encourage price-based use during periods of surplus supply and to remove current barriers to expansion of distributed generation and storage nodes and to enhance cybersecurity.

Further, both for transmission and distribution networks, the ability to forecast weather-based peaks and valleys in renewable power supply will help to optimise utilisation of the renewable capacity, avoid overloading lines, as well as effectively using storage (battery array) capabilities.

Other benefits can also be gained from utilising advanced distribution management solutions.

They will provide reconfigurable capacity, visibility into distributed generation, resiliency amid increasingly dynamic supply and demand, advanced situational awareness for operators and managers, and enhanced grid support for smarter meters, generators, and storage nodes.

However, to maximise value from distributed power a reality, developments in digital software will be required. For example, enhanced transparency into systems will better enable distribution to monetise their operations, while also helping them to better maintain, price and optimise distributed power and storage.

Connection of smart home and commercial devices will help incentivise consumers to preferentially use available power during surplus, low price, periods. For example, Iberdrola has adopted our next generation distribution solutions (Aspen OSI DERMS) to prepare Spain’s distribution networks for rapidly increasing renewables generation coupled with energy storage.

Power generation gaps are also being filled by the rapid growth and uptake of microgrids. The right digital solution enables optimised development of microgrids, integrated with regional grids and developed in a more cohesive, intelligent way. For example, Fortescue Metals Group is using our advanced distribution and microgrid solutions ensure 100% reliability of power that they generate and provide to their mining and mineral processing operations.

This approach promotes and enables entrepreneurial investment and innovation in new power generation strategies and connected storage innovation. Microgrids give local concentrations of power users to maximise their reliability.

The Opportunity Moving Forward

Without doubt, the global march to net zero carbon emissions is gathering pace, with more countries and companies committing to stringent targets and objectives. Green & blue hydrogen, carbon capture (CO2 capture and sequestration and Carbon Removal through DAC direct air capture), and digital grid resilience are only several of the strategies that industry will need to employ.

What is clear, is that effective use of digitalisation will be strategic for the winning entrants in the low-carbon economy. To achieve the required scope and scale of change, a born-digital strategy will be absolutely essential, to automate the engineering execution processes but also to equip the low-carbon assets such as green hydrogen with the systems needed to operate them reliably, safely and optimally at scale.

Assets intended to operate at a low carbon intensity level and accompanying carbon removal assets, will have an ever-increasing need to be equipped with smart measurement and smart automation at the so-called “edge.” This requires highly adaptable and flexible data backbones that can connect these data sources to the modelling, optimisation, monitoring and decision support systems.

Asset intensive industries will need to have a continuous carbon-intensity improvement program, just as they have continuous quality and safety improvement programs. And these will need to transparently use smart measurement devices and digital twin models to audit and report on sustainability metrics.

More information

www.aspentech.com

The Storing '20s: can the UK realise its offshore CCS ambitions?

It is already mid-2023. That leaves 6.5 years to reach that target from a standing start. How can that be done? Is it even possible? What needs to happen if we really are to mark this decade as 'the Storing '20s'? By Ben Cannell, Innovation Director, Aquaterra Energy.

The UK government recently announced it would create a 'treasure map' of potential carbon capture and storage resources beneath the North Sea. You may find it a curious name, but the ambition is serious: the UK aims to capture 10Mt of carbon dioxide a year by 2030 – "the equivalent of 4 million cars' worth of annual emissions".

Innovation will be needed across a variety of spheres, with unresolved questions regarding the economics, contractual models, reputational challenges, and engineering of North Sea CCS.

Economics: who pays and how much?

The climate case for CCS is clear: the Paris Agreement itself emphasises the need for carbon removals alongside emissions avoidance and reductions in Clause 1 of Article 4.

It is essential to deploy CCS, at scale, as soon as possible while other essential but earlier-stage decarbonisation technologies mature. What's more, even if we can reach a point of net zero new emissions as a society, there will remain a vital role for CCS to remove legacy emissions from the air and redress emissions 'overshoots'.

So, the question of whether CCS is necessary is a settled one. However, the questions of who pays and how much are less clear cut.

Most commentators seem to agree that the near-term economic case for CCS will come from coupling it with hard-to-abate industrial sectors such as cement production, plus a nascent blue hydrogen sector.

Later, as technologies such as direct air capture mature, location may become less restrictive, but in the short-term, geographic concentration will be vital to make project economics work.

We can then imagine a near-future where such companies pay a CCS operator to store their CO2 rather than simply release it into the atmosphere as per the status quo. However, it's worth noting there are a lot of steps along the value chain before that can happen. It will cost to capture the CO2 at the flue (or from the atmosphere), and it will cost to transport it via pipeline (and cost to set up that infrastructure) – all before the CO2 even gets offshore.

So, to the question of 'how much' – the answer is potentially quite a bit. Though there may be niche markets for products such as 'green cement' where the CO2 has been stored as opposed to released, we can't expect companies to do this out of the goodness of their own hearts.

One potential method is a carbon price, either through a tax or an emissions trading scheme. However, the price would need to be sufficiently high that it makes financial sense for companies to pay for CCS instead.

Contractual conundrums: human responsibility on a geological timescale

Even if we can set a price that effectively incentivises changing corporate behaviour, we have another conundrum: who is responsible for that CO2 that is stored under the North Sea? Who keeps an eye on it and ensures it stays put?

Of course, the CCS operator will take that role in the short-term. But when talking about climate change and carbon storage, we are discussing geological timeframes, not human ones. We want, and need, to ensure that carbon stays stored for thousands, if not tens of thousands of years.

You can almost certainly bet that the operator won't be around by then. Depending on how you measure, the oldest operating company in the world today is Japanese construction company Kongō Gumi, which was founded in 578. That's nearly 1,500 years – still an insignificance on a geological timescale, and most companies last nowhere near so long.

Ben Cannell, Innovation Director, Aquaterra Energy

The implication is that, like it or not, the responsibilities will eventually pass back to the state. There is no practical way to hold the private sector accountable over that timeframe. Therefore, a stakeholder relationship needs to be established where the government clearly sets out the operator's responsibilities and the timeframe it is expected to hold them for - plus provisions for ongoing risk mitigation when responsibility is passed on.

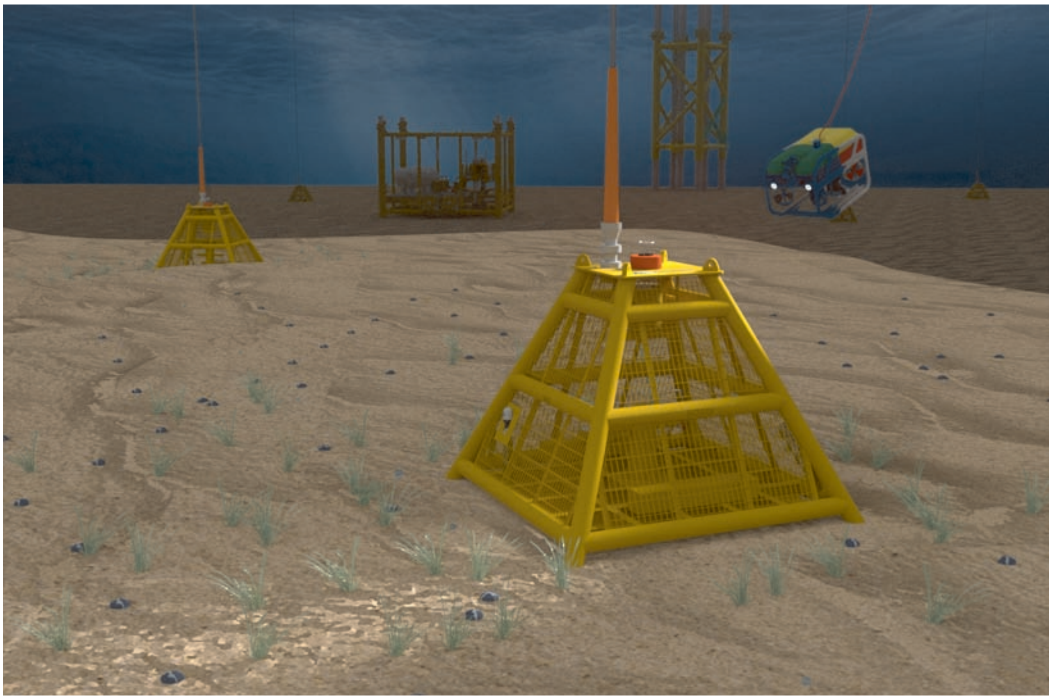
This is no mean feat. The nuclear industry has been grappling with similar issues for decades. The vast majority of our nuclear waste is held at ground or near-ground level (mainly at Sellafield), which scientists don't view as a long-term feasible plan. Consensus now seems to point to geological disposal facilities as the way forward, but it has taken decades to reach this point.

Of course, CO2 does not carry the same acute risks of radiation if it leaks, but it illustrates the difficulty of making geological timescale decisions with human timescale brains and institutions.

Public perception: waste not wanted

Another parallel to the nuclear sector – no one wants the waste in their back garden. Onshore CCS is probably unrealistic as a concept for that reason. The failed attempts to develop projects at Barendrecht in the Netherlands are illustrative in this respect.

Here, we're talking about storage beneath the North Sea, far from the vociferous objections of local communities. But that doesn't mean North Sea CCS is free of public perception challenges. Research shows mixed public feelings about CCS. Though people seem to understand the benefits and agree that 'CCS should be implemented in my country', they also worry that CO2 will leak back into the atmosphere, that it will be used to prolong the use of fossil fuels, and that science is underestimating the risks involved.



Seabed image - Aquaterra Energy's new tool for long-term integrity of CCS sites

Engineering: establishing excellence

I argue that – at least partially – these issues of public perception could be solved via an engineering solution. Consider monitoring: whether we are talking about utilising depleted hydrocarbon formations or saline aquifers, it is vital that we specify the highest standards. As the CO2 is injected, the operator needs to be able to demonstrate the CO2 plume is migrating within and filling the formation as expected by the reservoir engineering, and not entering areas it should not such as faults or previously abandoned legacy well locations. If it does so, this will demonstrate accurate knowledge of the formation and competence, therefore providing proactive reassurance in that an engineered plan is being executed. If it doesn't, injection can be paused to investigate and rectify any issues.

Subsurface repeat seismic monitoring or spotlight seismic imaging offers a proactive early warning system as well as reassurance that the injection process is going to the agreed plan. This can be coupled with water column monitoring – deploying reactive sensors to detect whether there has been a breach of CO2 – for additional reassurance.

However, it is essential that this monitoring continues after the field has been fully injected and resealed. This cannot continue indefinitely, however there will likely be a required monitoring period for injection operators post-sealing for a certain number of years, at which point the government will take over for a further defined stretch or until it is satisfied that the site is stable (e.g. by solidifying).

The catch with reactive monitoring is that these sensors are theoretically redundant – their inclusion is gold-plating in a sense. If the engineering has been done well to this point, and the proactive sensors confirm the injection has gone as planned, then they will never be used. If they are, something has gone very wrong indeed. Therefore, their inclusion is a tacit acceptance that something could go wrong – yet, it is vital to reassure the public and regulators that the asset is safely contained. Much like a fire alarm – you design so that you'll never need them, but people would rightly call you reckless if you tried to omit them.

There are other engineering challenges to solve of course. For example, a key point of difference for handling CO2 versus oil and gas, is temperature. High flow-rates of CO2 can produce a super cooling effect, which by and large, oil and gas equipment has not been designed for – steel can become brittle at low temperatures and would no longer perform to the standards expected. Equipment, such as riser systems, will need to be fabricated using special alloys to protect the areas that will be most exposed to these extreme low temperatures. Consideration will also be needed when it comes to managing the effects of heightened sweet corrosion on pipelines if they are to be redeployed as CO2 infrastructure.

From challenges to reality

However, from my perspective, these challenges are not the real hurdle. We have the knowledge and technology to tackle all of these engineering challenges quite quickly, and at Aquaterra Energy, we are already working with operators on a number of feasibility studies for North Sea CCS from vertical re-entry of legacy wells and their potential re-abandonment, as well as subsurface and water column monitoring.

Nevertheless, as engineers, we are downstream of the real blockers on the UK's CCS ambitions – we need our policymakers and regulators to address the small herd of elephants in the room, which are the unresolved economic and contractual questions – and we must keep one eye on perception issues too. If, and when, that happens – we're ready and waiting to do our part in making the Storing '20s a reality.

More information

www.aquaterraenergy.com

Cost-effective carbon capture for hard to abate industries with membranes

Compact Membrane Systems' Optiperm™ membrane technology can provide a high flow of gas at low pressure, enabling reductions to plant size and energy consumption, and a fully engineered capture cost under $50 per ton. By Nic Renard and Charlie Swartz, Compact Membrane Systems

Meaningfully mitigating the climate crisis and limiting global temperature increase to 1.5°C requires expanding beyond electrification and renewables to incorporate deep industrial decarbonization. Whereas power generation and transportation have begun their shift to a carbon neutral future, industrial decarbonization has yet to make meaningful progress.

All pathways toward a carbon neutral 2050 goal require CCUS on a massive scale in the industrial sector. The linchpin in such an effort is developing and deploying high efficiency and scalable gas separations that can successfully address the dilute nature of CO2 emissions.

Current carbon capture solutions such as amines and other solvent technologies have been used at large scale in chemical plants but have failed to demonstrate their ability to consistently and cost-effectively meet capture requirements often falling short of promised capture rates, and still saddled with a number of problems yet to be resolved (e.g. solvent degradation, ammonia emissions, high energy requirements, etc.).

Advanced membrane technologies hold the key to making CO2 emissions manageable at large and small scale, through modular, low-pressure, and low-cost separation that doesn't have accessory chemical emissions, regeneration requirements, or steam demand. Compact Membrane Systems (CMS) is in a preferred position to commercialise its Optiperm™ facilitated transport membrane technology and enable customers to unlock practical, near-term CCUS.

The Optiperm platform technology has been tested extensively in the lab at CMS and third-party facilities, and demonstrated in the field in an olefin-paraffin application. Throughout this ongoing test campaign, CMS' solution demonstrated high performance, low footprint, resistance to poisons, and ability to operate at low pressures making it ideal for point-source post-combustion carbon capture applications in several sectors such as steel, cement, chemicals, and blue hydrogen.

What Optiperm™ Carbon delivers

Optiperm Carbon is the variant of CMS' Optiperm membrane technology that targets post-combustion carbon capture applications in hard-to-abate industries. The fundamental strength of CMS membranes – and their unique power in these applications – is the ability to provide a high flow of gas at low pressure. This combination allows for a low-cost fully engineered solution by reducing the total plant size (CAPEX savings) combined with low energy consumption (OPEX savings).

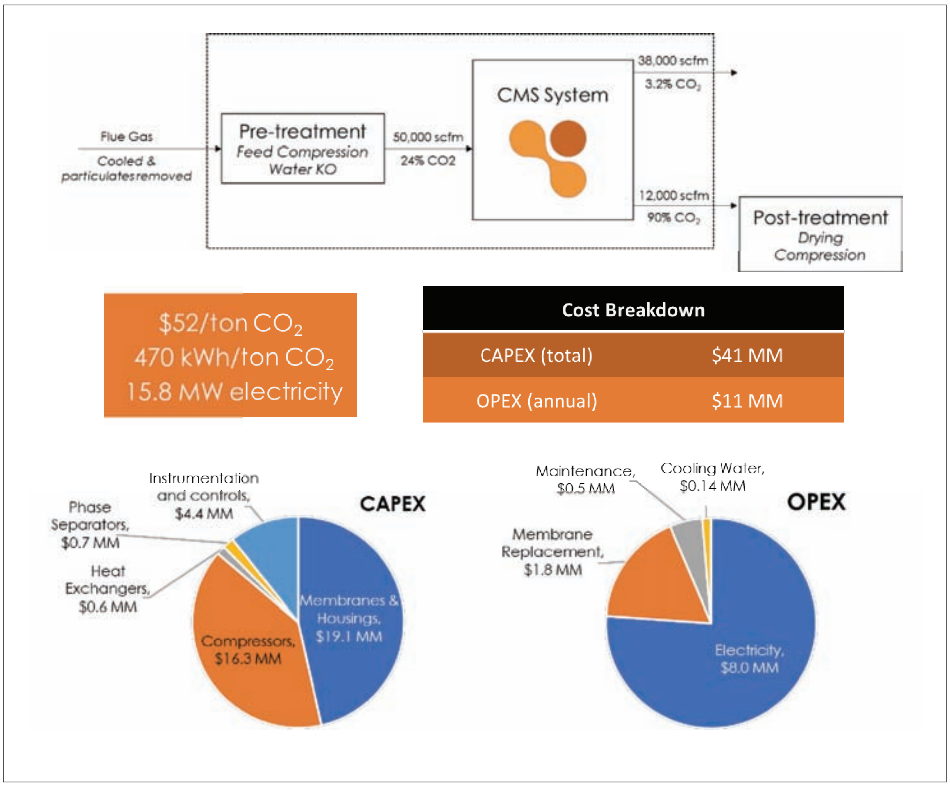
Beyond the cost unlock, CMS membranes can dominate several customer segments by combining a unique set of attributes: low-energy, fully electrified, bolt-on, poison resistant, field validated, and small footprint.

These attributes enable CMS to offer a winning near-term solution to a broad set of applications, thus addressing an $800bn market:

• Cement and other kiln processes where aversion to chemical solutions and limited access to water/steam and power are crucial.

• Steel plants, where other solutions can't tolerate the contaminants endemic to the process, nor can they always scale down to tackle individual distributed streams.

• Medium to small boiler applications (< 600 tpd) where existing solutions don't scale down.



Use case example – SMR to sequestration

• Hybrid systems working in conjunction with existing products to expand capacity.

• CO2 utilisation-driven applications where moderate purity CO2 is desired.

Use Cases

CMS developed new modeling capabilities to perform techno-economic analyses of various carbon capture use cases in its target markets. The two examples provided below serve to highlight some of the competitive strengths of CMS membranes in terms of cost, power needs and flexibility. Those analyses are performed based on membrane performance measured in the lab at realistic conditions, and verified externally, taking into account expected performance shift when scaling up.

All equipment costing numbers reflect 2019 DoE costing curves with 304 stainless steel and use installation factors based on CMS' experience in system design that are greater than those recommended by the DoE. Note that further optimization can be performed on a case-by-case basis to accommodate energy constraints, footprint requirements, or to incorporate heat and energy recovery.

Use case example - SMR to sequestration

A 50,000 scfm feed with 24% CO2, typical of a small blue H2 application was modeled. The system was optimized for minimal cost of capture with 90% CO2 purity and recovery targets at an electricity cost of $60/MWh.

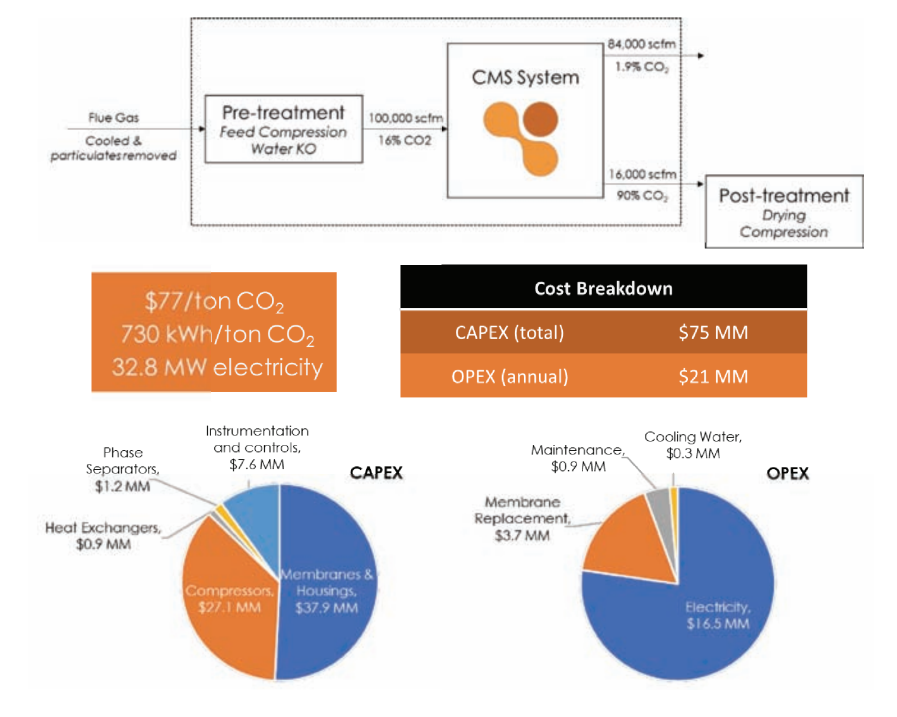
Use case example - cement sensitivity analysis

For this case, a 16% CO2, 100,000 scfm feed was considered. The mutli-stage CMS system was first optimized for minimal cost of capture to achieve 90% CO2 purity and recovery. A sensitivity analysis was then performed by varying the CO2 purity and recovery targets. The figures below show the optimized separation with $60/MWh electricity.

Economics

CMS can size and design optimal membrane systems for a variety of applications based on the third-party verified Optiperm performance data and on each application's specific conditions. The intrinsic flexibility and modularity of membranes enable CMS to develop systems taking into account customer specific needs and constraints, such as limitations in spare utility capacity, utility prices, physical footprint availability or flue gas stream conditions (pressure, temperature, composition, etc.).

As shown above, use case evaluations include comprehensive CAPEX, OPEX, and utility usage, as well as membrane sizing and sensitivity analysis.



Purity	>60%			90%			95%		
Recovery	>60%	90%	95%	>60%	90%	95%	>60%	90%	95%
Cost of Capture (/t)	$53	$58	$63	$70	$77	$84	$75	$82	$90
CAPEX (MM)	$38.2	$53.7	$64.9	$50.7	$74.6	$88.1	$59.1	$80.9	$97.0
OPEX (MM)	$11.5	$16.2	$18.6	$14.7	$21.4	$24.3	$16.0	$22.5	$26.0

Use case example – cement sensitivity analysis

Effects of Pressure

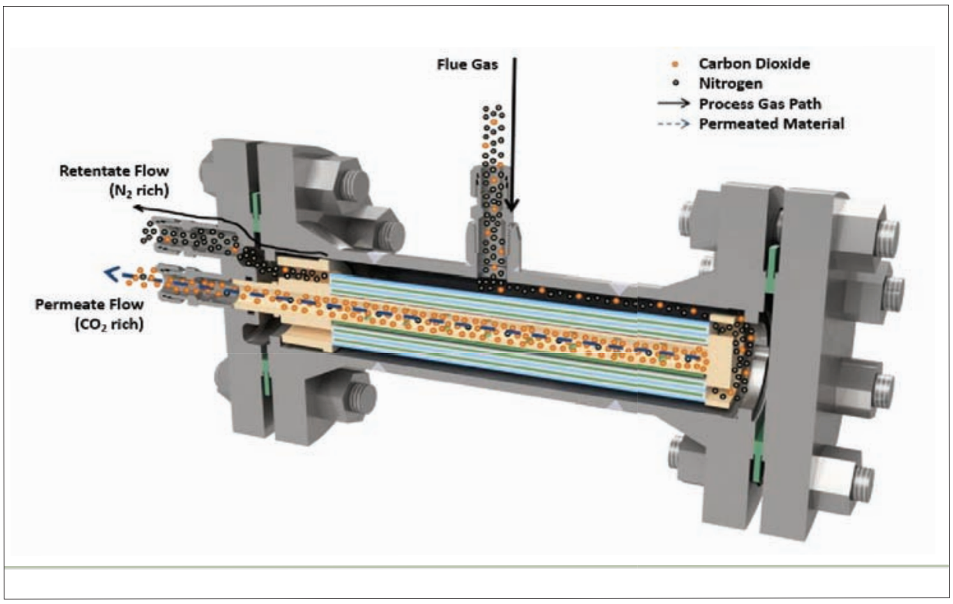
Whilst Optiperm's unique facilitated transport technology enables it to operate at low pressures, increasing pressure can be advantageous in certain scenarios. Indeed, a slightly increased pressure will enable the same separation to be performed over a reduced membrane area, which in turn reduces the overall system footprint and CAPEX, in exchange for a slightly higher OPEX.

This can be advantageous to a footprint-constrained customer, or one with low capital spend budget but high operational budget. CMS runs proprietary membrane models to examine these effects and optimize membrane system pressure to deliver the most economically attractive package and system design to the customer.

The permeate (CO2 rich stream) exits the membrane at approximately atmospheric pressure and will require compression to the pressure required for downstream use. However, in a point-source post-combustion application, where the flue gas stream almost always is at atmospheric pressure, it is much more economical to compress the smaller CO2 output stream than the 4-10 times larger feed stream.

Achievable Purity

As illustrated by the shown use cases, CMS' membranes intrinsic modularity enables their use in a range of applications with different feed and output stream concentration requirements. The latter is driven by the downstream use of the carbon, requiring CO_2 concentrations as high as 90-95+% for transport, and as low as 40-60% for certain utilization cases. This, coupled with CMS' proprietary modelling and optimizing capabilities, enables CMS to design a suite of standard low-cost modular systems that are optimized to each application's needs and constraints.



The Optiperm™ membrane

How it works

CMS developed a fluoropolymer membrane known as Optiperm that exploits a mass-transfer mechanism known as facilitated transport. Active elements in the membrane allow for the selective transfer of carbon dioxide molecules through the membrane. As nitrogen molecules do not have the same interaction, this difference in affinity allows CO_2 to pass through the membrane at significantly higher rates than N_2.

CMS has performed extensive testing in its own lab and at third-party facilities to establish the performance and stability of this mechanism. CMS has also deployed the platform technology in the field, in an olefin-paraffin separation application, at a Braskem site (see press release). The technology is now ready to be deployed in the field in a carbon capture application.

How is membrane performance characterized?

Permeance is the rate at which one component travels through a membrane surface area for a given driving force and is effectively a measure of separation processing volume. Increased permeance enables the processing of large streams with minimal surface area. This performance metric is typically expressed in GPU (gas permeation unit).

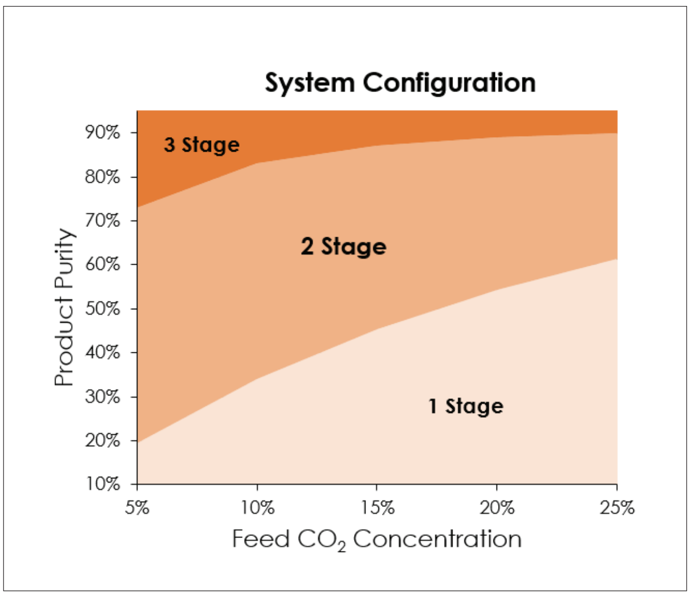
The selectivity of one component to another is the ratio of the permeance of the two components and is a measure of separation quality. This tells you how much CO_2 is passing through the membrane as compared to N_2.

Both metrics are a function of the membrane operating conditions and are only useful when measured at realistic field conditions (e.g. pressure, temperature, stage cut). CMS has tested hundreds of polymers and developed Optiperm™ to provide a unique combination of high permeance and high selectivity at field conditions, thus enabling attractive process economics in most use cases.

Operating conditions and stability

CMS has demonstrated cost-effective carbon dioxide separation at low pressures thus requiring only minimal compression of the flue gas stream (as low as 1.4 bara) and a vacuum on the permeate stream. This enables Optiperm to significantly reduce the balance of plant footprint and therefore the unit's capital and operational cost.

As with all facilitated transport membranes, Optiperm requires humidification of the process stream. CMS has developed and patented a proprietary humidification system within the module to ensure optimal performance. The membranes' intrinsic modularity enables Optiperm to cost-effectively concentrate a number of CO_2 streams destined for a wide range of utilization and sequestration applications, as illustrated in the figure below.



Operating conditions

A broad range of tests have demonstrated Optiperm membranes' resistance to common poisons in post-combustion flue gas streams such as SOx, NOx, H_2S, CO and other molecules, thus providing it with expected lifetimes of 6-10 years. This puts Optiperm apart from solvent technologies which tend to degrade and get used up by certain poisons, thus requiring bleed and feed systems to renew the solvent as well as fumes control systems to manage emissions caused by the degradation.

Further tests in real flue gas streams, representative of a number of applications (steel, kiln, petchem, etc.) will be taking place in 2023 and further validate Optiperm's resistance to poisons.

Field testing and beyond

Though not yet deployed in the field in a post combustion flue gas stream (see below for details of planned carbon capture pilots and demos), CMS' Optiperm facilitated-transport technology has been demonstrated in the field several times, and most recently in olefin-paraffin separation applications.

Optiperm successfully completed its first field demonstration at the Delaware City Refinery Company in 2018. The pilot showed stable membrane performance for 50+ days in the presence of poisons. The main objective of the pilot was achieved when the field results validated data collected in the lab.

A demonstration unit is currently operating at a Braskem manufacturing site. This demo plant demonstrates CMS' commercial-sized membrane modules in a multi-stage unit for olefin recovery from a polypropylene reactor purge with a full control system enabling the generation of on-spec product streams. Braskem Technology Improvements Manager Kevin Soucy has said that they are "very excited to continue to work with CMS through optimization and commercialization of their Optiperm technology". In fact, Braskem has signed-up for a paid demo plant to deploy Optiperm in a carbon capture application on a Braskem site in 2024 (see press release here).

Additionally, CMS is finalizing further deployments of its membrane systems in field rigs and demonstrations in a number of applications:

Three partners, voestalpine(steel), RHIM (kiln process) and petchem (TBA) are each funding the piloting of Optiperm™ Carbon modules in real flue gas streams and, if successful, the deployment of a 1+ tpd demo plant.

One of the world's largest oil & gas companies has tested modules at a third-party facility, in a test campaign entirely funded by them. Discussions are ongoing to follow-up with a larger demonstration program.

A large pipeline of additional customers are in active discussions with CMS to model their use cases and test the technology on their flue gas stream.

CMS will leverage these field tests and decades of experience commercializing membranes systems to deliver commercial carbon capture systems to the field as soon as 2026. CMS' in house capabilities coupled with the competencies and capabilities of its partners will enable CMS to quickly and reliably scale-up production for full commercial-sized modules for piloting and demonstration purposes in the short-term and commercial deployment in the medium term.

Company background

CMS was founded in 1993. CMS develops membranes for tough chemical separations in industrial gas and liquid applications and has developed and produced membranes for use in transformers, wind turbines, marine systems, pharmaceutical manufacturing, and bulk gasoline storage, among other applications.

Manufacturing and development are performed at our site in Newport, Delaware. CMS' team comprises of 20 employees with skills spanning across R&D, product development, systems modelling, business development, operations and management. CMS also has a handful of advisors with decades of experience in the oil & gas and membrane industries.

More information

Nic Renard

nrenard@compactmembrane.com

Charlie Swartz

cswartz@compactmembrane.com

www.compactmembrane.com

CO2 reduction via biomass conversion in energy and chemicals

The report from the Industrial Energy Transition and Decarbonization (IETD) Consortium (formerly the CO2CC Program) provides an overview of a range of products / applications before discussing individual routes in detail, reviewing emissions and costs compared to their fossil benchmarks.

The objective of the report is to summarize commercial and emerging biomass technologies for energy and chemicals and provide an overview of recent life cycle assessment (LCA) studies focusing on global warming potential (GWP).

The processing of biomass for energy, biomass-based fuels, and biomass-based chemical applications are promising approaches to decarbonising countries' economies and have become a growing sector.

In general, biochemicals can lead to reduced climate change impacts compared to fossil-based counterparts. Such reductions can be achieved through direct substitutions (e.g., bio-based ethylene to replace fossil-based ethylene) or indirect substitutions (e.g., bio-based resin to replace phenolic resin).

Possible mechanisms for biochemicals to reduce GHG emissions include:

• Carbon sequestration credit through biomass growth

• Reduced emissions from the manufacturing processes (e.g., reduced energy consumption)

• Reduced emissions from the use phase of the product (e.g., lower direct emissions, longer service lifetime)

• Reduced end-of-life (EoF) emissions (e.g., permanent carbon storage in landfill).

The report entails three Chapters: 1) Introduction, 2) Biomass Conversion in Energy, and 3) Biomass Conversion in Chemicals.

For Biomass Conversion in Energy, Chapter 2 reviews the climate change impacts of making transport fuels. It discusses making drop-in fuels via HEFA/HVO, pyrolysis, gasification and Fischer-Tropsch synthesis (Gas-FT), hydrothermal liquefaction (HTL), Alcohol-to-Jet (ATJ), and direct sugar hydrocarbons (DSHC), making biodiesel via trans-esterification, and making ethanol.

Further, Chapter 2 reviews the emissions of making renewable natural gas (RNG) via gasification or anaerobic digestion, making hydrogen via gasification and microbial fermentation. The chapter also covers direct biomass use for heat or combined heat and power (CHP), as well as the use of biogas for electricity and CHP.

For Biomass Conversion in Chemicals, Chapter 3 first provides an overview of biomass feedstocks, discusses carbon displacement factors, and discusses biobased value chains for chemicals. The chapter continues by reviewing the climate change impacts of biobased intermediates (alkanes, naphtha), syngas-derived chemicals, and C2-C6/6+ value chain chemicals (ethylene, benzene etc.)

The studies included in the report all include a life cycle component for GHG emissions calculations, and most of them are full life cycle assessments.

Key takeaways from the report

• Overall, 2nd generation non-food feedstocks seem to be the most promising. 3rd generation feedstocks, which mainly include micro-algae in all the studies reviewed, are still far from maturity with a technology readiness level (TRL) of 2-5 and tend to lead to lower greenhouse gas (GHG) reductions when compared with 2nd generation feedstocks.

• For 2nd generation feedstocks, several pathways look promising, depending on the feedstock considered. Waste oils and fats, such as waste cooking oil and tallow, and perhaps dedicated 2nd generation oily crops grown on marginal lands, such as jatropha and camelina, would likely be well suited for hydroprocessed esters and fatty acids (HEFA) or biodiesel.

• For processes that need an external hydrogen source, the electricity footprint is usually a very significant contributor to the overall life cycle GHG emissions. Hydrogen is currently still produced by steam methane reforming (SMR) of natural gas, but a couple of studies mentioned in this report highlight the interest in supplying hydrogen via other processes, such as biomass gasification or water electrolysis using low-carbon electricity.

• A possibility to reduce further GHG emissions from biomass conversion and use for energy purposes is the integration of CCS for some of the pathways discussed here. This could be possible for hydrogen production via gasification or renewable natural gas (RNG) production by gasification and by purification of biogas produced by anaerobic digestion.

• Biochemicals may lead to reduced climate change impacts compared to fossil-based counterparts. Such reductions can be achieved through direct substitutions or indirect substitutions. Possible mechanisms for biochemicals to reduce GHG emissions include: (1) carbon sequestration credit through biomass growth, (2) reduced emissions from the manufacturing processes, (3) reduced emissions from the use phase of the product, and (4) reduced end-of-life (EoF) emissions.

• A few bio-based pathways showed reduced energy consumption during the product manufacturing stage compared to the benchmarks. In other cases, there are energy consumption "hotspots" during the manufacturing stage.

• Besides higher than benchmark production costs, there is a significant challenge for the scaling up of production capacity for biochemicals. The higher costs can be attributed to feedstock procurement and complex manufacturing steps. Switching from dedicated feedstocks to marginal feedstocks may reduce the feedstock production cost.

More information

More information about this report and other deliverables of the IETD Consortium can be found at:

www.catalystgrp.com/tcg-resources/member-programs/industrial-energy-transition-and-decarbonization-ietd-consortium/

Projects and policy news

U.S. to invest up to $1.2B in DAC hubs

www.energy.gov

The U.S. Department of Energy (DOE) has announced up to $1.2 billion to advance the development of two commercial-scale direct air capture facilities in Texas and Louisiana.

These projects, the first of this scale in the United States, represent the initial selections from President Biden's Bipartisan Infrastructure Law-funded Regional Direct Air Capture (DAC) Hubs program, which aims to kickstart a nationwide network of large-scale carbon removal sites to address legacy carbon dioxide pollution and complement rapid emissions reductions.

The Hubs are expected to ensure meaningful community and labour engagement and contribute to the President's Justice40 Initiative. Together, these projects are expected to remove more than 2 million metric tons of carbon dioxide emissions each year from the atmosphere—an amount equivalent to the annual emissions from roughly 445,000 gasoline-powered cars and create 4,800 jobs in Texas and Louisiana.

The announcement will be the world's largest investment in engineered carbon removal in history and each Hub will eventually remove more than 250 times more carbon dioxide than the largest DAC facility currently operating. Their development will help inform future public and private sector investments and jumpstart a new industry critical to addressing the climate crisis on a global scale.

The two DAC Hubs selected for award negotiations will help further demonstrate the ability to capture and store atmospheric CO2 at scale.

To assess the viability of future DAC Hub demonstrations, DOE also announced 19 additional projects selected for award negotiations that will support earlier stages of project development, including feasibility assessments and FEED studies.

Acorn and Viking CCUS clusters to proceed through UK Track 2 process

www.gov.uk

New UK government funding will support industry to reduce its reliance on fossil fuels and slash carbon emissions.

On 30 March 2023, the UK Department for Energy Security and Net Zero launched a 4-week expression of interest process for transport and storage systems that believed they met the eligibility criteria set out in the CCUS Track-2 guidance.

Subject to final decisions, due diligence, consenting, subsidy control, affordability and value for money assessments, the government has concluded the Acorn and Viking cluster projects are best placed and it will now begin engagement, assessment of delivery plans and due diligence.

"In making this decision, we align with the Review of Net Zero chaired by Chris Skidmore MP, which included a recommendation that government should take a pragmatic approach to cluster selection by allowing the most advanced clusters to progress more quickly," said the UK Government.

"We recognise the importance of providing further certainty for industry and we will work with other T&S systems on future opportunities through the government's CCUS programme."

"Later this year, we will publish a vision for the UK CCUS sector, setting out how CCUS will support our net zero ambitions, to raise confidence and improve visibility for investors. Engagement with industry about future plans will continue, and extensive meetings are being held today as part of that."

Acorn also retains its status as a Track-1 reserve cluster and the government has reserved the right to enter into accelerated negotiations with Acorn in the event that one of the named Track-1 clusters encounters significant delivery challenges.

CCSA welcomes new Government Biomass Strategy

www.ccsassociation.org

The UK Government's Biomass Strategy sets outs positive steps toward delivering the UK's net zero agenda.

Biomass-generated power is a sustainable, renewable way of making energy by burning wood chips and other plant material. It can be used in power stations to make carbon neutral electricity, as the CO2 released when it is burnt is equivalent to what was absorbed by the biomass during its lifetime.

As well as power generation, biomass also has industrial uses. For example, it can also be converted into jet fuel known as Sustainable Aviation Fuel (SAF).

The Biomass Strategy makes clear Greenhouse Gas Removal (GGR) technologies are vital because they enable carbon-emitting sectors such as agriculture, cement and steel to continue while achieving net zero. BECCS is a key example of this technology and the strategy sets out "active work" in government to support it via development of the Power BECCS and GGR business models and clear guidance.

A report by the Government BECCS task and finish group published alongside the strategy sets out the "substantial opportunity for the UK to develop a leadership position on the delivery of sustainable BECCS & GGRs". Failure to pursue the technology now risks "innovation and associated export opportunities" for British businesses, increasing the cost of delivering net zero.

It follows an important announcement last week on the UK Government's support for two further clusters in Humberside and Scotland.

Ruth Herbert, CEO of the CCSA, said, "Today's publication of a Biomass Strategy for the UK is good news. Capturing carbon produced from burning biomass is an important part of the carbon removal toolkit to remove greenhouse gases from our environment, particularly for hard-to-decarbonise sectors like agriculture and aviation. It will help ensure we can protect jobs, maintain important industries and deliver our net zero ambitions."

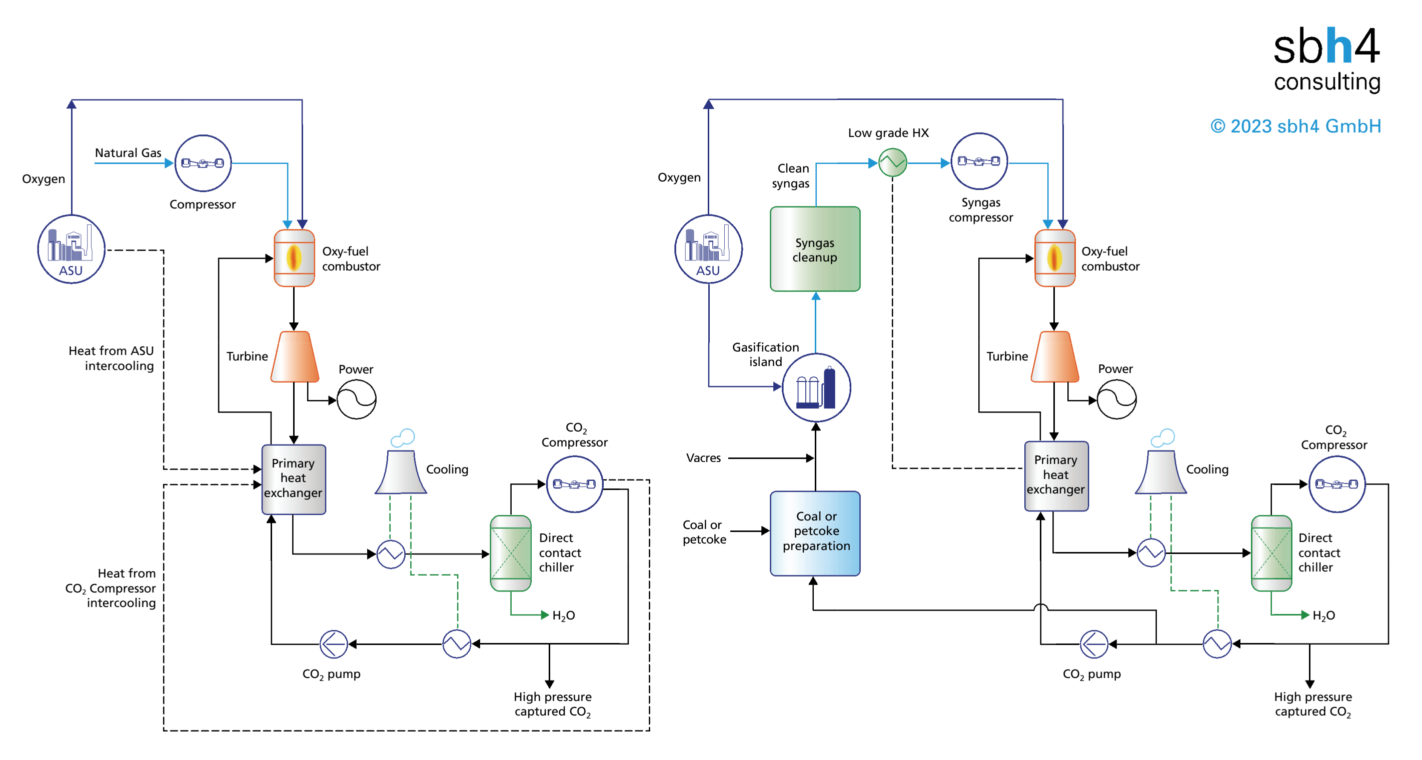
"BECCS is one part of the suite of carbon capture and storage solutions that has the potential to underpin the next industrial revolution. We urgently need HM Treasury to set out further detail on the scale and timing of support to BECCS and other potential carbon capture sites."

"Failure to act this Autumn would risk undermining investor confidence in the UK while others such as the United States race ahead in the development of this vital technology."

Oxy-fuel combustion for CO2 capture from thermal power generation

With the Allam-Fetvedt cycle CO2 capture is integrated into the process, providing a pure high pressure CO2 stream at high efficiency. By Stephen B. Harrison, sbh4 consulting.

The Allam cycle for natural gas or coal: oxy-fuel thermal power generation with integrated CO_2 capture



Classic Allam cycle for natural gas

Adapted Allam cycle for syngas from vacres, petcoke or coal gasification

Affordable, clean power is essential to drive sustainable economic development and prosperity. Renewables such as wind, solar, hydro, and tidal power will be integral in the energy mix, as will nuclear power generation.

Alongside those, the Allam-Fetvedt cycle can offer thermal power generation with zero CO2 emissions to air. Thermal power generation can thereby continue to contribute to the baseload capacity and compliment intermittent and variable renewable sources.

The Allam-Fetvedt cycle relies on oxy-fuel combustion which ensures that pollutant emissions are avoided and carbon dioxide from hydrocarbon combustion can easily be captured. It offers high-efficiency power generation from traditional fossil fuels in an innovative process that avoids greenhouse gas emissions, allowing coal and natural gas to contribute to a cost-effective, net-zero future.

Oxy-fuel combustion of natural gas enables CO2 capture

In the case of oxy-fuel combustion of methane, the main products are carbon dioxide (CO2) and water vapour. These can be separated simply by cooling the flue gas to condense the water vapour. The resultant CO2 can be liquefied or compressed and the transported from the site for utilisation or sequestration.

In the Allam-Fetvedt cycle, efficient heat exchange is essential to achieve a high process efficiency. In the cycle, the burner feed gases are pre-heated by the exhaust gases. The equipment used for heat recovery is a printed circuit heat exchanger. This is a mature technology that has been used at scale in the oil gas sector for decades. Its compact nature has made it popular for offshore deployment on rigs where space is at a premium.

The Allam-Fetvedt cycle leverages oxy-fuel combustion and takes the process further. It simultaneously produces high-pressure CO2 for sequestration and very high energy efficiency within the power generation cycle. CO2 from the Allam-Fedvedt cycle can either be directly liquefied or introduced into a CO2 pipeline without the need for additional mechanical compression energy to be expended.

Avoiding the pollution from air-fed combustion

In air-fed power generation using coal-fired burners, flue gas treatment is highly complex. A typical coal fired power plant will have filtration or electrostatic precipitation equipment to knock down dust and ash particles. It will also be fitted with flue gas desulphurisation where lime is reacted with sulphur dioxide to form gypsum. Then there is likely to be a DeNOx process based on selective catalytic or non-catalytic reduction of oxides of nitrogen (NOx) emissions to inert nitrogen gas. Mercury removal on activated carbon filters may also be required.

Finally, to reduce CO2 emissions, post-combustion carbon capture will need to be implemented from the coal fired power plant. Since air is used to introduce oxygen for combustion, a huge volume of nitrogen gas is also flowing through the power plant furnace the is contained in the flue gas. Picking out the CO2 molecules from the steam of nitrogen is very energy intensive and since the gas is at low pressure, the size of the equipment is extremely large.

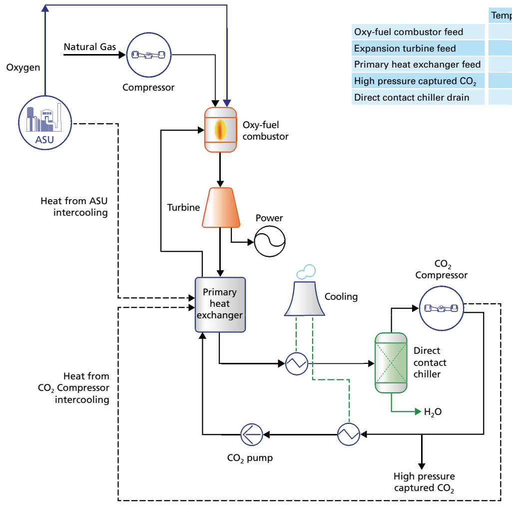
Integrated CO2 capture

CO2 capture is often divided into pre-combustion and post-combustion processes. Pre-combustion CO2 capture is possible on steam methane reformers within the process. It can take place at high pressure and high CO2 concentrations, reducing the capital and operating costs of decarbonisation.

Post combustion CO2 capture generally takes place at the end of a process where the gas stream is very low pressure, and the CO2 is often diluted with nitrogen from combustion air. Uniquely, the Allam-Fetvedt cycle enables low-cost post-combustion CO2 capture.

A steady flow of CO2 is recycled within the cycle as the thermodynamic working fluid. But, during combustion of the syngas or natural gas feedstock additional CO2 is generated. This is released from the cycle at about 80 bar. There is no other route out of the process for the CO2, so the capture rate is 100%.

The Allam cycle for natural gas: oxy-fuel thermal power generation with integrated CO_2 capture



			Stream composition, referenced to combustor feed			
	Temperature °C	Pressure bar	CO_2 wt%	Natural gas wt%	Oxygen wt%	H_2O wt%
Oxy-fuel combustor feed	700	300	94	1,25	4,75	0
Expansion turbine feed	1150	300	97,25	0	0	2,75
Primary heat exchanger feed	720	30	97,25	0	0	2,75
High pressure captured CO_2	60	80	100	0	0	0
Direct contact chiller drain	20	30	0	0	0	100

sbh4 consulting

CO2 as a power system working fluid

The US DOE-funded STEP demonstration project which has been executed by GE and GTI uses a closed cycle with supercritical al CO2 as the working fluid. The Italian startup Energy Dome uses sub-critical CO2 in a closed cycle in their CO2 battery, a technology aligned to long duration energy storage.

Beyond its use in modern power systems, CO2 is a versatile molecule. Its thermodynamic properties also mean it is ideal as the working gas in closed loop refrigeration cycles.

Conventional coal-fired power generation heats up steam, which is the working fluid within the power generation turbines. In conventional air-fed, gas-fired turbines, the nitrogen-rich combustion gases themselves drive the generator.

In the Allam-Fetvedt cycle, combustion gases are also used to spin the main turbine. However, in this case, a mixture of approximately 97.3% CO2 and 2.7% water vapour flows through the turbine.

The main turbine for the Allam-Fetvedt cycle was developed by Toshiba. The temperature and pressure mean that the CO2 is supercritical at the turbine inlet. And the presence of moisture means that carbonic acid formation is possible. Materials selection and coating technologies are the key to successful turbine production in this operating environment.

Syngas as an alternative gaseous fuel

Air separation is required to produce oxygen used in the Allam-Fetvedt cycle oxy-fuel burner. The use of oxygen, rather than air, as the oxidant source in gasification has significant cost and environmental benefits. Similarly, oxy-fuel gasification is a clean means of producing syngas, which is also a viable fuel for the Allam-Fetvedt cycle.

Coal, petcoke or vacres gasifiers can be operated at pressure. This enables cost effective pre-combustion CO2 capture. Similarly, when syngas is produced from natural gas through gasification (known as partial oxidation, or POx) the process can operate at up to 80 bar, meaning the CO2 capture equipment can be compact and CO2 is produced at high pressure, enabling efficient transportation off-site.

The release of CO2 at high pressure from gasification contrasts to post-combustion CO2 capture from conventional thermal power generation, where the CO2 capture equipment operates at close to atmospheric pressure. From these low pressures, CO2 must be compressed or liquefied to be moved to a storage or utilisation location. CO2 compression consumes parasitic power from the power generation process, resulting in a lower overall efficiency.

More information

sbh4.de

Researchers develop a sustainable gel film to capture CO2 with reduced energy

A gel developed at MIT made from commercially available materials and with a low regeneration energy could offer a low cost carbon capture method.

Direct air capture (DAC) technologies extract CO2 directly from the atmosphere at any location, but their practicality is limited by the higher energy needs and overall costs. In particular, most solid-sorbent-based systems cannot function well in humid conditions and have high regeneration temperatures or require vacuum conditions.

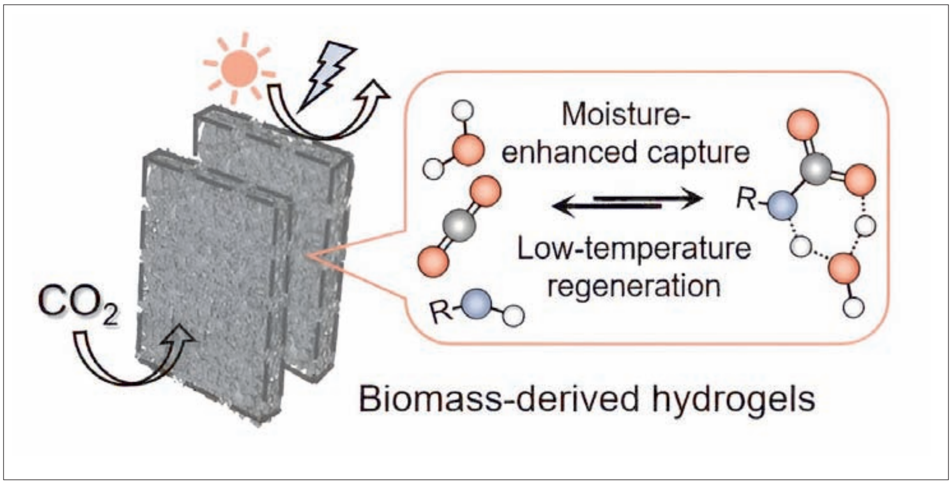


Fig 1. Schematic of the sustainable carbon capture hydrogels. Credit: Youhong Guo

Design of sustainable carbon capture hydrogels (SCCH)

To overcome these challenges, they developed sustainable carbon-capture hydrogels (SCCH) as a step-change material for CO2 capture with high uptake and exceptionally low regeneration energy (Figure 1).

The study is published in the journal Nano Letters.

In contrast to other sorbent materials where the inert water leads to energy-intensive thermal regeneration, water in hydrogels has a reduced evaporation enthalpy that can contribute to a lowered regeneration energy.

The SCCH consists of low-cost biomass konjac gum, thermo-responsive cellulose, and uniformly dispersed polyethylenimine (PEI). Another advantage of this SCCH is its unique hierarchical structure. The micro- and nanoscale pores enable CO2 transport and easy access to active amine sites.

Carbon dioxide capture performance

The precaptured water vapor enhances the CO2 binding with PEI, which leads to a much higher capture capacity under humid conditions (Figure 2, left). In addition, the captured CO2 releases at a low energy supply (Figure 2, right), which can be achieved by mild electric heating or solar irradiation without vacuum, as long as the temperature reaches ~60°C.

This is assisted by reduced evaporation enthalpy of water in hydrophilic hydrogels and the thermo-responsiveness of cellulose.

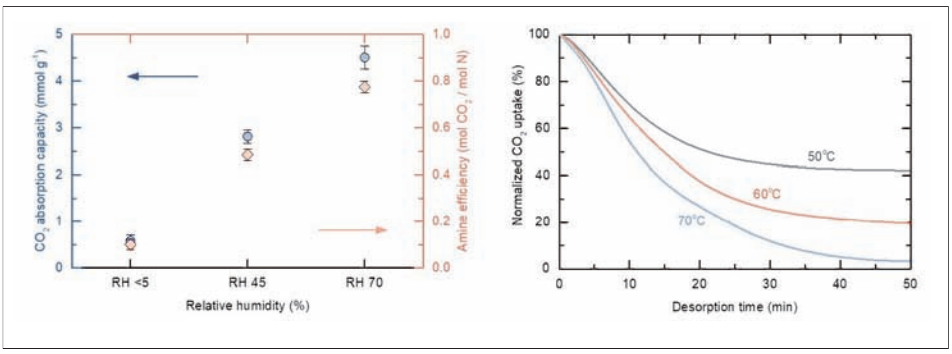


Fig 2. (left) moisture-enhanced carbon dioxide capture and (right) low regeneration temperature at ~60 degrees Celsius. Credit: Youhong Guo

They also highlight another advantage of the SCCH, which is the ease of preparation. The gel can be made with commercially available materials, dissolved in water, poured into a mold, and followed by a freeze-drying process.

This is scalable and durable in ambient air, which benefits practical application. With such a low regeneration temperature, our new hydrogels can be a game-changing materials platform for more sustainable air quality management and DAC technologies.

Youhong Guo is a Postdoc in the Department of Chemical Engineering at Massachusetts Institute of Technology, working with Prof. T. Alan Hatton. Her research interests are developing polymer materials for applications in energy and environmental sustainability.

More information

pubs.acs.org/journal/nalefd

Capture & utilisation news

Avnos secures $80m to develop direct air capture technology

www.avnos.com

The Los Angeles-based company developing Hybrid Direct Air Capture (HDAC™) technology has signed a funding and partnership agreement with ConocoPhillips, JetBlue Ventures and Shell Ventures.

Avnos said it will use the capital to deliver commercial-ready HDAC units by the end of 2025. Previously, Avnos has been awarded multi-million-dollar projects from the U.S. Department of Energy to demonstrate its HDAC solution in the field, and the U.S. Office of Naval Research to pilot CO2 capture and e-fuels production.

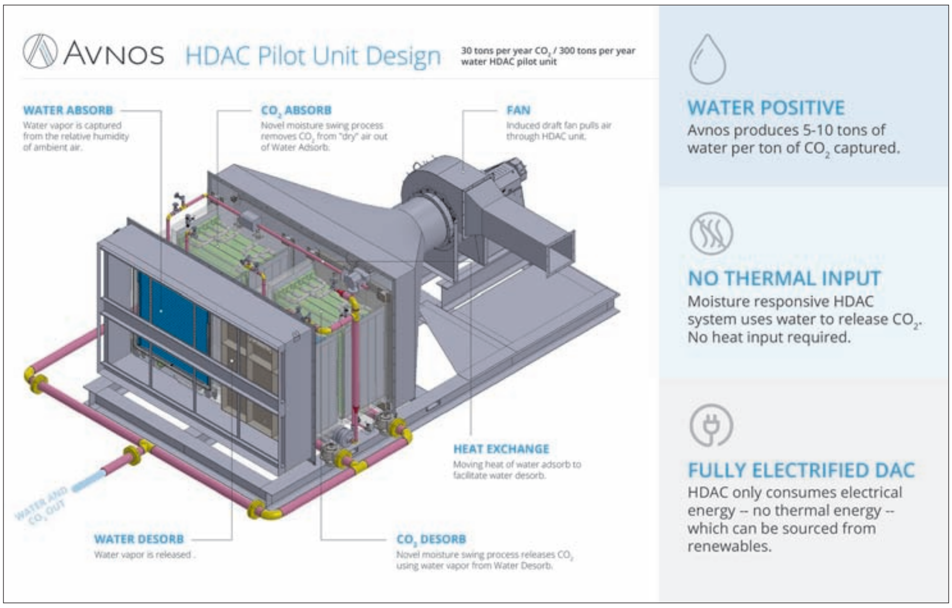
Avnos said its proprietary HDAC technology is the only carbon dioxide removal (CDR) solution that captures both CO2 and water from the atmosphere in a single system. While many other forms of Direct Air Capture consume several tons of water per ton of CO2 captured, Avnos produces five to ten tons of water for every ton of CO2 captured.

This innovative HDAC approach employs the captured water to drive a novel moisture-responsive CO2 adsorbent material, which eliminates the need for heat, thus reducing the system's energy consumption. As a result, the Avnos solution requires less than half the energy required by competitors, the company says.

"Adding blue-chip strategic partners such as ConocoPhillips, JetBlue Ventures, and Shell provides us with an incredible opportunity to access more resources, know-how, and global reach to meaningfully accelerate our deployment schedule," said Will Kain, CEO of Avnos.

"Ultimately, we will be able to remove more atmospheric carbon, faster, and at lower costs than we would have been able to on our own. This is a very exciting announcement at a very exciting time for our company."

Nearly all climate and energy models indicate the need for CDR technology to grow to billions of tons of annual capacity to make a significant impact on reducing emissions.



ANDRITZ carbon capture plant is now operating successfully at voestalpine

www.andritz.com

International technology group ANDRITZ has supplied its first carbon capture plant to the steel industry. The pilot plant started operating at voestalpine's steel mill in Linz, Austria, in the second quarter of this year.

The plant separates CO2 from the flue gases resulting from iron making using an amine-based process designed by ANDRITZ. The captured CO2 is filled into large industrial gas bottles and delivered to an Austrian energy storage company that is investigating new ways of making it available for re-use in steel production, fostering a sustainable carbon circularity and reducing the need for fossil fuel.

The plant was ordered by the K1-MET metallurgical competence center, a leading research body working with national and international partners like voestalpine to address issues such as energy efficiency, circular economy, and climate-neutral metal production. It helps to gain experience in plant operation, investigate new absorption media, and optimize the process.

Michael Derntl of K1-MET said, "Successful pilot operation of the carbon capture plant will help us to take an important step towards using this technology at an industrial scale in the steel industry."

With its carbon capture technology, ANDRITZ supports companies in decarbonizing their operations and creates the basis for storage or further processing and use of CO2.

Electrochemical cell could help industrial processes capture CO2

pubs.acs.org

Researchers reporting in ACS Central Science have designed a capture system using an electrochemical cell that can easily grab and release CO2.

tThe device operates at room temperature and requires less energy than conventional, amine-based carbon-capture systems.

Many industries are turning to electrification to help curb carbon emissions, but this technique isn't feasible for all sectors. For example, CO2 is a natural byproduct of cement manufacture, and thus a major contributor to emissions on its own. Excess gas can be trapped with carbon-capture technologies, which typically rely on amines to help "scrub" the pollutant by chemically bonding to it. But this also requires lots of energy, heat and industrial equipment — which can burn even more fossil fuels in the process.

The researchers say that this work shows that an electrochemical alternative is possible and could help make continuous CO2 capture-release technologies more practical for industrial applications.

Monitoring CO2 storage integrity and ensuring it stays there

The best way to be re-assured of CO2 storage integrity is probably 4D seismic – but it needs to be done differently to exploration 4D to keep the costs manageable. We explored the topic in a webinar. By Karl Jeffery.

It may seem that there are no easy ways to ensure that CO2 injected into subsurface storage stays there, if 4D seismic is prohibitively expensive, and surface monitoring will only let you know when its too late.

But 4D seismic for CO2 storage can be done in ways which are much less expensive than 4D seismic for exploration, we heard at a Finding Petroleum webinar on April 21, presented by Robert Hines, principal advisor CCUS at Inosys.

4D seismic, as used in oil and gas exploration, involves repeated, very expensive, high resolution seismic surveys in 3D, to determine how much oil and gas remains and where it is.

By subtracting one survey image from another, you can see how the subsurface is changing, whether from oil and gas extraction, or from CO2 injection.

There are examples of 4D seismic done on CO2 storage for Equinor's Sleipner field, where CO2 injection started in 1996.

The survey needs to be done very carefully to ensure that one survey can be compared with the previous one. And the processing is also very expensive and time consuming.

But CO2 storage projects will only have a limited budget for monitoring, with long term storage costs estimated to be as low as $10 per tonne of CO2.

But for CO2 storage, the most important survey is the first one, validating that CO2 is staying where it was intended to stay. After that, further surveys can be even more sparse in space and time, and may not be needed at all, Mr Hines said.

The process might be better termed 'model validation' than 4D seismic, Mr Hines said. It means being able to say to a regulator, 'we know what this is doing, it is behaving in exactly the modelled way, it's not going to come to the surface for 2 million years,' he said.

A range of different equipment can be used to record seismic data, including strings of devices towed behind vessels ("towed arrays"), fibre optic cables permanently installed on the seabed or in oilwells acting as seismic receivers, and 'nodes' on the ocean bottom.

The permanent solutions (ocean bottom nodes and fibre optic cables) are typically more expensive than using towed arrays, but offer a high degree of repeatability, because the recording device does not move, he said.

Regulators

CO2 storage regulations, particularly in the UK, are not particularly prescriptive, and there is scope for an alternative approach to be accepted, if it is backed with solid reasoning, Mr Hines said.

Politically, it is quite a difficult issue. Politicians would like risk to be zero. Technical people are aware that the risks are not zero, just as we see oil and gas seeping to the surface, although it can take millions of years to happen. But politicians are not easily satisfied at being told that the risk is very low but still exists.

It is fair to say, from a technical perspective, that the risks are extremely low. Consider the North Sea, where storage sites have salt layers above them, and the reliability of storage has been estimated by regulators to be 99.99 per cent, Mr Hines said.

Yet for an oil and gas company to say, 'trust us, it's safe, we don't need to monitor it,' that is a hard sell, Mr Hines said.

In the one project where CO2 storage has been analysed by 4D seismic, Norway's Sleipner field, the CO2 'plume' did take a different 'shape' in the subsurface to the one expected from the modelling.

Robert Hines, principal advisor CCUS, Inosys

But the 4D seismic still shows that the CO2 is nowhere near leaking and has offered re-assurance to regulators.

Surface monitoring

The other CO2 storage monitoring method is surface monitoring, either looking for CO2 gas bubbles in water, or analysing water and sediment for CO2 dissolved in it.

But unfortunately, these are extremely difficult to use to demonstrate containment, Mr Hines said.

A natural CO2 leak can be seen visually, and there is an example of a natural CO2 leak into water in Italy. The bubbles could be 'heard' using a sonar scan.

But if CO2 were to leak from a storage site to the seabed, it may well find multiple pathways through to the seabed, and so appear in multiple points, not necessarily above the storage site and may no longer be in a gaseous form.

Once released into water, CO_2 dissolves quickly. This would change the acidity of water, but the effects are quickly dissipated in a large volume of water.

Studies were done to see if CO_2 dissolved in seawater could be detected chemically but found no satisfactory proof that it could be, Mr Hines said. In one of the projects, indications of CO_2 could be detected in water very close to the known position of the leak, but that alone is not very helpful as a detection method. "Chemical detection really remains unproven."

There have been three big research programs in the UK so far, which have released CO_2 into the marine environment and measured how it effects seawater, using remotely operated vehicles and autonomous underwater vehicles, Mr Hines said.

One of these is the STEMM-CCS project on the Goldeneye CO_2 storage site in the North Sea, where CO_2 was injected 3m below the seafloor, with 4.2 tonnes CO_2 injected over 37 days. The other projects were similar.

Over the three experiments, the research showed that CO_2 bubbles were easy to detect with sonar. But chemical detectors, which aim to detect the CO_2 from analysing water samples, did not prove to be so useful, Mr Hines said. They showed that if you can drive a sensor right up to the leak point, it can be detected, but that is not a very practical monitoring method.

In one of the experiments, CO_2 was injected 11m deep into sediment, and only 15 per cent of CO_2 escaped, the rest was trapped by sediment.

A point to note here is that the volumes of CO_2 used in the test (e.g., 4.2 tonnes injected over 37 days) could be much smaller than the volumes likely to be leaked should any leak occur from geological storage, he said.

Another issue with shallow monitoring is that the leak is going to be "pretty well established" by the time we detect it, he said, so perhaps too late to do anything to stop it.

There are concerns that old and abandoned oil and gas infrastructure in an unknown condition could provide a pathway. This might be considered 'extremely unlikely', he said. But a surface monitoring technique would be useful in detecting it.

Most jurisdictions are asking for shallow monitoring as a condition of doing CO_2 storage, Mr Hines said.

Most regulations do not define specifically what the frequency of any monitoring should be, saying only that it can be driven by the risk assessment, putting most resources on the most likely risks, he said. "You can have a pragmatic approach to that, government bodies are open to listening."

More information

You can see Robert Hines' Apr 21st, 2023 webinar online at:

www.findingpetroleum.com/home/pastEvents.aspx

Transporting frozen CO2 by box container - seeking research partners

Henrik O Madsen, former CEO of DNV, is seeking partners for a Euro 2m project to assess the transport of CO2 in frozen, pelletised form in box containers. By Karl Jeffery.

Does it make sense to transport CO_2 as frozen pellets in a box container?

There is growing discussion in the industry about the need to transport CO_2 by ship where pipelines are not available. The discussions usually lead to the assumption that the best way to do it is with tankers, carrying CO_2 as a liquid.

But there are disadvantages to using tankers. They are expensive to build. To achieve a low cost per tonne transported, we will need large tankers, which means higher upfront expenditure, which is hard to get funded. Such large vessels may only serve a single CO_2 source and CO_2 injection point.

And many berths do not have the water depth or space to accommodate large vessels.

If there is a need to move CO_2 on land, the only option normally considered is transporting it in liquid form in a road tanker, although very few high pressure, low temperature road tankers have been built.

If the CO_2 is frozen into pellets and put into box containers instead, we can make use of the existing, low-cost box container infrastructure we already have.

We will need a design of containers with thick (25cm) insulation, which does not sound too complicated. Also, a system for discharging the CO_2 pellets into another device, where the CO_2 can be transformed into a liquid or high-pressure gas, ready for pipeline transport and injection into the subsurface. This also does not sound too complicated.

The critical issues are probably the energy cost of freezing CO_2 into pellets, and the amount of CO_2 in the box container which gasifies and escapes through the pressure release valve.

Also whether there would be public and regulatory acceptance for a box container which would slowly emit very small amounts of CO_2 as some of the CO_2 gasifes due to the insulation not being 100 per cent resistant to flow of heat.

The only way to find these answers is to investigate in more depth and probably to build prototype systems.

Companies may be willing to pay Euro 20 per tonne for the transport part of the capture, transport, and storage process.

The box container transport option has another advantage over tanker shipping, in that the container can be used as intermediate storage as well as for transport – no onshore storage tanks are required. The box container can easily be moved along land as well as by sea.

Moving CO_2 by box container could also make it easier to bring into e-fuel production, where hydrogen made from renewables is reacted with CO_2 to make a liquid fuel.

The frozen CO_2 can be transported at atmospheric pressure, while liquified CO_2 requires a pressure of above 5 bar. This adds to the cost of making a tanker. It means transport as a solid is easier and safer. (Note there can be safety implications if solid CO_2 gasifies and leaks, such as if CO_2 displaces oxygen and makes atmosphere impossible to breathe in, or if it causes frostbite).

Solid CO_2 exists at atmospheric pressure and temperature of about -80 degrees C.

Henrik O Madsen, who served as CEO of DNV from 2006 to 2015, and currently serves as executive business advisor with Mitsubishi Heavy Industries EMEA, is interested in putting together a team of companies to fund a project to investigate the viability.

He estimates that the technology could be fully evaluated and developed to technology readiness level 6, "system prototype demonstration in a relevant environment" for Euro 2m.

Exploring the feasibility

The big question is probably the energy cost of converting gas phase CO_2 into solid pellets. Mr Madsen estimates that the energy cost of converting CO_2 into pellets is double the cost of liquefying it.

Technology to convert liquid CO_2 into pellets, known as 'dry ice,' is commercially available. For example, an off the shelf "dry ice pelletiser" is available from ASCO Carbon Dioxide Inc, a company headquartered in Switzerland. According to data on its website, it costs $150k, with capacity of 750kg/hr, power consumption of 19 KW, and dimensions 1.7 x 1.1 x 3.86m.

These CO_2 dry ice pellets are used for sandblasting, for cleaning up fire damaged properties, aged brick, and stonework.

Mr Madsen envisages that there could be twenty-five tonnes CO_2 stored in a standard 20-foot container. Standard box containers normally take 21.6 tonnes, and" heavy tested" higher specification containers normally take twenty-eight tonnes.

The box container would be fitted with 25 cm thick insulation, about ten times stronger than what is normally used in refrigerated containers. There would not need to be any active cooling system on the container.

Mr Madsen envisages that the solid CO_2 would gasify at about 0.1 to 0.2 per cent per day, released through a pressure release valve, which should be acceptable. The CO_2 could be poured into the container in pellet form.

Container transport cost itself can be pretty cheap – for example the costs of shipping a twenty-foot box from Felixstowe (UK) to Rotterdam can be around $500, according to online estimates. If this carries 25 tonnes of CO_2, then the cost per tonne is just $20. This cost is based on booking a single container - with large volume contracts, perhaps chartering a whole container ship, it would be much lower.

"The transport cost should we well within the boundaries of what the value chain can absorb," Mr Madsen says.

The CO_2 would need to be converted to gas form for injection into the subsurface. Mr Madsen envisages this could be done by loading the CO_2 into a pressurized receiving facility, where it would be converted to liquid form, so it can flow through a pipeline. Some energy must be added, such as from sea water at atmospheric temperature, using a heat exchanger.

Project proposal

Mr Madsen is seeking funding of Euro 2m to develop the project, including developing systems to freeze CO_2, design of the container, design of the loading and unloading systems, constructing a prototype container, evaluating transport economics, reviewing offloading options, building a prototype receiving facility, evaluating safety and regulatory requirements, economic analysis, making communications and training material, studying Co_2 thermodynamics, studying insulation materials, reviewing port safety, and overall project management.

He envisages that this funding could be found from 4-5 main sponsors contributing Euro 300k, 5- 7 sponsors contributing Euro 100k, and further participants joining on an 'in-kind' basis.

The project team does not intend to assert IP rights for any individual elements or for the complete system – the 'technology' will be free to use. However individual partners developing specific technology elements, such as the refrigerated container design or receiving facility, may choose to assert IP rights for their own contributions.

Mr Madsen seeks for the project to run from Oct 1, 2023, to July 31, 2024,

He is not seeking to make a profit out of the project, just covering his own direct costs and a fee for management.

More information

Mr Madsen can be contacted on:

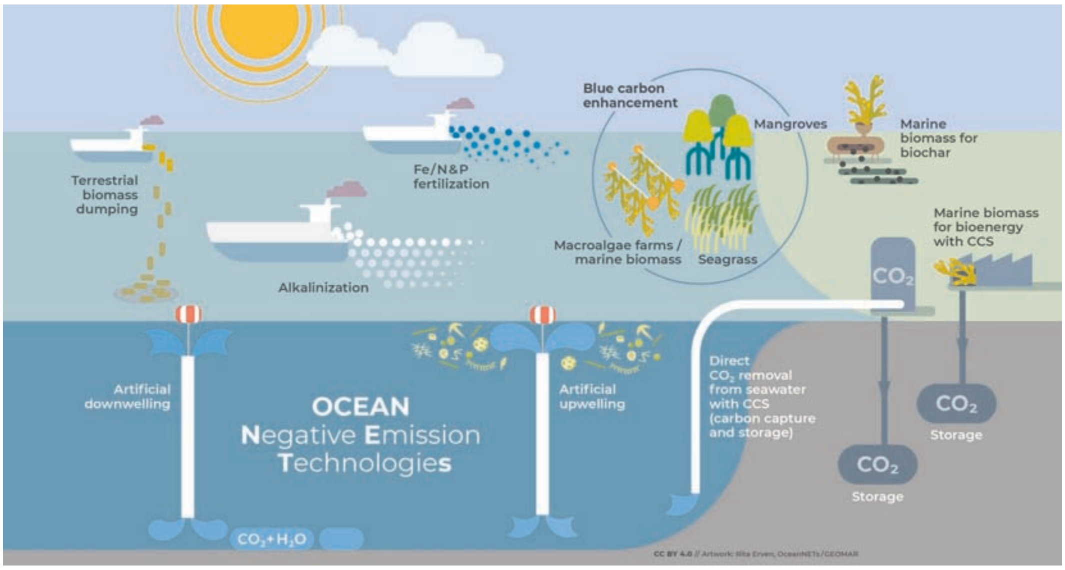
henrikomadsen@gmail.com

www.decarbonice.org

Regulation of ocean-based negative emissions technologies

Research Institute for Sustainability Potsdam (RIFS) researchers Lina Röschel and Barbara Neumann describe the challenges that these technologies present for both the marine environment and society, and identify cornerstones for their responsible use.

The existing regulatory and institutional frameworks for international ocean governance do not provide a comprehensive framework for the governance of these emerging technologies, the authors conclude. Instead, an approach is needed that integrates foresight mechanisms, considers the potential unintended impacts of these technologies on the ocean, and engages with diverse stakeholders.



Overview of ocean-based negative emissions technologies researched in EU-Horizon Project "OceanNETs". CC BY 4.0, Artwork: Rita Erven, GEOMAR/OceanNETs

According to scientists, the ocean's capacity to remove and store carbon dioxide from the atmosphere could be enhanced by various means, including the addition of alkaline substances such as olivine into the upper ocean, for example. This process, also known as alkalinization, harnesses chemical processes to alter the geochemistry of seawater and thereby increase the uptake of carbon dioxide from the atmosphere.

Other potential methods rely on restoring or expanding coastal ecosystems such as mangrove forests, which can absorb and store carbon dioxide in underlying sediments.

Unintended impacts could occur far from deployment sites

In their study, which was conducted as part of the EU-funded research project OceanNETs, the RIFS researchers offer an overview of the potential impacts of eight ocean-based negative emissions technologies on the marine environment and ecosystem services. Building on this, they analyse the existing governance framework and the demands that the deployment of these technologies would place on it.

The study also examines the potential unintended impacts of the selected technologies. Due to ocean currents, these could unfold far from initial deployment sites.

"This aspect must not be disregarded in decision-making processes. What is needed is a broader perspective that considers how the potential impacts of negative emissions technologies will interact with the objectives of existing agreements governing marine environmental protection, biodiversity conservation or even socio-economic issues relating to sustainable development – in addition to international agreements that explicitly address, promote, or restrict their use," explains Lina Röschel.

The current international governance system, with its diverse agreements and regulations, institutions and responsibilities, is too fragmented to meet the complex requirements, according to Röschel.

Foresight key to good governance

According to the researchers, a foresight-oriented approach is needed in order to comprehensively and effectively regulate the use of these technologies in the future.

"It is important that political, scientific, and societal actors engage with these issues today and develop approaches for the control and regulation of negative emission technologies – even if they are still under development in many cases, and their potential impacts cannot be precisely quantified," says co-author Barbara Neumann, who argues that trade-offs should be minimised, and benefits maximized and distributed fairly across the globe.

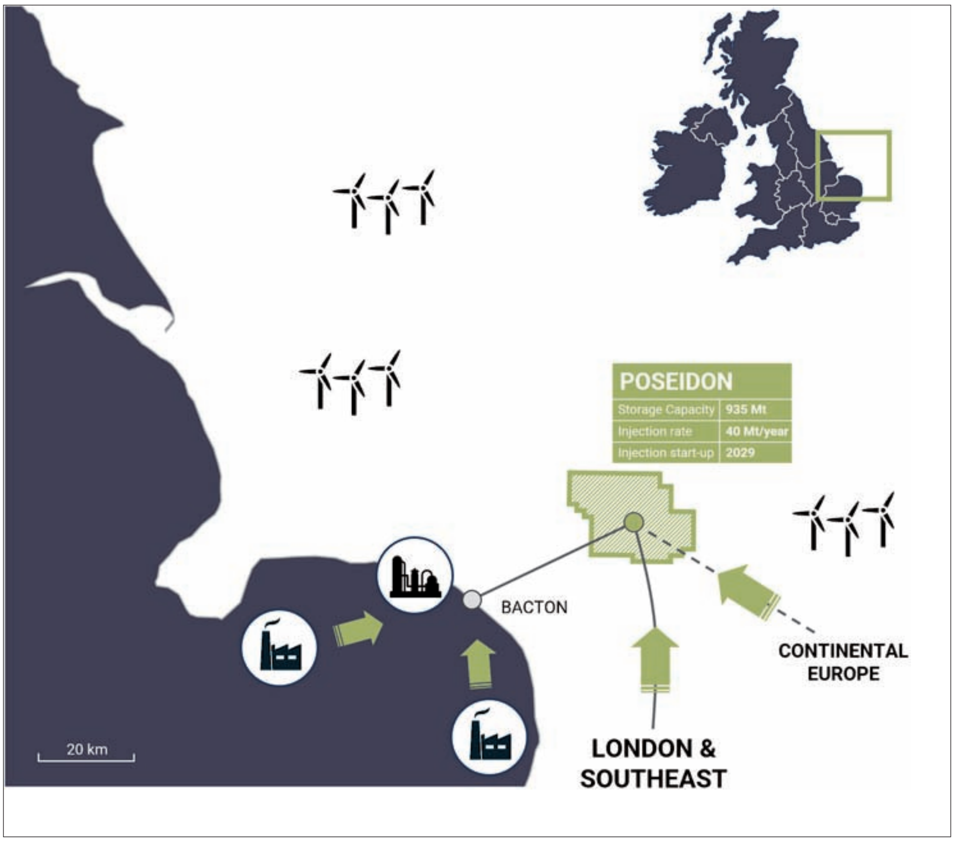
The study is part of a broader research effort on the regulation of ocean-based negative emission technologies that also considers the institutions, actors, processes, and policy instruments involved. Later this year, the team from the RIFS Ocean Governance research group will host a scenario workshop to consider how the various challenges could be addressed together with other experts.

More information

www.rifs-potsdam.de

Licence awards for UK Poseidon and Orion CCS projects

Perenco UK and partner Carbon Catalyst Ltd (CCL) have been awarded a licence to progress the Poseidon CCS project encompassing the Leman gas field in the Southern North Sea and two further licences to progress the Orion project.



Leman is one of the largest geological structures in the Southern North Sea sector of the UK Continental Shelf (UKCS) and offers a mixture of depleted gas reservoirs and saline aquifers in which to permanently store recovered CO2.

Leman is connected via pipeline to the PUK Bacton Terminal, which will receive and process CO2 from various onshore sources and send offshore to inject into reservoir rocks for permanent geological storage.

Henry Morris, Executive Director at Carbon Catalyst, commented, "Poseidon has the potential to make a very material contribution to the decarbonisation of the UK economy by storing up to 40 million tonnes of CO2 per year into the giant depleted Leman gas field and overlying aquifer system. CCL is looking forward to supporting Perenco as they progress through the appraisal period towards final investment decision, with the ultimate goal of achieving first CO2 injection by 2029."

The project, which has the potential to significantly decarbonise both the East and Southeast of England, is due to come online by 2029. Initial CO2 injection rates will be circa 1.5 million tonnes per annum (Mtpa), ramping up to 40 Mtpa, over a 40-year period.

It will immediately move into further detailed appraisal of the storage sites and commence work, with our mid-stream and up-stream partners, to bring the selected concept to an on-time and on-budget delivery.

Orion

The Orion Project is designed to deliver an initial injection capacity of 1 million tonnes per annum (Mtpa), rising to 6 Mtpa, and commence injection in 2031. The full project encompasses both the decommissioned Amethyst field and the currently producing West Sole field, using depleted gas reservoirs for the permanent storage within geological formations of captured carbon dioxide.

Perenco owns and operates significant gas infrastructure in the Humberside area, including its Dimlington Terminal, and will evaluate the possibility to reuse existing assets, such as strategic pipelines, to facilitate the project.

Orion has the potential to complement other CCS projects currently in development, providing additional capacity for the decarbonisation of Humberside and adjacent areas over a 30-year period.

The award of the Poseidon and Orion CCS licenses in the UK, with Perenco as operator, formalises the start of a new strategic division within the Perenco Group.

Based in its London head office, the new Perenco CCS Department is building a team of diverse competencies with the goal to assess and deliver these and other opportunities for carbon storage projects in the UK North Sea and internationally.

Commenting on the award of the licences, Jo White, General Manager Perenco UK, commented, "Following the recent announcement of the Poseidon Project, today's news is another important step in our CCS strategy and our ambition to use our extensive technical expertise in the gas industry in support of UK's decarbonisation goals."

More information

www.perenco-ccs.com

www.carboncatalyst.co.uk

Sandia successfully tests heat-powered system to monitor CO2 storage

Researchers at Sandia National Laboratories recently designed, built and lab-tested a device that can use the temperature difference caused by periodically pumping carbon dioxide down a borehole to charge batteries to someday power underground sensors.

"Ideally, you would have continuous underground sensing, with several different types of sensors, that would tell you how the carbon dioxide is moving, if it is reacting with the groundwater or the minerals," said Charles Bryan, a Sandia geosciences engineer and leader of the project to develop the device. "You could demonstrate that it's not moving out of the reservoir. However, it's difficult to run power down a borehole: You can't just have wires running down a working borehole."

As heat flows from the hot earth through the device to the cooler carbon dioxide, it creates a voltage that can be used to charge a battery and eventually power sensors. The Sandia-developed device works similarly to the radioisotope thermoelectric generators used to power NASA space probes and even Mars rovers, said Ramesh Koripella, a Sandia materials scientist on the project.

How Sandia National Laboratories' device could produce electricity at a carbon dioxide storage reservoir

While NASA's radioisotope thermoelectric generators use the temperature difference from hot plutonium pellets and the cold of space to produce power, Sandia's thermoelectric generator device uses the temperature difference from the hot Earth thousands of feet down and the carbon dioxide being pumped down. This technology is not nearly as efficient at producing electricity from heat as the internal combustion engine in most cars, Koripella said. However, it has no moving parts that could jam, making it ideal for hard-to-reach places such as space and deep boreholes.

Building a heat-powered generator

The device is a multilayered tube with an array of 1-by-1-inch square thermoelectric generators, Bryan said. Each of these thermoelectric generators can turn the heat flowing through them into a voltage and then power, Koripella said.

The inner tube is built to withstand the temperatures and pressures from carbon dioxide being pumped through it, while the outer tube is built to withstand the temperatures and pressures from being deep underground, Bryan said. In the area between those two, reside the electronics to capture and convert the voltage from the thermoelectric generators to charge a battery. Former Sandia mechanical engineer Adam Foris came up with the original design for the tube-like device, he added.

Koripella selected the right commercially available thermoelectric generators for the device and led the development of a small circuit board that converts and evens out the energy from the generators so that the device can charge a battery without damaging surges, Koripella said. He added that it was quite a challenge to find batteries that work above 160 degrees Fahrenheit, which is the typical temperature downhole at the depths used for carbon sequestration.

Power generation by the initial, foot-long prototype was tested in the lab by Sandia geosciences engineer Tom Dewers. He also used thermal imaging and computer modeling to look at how the temperature changed around the device when hot or cold fluid flowed through it, Dewers said. The modeling and tests helped the team refine the prototype for an in-the-field test.

Refining the device design

The field-test prototype, which ended up being slightly more than three feet long, was developed by Sandia mechanical engineer Jiann-Cherng Su, who introduced several innovations and improvements to the design, Bryan said.

The team made several improvements in the second prototype to ensure the thermoelectric generators had good contact with the inner and outer shells, and that the heat could not take a shortcut around the generators through the rest of the device, Koripella added. For the field-test prototype, they added thermal insulators around the device and replaced the heat-highway metal screws that held the thermoelectric generators together with spring-based clamps, he said.

Sandia geosciences engineer Jason Heath gathered data on an active carbon dioxide injection site to inform the building of the device for field conditions and led the selection of a site for the field test. Ultimately, the team selected the APS Technology Drilling Test Facility, Bryan said.

"They have an amazing array of facilities for designing, building and testing downhole tools," said Dewers, who went to the site for the field testing. "They were an ideal company for us to work with. The APS folks were great and patient with us and had a lot of good suggestions."

Successful underground testing

For the first field test, Dewers inserted the field-test prototype into a shallow borehole in one of APS's testing rooms. The researchers lowered the device to a depth of 62 feet. Then they pumped 170-degree water through the interior tube of the device to test the thermoelectric generators and the rest of the system.

Unfortunately, during the test the device sprung a leak, damaging the power conditioning board and battery, Dewers and Bryan said. Working with Dewers, APS was able to find and fix the leak location, dry out the device and replace the damaged parts. The second test, a repeat of the first, was a success.

The team also tested how well the field prototype could survive high-pressure environments. They subjected the inner shell of the device to pressures 400 times atmospheric pressure and the outer shell of the device to pressures 34 times atmospheric pressure. They also heated up the device inside the pressure chamber and measured the current from the thermoelectric generators, ensuring they worked under pressure.

"We successfully generated sufficient current to power downhole sensors with limited current draw," Dewers said. "In that respect, it was a successful device, but it was limited in terms of how long we could deploy the device."

Future improvements and tests

To test the device for longer times, they need to install more memory, Dewers and Bryan said. Additionally, Koripella would like to rebuild the power conditioning board so that it will work with higher temperature differences and possibly add a diode so that the board can charge the battery regardless of whether hot or cold fluids flow through the device, he said.

Before the device is ready for a long-term field test at a carbon sequestration site, Bryan would like to collaborate with downhole sensor researchers to ensure that the power conditioning board can provide the right power for their sensors. The ultimate test of the thermoelectric device would be to see if it can power hardwired sensors downhole.

The kinds of sensors the device could power include pressure sensors, sensors to detect microseismic events, and those to monitor the health of the borehole, such as whether carbon dioxide is leaking up from the reservoir through the borehole, Bryan said.

Bryan added that the same thermoelectric technology could also be used to power sensors for other underground applications such as monitoring oil and gas exploration and production, but this would require periodically pumping hot or cold fluid down the borehole to maintain a temperature difference between the inside and outside of the device.

"I think the design is really innovative, really clever," Bryan said. "We had to overcome several obstacles; it was much harder than we thought to get this done. We were all excited when the field test was successful."

The project was funded by the Department of Energy's Office of Fossil Energy and Carbon Management through the National Energy Technology Laboratory. The team is currently pursuing additional funding to continue their research.

More information

www.sandia.gov

'World-class' study highlights CCUS potential for North Sea 'super basin'

A research study led by the University of Aberdeen has identified areas of a North Sea gas 'super basin' with the greatest potential for storing industrial carbon emissions.

Described as 'world-class research' by the UK Regulator, the North Sea Transition Authority (NSTA), scientists from the University's Centre for Energy Transition used subsurface data and techniques usually employed in oil and gas exploration, to produce a detailed technical study of the Anglo-Polish Super Basin in the Southern North Sea to determine its suitability for carbon capture, utilisation and storage.

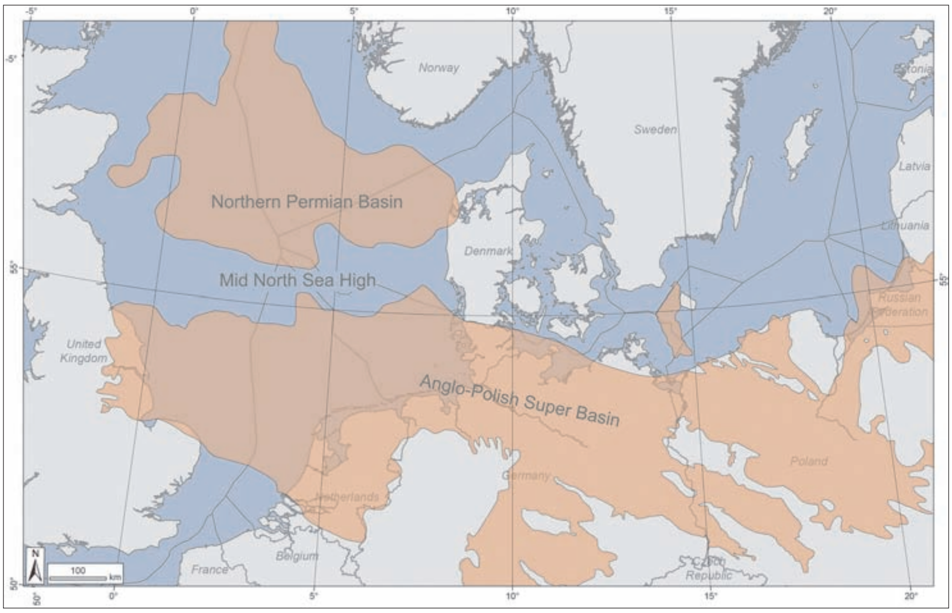
Dr Nick Richardson, Head of Exploration & New Ventures at the UK's regulator for Carbon Storage activities, the North Sea Transition Authority, said, "The Aberdeen University-led team has made a timely and incisive contribution with this world-class research that puts the UK's storage resource capability on the map as a leading destination for the sequestration of industrial emissions from across Europe.

"By establishing a consistent regional geological framework, this work will assist the evaluation of storage sites within the Southern North Sea, allowing the optimisation of their exploitation and supporting assessments of risk and uncertainty. It will also aid regulatory and marine planning bodies in their ongoing efforts to identify synergies between offshore activities, and maximise opportunities for innovation and collaboration on the pathway to net zero."

The results confirm the huge potential of the area – a globally important hydrocarbon basin – as a future CCUS hub where industrial emissions can be safely stored in former gasfields and other geological formations.

If used in this way, the basin could play a major role in helping European nations sequester carbon emissions and meet net zero targets while promoting energy security, protecting industrial activity and prolonging the life of North Sea basin infrastructure.

As well as showing the geological criteria that determine the areas with the greatest potential, the study also highlights the need to assess non-geological risks – such as the potential for leaks along legacy wells and the need to avoid co-location conflicts with other stakeholders such as windfarm operators or the fishing industry.



Location and extent of the Anglo-Polish Super Basin and its northern counterpart, the Northern Permian Basin. Both basins and the Mid North Sea high that separates them formed in response to north-south Permian rifting

The research provides a framework that can be used to determine CCUS suitability in other major basins around the world, as part of global efforts to safely store billions of tonnes of CO2 in geological formations.

The two-year study funded by the Net Zero Technology Centre was led by Professor John Underhill, Director of the University's Centre for Energy Transition, along with colleagues from Heriot Watt University in Edinburgh. It was published in the AAPG Bulletin, a major international journal.

Professor Underhill said, "The study highlights the areas where the best carbon stores are located and provides a basis to evaluate and rank sites."

"Perhaps just as importantly, it also demonstrates the urgent need for regulators and stakeholders to work together to resolve any issues that may arise from the co-location and overlap of technologies to avoid competition for the offshore real estate. This is vital in ensuring that the UK remains on track to retain energy security and meet its net zero emission targets.

"The study also has global relevance and application, and the workflow we have used has already been adopted by other countries. We have also used it to undertake studies in other parts of the UK as well as in Malaysia, Egypt and Brazil."

More information

www.abdn.ac.uk

pubs.geoscienceworld.org

Transport and storage news

Wärtsilä offers onboard carbon capture and storage feasibility studies

www.wartsila.com/marine

Technology group Wärtsilä is now offering CCS feasibility studies to shipowners and operators, in another milestone on its journey to research, develop and bring to market maritime CCS technologies.

The studies have already been conducted on a range of vessel types including ro-ro and ro-pax vessels, a drill ship, a container vessel and a gas carrier.

The process takes four to six months of study and design work. Wärtsilä Exhaust Treatment's experts are involved in ship design at an early stage to conduct engineering work to understand how CCS can be smoothly integrated once the technology is launched to market.

Wärtsilä is conducting the feasibility studies across both newbuild and existing vessels. Retrofit CCS installations will be significantly smoothed by the presence of a scrubber onboard. Wärtsilä Exhaust Treatment is already offering CCS-Ready scrubbers to the market, which are integrated onboard in a way that enables a CCS system to be added easily in the future once the technology is commercialised.

Once completed, the CCS feasibility study work enables Wärtsilä to provide customers with a fully rounded commercial offer that can be shared with shipyards to get an exact quote for installation. During the feasibility studies, Wärtsilä's experts closely examine the existing naval architecture of the ship and work to understand how the power, space and exhaust demands of CCS can be accommodated onboard. Owners will receive a qualified analysis of the costs of CCS integration, and a clear list of considerations on how a potential retrofit would be conducted in the least intrusive way.

Conducting the studies today enables Wärtsilä to bring forward the early stages of CCS integration and, in doing so, lower the barrier to entry once the technology is commercialised in the near future. The studies also serve to educate customers on the upsides and particular considerations associated with installing CCS onboard their vessels. Finally, as the studies will run in parallel with the implementation of new environmental regulations for shipping, owners who conduct them today will be 'ahead of the curve' versus their peers.

Sigurd Jenssen, Director, Wärtsilä Exhaust Treatment, said, "Launching these feasibility studies and being able to offer them to market is the exciting latest step in our process of bringing carbon capture and storage to market in shipping. It builds on the market-leading work we are conducting in our test hall in Moss, where our technology is already demonstrating our targeted 70% capture rate, and enables us to directly engage with customers to smooth the CCS adoption process in the near future."

Scottish scientists receive funding for mineralisation study

www.carboncapture.eng.ed.ac.uk
www.carbfix.com

A team of Scotland's leading Earth scientists has received £1 million of UK Government funding to develop new ways to measure the capture of carbon dioxide in volcanic rock.

The INCLUSION project, in collaboration with Carbfix and the Scottish Universities Environmental Research Centre (SUERC), has been awarded £1 million of funding from the Natural Environment Research Council (NERC)'s Pushing the Frontiers scheme.

The scientists will work with Icelandic mineralisation operator Carbfix to test new methods to track the carbon dioxide being captured from the country's largest geothermal power plant and verify its safe and permanent storage.

Professor Fin Stuart, Director of SUERC, said, "We will determine the unique chemical fingerprint of the injected CO2 at Carbfix, and record how that changes during the storage process. This will enable us to determine how, and how much, CO2 is stored and provide confidence in the amount of CO2 that can be stored by mineralisation in the future, which can also aid participation in carbon credit schemes."

Mineralisation has been used successfully in Iceland, where the reactivity of the basalt volcanic rock converts the carbon dioxide rapidly into new minerals, safely locking it away underground.

Dr Stuart Gilfillan, of the University of Edinburgh, and his team will use mineral analysis techniques and a novel CO2 fingerprinting tool, currently being patented by Edinburgh Innovations, the University's commercialisation service.

Dr Gilfillan said, "This project will combine the state-of-the-art scientific laboratory facilities available in Scotland with the world's leading CO2 mineralisation project to provide essential understanding of how to safely lock away CO2 underground in basalts."

"We will also develop our understanding of the reactivity of basalt and other volcanic rock, to understand the potential of mineralisation in other parts of the world, such as Scotland."

Equinor acquires stake in Bayou Bend CCS

www.equinor.com
www.chevron.com

Equinor has acquired a 25 percent interest in one of the largest US carbon capture and storage projects located along the Gulf Coast in Southeast Texas.

Bayou Bend is positioned to be one of the largest CCS solutions in the US for industrial emitters, with nearly 140,000 acres of pore space for permanent CO2 sequestration and potential storage resources of more than one billion metric tons. The Bayou Bend total acreage includes nearly 100,000 acres onshore in Chambers and Jefferson Counties, Texas, and approximately 40,000 acres offshore Beaumont and Port Arthur, Texas.

"Commercial CCS solutions are critical for hard-to-abate industries to meet their climate ambitions while maintaining their activity. Entering Bayou Bend strengthens our low carbon solutions portfolio and supports our ambition to mature and develop 15-30 million tonnes of equity CO2 transport and storage capacity per year by 2035. Our experience from developing carbon storage projects can help advance decarbonization efforts in one of the largest industrial corridors in the US," said Grete Tveit, senior vice president for Low Carbon Solutions in Equinor.

Bayou Bend is a joint venture between Chevron U.S.A. Inc., through its Chevron New Energies division, Talos Energy Inc., through its Talos Low Carbon Solutions division, and Equinor.

ANDRITZ CO2 capture plant operating at voestalpine steel mill in Linz

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