Carbon Capture Journal

# The Oil & Gas Issue

CCS is back on the EU agenda and the oil & gas industry can help

Industrial CO2 capture: the case of LNG plants

ACT Acorn full-chain integrated project

May / June 2018 Issue 63


Offshore power generation with CCS - SINTEF's CEPONG project

Reducing methane emissions with bacteria - and making bioplastic

Researchers find CCS a financial opportunity for U.S. biofuels

New CO2 Capture Plant in Japan supplies liquefied CO2 production

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*Front cover:*

*The Regenerative Froth Contactor–Reactor (RFC) pilot plant at Hazelwood power station in Australia has shown that the technology can increase process productivity and reduce the size of the footprint (pg. 15)*

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## Leaders - CCS in the Oil & Gas Industry



## Projects and policy



## Capture and utilisation



## Transport and storage

# "CCS will never fly!" - How the oil & gas industry can contribute to EU CCS

**National governments, EU institutions and industry all need to work together to prepare for the deployment of CCS solutions. The oil & gas industry can help.**

*By François-Régis Mouton, IOGP's Director EU Affairs*

Over the last few years, every time I would mention CCS to EU policymakers, their most common reaction was to snicker and say something along the lines of «come on, we know CCS is never going to fly». Today, as the Paris Agreement commitments start to materialize, I wouldn't go as far as to say that they're all believers, but I think it's fair to say policymakers are curious to hear more.

The Paris Agreement and the realization that all sectors of the economy will have to be involved in the decarbonization process has definitely helped in that regard. The IPCC sees CCS as a key technology to deliver the negative emissions required in 101 out of 116 possible scenarios limiting global warming to well below 2°C[1]. Likewise, the IEA gives an important role to CCS (the third lever after energy efficiency and renewables[2]) in the GHG mitigation effort of its long-term projections.

But what could be the perfect argument for advocates of CCS is used by anti-oil & gas environmentalist movements who point out, rightly so I must admit, to the current gap between deployment expectations and reality. Still, is it reason enough to "shoot the ambulance" as we say in France? And more importantly, how do we pick up the pace?

Naturally, the oil & gas sector has extensive experience in CCS technology itself but also in exploration skills, geology, reservoir engineering, chemistry and large-scale project management which are all essential to the development of CCS projects. And yet CCS is much more than just 'an oil & gas thing' – it is a technology that will become crucial for much of the industrial sector, which makes up for around 20% of EU GHG emissions.

European policymakers are currently looking at a new energy Roadmap to 2050, one which would put the EU in line with the more ambitious side of the 80-95% GHG emission reduction spectrum currently in place.

This effort will require an extra push into all sectors of the economy, including those that are difficult to decarbonise (the ones to which variable renewable electricity and energy efficiency can't provide convincing solutions). Indeed, many industries create CO2 as a byproduct of their industrial processes, not because they necessarily use carbon intensive energy sources. For them, capturing and disposing of that CO2 may well be the only option to exist in a Europe that aims to be competitive while bringing its emissions down to zero.

Part of this will be done through energy efficiency and fuel-switching (including coal-to gas), but in many cases, CCS will be a prerequisite. If we want to prepare for the deployment of CCS solutions in the long term, we need to get the fundamentals in place now.

## How can the oil & gas industry contribute?

Our sector has extensive experience with CO2 management, from capture and transport to safe storage. This expertise can be beneficial for other industrial sectors as well – CCUS opens opportunities for new business models where our industry has real strengths to play on and experience to leverage. We can group these solution in two categories where our industry will play a part: post-combustion and pre-combustion.

Post-combustion solutions are those that typically come to policymakers' mind when discussing CC(U)S. Recently, projects such as that of the Port of Rotterdam in the Netherlands, or Northern Lights in Norway, gained traction within interested policymaking circles.

*"CCS is much more than just 'an oil & gas thing' – it is a technology that will become crucial for much of the industrial sector" – François-Régis Mouton, IOGP Director EU Affairs*

In these projects, industrial installations find themselves in need of CO2 disposal (refineries, cement factories, chemical plants, etc.) or supply solutions (horticultural firms). Once captured, part of the CO2 would be transported by pipeline (Port of Rotterdam) or by ship (Northern Lights) and stored into depleted fields in the North Sea, and the rest supplied to industrial users on the ground, contributing to the creation of a circular economy cycle.

But such economies of scale can also be achieved at the pre-combustion level, by stripping natural gas from its carbon and turning it to 'blue hydrogen', to be used as feedstock or energy source by industrial users and households. There too Europe leads the way, with promising projects such as the Leeds and Manchester-Liverpool Hydrogen projects in the UK, and the Magnum project in the Netherlands.

In Leeds, it's essentially about determining the feasability of converting the existing gas infrastructure into one for hydrogen, with a po-

1. IPCC (2014): Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.
2. IEA: World Energy Outlook 2017. CCS accounts for 9% of GHG savings needed to move from the IEA's New Policies Scenario to the Sustainable Development Scenario

tential extension to the entire UK should results be conclusive. In Manchester and Liverpool, hydrogen made in large part by conversion of natural gas through Steam Methane Reforming and storage of the CO2 in the Irish Sea, would be supplied to car manufacturers and refineries, as well as households. At a smaller scale, the conversion of one of the three Magnum gas power plant units of Eemshaven into one running on hydrogen, combined to CCS, is another exciting project our industry is working on.

Natural gas-to-hydrogen conversion with CCS catches EU policymakers' attention every time I mention it. CCS as a technology that works; we know it, they know it. The problem lies in economics most of the time, infrastructure, and sometimes public acceptance in countries such as Germany.

EU Member States need to realize that the challenges they face now will require solutions parallel to those that have been prioritised this far. By supporting the development of renewable electricity sources – through funding for research, support mechanisms, and even specific targets – renewables have become an important source of cleaner energy in Europe, and their share will continue to grow. But variable renewable energy alone won't cut it if we are to achieve deeper decarbonisation.

Previous funding programmes at the EU level have failed to help realise the potential of CCS. The next ones have to make sure that projects of scale can benefit too – if not from one fund alone, then in combination with several. National governments, EU institutions and industry need to work together on this. The realisation of such impactful projects will see significant emission reductions today, while providing building blocks for tomorrow's challenges.

CCS has to be put on equal footing with other CO2 abatement solutions. Governments, when developing their strategies towards 2050, need to bear in mind the final goal at the end of the century. Preparing for CCS now has to be part of it.

### More information

The International Association of Oil & Gas Producers (IOGP) is the voice of the global upstream industry.

**www.iogp.org**

# Paris targets can be met if fossil fuel producers pay for CO2 storage

**A new study by SCCS scientists suggests that the Paris Agreement's climate targets can be met rapidly if fossil fuel producers are obliged to pay for the storage of progressively increasing amounts of carbon emissions resulting from their products.**

The researchers from the University of Edinburgh analysed different policy mechanisms and concluded that carbon pricing and carbon trading permits had not been effective to date in adequately tackling greenhouse gas emissions. Instead, they argue for a simple "certificate system" whereby fossil fuel companies pay for the secure geological storage of a proportion of each tonne of fossil carbon they produce.

Carbon capture and storage (CCS), the suite of technologies that will enable this, is already operating in many countries but, says the study, the speed of construction is 100 times too slow to meet the 1.5°C climate challenge. By comparing diverse technologies for re-capturing carbon, the researchers show that CCS is the most rapid and cost-effective for storing the immense tonnages required.

The study forms part of a themed issue of the Philosophical Transactions of the Royal Society in which climate change experts compare a range of projected changes for a world at temperature increases of 1.5°C and 2°C. Their combined analysis suggests that limiting warming to 1.5°C is still possible if the global response to climate change is strengthened and accelerated.

Prof Stuart Haszeldine, The University of Edinburgh and SCCS Director, said, "The Paris Agreement of 2015 made an unprecedented pledge to hold global warming to within 1.5°C. That means leading industrial nations must achieve net zero carbon emissions before 2050. However, despite the welcome growth of clean energies and energy efficiency measures, the world's carbon emissions are higher than ever, and continue to increase yearly. And fossil fuel producers continue to avoid having to pay for the impact of their products."

"Carbon storage is a reliable remedy that the world will need if humans continue to over-extract and burn fossil fuels. It can be embedded into our existing industries with very little change, through our suggested certificate system. Starting small will ensure that fossil fuel producers can deploy storage technology at low cost. A stepped progression in the mechanism will ensure that producers pay for their share of climate clean-up. Governments need to rapidly enforce carbon storage if we are get anywhere close to our necessary response to the threat of climate change. A failure by current generations to act now with great ambition is gambling with the social and physical survival of future societies."

"The Royal Society's volume of highest quality international research clearly explains the benefits of limiting climate warming. Those benefits include a decreased risk of food shortages in emerging nations, global GDP wealth up to 13% greater by 2100, and up to 14% more land available for plant and animal species habitat refuges."

The special issue of the Philosophical Transactions of the Royal Society consists of review papers, opinion pieces and original research, and has been organised and edited by Dann Mitchell, Myles R Allen, Jim W Hall, Benito Mueller, Lavanya Rajamani and Corinne Le Quéré.

### More information

**www.sccs.org.uk**

**royalsociety.org**

# Industrial CO2 capture: the case of LNG plants

**The paper explores the opportunites, technical and economic viability of applying CCS to LNG export facilities.**

*By Jorge Arizmendi-Sanchez (Costain), Jasmin Kemper (IEA-GHG)*

## Industrial CCS schemes

Electricity generation is the largest single source of global greenhouse gas emissions, accounting for over one quarter of the total. Therefore, initial implementation of CO2 Capture and Storage (CCS) schemes have targeted power generation plants, particularly coal fired power plants.

Industrial activities contribute over one fifth of global CO2 emissions, but the sources are largely dispersed. CCS for individual industrial facilities is uneconomic. Strategies to make the implementation of industrial CCS more viable include CCS hubs and clusters. These are schemes that combine the emissions from several industrial facilities and have access to shared capture, transport and storage infrastructure. This has the aim of reducing the specific capture costs and make the project economics attractive.

Successful implementation of industrial shared CCS schemes requires various conditions to be met. It is essential that the users of CCS infrastructure are in a relatively small geographical area. All industrial partners need to have similar motivations, i.e. industrial facilities subject to similar economic or environmental drivers, with corporate strategies (e.g. investment priorities) aligned within similar time frames to allow commitment to the scheme.

The ultimate condition for the successful implementation of the CCS scheme, which is applicable to all sources of CO2 (power generation, industrial or any other) is the availability of storage options and the cost associated with the development of the transport and storage infrastructure.

The costs can differ substantially depending on e.g. proximity and nature of storage sites (e.g. aquifer or depleted fields), development costs (e.g. installation of pipelines, injection wells and monitoring facilities), opportunity for Enhanced Oil Recovery, etc.

## Opportunities for CCS in LNG plants

Liquefied Natural Gas (LNG) export terminals may represent an opportunity for implementation of industrial CCS. The power requirements of a typical baseload liquefaction plant of a nominal capacity of 5 million tonnes per annum (mtpa) of LNG are of the order of 230 MW, about 80% for mechanical drive and 20% for power generation.

CO2 emissions from the burning of fuel gas for power are about 3000 tonnes of CO2 per day, equivalent to about 1 mtpa of CO2. This is comparable to existing full-scale capture plants where post-combustion CCS projects have been implemented (e.g. Boundary Dam in Saskatchewan and Petra Nova in Texas), so a similar plant size and associated investment could be anticipated.

Baseload LNG plants remove essentially all CO2 in the natural gas feed to avoid freezing in the liquefaction process. The bulk of the separated high purity CO2 is vented to atmosphere unless there are commercial and / or environmental reasons. The required CO2 capture facilities would potentially be limited to CO2 dehydration (depending on the presence of other acid gas components also being removed) and compression for transport to storage.

## Technical feasibility

### CO2 Capture from Combustion Processes

The major emitters of CO2 in a baseload LNG plant are the gas turbines that drive the refrigerant compressors. Baseload LNG plants are generally built with on-site power generation using gas turbines in a simple cycle, which also contributes to the site emissions.

Post-combustion capture with chemical absorption processes can be expected to be the route of choice for CCS implementation in new LNG plants or as retrofit to existing plants. Post-combustion can be installed without affecting the availability of the liquefaction process, requiring a minimum number of modifications to the liquefaction plant (consisting mainly of tie-ins). However, the implementation of post-combustion capture is not straightforward.

Chemical absorption processes are energy intensive due to the heat required for solvent regeneration. In an LNG plant heat is available from gas turbine exhausts, so the full heating duty can be provided by waste heat recovery. The plant design needs to consider the increased backpressure in the gas turbine outlet as this impacts the performance and efficiency of the liquefaction process and reduces plant capacity.

The footprint for the CO2 capture plant and associated systems (e.g. cooling, power generation, ducts) is significant due to the large volumes of hot low-pressure flue gases. The size of a CO2 capture plant for a typical baseload liquefaction train is comparable to the largest CO2 capture plants currently installed, with equipment near physical construction limits.

The installation of tie-ins and the large interconnecting flue gas ductwork may represent a challenge, potentially requiring substantial modifications to the pipework and structures of existing plants or considerable space allowances for new build capture-ready plants. For the latter, layout issues could be tackled by considering the readiness of key tie-ins, location of emission sources close to the capture plant, etc.

### CO2 Capture from Gas Processing

Feed gas to an LNG plant is treated to remove components that can freeze (including CO2, water and heavy hydrocarbons) as the natural gas is liquefied. Other impurities are also removed as required (e.g. sulphur compounds, nitrogen and mercury). CO2 is removed from the feed gas in the Acid Gas Removal Unit (AGRU) using a chemical absorption process. High purity CO2 is produced at near atmospheric pressure and in approach to ambient temperature.

The CO2 content in feed gas is typically of the order of 2 mol%. All of the existing LNG plants with similar CO2 content in feed gas vent the separated CO2 to atmosphere. Higher CO2 content in feed gas will result in larger volumes of CO2 being vented, leading to a more significant environmental impact and emission costs, which could justify sequestration of CO2. This is the case for the only two CCS schemes existing on LNG liquefaction facilities i.e. Snøhvit LNG (feed gas with about 8 mol% CO2) and Gorgon LNG (feed gas with up to 14 mol% CO2).

The infrastructure required for sequestration of CO2 is potentially limited to purification (mainly dehydration) and compression of the CO2 that is otherwise vented. If H2S and sulphur compounds, plus heavy hydrocarbons, are also dissolved and then stripped from the AGRU solvent (together with CO2), the acid gas stream may need to be incinerated. Additional processing would then be required to remove oxygen and SO2 from the CO2 stream.

## Economic feasibility

Cost estimates have been developed for the capture and compression of CO2 separated from LNG feed gas (by the AGRU) and from flue gases (by a post-combustion capture plant) for a typical 5 mtpa LNG plant. Capital costs associated with the transport and storage infrastructure are excluded, but a nominal specific cost (€10/tCO2) is assumed.

CO2 emissions are shown in Figure 1, considering two cases with feed gases of low (2 mol%) and high (14 mol%) CO2 content. Whilst the CO2 vented from the AGRU constitutes about 20% of the total emissions for low content of CO2 in feed gas, the proportion increases to about 60% of the total emissions for high content of CO2 in feed gas.

Estimated specific costs are shown in Figure 2. The capture costs associated to CO2 from

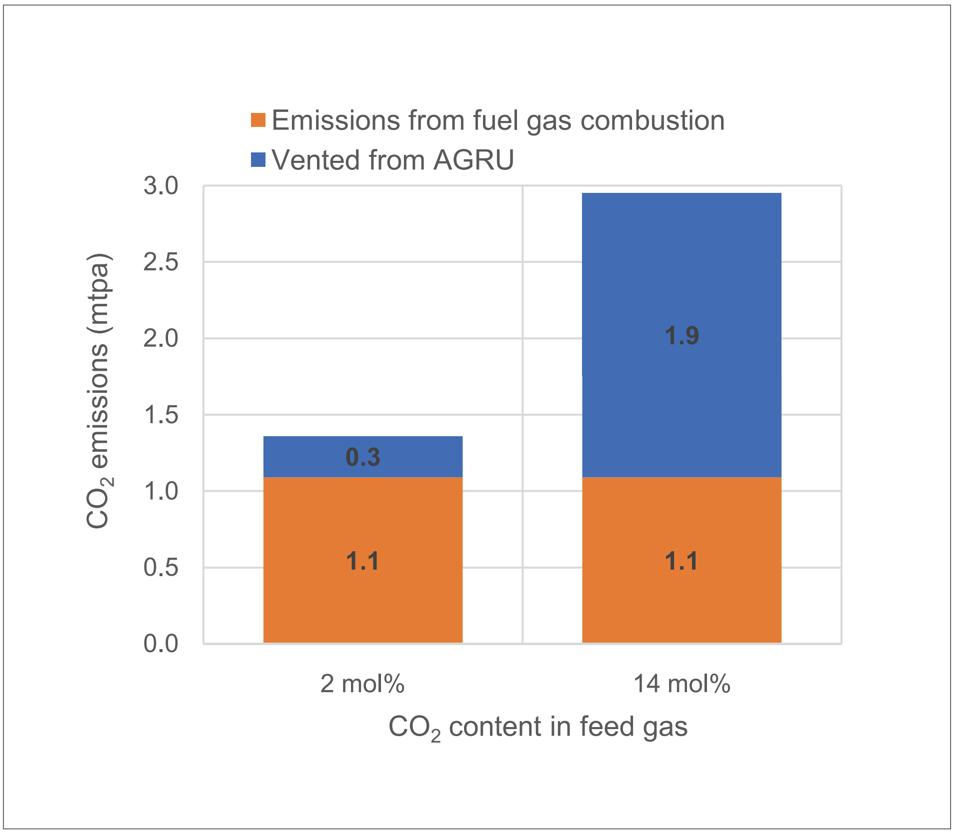



*Figure 1. CO2 emissions*

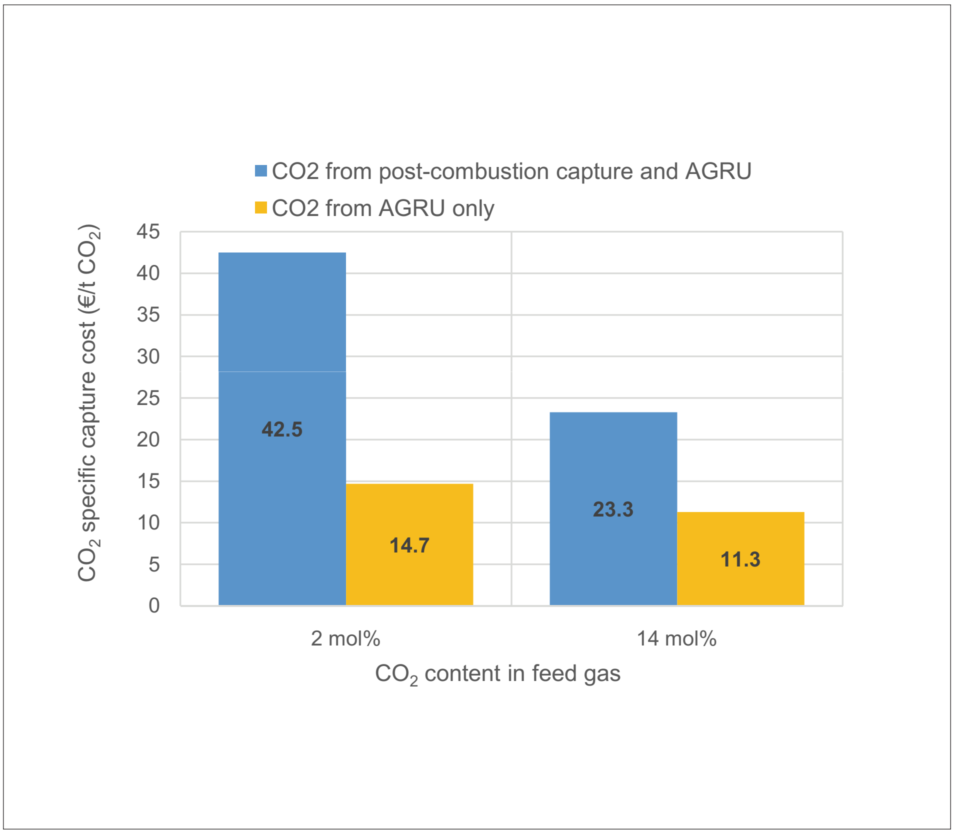



*Figure 2. CO2 specific capture costs*

the AGRU are significantly lower than the costs of post-combustion capture. This indicates that the potential for implementation of a CCS scheme is greatly increased if only the CO2 from the AGRU is captured and stored. The specific capture costs reduce with increased CO2 content in feed gas.

The estimated minimum CO2 emission costs that could make implementation of CCS economically attractive (i.e. CO2 capture cost being lower than the CO2 emission cost) and for the cases under consideration are of the order of €60 to €120/t CO2 (see Figure 3). Current world emission policies set CO2 emission cost at a relatively low value (if any), with most emissions currently priced at less than about €10/t CO2. This indicates that based only on project economics, implementation of post-combustion capture would only occur if high CO2 emission costs are imposed.

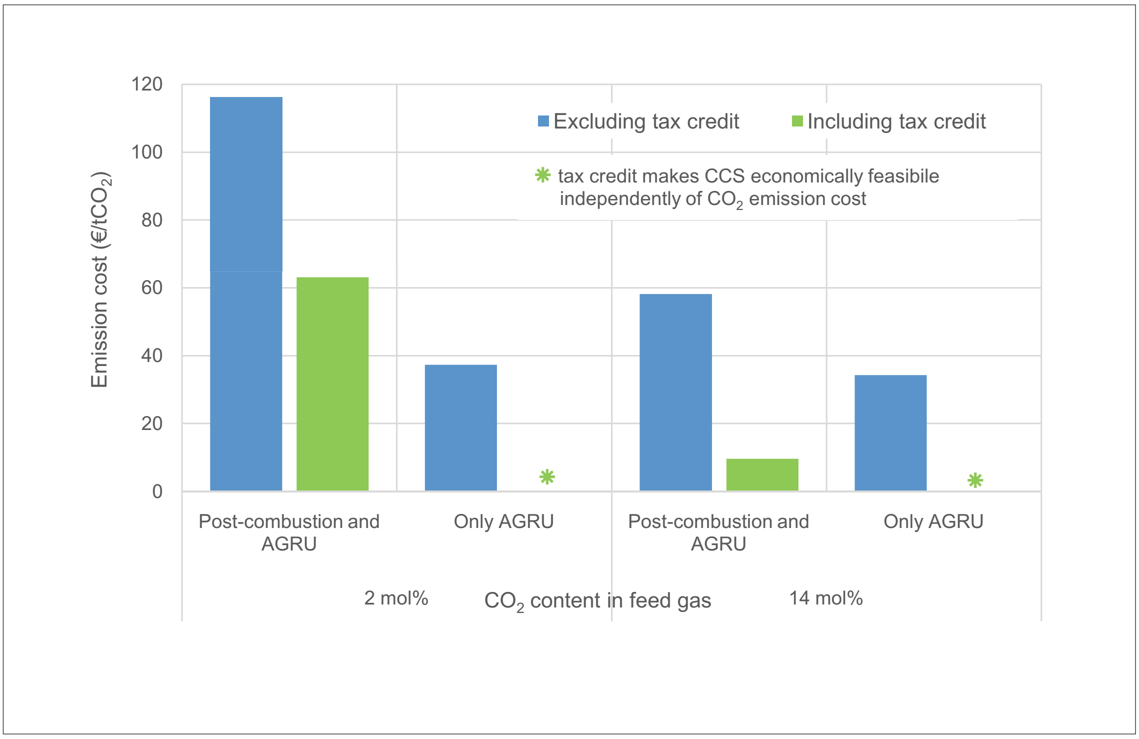



*Figure 3. Minimum CO2 emission costs to make CO2 capture economically feasible*

When a CCS scheme only considers sequestration of the CO2 from the AGRU, the minimum emission cost required to justify the scheme is of the order of €30/t CO2 (see Figure 3). This is within some current environmental policies (e.g. emission costs in Norway and Finland), which shows the increased potential of this route for implementation of CCS (e.g. as in the case of Snøhvit and Sleipner).

The prospects of CCS could also benefit by CO2 tax credits, like the US 45Q tax incentive offering $50 (€40) per tonne of CO2 captured in underground storage. This would potentially make the economics of CCS of CO2 from the AGRU feasible, regardless of the emission cost (see Figure 3).

## Potential for industrial CO2 capture

Although the technical feasibility of post-combustion capture could be proven, implementation is complex and costly. Economic feasibility would depend on many incentives such as CO2 emission costs, funding and tax credits to balance out the significant capital and operating costs. Implementation of post-combustion CCS schemes as retrofits on existing (non-capture ready) plants appears difficult, due to technical challenges and the impact on the LNG production economics.

Sequestration of CO2 vented from the AGRU will play an important role in the implementation of CCS in LNG plants, due to the lower cost than post-combustion capture. Project costs (excluding transport and storage infrastructure) are one order of magnitude lower than the full scale post-combustion capture costs.

The reduced scope and costs to implement CCS for high purity CO2 streams (compared to post-combustion capture) has led to the successful implementation of a significant proportion of large-scale CCS projects associated to natural gas processing, e.g. Val Verde and Century (Texas), Shute Creek and Lost Cabin (Wyoming), Uthmaniyah (Saudi Arabia), Lula (Brazil), Sleipner and Snøhvit LNG (Norway) and Gorgon LNG (Australia).

Sequestration of CO2 from the AGRU will be a precursor for full scale industrial CCS from combustion processes by making financing feasible and risks (technical and commercial) manageable. This applies not only to LNG plants, but potentially to gas processing plants where CO2 is removed as part of the core process and vented as a high purity stream. By analogy, potential for early implementation of CCS for decarbonisation of industrial activities exists in processes where CO2 is generated as a by-product and vented in the absence of utilisation options. This is the case of hydrogen production and ammonia synthesis by steam methane reforming.

## Acknowledgements

This paper has been produced as part of the study "Techno-economic Evaluation of CO2 Capture in LNG Plants" commissioned by IEA-GHG (Reference IEA/CON/16/235). The authors would like to thank the contribution of Terry Tomlinson and Adrian Finn to the technical review of the study and this paper.

### More information

Costain Group plc is one of Britain's largest technology based construction and engineering companies.

**www.costain.com**

# Shell Sky Scenario - a possible future?

**Shells' Scenarios offer descriptions of what could be done – plausible pathways for the future and useful insights along the way. Sky is an ambitious scenario to hold the increase in the global average temperature to well below 2°C. CCS is a key component up to 2070.**

Sky begins with the current structure of economic sectors and government policies and the capacity for change that exists now. It then assumes very aggressive, but plausible, capacity-building and ratcheting of policy commitments through the first two five-year review cycles embodied in the Paris agreement.

Beyond that time-frame, there are naturally rather greater uncertainties about how policies and technology may be developed and implemented globally. So, the scenario progressively becomes driven simply by the ambitious goal to achieve net-zero emissions by 2070, taking full account of the characteristics of scale, technological substitution, and investment in the various sectors of different national economies. Such a goal-driven scenario is sometimes referred to as "normative."

"By adopting an approach grounded in the current reality of the energy system but then combined with a specific long-term goal, we intend Sky to be both an ambitious scenario and a realistic tool for practical considerations today."

### Key changes needed to meet the Sky Scenario

Sky requires a complex combination of mutually reinforcing drivers being rapidly accelerated by society, markets, and governments. From now to 2070:

1. A change in consumer mindset means that people preferentially choose low-carbon, high-efficiency options to meet their energy service needs.

2. A step-change in the efficiency of energy use leads to gains above historical trends.

3. Carbon-pricing mechanisms are adopted by governments globally over the 2020s, leading to a meaningful cost of CO2 embedded within consumer goods and services.

4. The rate of electrification of final energy more than triples, with global electricity generation reaching a level nearly five times today's level.

5. New energy sources grow up to fifty-fold, with primary energy from renewables eclipsing fossil fuels in the 2050s.

6. Some 10,000 large carbon capture and storage facilities are built, compared to fewer than 50 in operation in 2020.

7. Net-zero deforestation is achieved. In addition, an area the size of Brazil being reforested offers the possibility of limiting warming to 1.5°C, the ultimate ambition of the Paris Agreement.

"Additionally, we are publishing extensive quantitative data sets for the Sky scenario, so that others can inspect and make more use of this information themselves."

In Sky, beyond 2070, carbon capture levels off at around 12 Gt per year, but fossil fuel use continues to decline. This takes the overall energy system into negative emission territory, which draws down on accumulated carbon within the biosphere. As a result, warming peaks during the 2060s and declines through the balance of the century.

## Electricity - a new energy system

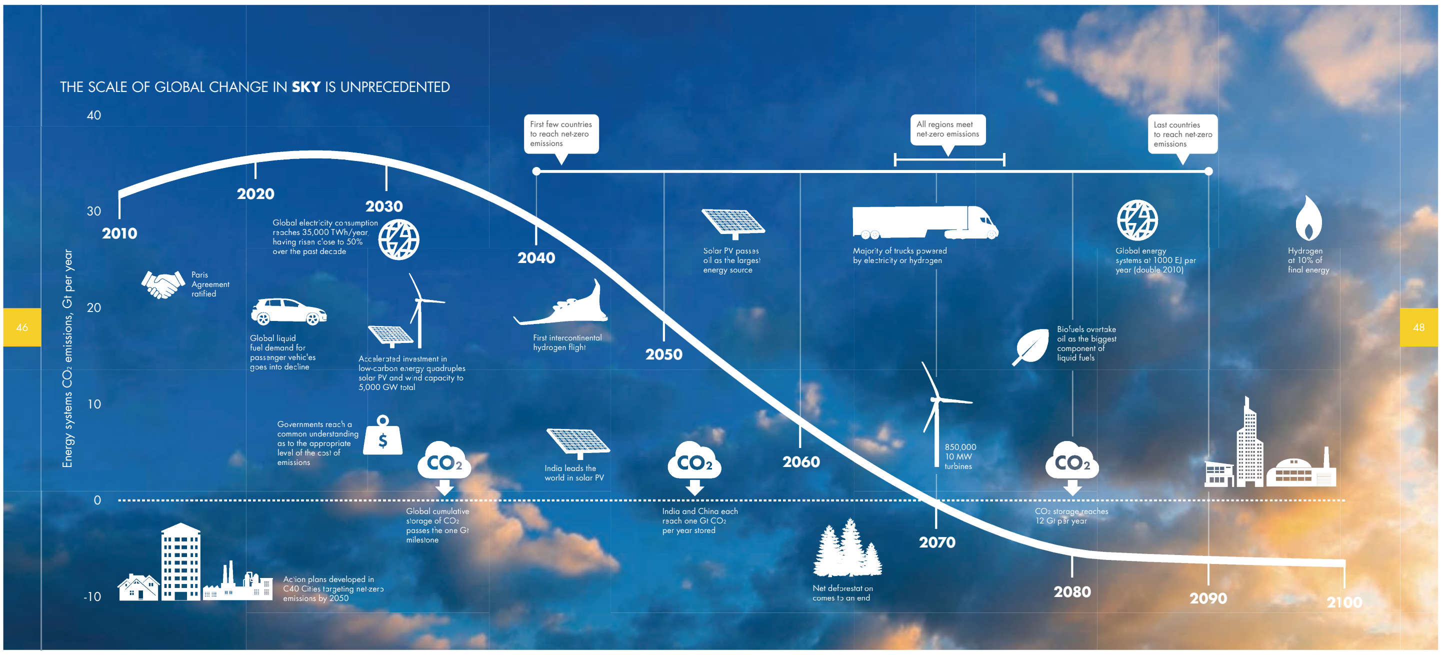
By the 2070s, the power generation sector has progressed through two radical transformations. The first is one of scale, with electricity approaching a five-fold increase over 2017 levels. The composition of sources has also changed, with fossil fuels effectively absent from the sector and solar meeting over half of global electricity needs in 2070 and still increasing.

A new addition to the sector is generation from biomass combustion, which is linked with CCS to offer an important carbon sink.

In Sky, the first clear signs of the transition emerge in the 2020s, with oil demand stagnating, coal declining, natural gas growing as it replaces coal, and solar closing in on nuclear as the largest non-fossil part of the energy system. By 2070, oil production remains at some 50-60 million barrels per day due to the broad swathe of services that it still supplies. Non-road transport continues to make significant use of liquid hydrocarbon fuels, with overall growth through to 2070. Biofuels supplement the liquid fuel mix, with hydrogen playing an increasing role after 2050.

Natural gas, both as pipeline gas and LNG, plays an important early role in supplanting coal in power generation and backing up renewable energy intermittency as wind and solar grow in the power sector. But as solar PV expands rapidly, as battery costs fall, and as the high cost of carbon emissions bites, even natural gas succumbs to the transition. It is the last fossil fuel to peak, with demand falling rapidly after 2040. By 2055, natural gas use for power generation is back to 2015 levels globally.

By the middle of the century the energy mix is starting to look very different, with solar emerging as the dominant primary energy supply source by around 2055. Energy system CO2 emissions peak in the mid-2020s at around 35 gigatonnes (Gt), after which a continuous decline sets in.




## Other greenhouse gases and non-energy sectors

Sky arrives at net-zero CO2 emissions for the global energy system by 2070, although with a varied distribution among different sectors and countries. That covers all the carbon contained within the coal, oil, and gas used for energy, but excludes feedstock for non- energy products, such as plastics.

But numerous other human activities have changed the trace gas composition of the atmosphere, which have also contributed to warming the climate system. Cement manufacture is one example, where the calcination of limestone releases CO2.

The agricultural system has added to the methane in the atmosphere due primarily to bovine livestock and rice growing. Land-use change over the course of several centuries, such as deforestation and agricultural degradation of soil, has also lowered the carbon-carrying capacity of the land-based

Although the emphasis in Sky has been on energy system CO2 emissions, a view on all aspects of greenhouse gas emissions is needed to complete the scenario and understand the potential rise in surface temperature.

## Achieving the balance - remaining emissions

In Sky, fossil fuel use declines sharply after 2030 – but it cannot be eliminated in all sectors to the extent that warming is limited to well below 2°C. Even with a broad suite of technologies available and a 50-year timeframe for deployment, not all technologies and energy services can be swapped out for non-emitting alternatives at the necessary pace. Indeed, in so-called "hard-to-abate" sectors, practical alternatives have yet to be developed, and innovation rather than deployment is still the current order of the day.

## Removing carbon through use

Carbon capture and use (CCU) operates very differently from CCS (permanent geological storage). There are examples of capture and use in practice today, such as the conversion of CO2 to certain chemicals (for example, urea, the basis for fertilisers) and the production of plastics such as polycarbonates. These processes all require CO2 as a feedstock, but are not necessarily designed to store it permanently. If the carbon is returned to the atmosphere, such as through the degradation or incineration of the product that is made, then the net impact of the process may be zero in terms of atmospheric CO2 levels.

In a future energy system, there are two ways in which CCU could become effective:

• CCU might be focused on manufacturing synthetic hydrocarbon fuels, which could displace the need for fossil hydrocarbons. However, the synthetic fuels industry would need substantial technological innovation and then would need to scale very significantly before it could have a material impact, so this route is unlikely to be a significant contributor over the timescale addressed in Sky. Synthetic fuels are not a sink in themselves, since once they are made and used, the CO2 is returned to the atmosphere.

• CCU could be applied to the manufacture of certain goods – for example, building materials or plastics. But to act as a mitigation mechanism akin to CCS, CCU must lead to more-or-less permanent storage. The total stock of the product must be maintained for a very long time (at least a century or more) for CCU to approach CCS equivalence. In Sky, fossil fuels and bio-feedstocks are used to make such products, acting as an effective carbon sink.

This situation means that assigning a mitigation value to CCU plays a critical role. Doing so for CCS is a relatively simple task – each tonne stored can be counted as permanent mitigation and will contribute to the overall task of reaching net-zero emissions. The same cannot be said for CCU. While carbon can be embedded in urea or polycarbonates, there is no established protocol to define this as permanent mitigation. Work remains to be done in this field.

### More information

Download the scenarios:

**www.shell.com/scenarios**

# ACT Acorn - a scaleable full-chain industrial CCS project

**The aim of the Acorn project is to deliver a low-cost carbon capture and storage system in north east Scotland by 2023, building on existing research, such as an appraisal of potential CO2 storage sites and options to re-use oil and gas assets, to move the Acorn project from proof-of-concept towards design studies.**

The ACT Acorn project brings together scientists and industry experts from the UK, the Netherlands and Norway, whose expertise will contribute to one overarching goal – the delivery of a full-chain carbon capture and storage (CCS) project in north-east Scotland by 2023, as part of a programme of clean industrial growth.

By exploring a variety of opportunities, issues and challenges, the 19-month project will produce a compelling business and policy case to attract developers and public funding. It will also provide a blueprint for the decarbonisation of regions dependent on the fossil fuel industry and its products.

It will consider the most cost-effective and efficient options for building out from the initial project; to provide an integrated CCS hub by the 2030s, which would contribute to Scotland's climate change action, seed a CCS industry in the UK for clean industrial growth and potentially serve other European regions.

The ACT Acorn project involves researchers from three European countries and from eight partner organisations. The combined work will deliver final results in early 2019 to underpin the delivery of a low-cost CCS system in north-east Scotland by 2023.

The ACT Acorn consortium is led by Pale Blue Dot Energy and includes Bellona Foundation, Heriot-Watt University, Radboud University, Scottish Carbon Capture & Storage, University of Aberdeen, The University of Edinburgh and University of Liverpool.

## Key objectives

ACT Acorn, which is supported by the European Union, will:

- Consider how a project, such as Acorn, can support a just transition to a decarbonised future
- Rigorously assess a shortlist of geological CO2 storage sites below the North Sea
- Explore options for re-using oil and gas assets, such as pipelines and platforms
- Consider a stepped approach to developing CCS in north-east Scotland to minimise cost
- Explore build-out options from St Fergus to create a national CCS network
- Outline the potential for producing hydrogen from natural gas with CCS
- Provide valuable knowledge for similar developments in other North Sea regions

## Summary

St Fergus will be a key UK Carbon Capture & Storage (CCS) hub location. Acorn enables the production of hydrogen at St Fergus, which can help decarbonise UK heat demand. St Fergus is the best location in the UK to initiate hydrogen production by decarbonising natural gas.

CO2 can be imported via Peterhead Port and transferred to St Fergus in liquid phase through a new purpose-built pipeline. Peterhead Port could import up to 16MT/yr CO2 by 406 ship movements from European ports. For import quantities in the range of 5 to 10MT/yr, a fleet of three or four vessels is required.

Feeder 10 provides an existing pipeline to enable effective decarbonisation of industrial emissions at Grangemouth.

Due to its location, existing natural gas hub and pipeline connections, St Fergus will be one of three or four key UK coastal hub locations for CCS.

The initial capture volumes from St Fergus are intended to initiate the Acorn project. However, the real opportunity lies in the build-out enabled by the capacity of the already installed infrastructure and the new decarbonisation opportunities which the expansion enables.

Acorn enables the potential for hydrogen manufacture at St Fergus as an initial step in decarbonising gas in the UK. Natural gas would be used in Steam Methane Reformers to produce hydrogen whist capturing the CO2. Hydrogen can then be exported in the gas transmission system or used locally, whilst the CO2 is transported and stored offshore. St Fergus is the best location in the UK to initiate hydrogen production by decarbonising natural gas. This is because it is both an important natural gas import facility, and lies close to significant CO2 storage facilities, with three redundant but re-usable offshore pipelines.

Details are provided for importing CO2 via Peterhead Port and transferring it by pipeline via Peterhead Power Station to St Fergus in a new line designed for carrying liquid phase CO2 at ~120bar. The power station is included to provide land for facilities, access to waste heat for warming the imported CO2 and provision of power and utilities.

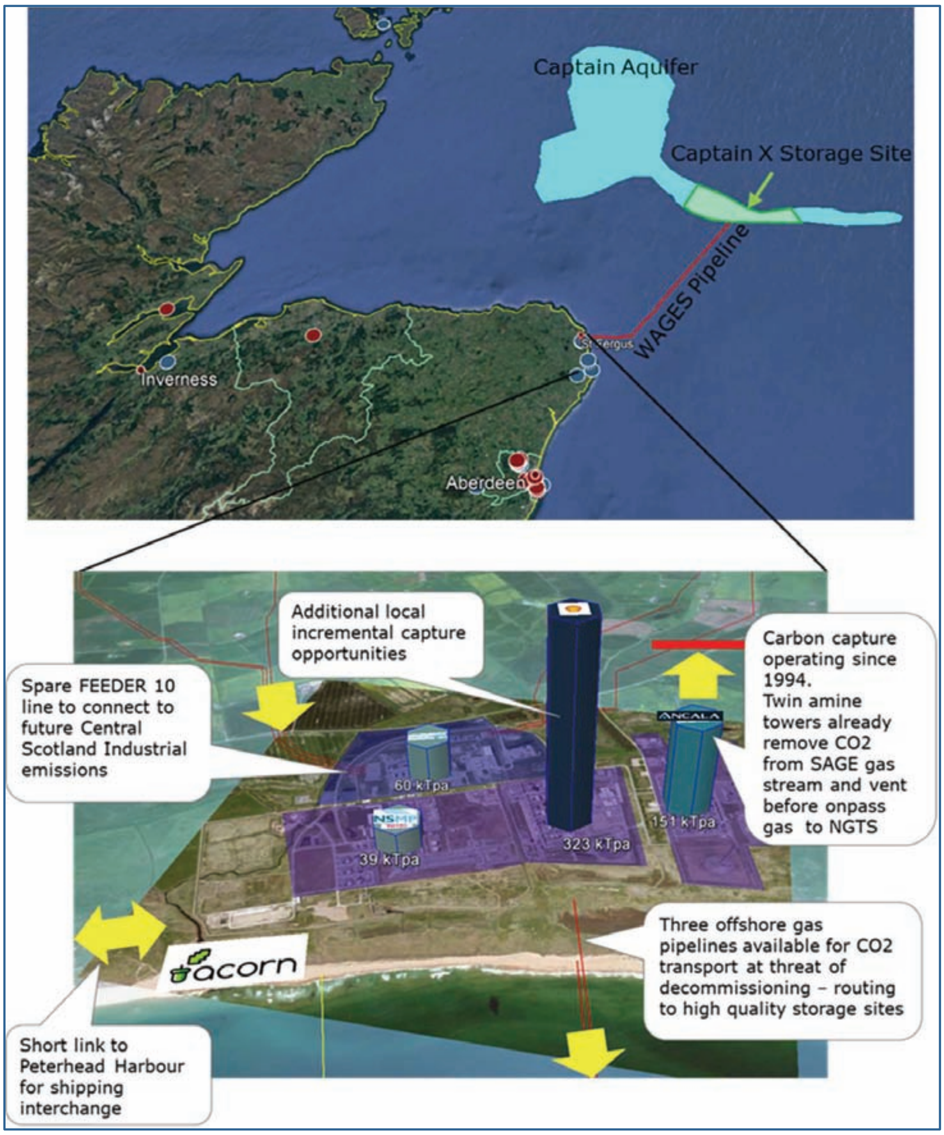
Peterhead Port has ample capacity for the import quantities envisaged for early build-out phases and a maximum practical capacity of 16.2MT/yr.

For import quantities in the range of 5 to 10MT/yr, a fleet of three or four tankers of 30,000 to 50,000 deadweight tonnage (equivalent to 24,000 to 40,000 T CO2) size will be required to service routes from CO2 export hubs within the North Sea area.

CO2 supply via Feeder 10 was analysed in ACT Acorn Deliverable 17 (D17). This confirmed that Feeder 10 was a viable route by which CO2 emissions from industrial sources at Grangemouth could be transported to St Fergus.

The Grangemouth industrial cluster presents the best location in Scotland for developing Carbon Capture & Utilisation (CCU) opportunities, with the potential link to higher volume CO2 capture and transport through Feeder 10 to the Acorn project. Given its location and site-based constraints it is unlikely that St Fergus will be a suitable site on which to develop commercial scale CCU projects.

The opportunities for physical linkage of bioenergy projects with the Acorn project are limited, but considerable opportunity exists for development of synergies and the development of bioenergy as part of the integrated energy mix, which includes consideration of CO2 emissions and new energy vectors such as hydrogen.




*Acorn Outline Minimum Viable Development Plan*

## Expansion options

Many CCS projects have been burdened with achieving "economies of scale" immediately to be deemed cost effective. This inevitably increases the initial cost hurdle to achieve a lower lifecycle unit cost (be that £/MWh or £/T) which raises the bar from the perspectives of initial capital requirement and overall project risk.

The Acorn development concept use a Minimum Viable Development (MVD) approach. This takes the view of designing a full chain CCS development of industrial scale (which minimises or eliminates the scale up risk) but at the lowest capital cost possible, accepting that the unit cost for the initial project may be high for the first small tranche of sequestered emissions.

Acorn will use the unique combination of legacy circumstances in North East Scotland to engineer a minimum viable full chain carbon capture, transport and offshore storage project to initiate CCS in the UK. The project is illustrated above and seeks to re-purpose an existing gas sweetening plant (or build a new capture facility if required) with existing offshore pipeline infrastructure connected to a well understood offshore basin, rich in storage opportunities. All the components are in place to create an industrial CCS development in North East Scotland, leading to offshore CO2 storage by the early 2020s.

A successful project will then drive further growth and incremental development as and when CCS becomes more commercially viable in the UK, thus minimising any potential regret costs should CCS not be adopted more widely. This will provide a cost effective practical stepping stone from which to grow a regional cluster and an international CO2 hub.

The seed infrastructure can be developed by adding additional CO2 capture points such as from hydrogen manufacture for transport and heat, future CO2 shipping through Peterhead Port to and from Europe and connection to UK national onshore transport infrastructure such as the Feeder 10 pipeline which can bring additional CO2 from emissions sites in the industrial central belt of Scotland including the proposed Caledonia Clean Energy Project.

### More information

Taken from ACT Acorn project briefing and expansion option reports. Download the full reports at:

**www.actacorn.eu**

**www.pale-blu.com**

# Offshore power generation with CCS

**In a decade, offshore power generation with CCS may supply cost-competitive green electricity to limit the climate impact of offshore oil and gas production facilities around the world.**

In countries with significant offshore oil and gas activities, reducing the climate impact of these operations is an important requirement to fulfil their commitments under the Paris Agreement. This is for example the case of Norway in which 28% of CO2 emissions take place offshore. In the early 90s, Norway introduced a carbon tax on offshore CO2 emissions to avoid release to the atmosphere of native CO2 which can be associated with natural gas production. This resulted in the implementation of the first two CCS projects considering offshore CO2 storage: Sleipner (1996) and Snøhvit (2008).

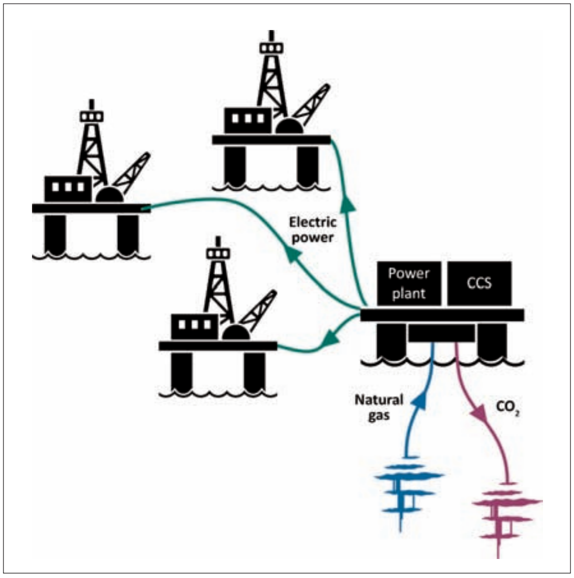
However, beyond this first strong decision, the Norwegian Parliament also resolved in 1996 that the use of electrical power supplied from the mainland should be considered in connection with all offshore development projects in order to make oil and gas production on the Norwegian Continental Shelf more climate-friendly. The first serious debate on this subject was in 2014, when Statoil was required by this parliamentary resolution to supply power from the mainland to the giant Johan Sverdrup field.

Indeed, in the vast majority of cases, the power requirements of offshore oil and gas operations are currently met using offshore gas turbines. In such cases, every oil and gas production facilities is equipped with dedicated gas turbines, of varying efficiency, which results in CO2 emissions as a by-product. Electrification of offshore production facilities, as done in the Martin Linge platform operated by Statoil, is a way to significantly reduce the climate impact of these operations.

SINTEF has now completed a study that shows that a number of future fields in the North Sea could obtain green electricity by alternative means and at costs which are competitive with electrifications. In this concept, referred as CEPONG for Clean Electricity Production from Offshore Natural Gas, all oil and gas production facilities in an area will be supplied by a power generation infrastructure equipped with modern high-efficiency combined cycle installation, as well as carbon capture and storage (see illustration).

The CEPONG study, financed by Statoil, Neptune Energy, TechnipFMC and partly funded by Gassnova through the CLIMIT programme, looks at potential implementations in around a decade. By then, the current and forthcoming CCS demonstration projects, as well as the current research and development effort will have helped overcoming the additional costs associated with CCS demonstration.

Taking into account the effect of the anticipated technological development in this field, this study shows that the CEPONG concept can produce flexible green electricity that is competitive with power supplied from the mainland. However, the concept cost performances will depend strongly on the distance of the targeted production facilities from the coast.




*Schematic illustration of the CEPONG concept toward decarbonising offshore oil and gas production facilities. Illustration: Astrid Lundquist / SINTEF*

The study shows that electrification by means of cables from the mainland is an attractive solution to decarbonise offshore oil and gas production facilities located up to 150 km from mainland. On the other hand, the CEPONG concept will be a more suitable mean of decarbonisation for oil and gas production facilities located at least 150-200 km from the mainland.

One of the strong advantages of the CEPONG concept is its capacity to run on low-quality, uneconomic or stranded gas resulting in significantly lower gas costs for the concept. Indeed, extensive pretreatment is normally associated with gas production to meet the transport specification by removal of, among other things, liquid fractions (condensate), hydrogen sulphide and carbon dioxide which accompany it from the reservoir.

In the CEPONG concept, almost all such treatments of the gas become unnecessary. Indeed, after removal of sulphur, the natural gas can be burnt in a turbine almost unaltered. Such simplification would thus result in both lower costs for the concept and enable valuation of natural gas currently considered as uneconomic such as, for example, small gas fields with mid-large CO2 content.

In addition to playing a role in the decarbonisation of the offshore oil and gas industry, the CEPONG concept can under certain circumstances produce flexible "green" gas power that can be transported to shore. Used in this way, the concept could thus, when economically suitable, provide support to the decarbonisation of mainland electricity. Beyond its potential for developed countries, this scenario could also support the increasing clean power demand in African, Latin American and South-east Asian nations. In this case, it can ensure that offshore field development becomes more climate-friendly, while supplying electricity to communities where power supply is currently inadequate. In this way, it may benefit both household and business.

## More information

Simon Roussanaly Research Scientist, Rahul Anantharaman Research Scientist, and Jon Magne Johansen Business developer, all at SINTEF.
**www.sintef.no**

# Reducing methane emissions with bacteria

As part of the Future Energy Systems research initiative, University of Alberta biological sciences researchers are genetically engineering non-hazardous bacteria that consume methane, one of the most potent greenhouse gases, and turn it into fuel.

Methane is a major player in climate change. "When we call it natural gas and burn it for power, methane does reduce emissions compared to coal," Sauvageau explains. "But if it gets into the atmosphere without being burned, it actually has a stronger global warming effect than CO2."

Methane is 25 times more potent than carbon dioxide, so in 2016, Canada, the United States and Mexico committed to reduce their methane emissions by 45 per cent by 2025. Since 44 per cent of Canada's (and 70 per cent of Alberta's) methane emissions come from the oil and gas sector, meeting those targets means regulations forcing producers to capture "fugitive" emissions.

"To offset the cost of capturing the methane you could just sell it as natural gas," Stein suggests. "But you could also find a way—using naturally occurring bacteria—to turn it into a more valuable fuel, or even a product that doesn't release carbon dioxide at all."

Scientists have known for decades that bacteria can be modified to convert methane into other products, but no one has managed to fully scale it up.

"In the old days, a biological scientist could stay in her lab modifying bacteria and testing them in isolated conditions," Stein explains. "But what works in a Petri dish doesn't necessarily work at industrial scale."

She likens it to training a worker to produce a certain product, but not worrying about the design of the factory. When millions of these workers come together in a factory that doesn't have the right layout, equipment or working conditions, they can be forgiven for simply staring at each other in confusion.

"No matter how perfectly suited to the job, a million individuals without organization is usually just a mob," Sauvageau says.

The trick is to build factories that suit the workers—"reactors" that could range in size from a bathtub to an Olympic-sized swimming pool.

So, as Stein's lab genetically modifies bacteria, Sauvageau's team runs experiments to identify the optimal conditions for their work. Variables can include the size of chambers, layout, temperature and nutrients, and once they find an optimal condition, that information is fed back to further customize the bacteria meant to function within it.

*Future Energy Systems investigators Dominic Sauvageau and Lisa Stein*

"Our team members interact on a daily basis and our teams meet every two weeks," Stein says. "Constant communication means we can move fast."

Together, they're working with Mango Materials—a California bioenergy startup whose other research partners include NASA—to pilot a reactor that captures methane from wastewater treatment and uses bacteria to convert it into bioplastic.

The composition of captured methane varies depending on its source, so Stein and Sauvageau are creating a platform of a half-dozen bacteria genetically engineered to work in different circumstances.

"No single type of bacteria will do every job," Sauvageau explains. "We're creating a roster of different bacteria with matching reactors that can be customized to different industrial applications."

These bacteria will use methane to produce a variety of products. One is butanol, an alcohol fuel that can either run unmodified gasoline car engines or be mixed into diesel fuel to reduce soot emissions. Others include isoprenoids, chemicals that usually come from petroleum, which can be used as biojet fuel.

"By creating these materials from methane, we reduce our need to extract fossil fuels from the ground," Stein says. "Instead of digging new carbon out of the Earth and expelling it into the atmosphere, we recycle what's already out here."

Recycling methane emissions and reducing the need for new extraction sounds promising, but neither Stein nor Sauvageau see it as a silver bullet for climate change.

"Our platform is just one part of what needs to be a system-wide solution," Sauvageau says. "Eventually our energy infrastructure will change, and we may not rely as much on combustion engines—or hydrocarbon fuels."

But if our system no longer requires hydrocarbons, would the bacteria find themselves out of a job? Stein doubts it. "We're learning a lot about how to work with these bacteria," she says. "I'm pretty sure we can coax them to make something else."

## More information

Image and story courtesy of Folio.ca

**futureenergysystems.ca**

# Researchers find carbon capture a financial opportunity for U.S. biofuels

**With recent tax credits and other policies, removing carbon dioxide from the atmosphere and storing it underground is not only possible but profitable for U.S. biofuel refineries.**

Although considered critical to avoiding catastrophic global warming, the feasibility of removing carbon dioxide from the atmosphere and storing it underground – known as negative emissions – has been in question.

"There's really no scenario that meets the world's climate goals without negative emissions," said Katharine Mach, a senior research scientist at Stanford's School of Earth, Energy and Environmental Sciences. "But most technologies for carbon removal are immature, largely unavailable or expensive."

But researchers at Stanford and other institutions have found new hope for cost-effective carbon capture and sequestration (CCS). Their study, published April 23 in Proceedings of the National Academy of Sciences, runs the numbers on different options for removing carbon dioxide from the atmosphere in the U.S. and finds opportunities where it is not only commercially feasible with existing technology, but profitable.

The most widely discussed strategy for removing carbon dioxide from the atmosphere involves growing plants, which absorb CO2, as a first step. Those plants can then be processed to produce energy, and any resulting CO2 emissions from that energy production would be captured and stored underground.

While it seems straightforward, these technologies – known as bioenergy with carbon capture and sequestration, or BECCS – have not been fully developed and many areas don't have geology that's suitable for storing CO2. What's more, pipelines would need to be built to take CO2 from bioenergy plants to areas suitable for storage. There are also serious questions about how BECCS would scale globally and compete with plants grown for food production or impact ecosystems and biodiversity.

However, the group found that one type of BECCS technology could work immediately for U.S. ethanol producers. What's more, given current and predicted future financial incentives, the approach could even turn a profit.

"We found that between tax credits for CCS and upcoming financial incentives from low-carbon fuel standards, CCS is an untapped financial opportunity for ethanol producers across the U.S.," said Daniel Sanchez, a postdoctoral scholar with the Carnegie Institution for Science and lead author on the paper.

The United States is the largest producer of ethanol in the world, producing 15.8 billion gallons in 2017. Ethanol is made by fermenting biomass such as corn, which produces a high-purity CO2 by-product that is easier and cheaper to capture, compress and inject underground than other emitted sources of CO2. Right now, these emissions are largely vented to the atmosphere in the process of making ethanol.

"Negative emissions at biorefineries is commercially ready and affordable. It offers a compelling way to build the real-world experience we need to develop future BECCS technologies," said Mach.

The researchers estimate that 60 percent of all CO2 emitted annually through the production of ethanol at the country's 216 biofuel plants (about 1 percent of all CO2emissions from the U.S.) could be captured at low cost, under $25 per metric ton of CO2.

Further, if credits for captured CO2 were set at $60 per metric ton, it could incentivize sequestration of 30 million metric tons of CO2 each year that are otherwise vented into the atmosphere – equivalent to emissions from powering 3.2 million homes for one year – and pay for the construction of 4,300 miles of pipeline infrastructure needed to transport the CO2 for storage at appropriate sites across the country.

These incentives are in line with new tax credits included in the Bipartisan Budget Act of 2018 signed by the president in February. The bill amended section 45Q of the tax code so that power plants or CO2-emitting facilities are eligible for tax credits for captured CO2 for up to 12 years.

"There are many ways to incentivize and unleash negative emissions technologies, one of which this administration and Congress may have just put into place," said Mach.

Another financial incentive comes in the form of low-carbon fuel standards, such as those implemented in Oregon, California and British Columbia. It works by giving tradeable credits for fuels that exceed the standard and deficits to those who don't.

Right now, accounting for CCS isn't included in the standards, but on April 27, California will consider updating its rules to include new protocols that would quantify the value of carbon removal in the fuel production process. If adopted, fuel producers could collect more credits by selling lower-carbon ethanol in California.

"This is an opportunity not only for biofuel producers to make profits, but also for CCS technology to be more widely piloted and developed. This is an essential first step if we're going to deploy carbon removal at levels necessary to keep dangerous climate change in check," said Sanchez.

Daniel Sanchez is also a AAAS Congressional Science and Engineering Fellow.Katharine Mach is also an adjunct assistant professor at Carnegie Mellon University, visiting investigator at the Carnegie Institution for Science and director of the Stanford Environment Assessment Facility at the Stanford Woods Institute for the Environment. Additional authors are from the International Institute for Applied Systems Analysis, the Lawrence Livermore National Laboratory and the Carnegie Institution for Science.

## More information

**www.stanford.edu**

**www.llnl.gov**

# New gas-to-liquid absorption technology poised to significantly reduce CO2 capture costs

A technology initially developed as a biological-chemical filter for the U.S. military is poised to revolutionize gas-to-liquid absorption processes and significantly reduce the cost of capturing carbon dioxide, proponents say.

*By Mark Lowey, EnviroLine*

"There are three things that are really holding back carbon capture, utilization and storage. They are capital cost, operating cost and plant size," says Richard Adamson, chief executive officer of Industrial Climate Solutions Inc. (ICSI), a Canadian technology company based in Calgary, Alberta.

For many industrial processes the first step in CO2 capture is contact between a liquid, such as a solvent, and process gas or flue gas. At each of the 17 large-scale CO2 capture plants around the world stands a huge gas-liquid absorption tower. This piece of equipment often represents 25 per cent or more of the overall capital cost. "What if we could reduce the size of the front-end contactor (which holds the solvent) to one-fifth the size of those conventional towers, while improving the robustness of the capture process?" Adamson says.

Regenerative Froth Contactor-Reactor (RFC) technology, a gas-liquid absorption and three-phase (able to handle gases, liquids and solids) contactor developed by Westec Environmental Solutions LLC, "opens the door to significant size reductions and cost savings for post-combustion CO2 capture applications," he says. "This is a key enabling step in advancing carbon capture, utilization and storage from demonstration projects to integrated regional industrial emissions management systems."

Tests of RFC technology – including a pilot in real-world operating conditions at a coal-fired power plant in Australia – show the technology can cut in half the footprint area and reduce the height of the gas-liquid absorption column by 50 to 60 per cent, compared with conventional absorption columns. With its novel contactor design, RFC increases process productivity by four to five times compared with conventional absorbers, testing indicates.

*The Regenerative Froth Contactor-Reactor (RFC) pilot plant at Hazelwood power station in Australia has shown that the technology can increase process productivity and reduce the size of the footprint and the absorber column compared to other CO2 capture systems*

"The Regenerative Froth Contactor is the only contactor in the world that can not only tolerate entrained solids without fouling, but works effectively with a whole class of precipitating solvents," Adamson says. ICSI has partnered with Westec Environmental Solutions (WES), based in Kahului, Hawaii, to commercialize the technology, which WES has spent a decade and more than US$4million to develop.

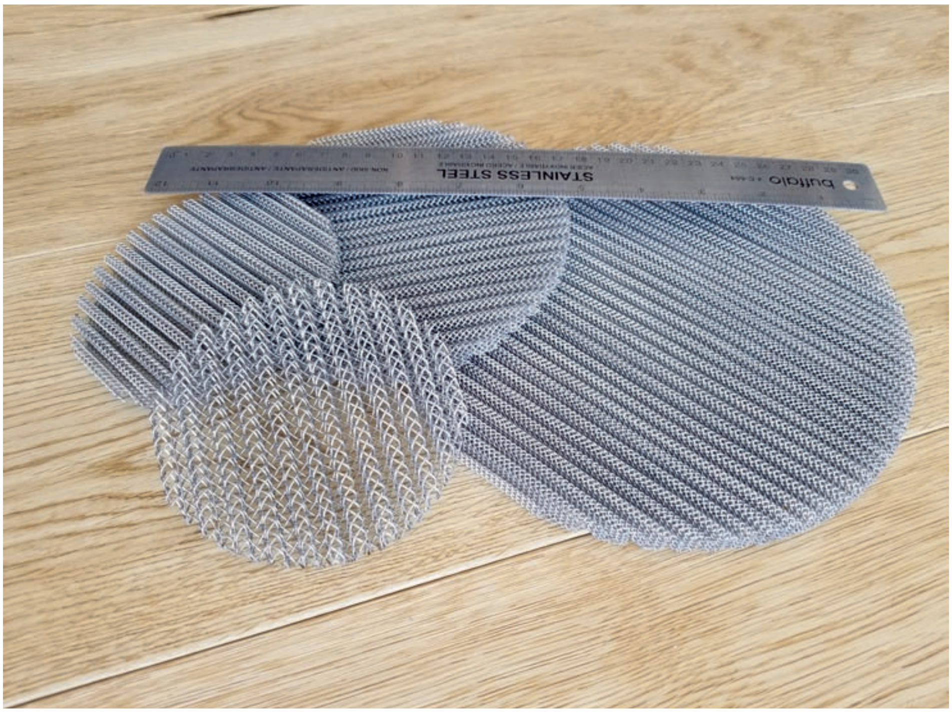
WES is also collaborating with SINTEF Norway, the largest independent research organization in Scandinavia, in current testing of the RFC technology in a project in Trondheim, Norway. The INSPIRE project is led by SINTEF and funded by CLIMIT, Norway's national carbon capture and storage research funding program. WES is developing a unique contactor design to be used with a novel, more efficient precipitating solvent developed by SINTEF.

"I believe this project offers a clear route to cost-reducing innovations, thanks to its uniquely international and multidisciplinary approach," Ugochukwu Edwin Aronu, SINTEF research scientist and project leader, said when the project was announced last year. "For the first time, an advanced precipitating $CO_2$ capture technology will be demonstrated in a full-height, state-of-the-art pilot plant facility, integrating two unique solvent and contactor technologies. Successful demonstration will take this technology a step closer to commercialization."

Precipitating solvents have shown great potential for cutting $CO_2$ capture costs by 30 per cent or more, by significantly reducing energy usage in the solvent-regeneration stage. "But the problem with conventional contactors is, if you have precipitate forming in the contactor, they'll plug up," Adamson says.

In contrast, the RFC contactor, with its co-flow design and highly turbulent flow, handles the drop-out of precipitates with no fouling or performance degradation. In fact, the technology may allow several promising precipitating solvents that were set aside to be reconsidered for $CO_2$ capture.

"It's one of the key advantages of getting this technology commercialized, which will open up several applications," says Bill Hargrove, chief technology officer at Westec. "It may simplify the entire process flow of the whole industrial site."




*The stainless steel mesh screens used in the RFC contactor. Unlike conventional absorbers, the gas and liquid both flow downward creating an unstable flow that creates a froth, increasing the surface area*

## RFC technology's unique approach

In capturing $CO_2$ or other industrial flue gases, the key factors are: the surface area between the gas and the solvent; the length of gas-solvent contact time; the mixing of the gas with the solvent; and the chemistry of the solvent.

Inside a conventional absorption column, the contactor typically consists of "structured packing" material and involves a counter-flow arrangement where the gas flows up the column and the solvent flows down. The solvent slowly trickles over the packing material, which provides the surface area. The height of the column provides the contact time between the gas and the liquid.

But the RFC technology uses a completely different "co-flow" arrangement, where the gas and the liquid both flow downward through a series of convoluted screens made of woven mesh stainless steel. This creates an unstable flow, Adamson says. "You have pulsing bands of froth that propagate down through the column. So your surface area is now millions of fine bubble walls and droplets instead of the actual physical packing material. You've always got the freshest possible solvent in touch with the gas phase." Because of the higher gas velocity in the RFC column, its cross-section is reduced compared with a conventional column. Also, the mass transfer of gas to liquid is about five times higher per unit of volume in the RFC column, which dramatically reduces the required column height.

This means the cross-sectional area of the RFC absorption column may need to be only half as much as that of a conventional column, Adamson says. "So your footprint's already been reduced in half." Moreover, he adds, only about 40 per cent of the packing height is required with RFC technology, compared with conventional columns, to achieve the same amount of mass transfer, or tonnes of $CO_2$ captured. "This is more than an incremental change. This is a step change in that front-end absorber process."

## Moving toward integrated carbon management systems

Shrinking the size of the absorber system offers capital cost savings beyond the cost of the equipment itself. With very large conventional columns, there's also the cost of moving all the material to site, fabricating the column and associated infrastructure onsite, the amount of labour involved in erecting the tower, and the size of the cranes and the foundation. RFC technology promises to significantly reduce these capital costs, while using precipitating solvents that would also cut operating costs.

RFC technology's much smaller size also opens the door to new approaches for both manufacturing and deploying absorption columns. "When you reduce the size, especially the cross-sectional area, for smaller industrial emitters you can go to prefabricated fiberglass absorption columns, for example," Adamson says. For multiple emission point sources – like those found in a refinery – instead of having to do a large and expensive engineering and construction project for each emissions source, the technology offers the potential to build a relatively small foundation and erect a prefabricated column for each source – again reducing overall project costs.

The next logical step would be deploying RFC technology in an industrial-regional cluster with, say, a refinery and a fertilizer plant and other different types of CO2-emitting industrial facilities adjacent to each other. Prefab absorption columns and circulating pumps could be installed at all the point emission sources. The cluster would have one centralized solvent-regeneration centre, such as a utility-scale cogeneration plant that pipes both rich and lean solvent in a loop and integrates waste heat – similar to a district energy system.

"So essentially the rich solvent and lean solvent loop becomes a CO2 management system instead of a single, end-to-end carbon capture plant for each site," Adamson says. "Achieving these innovative and efficient systems all depends on driving the cost out of that front-end absorption process."

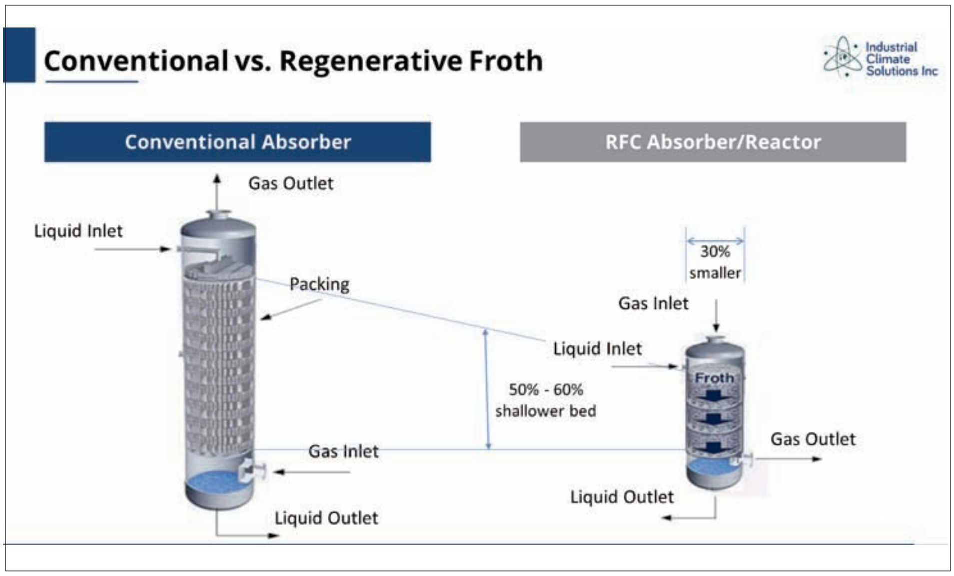
## History of technology's development

Development of RFC technology began in 2000, when entrepreneur environmentalist Jeff Reiss and self-taught inventor Roy Pellegrin, working in a garage on Maui, Hawaii, came up with a foam-based system for capturing and filtering drywall dust at building sites. Peletex Inc., a Maui-based company, developed the technology into a cutting-edge indoor air quality filter. From 2005 to 2007, through a contact with the Office of Naval Research, Peletex worked on a biological-chemical filter for the U.S. Navy, to protect personnel from weaponized virus and nerve agents. Tests showed the technology could filter submicron scale particulates and gases at up to 99.999 per cent level under extreme conditions. In 2009, Peletex partnered with a Chicago-based management and marketing company to form Westec Environmental Solutions and develop other applications, including CO2 capture.

Hargrove says Westec's engineers rediscovered a naturally occurring phenomenon – first reported more than four decades ago – called pulsing, which happens spontaneously in a co-current flow of liquid and gas. In the pulsing mode, the flow separates into two distinct regions: a gas-continuous region and a bubbly flow region. Westec's big breakthrough was being able to generate the pulsing to start at the top of the absorption column, while using rest of the column height to propagate the pulse. The company's patented design reduced by more than 30 times the drop in pressure that would otherwise have made the mass transfer of liquid to gas inefficient. "That's the secret – how we're able to reduce the pressure drop – by configuring different types of screens at the top," Hargrove says.

*A three-metre-high absorption column setup for tests to compare performance of RFC absorber side-by-side with conventional absorber at the Maui laboratory*

From 2012 to 2014, a 10-centimeter (four-inch)-diameter RFC contactor was designed and pilot tested under real-world conditions in a flue gas slipstream at the Hazelwood




*Comparing RFC absorption column size and components with conventional columns. The smaller size contributes to reduced capital costs* coal-fired power plant near Melbourne, in a project led by Australian firm CO2CRC. In terms of the RFC contactor's performance, Hargrove says, "We were able to precisely match the measurements we made in our laboratory in Maui to what we got with real flue gas. We confirmed the higher mass transfer per unit volume with our contactor."

Westec's current project with SINTEF Norway started last year, with a study that confirmed the RFC contactor and SINTEF's precipitating solvent would work together. The first half of the second phase of the project – testing a 10-centimeter-diameter RFC contactor and the solvent – has been completed. "We passed the go-no go decision point to proceed with the second part. We had no clogging or fouling issues," Hargrove says. The next step, to last for a year, is to test the RFC contactor and solvent in a scaled-up, 20-centimeter (eight-inch)-diameter contactor.

## Next steps to commercialization

Industrial Climate Solutions and Westec Environmental Solutions announced a license agreement, to commercialize the RFC technology, in March at the GLOBE Forum and Innovation Expo 2018 in Vancouver, British Columbia. The license covers CO2 and other gas absorption, particulate removal, desulfurization, scrubbing, sparging (removing dissolved gases/volatile compounds in a liquid), chemical reactor, and all other applications.

Adamson says ICSI and WES plan this year to scale up the RFC absorber from 10 centimeters in diameter to approximately 1.2 meters (four feet), and test and optimize this system under controlled laboratory conditions. In 2019, the companies intend to test this industrial-sized system a field pilot at an operating facility. The system would capture about 30 tonnes of CO2 per day off a natural gas-fired boiler, or approximately 45 t/d at a coal-fired power plant.

As for the timing to commercial deployment, Adamson notes that recent changes to the Q45 federal tax credit in the U.S., to support development of commercial CO2 capture and pipeline projects, has rekindled industry interest in utilizing CO2 in enhanced oil recovery projects. "There's a possibility that some of those CO2-EOR projects are going to go ahead," he says. "The question is, can we run fast enough to have an industrially ready product in time for their decision processes?" The companies' strategy is to simultaneously pursue multiple applications and markets for their enabling platform technology, which Adamson says "can have high impact in a lot of different markets and applications."

A major investor in Westec Environmental Solutions is Verditek PLC, publicly traded (as LSE/AIM: VDTK) on the London Stock Exchange's AIM Market. "We are excited that ICSI, based in Calgary, Canada where carbon capture technology is thriving, is partnering with WES to take this disruptive technology to market," says Geoff Nesbitt, Verditek's chair and chief executive officer. "Verditek is passionate about taking pioneering science from the lab into real-world commercial engineered solutions, Nesbitt says. "The partnership with ICSI will help WES accelerate its market penetration and help customers realize the extensive benefits of this cutting-edge clean-tech solution."

*"What if we could reduce the size of the front-end contactor (which holds the solvent) to one-fifth the size of those conventional towers, while improving the robustness of the capture process?" – Richard Adamson, chief executive officer of Industrial Climate Solutions*

## More information

Mark Lowey is the managing editor of EnviroLine in Calgary, Alberta and a communications advisor to Industrial Climate Solutions Inc.

**www.envirolinenews.ca**

**www.icsolutions.work**

**wes-worldwide.com**

# New CO2 Capture Plant in Japan supplies liquefied CO2 production

**After the success of the world's largest CO2 capture plant, the Petra Nova Project, Mitsubishi Heavy Industries Engineering (MHIENG) has delivered another CO2 capture plant in Japan with different application and end use.**

The capture plant located in Kurashiki City of West Japan is currently capturing 283 tonnes of CO2 every day and delivering to an adjacent CO2 liquefaction facility for high-purity liquefied food grade CO2 production.

Nippon Ekitan, the owner of the new CO2 capture and liquefaction plants, is the top manufacturer of liquefied CO2 and dry ice for various uses in the market of Japan. In the past, the liquefied CO2 product was mostly obtained by liquefying and refining the industrial gas from high-CO2- concentration-gases provided by petrochemical companies and ammonia manufacturers.

However, the supply of the high CO2 concentration gas has dropped in recent years particularly in West Japan. It has become necessary to seek resources other than high-CO2-concentration gas sources for the liquefied CO2 to meet the demand.

To stably supply liquefied CO2 without costly long-distance transportation, the CO2 capture technology developed by MHIE gives an alternative option for Nippon Ekitan to acquire CO2 economically even with a relatively lower concentration of CO2 in the source gas.

In this new CO2 liquefaction facility, firstly the CO2 is captured from the low-CO2-concentration industrial gas provided by the nearby Mitsubishi Chemical Mizushima Plant in the CO2 capture plant, and then liquefied and refined by the liquefaction plant. The CO2 capture process is considered the next generation model of liquefied CO2 production by Nippon Ekitan and provides flexibility in CO2 sources while contributing to the mitigation of carbon emissions through reuse.

The extensive experiences that MHIENG have in CO2 capture technology is a crucial part in this project. MHIENG licensed its patented CO2 capture technology, known as the KM CDR Process™, supervised the basic engineering design, and supplied the core equipment.

*The Nippon Ekitan pilot plant is capturing 283 tonnes of CO2 per day*

The KM CDR Process™, developed jointly by the Kansai Electric Power Co., Inc. and Mitsubishi Heavy Industries, Ltd., the parent company of MHIENG, employs a proprietary KS-1™ high-performance solvent, renowned for its great absorption capacity, low energy requirement and low degradation rate compared to conventional solvents.

The KM CDR Process™ has been successfully demonstrated in over a dozen commercial plants since 1999, capturing CO2 from various sources including natural gas-fired and coal-fired flue gases. All business rights related to this technology was transferred to MHIENG on 1 January, 2018. The captured CO2 has been used for enhancing chemical production such as methanol and urea, geological storage, and enhanced oil recovery (EOR).

The flue gas containing CO2 is cooled in a flue gas quencher with condensation of excess water before entering the CO2 absorber, where the CO2 is selectively absorbed by contacting with KS-1™ solvent. The CO2-rich solvent is then sent to the CO2 regenerator, which heats up the solvent to high temperature so that CO2 can be released from the solvent to gas phase.

High purity of CO2 is obtained after cooling and removing excess water. The CO2-lean solvent is circulated back to the CO2 absorber for reuse. Further CO2 compression and dehydration depend on the end use requirement. Other proprietary features developed by MHI's R&D center such as the energy saving system and the amine emission reduction system minimizes the energy consumptions and environmental impact.

Following the Petra Nova and the Nippon Ekitan Projects, the next CO2 capture plant using the KM CDR Process™ will be constructed in Perm, Russia for Metafrax, Russia's largest methanol manufacturer and is expected to come online in 2021. The plant will capture 1,200 tonnes of CO2 per day from a reformer burner flue gas to produce ammonia, urea, and melamine.

**More information**

**www.mhi.com**

# Stronger CCS Advocacy - a new campaign group for Europe

A group of individuals who have worked to champion CCS in Europe, but with little progress to date, are proposing a new Brussels-based organisation which would complement existing groups but address broader public and political issues while avoiding technocratic ones.

## Europe's lost years

In March 2007 the European Council called for up to 12 CCS demonstration projects to be in operation across Europe by 2015. Scores of proposals for CCS plants were subsequently put forward by potential developers, and a range of small pilot plants have since operated successfully, but more than a decade later the construction of not one additional commercial-scale project has yet been authorised.

A false assumption was made by policymakers that the CO2 price created by the EU emissions trading system would be sufficient to drive forward private sector investment in CCS – although the same argument was not used where the promotion of electricity from renewable sources was concerned; instead, targets were set and large public subsidies provided.

Financial support from EU member states was needed but was not forthcoming. A European funding mechanism (the 'NER300') linked to the CO2 price was introduced with the aim of providing significant assistance, but the collapse in the CO2 price and restrictive rules governing allocation of the limited funds available frustrated the aspirations. The money that was potentially available has not been spent.

It is intended that the flaws will be corrected through the successor mechanism, the Innovation Fund, which will make available EU financial support derived principally from the sale of 400 million emission unit allowances at what is expected to be a much higher price, but the rules for its use have not yet been determined. It is not clear whether emphasis will be given for the money to be used to support CCS development.

Had the European Council taken steps to ensure that its 2007 ambitions were realised, and had it put in place policy measures that could have driven forward the investment, it can be assumed that CCS would now be firmly established as a key component of EU climate policy. Experience gained would have stimulated innovation and reduced costs. Scores of additional CCS projects would now be underway across Europe, with pipeline transport infrastructure to offshore storage areas being developed to serve the continent's major industrial clusters.

### The want of advocacy

There is no organisation that exists at a European level solely to campaign and lobby for the deployment of CCS technology. This is in marked contrast to the strength of organised political advocacy that is used to promote other technologies intended to reduce CO2 emissions, including not only the energy conservation and renewable electricity lobbies but also the nuclear and gas industries.

The new group's task will be to create the political will to take CCS deployment forward.

It has been argued that in no European country, with the possible exception of Norway, do politicians risk having to pay a political price for not supporting CCS. By raising awareness of the importance of CCS to our global future this situation must be changed.

The development of good policies is essential, and existing organisations have contributed greatly, but the policies will not be applied unless the political will exists to do so.

Winning political support requires engagement with the practitioners, directly in person or indirectly through the media and through those who influence them. The enthusiasm of political champions can carry much weight, but it has to be won. Sometimes this will be achieved by bringing the right people together. Sometimes it will require a more robust approach.

## Is the tide turning?

European Commission officials freely acknowledge that CCS has been given less and less attention over the years, arguing that without the support of member states their ability to act is constrained.

To demonstrate their continued belief in the importance of CCS they point to their hopes for the Innovation Fund and to the useful research funding that has been allocated to projects that aim to strengthen our knowledge of CCS technology and reduce its costs. They emphasise that taking forward carbon capture storage and use (CCS/U) is one of the ten key actions identified in the Strategic Energy Technologies (SET) Plan. They highlight the funding that is likely to become available through the Connecting Europe Facility for a number of CCS Projects of Common Interest (PCI), all of which would be of undoubted value and which should stimulate interest in the potential of CCS.

Significant developments away from Brussels include the announcement by the Dutch government of ambitious plans to deploy CCS to reduce emissions from industry, and these are complemented by the Port of Rotterdam Authority's proposals to create a collection hub for CO2 from local industrial installations and later perhaps from sites in Germany and Belgium. A decision is awaited on whether Norway will fund the capture of CO2 from cement, fertiliser and waste-to-energy plants.

Proposals by Statoil, in partnership with Shell and Total, to make commercially available a CO2 storage site off the coast of Norway, and by Statoil to convert to hydrogen a unit at the Magnum gas power station in the Netherlands, open up great possibilities for the future. At least three industry-focused CCS projects are being promoted in the UK in addition to hydrogen substitution of methane in domestic gas networks. While across the Irish Sea plans have been prepared to capture CO2 from gas fired power stations in Cork, and thereafter from industrial installations in the same locality.

These initiatives offer encouragement and inspiration but there is as yet no certainty that the projects will come to fruition. The personal commitment of the Climate Commissioner to CCS has always been clear, but his soundings have suggested that support from the European Council for new initiatives has been lacking. The balance of argument will not be helped by the likely departure of the UK from the decision-making process.

Discussion of CCS technology and its emissions reduction potential is largely absent from key EU policy debates, and misinformation continues to be rife. In the past four years the European Parliament has adopted no report specifically on CCS and made hardly any reference to it. Only two meetings to promote CCS projects have taken place and they have been attended by fewer than six MEPs in total.

## What will the new group do differently?

We will challenge them to explain how the Paris goals can be met by 2050 in the absence of widespread deployment of CCS. We will challenge them to explain why no business case has been created to justify CCS investment. We will challenge them to justify strategies that are contrary to the recommendations of the IPCC and IEA. We will challenge them to admit that a strategy that does not wholly embrace CCS will prove more costly to European taxpayers. We will challenge them to prevent Europe's technological leadership falling behind that of the China.

Challenge is an essential component of political dialogue. It generates publicity, raising the profile of an issue, increasing awareness and stimulating debate. It forces policymakers to consider their position and provide a response. It is a crucial means of securing the political will to secure the policy changes required.

The campaign group will challenge policymakers. It will make waves, rocking the boat and making decision-makers sit up and take notice. In this its work will be entirely complementary to CCS-supportive organisations that provide policymakers with financial and technological solutions.

The group's role will not be to carry out primary research or develop strategy options, for this is done by others. Rather, its role will be to foster political enthusiasm where possible, and to stir policymakers where it is not. Similarly, it will avoid recommending particular measures that might be adopted to bring CCS to fruition, not least because its supporters are likely to hold different views.

At this time what matters is recognition that governmental measures are needed to take CCS forward. The range of options can be suggested, but it is for policymakers to choose.

The group must make CCS relevant. It must make CCS a key component of EU climate policy. And it must insist again and again that it is for policymakers to introduce measures that will create a business case for CCS investment.

### Objective 1 - Media Profile

To influence policymakers we need to raise both public and political awareness of CCS. This will require a pro-active media communications programme. It will highlight the positive developments taking place around the world, suggesting that Europe is losing out. It will vigorously rebut claims that CCS is unproven, unsafe or too costly. It will emphasise the importance of the technology to reduce emissions from energy intensive industries and industrial processes.

### Objective 2 - Political Engagement

CCS has too often been the forgotten partner in discussions about climate policy. Commission officials give their views at forums in Brussels several times each week and rarely face challenge on the issue. A continued softly-softly approach is insufficient; if CCS is to feature in future strategy then it has to become part of the debate. Vigorous interventions are required to make the case for deployment of the technology, the need for measures to promote investment, and the inadequacy of approaches that do not recognise its crucial importance.

Preparation of the Mid-Century Climate Strategy will provide the focus for our attention. It is likely that policy ideas will be contributed by other CCS supportive bodies. The task of our campaign group will be encourage the Commission to adopt them by raising awareness of the need for CCS and making this a live issue on the political agenda.

### Objective 3 - Co-ordination and Concerted Effort

Although CCS advocacy in Brussels and in most national capitals is insufficient there is no great shortage of potentially vocal supporters of the technology. In addition to the specific CCS-promotion bodies they include business leaders, trade unions, city mayors, NGOs, many hundreds of academics, and some additional politicians. For want of organisation this resource is hardly being used at present.

The new campaign body should take the initiative to harness this support in order to secure positive endorsements for CCS through the media and directly to influence policy makers. Working with ZEP, Bellona, CCSA and GCCSI and the research bodies, all of which share the objective of securing CCS deployment and have complementary roles, it should seek to identify opportunities where a concerted approach could influence the shaping of policy instruments, and thereafter work to bring this to realisation.

### Scope & Longevity

Urgency is the word that shapes our thinking. Action is needed now, and delay may make success impossible.

Our primary task will be to influence the shape of climate policy as determined in Brussels, and perhaps over a relatively short period of one or two years. Most of the work will take place close to the EU institutions, although given the leadership on CCS being shown by the Dutch government we can envisage a role for the campaign group in the Netherlands.

## More information

Chris Davies, a former British MP and CCS rapporteur at the European Parliament has offered to provide services on a temporary basis and pro bono while the group is brought into being.

**CCS@ccscampaigngroup.eu**

# Algae and BECCS to produce food, electricity and reduce CO2

**Scientists from Cornell, Duke University, and the University of Hawaii at Hilo are using algae, eucalyptus and bioenergy with carbon capture and storage (BECCS) to help power and provide food protein to large regions of the world – and simultaneously remove carbon dioxide from Earth's atmosphere.**

The paper evaluated the sustainability of integrating algae production with bioenergy CCS (called ABECCS). The motivation was to devise an affordable system that removes CO2 from the atmosphere without negatively impacting food security.

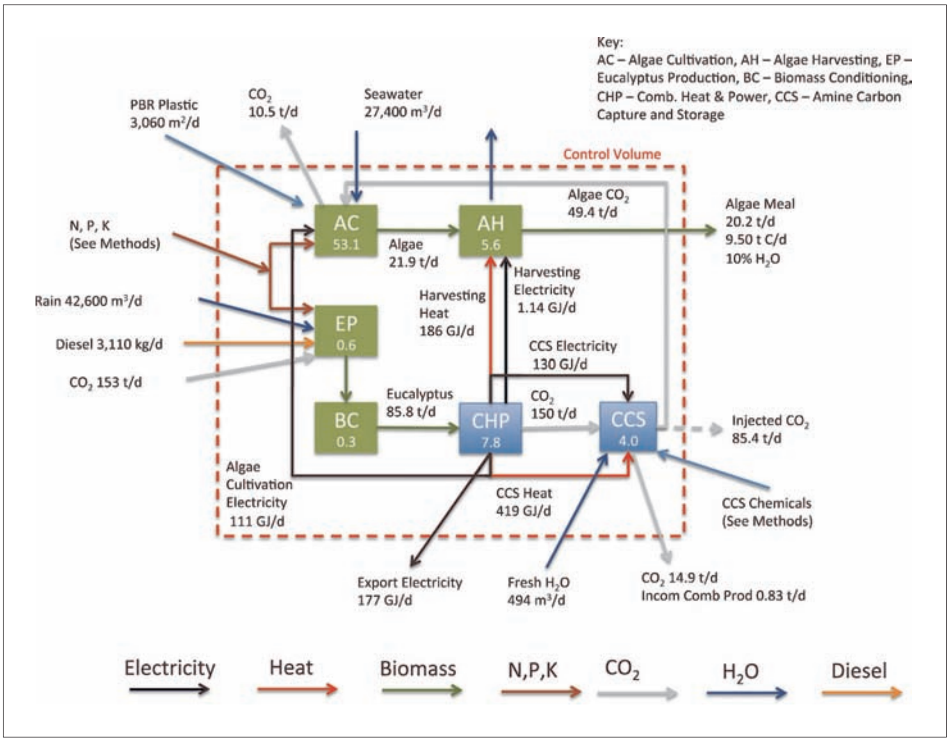
In the ABECCS system, soy cropland is replaced by eucalyptus forests used for BECCS that provides marine algae with CO2, heat, and electricity.

The system is economically viable when receiving $600/t of algae and $278/t of CO2 sequestered. With favorable economic conditions, ABECCS could contribute to the reduction of CO2 in the atmosphere in a sustainable way.

"Algae may be the key to unlocking an important negative-emissions technology to combat climate change," said Charles Greene, Cornell professor of Earth and Atmospheric Sciences and a co-author of the new research reported in Earth's Future, published March 24 by the American Geophysical Union.

"Combining two technologies – BECCS and microalgae production – may seem like an odd couple, but it could provide enough scientific synergy to help solve world hunger and at the same time reduce the level of greenhouse gases that are changing our climate system," Greene said. Based on an idea first conceptualized by co-author Ian Archibald of Cinglas Ltd., Chester, England, the scientists call the new integrated system ABECCS, or algae bioenergy with carbon capture and storage.

The ABECCS system can act as a carbon dioxide sink while also generating food and electricity. For example, a 7,000-acre ABECCS facility can yield as much protein as soybeans produced on the same land footprint, while simultaneously generating 17 million kilowatt hours of electricity and sequestering 30,000 tons of carbon dioxide per year.




*Process flow diagram for the integrated algae-and-forestry bioenergy carbon capture and storage (ABECCS) facility. Capital costs for each component are shown beneath the component label in millions of dollars. The overall facility includes 2800 ha (6920 ac), which is 96% eucalyptus forest and 4% algae production*

The ABECCS system's economic viability depends on the value of the nutritional products being produced and the price of carbon. Even without a price on carbon, microalgae production – in a fish-farming, aquacultural sense – is commercially viable today if the algae are priced as a fishmeal replacement in aquafeeds.

"In the future, as the price of carbon increases, ABECCS has the potential to reduce carbon dioxide in the atmosphere in an environmentally sustainable and profitable way," said Greene, who is a fellow at Cornell's Atkinson Center for a Sustainable Future.

In addition to Greene and Archibald, the research, "Integrating Algae with Bioenergy Carbon Capture and Storage (ABECCS) Increases Sustainability," was led by Colin M. Beal, University of Hawaii at Hilo. The co-authors were Mark E. Huntley, University of Hawaii at Hilo and Cornell visiting scholar, biological and environmental engineering; and Zackary Johnson of Duke University.

Funding for the research was provided by the U.S. Department of Energy.

## More information

**www.atkinson.cornell.edu**

# Cement technology roadmap plots path to cutting CO2 emissions 24% by 2050

**A combination of technology and policy solutions could provide a pathway to reducing direct carbon dioxide emissions from the cement industry according to the IEA and Cement Sustainability Initiative.**

The technology roadmap, called Low-Carbon Transition in the Cement Industry, updates the first global sectoral roadmap produced in 2009. It aims to identify and develop international collaborative efforts and provide evidence for public and private sector decision-makers to move towards a more sustainable cement sector that can contribute to long-term climate goals.

The cement sector is the third-largest industrial energy consumer in the world, responsible for 7% of industrial energy use, and the second industrial emitter of carbon dioxide, with about 7% of global emissions. Cement is the key ingredient of concrete – which is used to build homes, schools, hospitals and infrastructure, all of which are important for quality of life, social and economic wellbeing.

As global population rises and urbanization grows, global cement production is set to increase between 12 to 23% by 2050.

Despite increasing efficiencies, direct carbon emissions from the cement industry are expected to rise by 4% globally by 2050 under the IEA Reference Technology Scenario (RTS), a base case scenario that takes into account existing energy and climate commitments under the Paris Agreement.

Realising the IEA's more ambitious 2°C Scenario (2DS) by 2050, which seeks to limit average global temperature increases to 2°C, implies significantly greater efforts to reduce emissions from cement makers.

The low-carbon transition of the cement industry can only be reached with a supportive regulatory framework as well as effective and sustained investments. Meeting the RTS already requires additional cumulative investments compared to the status quo. Achieving the transformation described by the 2DS could mean up to a doubling of these investments compared to the RTS.

Governments, in collaboration with industry, can play a determinant role in developing policy and regulatory mechanisms that unlock the private finance necessary for such a boost in investment.

As a flagship sectoral project of the World Business Council for Sustainable Development (WBCSD), the CSI is a global effort currently gathering 24 major cement producers having operations in more than 100 countries and who have integrated sustainable development into their business strategies and operations.

"The cement industry is a major part of the global economy, but also an important source of global energy demand and carbon emissions. It is therefore essential that policymakers and industry work together to ensure best-practices are adopted that put the industry on a long-term sustainable path that is compatible with our long-term climate goals," said Dr. Fatih Birol, the IEA's Executive Director.

Mr. Philippe Fonta, Managing Director, CSI of WBCSD added, "The CSI is happy and proud to have developed this roadmap update in partnership with the IEA. The first exercise carried out in 2009 had demonstrated its added value to help the sector identify solutions and enablers to reduce its CO2 emissions and it was essential to adjust this projection with the latest robust emissions data from the CSI's Getting The Numbers right (GNR) database and the potential of latest technologies developed by the European Cement Research Academy (ECRA)."

The roadmap uses a bottom-up approach to explore a possible transition pathway based on least-cost technology analysis for the cement industry to reduce its direct CO2 emissions in line with the IEA's 2DS. Reaching this goal would require a combination of technology solutions, supportive policy, public-private collaboration, financing mechanisms and social acceptance.

Improving energy efficiency and switching to alternative fuels, in combination with reducing the clinker content in cement and deploying emerging and innovative technologies like carbon capture and the use of alternative binding materials are the main carbon-mitigation methods available in cement manufacturing.

Further emissions savings can be achieved by taking into account the overall life cycle of cement, concrete and the built environment. This can include optimising the use of concrete in construction by maximising design life of buildings and infrastructures, encouraging reuse and recycling, reducing waste and benefiting from concrete's properties to minimise energy needs for heating and cooling of buildings.

The roadmap outlines policy priorities and regulatory recommendations, discusses investment stimulating mechanisms and describes technical challenges with regard to research, development and demonstration

### More information

**www.iea.org**

**www.wbcsdcement.org**

# Projects and policy news

## Carbon XPRIZE announces ten finalists

**carbon.xprize.org**

**The 10 finalists, each taking home an equal share of a $5 million milestone prize, will demonstrate CO2 conversion in real world conditions.**

The four-and-a-half-year $20M NRG COSIA Carbon XPRIZE challenges teams to transform the way the world addresses carbon dioxide (CO2) emissions through breakthrough circular carbon technologies that convert carbon dioxide emissions from power plants into valuable products.

The 10 finalists, each taking home an equal share of a $5 million milestone prize, were revealed today at Bloomberg New Energy Finance's Future of Energy Summit in New York City.

Ranging from carbon capture entrepreneurs and start-ups to academic institutions and companies that have been tackling the challenge for more than a decade, the finalists hail from five countries and have already demonstrated conversion of CO2 into a wide variety of products, such as enhanced concrete, liquid fuels, plastics and carbon fiber.

The universe of potential CO2-based products crosses a variety of energy sectors, industrial processes and consumer products. Each finalist team passed a first round evaluation based on the amount of CO2 converted into products, as well as the economic value, market size and CO2 uptake potential of those products.

"These teams are showing us amazing examples of carbon conversion and literally reimagining carbon. The diversity of technologies on display is an inspiring vision of a new carbon economy," said Dr. Marcius Extavour, XPRIZE senior director of Energy and Resources and prize lead.

"We are trying to reduce CO2 emissions by converting them into useful materials, and do so in an economically sustainable way."

The NRG COSIA Carbon XPRIZE finalists were chosen from a field of 27 semifinalists by an independent judging panel of eight international energy, sustainability and CO2 experts. The competition is divided into two parallel tracks with five teams competing in each:

• The Wyoming Track includes five teams that will demonstrate conversion of CO2 emissions at a coal-fired power plant in Gillette, WY:

• Breathe (Bangalore, India) – Led by Dr. Sebastian Peter, the team is producing methanol, a common fuel and petrochemical feedstock, using a novel catalyst.

• C4X (Suzhou, China) – Led by Dr. Wayne Song and Dr. Yuehui Li, the team is producing chemicals and bio-composite foamed plastics.

• Carbon Capture Machine (Aberdeen, Scotland) – Led by Dr. Mohammed Imbabi, the team is producing solid carbonates with applications to building materials.

• CarbonCure (Dartmouth, Canada) – Led by Jennifer Wagner, the team is producing stronger, greener concrete.

• Carbon Upcycling UCLA (Los Angeles, CA, USA) – Led by Dr. Gaurav Sant, the team is producing building materials that absorb CO2 during the production process to replace concrete.

• The Alberta Track includes five teams that will demonstrate conversion of CO2 emissions at a natural gas-fired power plant in Alberta, Canada:

• C2CNT (Ashburn, VA, USA) – Led by Dr. Stuart Licht, the team is producing carbon nanotubes.

• Carbicrete (Montreal, Canada) – Led by Dr. Mehrdad Mahoutian, the team is producing cement-free, carbon-negative concrete that uses waste from steel production as an alternative to traditional cement.

• Carbon Upcycling Technologies (Calgary, Canada) – Led by Apoorv Sinha, the team is producing enhanced graphitic nanoparticles and graphene derivatives with applications in polymers, concrete, epoxies, batteries and pharmaceuticals.

• CERT (Toronto, Canada) – Led by Dr. Alex Ip of the Sargent Group at the University of Toronto, the team is producing building blocks of industrial chemicals.

• Newlight (Huntington Beach, CA, USA) – Led by Mark Herrema, the team uses biological systems to produce bioplastics.

To win a place in the finals, the semifinalist teams had to demonstrate their technologies at pilot scale at a location of their choosing. Over the course of a 10-month period, semifinalist teams were challenged to meet minimum technical requirements and were first audited by independent verification partner Southern Research.

Teams were then evaluated by the judges based on how much CO2 the team converted into products; the economic value, market size, and CO2 uptake potential of those products; the overall CO2 footprint of their process; as well as energy efficiency, materials use, land use, and water use.

In the finals, teams must demonstrate at a scale that is at least 10 times greater than the semifinals requirements at one of two purpose-built industrial test sites. Teams competing in the Wyoming track will test their technologies at the Wyoming Integrated Test Center (ITC), a cutting-edge carbon research facility in Gillette, WY, USA, co-located with the Dry Fork Station coal power plant.

Teams competing in the Alberta track will test their technologies at the Alberta Carbon Conversion Technology Centre, a new carbon conversion research hub co-located with the Shepard Energy Centre natural gas power plant in Calgary, Alberta, Canada.

"We're excited to support these teams as they scale up and start demonstrating under realworld conditions at the industrial test centers. This is the final, most ambitious stage of this prize competition," added Extavour.

The NRG COSIA Carbon XPRIZE is a part of XPRIZE's growing portfolio of Energy and Resources prizes and long-term vision for accelerating revolutionary energy technologies to help move the world towards a clean, abundant energy future.

## NETL releases Carbon Capture Simulation Toolset as open source software

**www.acceleratecarboncapture.org**

**The CCSI Toolset is a suite of computational tools and models designed to help maximize learning and reduce cost and risk during the scale-up process for carbon capture technologies.**

The Carbon Capture Simulation Initiative (CCSI), led by the Office of Fossil Energy's (FE) National Energy Technology Laboratory (NETL), has released the CCSI Toolset as open source software.

The release makes the toolset code available for researchers in industry, government, and academia to freely use, modify, and customize in support of the development of carbon capture technologies and other related technologies. The toolset is hosted on GitHub.

Since the release of CCSI's first toolset in 2012, the initiative exceeded goals, and earned an R&D 100 Award – an "Oscar of Innovation" – as one of the top 100 technology products of 2016. The major capabilities of the CCSI Toolset include:

Rapid Computational Screening: Enables the comprehensive screening and evaluation of promising concepts at all scales (molecular through system-level) with a full understanding of underlying uncertainty and its spread throughout multi-scale analyses.

Accelerated Design & Evaluation: Reduces the time needed to design and troubleshoot new devices and processes by using optimization techniques that focus technology development within the best overall system context. This effort is supported with detailed, validated models to better understand and improve the performance of complex systems. These models also help to maximize learning during each stage of the development process from laboratory to pilot to demonstration to commercialization.

Risk Management Support: Supports quantitative predictions of the performance ranges of devices and processes during scale-up. Uncertainty Quantification (UQ) is based on fundamental, rigorously validated simulations that consider model and parameter uncertainty. UQ also identifies which data is the most critical to obtain and helps determine how best to conduct testing to maximize the information that is obtained. UQ evaluates the risk and utility assessment in decision-making (which will be unique to each facility) to more accurately understand the impact of uncertainties to economic, environmental, and other planning decisions

## SaskPower CCS surpasses 2 million tonnes

**www.saskpower.com**

**Since operations began in October 2014, the carbon capture and storage (CCS) process at SaskPower's Boundary Dam Power Station has prevented a total of more than two million tonnes of carbon dioxide from entering the atmosphere.**

"With this milestone, the people of Saskatchewan can be proud that we are making a difference in a concrete way," said Minister Responsible for SaskPower Dustin Duncan. "The United Nations has said that CCS is essential to addressing climate change, and Saskatchewan is a global leader. It's a commitment to environmental sustainability that we are making to future generations."

"It's been an incredible opportunity to explore this groundbreaking technology as part of our power generating fleet," said SaskPower President and CEO Mike Marsh. "BD3 continues to provide electricity to more than 100,000 of our customers. What's more, it's doing so with coal, and in a way that makes it one of the cleanest-burning fossil fuel units on Earth."

The Boundary Dam CCS project in Estevan, Saskatchewan, is one of many initiatives the corporation is pursuing to keep up with the ever-growing demand for power in Saskatchewan. CCS is part of the company's long-term strategy to keep growing with demand, while meeting environmental regulations and reducing the company's carbon footprint. The strategy will reduce SaskPower's greenhouse gas emissions by 40% from 2005 levels, by 2030.

## Federal Funding to Expand UK CAER Carbon Capture Research

**www.uky.edu**

**The University of Kentucky Center for Applied Energy Research (CAER) was one of nine organizations selected to receive Phase I funding of a three-phase project as part of the U.S. Department of Energy's (DOE) Fossil Fuel Large-Scale Pilot program.**

UK CAER will receive over $940,000 from DOE's Office of Fossil Energy and the National Energy Technology Laboratory (NETL) to advance its carbon dioxide capture research and development.

According to principal investigator Kunlei Liu, this Phase I funding will allow UK CAER to advance its four-pronged CO2 capture system to a 10 megawatt scale. UK CAER's Power Generation Research Group is a global leader in building, developing and demonstrating post-combustion carbon capture systems. In fact, UK CAER's current 0.7 megawatt small pilot CO2 capture facility that operates at Kentucky Utilities' E.W. Brown Generating Station in Burgin, Kentucky, has led to scientific and engineering breakthroughs in the field.

This new federal funding will allow UK CAER to advance that research by nearly 10 times, leaving the technology only one step away from commercialization.

"This project will allow us to leverage the unique carbon dioxide capture expertise we have developed at UK CAER over the past decade to tackle a new and exciting next step in its implementation," said Heather Nikolic, a principal research engineer at UK CAER.

The center's post-combustion system features modular equipment and free-standing columns with built-in advanced controls to continually minimize the CO2 capture energy penalty while responding to a dynamic external demand. The new system will combine several facets to simultaneously address capital cost, energy consumption, load change and environmental impact.

"I often remind our team that this project would not be possible without the many partners who have assisted us and collaborated with our researchers over the years," said Liu, associate director for research at UK CAER and associate professor in UK's Department of Mechanical Engineering. "This project is another great example of that. In addition to our colleagues at DOE, we will be partnering with several institutions and industry partners to ensure success."

Project collaborators include LG&E and Kentucky Utilities, Carbon Clean Solutions, University of Texas at Austin, Membrane Technology Research, Electric Power Research Institute, Huaneng Clean Energy Research Institute, Koch Modular Process Systems, Worley Parsons and Smith Management Group.

# Capture and utilisation news

## SoCalGas and Opus 12 develop technology to convert CO2 to methane

**www.socalgas.com**

**www.opus-12.com**

**A new electrolyzer technology can convert the unwanted carbon dioxide in raw biogas directly to pipeline quality natural gas using renewable electricity, simplifying the process of storing surplus renewable electricity as renewable natural gas.**

The companies have successfully demonstrated the new process to convert the carbon dioxide in raw biogas to methane in a single electrochemical step, a critical improvement in the science of upgrading biogas to pipeline quality natural gas, and a simpler method of converting excess renewable electricity into storable natural gas.

Opus 12, a clean-energy startup incubated in the prestigious Cyclotron Road program at Lawrence Berkeley National Lab, used a new type of Polymer Electrolyte Membrane (PEM) electrolyzer to convert carbon dioxide to methane, showing that instead of wasting the carbon dioxide in raw biogas, it can be converted to methane using renewable electricity.

The research is part of SoCalGas' development of technologies known as power-to-gas (P2G), a cutting-edge method of storing excess renewable energy. Because gases can be easily stored for long periods of time using existing infrastructure, power-to-gas technology has two distinct advantages over storing renewable electricity in batteries.

The nine-month study was funded by SoCalGas along with two start-up-funding organizations, the Rocket Fund of Caltech's FLOW program and Elemental Excelerator.

"Southern California has ideal conditions for this type of solution, with significant biogas resources and high penetration of renewable electricity," said Nicholas Flanders, Opus 12's chief executive officer. "SoCalGas has identified this regional advantage, and with their scale and expertise in P2G and biogas, the company has been the ideal partner for this project."

Raw biogas is mostly methane, but also contains about 30 to 40 percent carbon dioxide, which is typically vented to atmosphere in a biogas production facility. While other power-to-gas systems convert water into hydrogen and oxygen using renewable electricity, Opus 12's method would likely be implemented adjacent to biogas production so it can make use of a greenhouse gas that would otherwise contribute to climate change.

This feasibility study was the first phase of research that will also explore new catalysts, modifying the catalyst layer formulation, and other ways to enhance the system's methane conversion performance.

## Total joins CO2 Solutions' Valorisation Carbone Québec project

**www.co2solutions.com**

**Total has joined the Valorisation Carbone Québec ("VCQ") Project as its first industrial partner.**

The industrial partner category is one of five partnership types in the VCQ Project along with the founding, supplier, utilization technology and end use. Industrial partners make financial contributions to the VCQ budget in exchange for project data. The amount of these contributions is undisclosed for competitive reasons.

To date, eleven different organizations have confirmed their participation as partners in one or the other categories of the VCQ Project making it a truly broad effort to address CO2 mitigation through carbon capture and utilization.

The objective of the VCQ Project is to develop and demonstrate commercially viable end-to-end solutions to capture and utilize CO2 in various applications while at the same time reducing greenhouse gas (GHG) emissions.

"CO2 Solutions is excited to welcome Total into the VCQ Project," stated Evan Price, President and Chief Executive Officer of CO2 Solutions. "The strong interest shown by Total confirms the importance and pertinence of the VCQ project to address industry's desire to reduce their carbon footprint while creating economic opportunities through the full industrial carbon cycle."

"This is a further example of how the VCQ Project, the world's most comprehensive and ambitious CO2 capture and utilization project, continues to draw strong and committed partners. We look forward to attracting additional industrial partners to the project in the near future."

## CleanO2 carbon capture unit installed at LUSH Cosmetics headquarters in Vancouver

**www.fortisbc.com**

**The pilot program uses first-in-the-world carbon capture technology that takes the extra heat and emissions released from commercial-sized boilers and furnaces and turns it into something useful.**

The unit captures carbon, which would otherwise be vented into the atmosphere, and turns it into sodium carbonate (soda ash), a versatile mineral used to make pharmaceuticals and manufacture glass as well as soap. In addition, the unit enables energy savings by taking the extra energy produced and redistributing it for heating needs around the building.

"This innovative technology helps our customers manage their energy usage and aligns with our province's goals for carbon reduction," said Jason Wolfe, director, energy solutions at FortisBC. "Our commercial customers are receiving the benefit of using natural gas and through this technology they are reducing their emissions and also being more efficient in their energy use."

The carbon capture process can allow customers to reduce up to 13 tonnes of carbon emissions per unit per year. The technology also decreases energy consumption by up to 10 per cent depending on the boiler or furnace size.

FortisBC develops pilot programs to collaborate with innovative technology and companies that align with its objectives in energy conservation, while servicing customer needs.

The University of the Fraser Valley (UFV) in Abbotsford is scheduled as the next install as part of FortisBC's carbon capture pilot program. Other organizations signed on to the carbon capture pilot program include Cadillac Fairview Richmond Centre and the Blue Horizon Hotel.

## Aberdeen-based spinoff pioneering carbon conversion reaches XPRIZE finals

**www.abdn.ac.uk/ccm-carbon-xprize**

Carbon Capture Machine (UK) Ltd, a University of Aberdeen spin-out company, is the sole European team to reach the finals of the NRG COSIA Carbon XPRIZE, a major international competition that incentivises the development of breakthrough carbon conversion technologies to reduce global CO2 emissions.

The 10 finalists in the NRG COSIA Carbon XPRIZE split an equal share of a USD $5 million milestone prize, as part of an overall $20 million prize purse as teams compete to develop technologies that convert CO2 into valuable products.

The Carbon Capture Machine team was formed at the University in 2016, and comprises a multi-disciplinary group of academics.

By reaching the final 10 of the competition - from an initial field of 47 international competitors - the team receives funding that will help them further develop pioneering technology capable of capturing CO2 from large industrial emission sources, and turning it into valuable carbon-negative industry feedstocks and building materials for use in construction projects.

Dr Mohammed Imbabi from the University's School of Engineering and Emeritus Professor Fred Glasser, Chair in Chemistry conceived and developed the technology over several years. Together with Professor Zoe Morrison, formerly of the University of Aberdeen Business School, and others, they form the team competing in the Carbon XPRIZE finals.

Dr Imbabi hailed the team's achievement as a major milestone in their journey to perfect a technology that can significantly reduce global CO2 emissions and profitably provide sustainable materials for use in construction and other applications worldwide.

Dr Mohammed Imbabi said, "By de-carbonising at source and converting CO2 into sustainable products and materials we can have a major impact in reducing global CO2 levels."

"As a team we firmly believe that what we are developing here in Aberdeen has the potential to be a game-changer in carbon capture and utilisation, and our progression to the final of the Carbon XPRIZE is testament to this belief. We are grateful to have received backing from the University in supporting the research that underpins our technology, and in helping create a spin-out company, CCM (UK) Ltd, that is poised to commercialise the technology globally."

"Another major factor in our success continues to be the multi-disciplinary structure of our team, which comprises experts from engineering, chemistry, business, economics and social sciences, all of whom have worked tirelessly to help us reach this stage."

Dr Imbabi explained that the team's initial aim in developing the technology was to deploy it for use in large-scale industrial settings, de-carbonising at source from power stations, factories, and other major CO2 sources.

He added, "In the future, we envisage that it can also be scaled down and miniaturised for use across a wide range of emission sources, from different transport platforms to people's homes. By de-carbonising at source and converting CO2 into sustainable products and materials we can have a major impact in reducing global CO2 levels."

# Transport and storage news

## DOE announces $9m for CO2 storage with EOR projects

**netl.doe.gov**

Up to $9 million in federal funding for cost-shared research and development are available for "Developing Technologies for Advancement of Associated Geologic Storage in Basinal Geo-Laboratories."

The National Energy Technology Laboratory (NETL) will manage the selected projects. These projects will address technical research needs and key challenges in advancing associated storage within DOE's Carbon Storage Program. Projects will advance technologies— through computational, analytical, bench-scale, and field laboratory studies — in storage complexes in diverse geologic settings.

Associated geologic storage refers to the storage of carbon dioxide along with enhanced oil recovery (EOR) and/or enhanced gas recovery operations. It also includes saline storage where a project in a storage complex involves stacked saline and oil/gas reservoirs. Carbon dioxide storage, in association with EOR, offers a means to help offset capture, transportation, and storage costs—thereby accelerating the implementation of geologic storage.

A new, potentially large opportunity for geologic storage is associated with residual oil zones and tight oil formations. This FOA focuses on R&D that is specific to various basins representing diverse geologic settings throughout the United States (e.g., Appalachian, Williston, Illinois, Michigan, Permian, and Gulf Coast Region) where there are opportunities for associated storage.

# $2.5M grant funds real-time monitoring of underground carbon

**Researchers from Penn State, Lawrence Berkeley National Laboratory, and the University of Texas at Austin are partnering on a new $2.5-million project to illuminate what happens to carbon dioxide during underground sequestration.**

**www.psu.edu**

The team will use seismic data collected through a novel real-time monitoring system to track the spread of carbon dioxide underground. The four-year project is being funded by the U.S. Department of Energy.

The main goal of carbon sequestration is to reduce carbon dioxide emissions into the atmosphere. Sequestration involves injecting carbon dioxide into a contained space for long-term storage. The project is investigating underground sequestration in a reservoir, such as a saltwater aquifer or a mineral deposit. At high pressure, carbon dioxide will fill up pore space in rocks or dissolve into saltwater, but researchers still do not have a clear picture of where the carbon dioxide migrates in a reservoir and whether it has a chance to leak out of the reservoir or injection well.

To address this, Tom Daley, staff scientist, Lawrence Berkeley National Laboratory, and project collaborator, developed real-time monitoring equipment in 2007 that is installed during the construction of an injection well. Several times a second the equipment emits an energy pulse that vibrates the material it passes through. By analyzing the vibration that echoes back to the monitoring device, researchers can create a relatively clear picture of the subsurface. However, the presence of carbon dioxide affects how seismic waves travel underground, and nobody had developed a reliable way to use seismic data to track the volume of carbon dioxide until now.

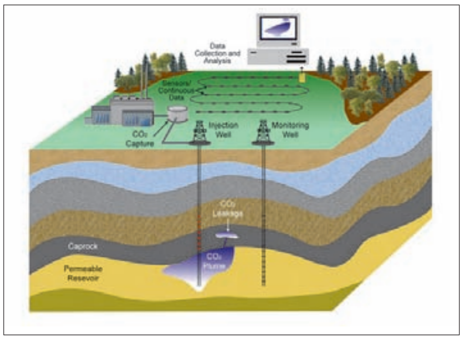
Tieyuan Zhu, assistant professor of geophysics, and associate, Institute of Natural Gas Research, Penn State, recently discovered that the amount of seismic-wave energy loss is highly sensitive to the saturation of carbon dioxide. He found that in one sequestration site in Frio, Texas, it was possible to interpret these data to understand the saturation of carbon dioxide in the reservoir. He is combining this knowledge with a state-of-the-art seismic analysis technique, known as full waveform inversion, to develop a tracking algorithm for use with the DOE's real-time monitoring system.

"This new technology that we're developing is something we couldn't even imagine five or 10 years ago," said Zhu, principal investigator on the project. "Our goal is to develop new data-processing tools that will enable the DOE's real-time monitoring system to accurately map the underground carbon dioxide."

Tracking the flow and concentration of carbon dioxide underground is a complicated task. The team will start with an initial estimated picture of the subsurface geology, which is the specialty of co-principal investigator Sanjay Srinivasan, professor and head of the John and Willie Leone Family Department of Energy and Mineral Engineering.

"When you inject carbon dioxide into the ground, there's the potential for it to leak out or go places you don't want it to go," said co-principal investigator Eugene Morgan, assistant professor of petroleum and natural gas engineering, Penn State. "This project will also help us identify potential leaks while also making sure that we're maximizing storage potential."

Using the seismic data collected during injection, the researchers will continually refine the picture of what's happening underground as carbon dioxide first spreads and then increases in concentration in different rock features. They will pair together a variety of computer models implemented in the petroleum and natural gas industry as well as those used to measure earthquakes. Just like in hurricane prediction, the team will use the continual addition of new data to reduce the uncertainty of their picture of underground carbon dioxide storage. Through this work, the team is transforming their initial data into a 3-D picture of the reservoir and carbon dioxide saturation that is updated in near-real-time.




*After carbon dioxide is injected underground, a network of real-time sensors, located in the injection well, adjacent boreholes, and above ground, emit pulses of energy and capture the returning seismic data. Image: Penn State College of Earth and Mineral Sciences*

The majority of this work will be processed on supercomputers managed by the Penn State Institute for CyberScience.

In addition to analyzing data from the new monitoring equipment, the team will conduct a small-scale laboratory experiment to validate their tools at the Lawrence Berkeley National Laboratory.

"We are at the cusp of implementing some large-scale carbon-sequestration projects, but what is stopping federal agencies from moving forward is an uncertainty of where the injected carbon dioxide goes," said Srinivasan. "Our project will go a long way toward developing technologies to not only figure out where the carbon dioxide is going but also to identify potential issues that might arise during the process so that they can be mitigated."

Jonathan Ajo-Franklin, staff scientist and head of the geophysics department, Lawrence Berkeley National Laboratory, is a co-principal investigator on the project. Alexander Sun, senior research scientist, Bureau of Economic Geology, University of Texas at Austin, is also involved in the project.

# New research gives precise look at underground CO2 abatement process

**New research by scientists at Washington University in St. Louis sheds light on what happens underground when CO2 is injected into basalt.**

Environmental scientists trying to mitigate the effects of CO2 have experimented with injecting it deep underground, where it becomes trapped. These trials have mainly taken place in sandstone aquifers, however, the injected CO2 primarily remains present as a bubble that can return to the surface if is there are fracture in the capping formation.

A different approach using basalt flows as injection sites, chiefly at the CarbFix site in Iceland and in Washington state, has yielded dramatic results. Metals in basalt have the ability to transform CO2 into a solid inert mineral in a matter of months. While the new method holds promise, the underground injections can be imprecise, difficult to track and measure.

Now, new research by scientists at Washington University in St. Louis sheds light on what happens underground when CO2 is injected into basalt, illustrating precisely how effective the volcanic rock could be as an abatement agent for CO2 emissions.

The research, led by Daniel Giammar, the Walter E. Browne Professor of Environmental Engineering in the School of Engineering & Applied Science, was conducted in collaboration with researchers at Pacific Northwest National Laboratory and Philip Skemer, associate professor of earth and planetary sciences in Arts & Sciences at Washington University.

"In a field site, you inject the carbon dioxide in, and it's a very open system," Giammar said. "You can't get a good constraint in terms of a capacity estimate. You know you made some carbonate from the CO2, but you don't really know how much. In the lab, we have well-defined boundaries."

To obtain a clearer, quantifiable look at carbon trapping rates in basalt, Giammar collected samples of the rock from Washington state, where researchers previously injected a thousand tons of CO2 gas deep underground into a basalt flow.

He placed the rocks in small reactors that resemble slow cookers to simulate underground conditions, and then injected CO2 to test the variables involved in the carbonization process.

"We reacted it at similar pressure and temperature conditions to what they had in the field, except we do all of ours in a small sealed vessel," Giammar said.

"So we know how much carbon dioxide went in and we know exactly where all of it went. We can look at the entire rock afterwards and see how much carbonate was formed in that rock. "

*Environmental scientists testing carbon dioxide abatement are using underground basalt flows to contain and convert the gas to an inert mineral. A new series of experiments conducted at Washington University give a new, precise look at the process. (Photo: Joe Angeles/Washington University)*

The lab kept the basalt in the pressurizers and followed up, using 3-D imaging to analyze their pore spaces at six weeks, 20 weeks and 40 weeks. They were able to watch moment to moment as the CO2 precipitated into mineral, the exact voids within the basalt it filled, and the precise spots in the rock where the carbonization process began.

Once all of the data were collected and analyzed, Giammar and his team predicted 47 kilograms of CO2 can be converted into mineral inside one cubic meter of basalt. This estimate can now be used as a baseline to scale up, quantifying how much CO2 can effectively be converted in entire areas of basalt flow.

"People have done surveys of available basalt flows," Giammar said. "This data will help us determine which ones could actually be receptive to having CO2 injected into them, and then also help us to determine capacity. It's big. It's years and years worth of U.S. CO2 emissions."

Giammar's lab is currently sharing its results with colleagues at the University of Michigan, who will assist in developing a computational model to further help researchers to look for a solid fix for CO2 abatement.

The Washington University researchers have also been invited to take part in the second phase of the U.S. Department of Energy's Carbon Storage Assurance Facility Enterprise, or CarbonSAFE, which investigates new technologies for CO2 abatement.

## More information

**www.wustl.edu**