Carbon Capture Journal

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Critical decarbonization technologies need 10x investment says WEF report

Innovative, early-stage technologies like hydrogen-based fuels, carbon capture and bioenergy are in urgent need of funding to scale globally and help organizations hit zero emission targets says a World Economic Forum report.

Experts from over 50 financial institutions, including banks, insurers, and asset managers, and the public sector, have come together to develop financing blueprints and policies to mobilize investment in these technologies.

To scale these technologies and take them to market, at least a tenfold increase in investment is needed, according to the "How to Finance Industry Net-Zero" report.

Released by the World Economic Forum and Oliver Wyman, the report outlines how to address the supply-and-demand-side gap and take these technologies to the next level.

Part of the Forum's Financing the Transition to a Net-Zero Future Initiative, the report focusses on how to steer capital to breakthrough technologies and drive a more sustainable future.

The report outlines three fundamental findings to close this supply-and-demand-side green investment gap:

• The innovative blending of capital supported by an enabling ecosystem is needed, where different sources of public and private capital are brought together in technology-specific financing blueprints. To do this effectively, mechanisms that activate collaboration among multiple stakeholders are necessary.

• Transformative business models are essential, where industry participants and capital providers work together to establish new contracts and ways of doing business to increase the probability of commercial success.

• Targeted public intervention is critical, focused on the design of incentive schemes rewarding early movers adopting innovative technological solutions and de-risking schemes to mitigate investment risks unique to these innovative solutions.

"The challenge ahead is significant, but not insurmountable," said Derek Baraldi, Head of Sustainable Finance and Investing, at the World Economic Forum. "If executed thoughtfully, the mobilization of finance to breakthrough technologies presents a tremendous investment opportunity. This study found that there is a real appetite from industry for thoughtful partnership and collaboration between private and public capital providers."

"Organisations have announced ambitious pledges to finance the transition to net-zero but the progress made to date is not enough," added Ted Moynihan, Managing Partner and Global Head of Industries, Oliver Wyman.

"There is a huge gap in financing of early-stage decarbonization technologies, which will be absolutely critical to achieving our targets from 2030 to 2050. With more research breakthroughs coming, we are now in a vital moment to accelerate the mobilization of capital towards decarbonization technologies in hard-to-abate industries."

While the transition will likely be complex, there is a real appetite from industry for thoughtful partnership and for collaboration between private and public capital providers. It is mission critical to capitalize upon this appetite immediately through meaningful, structural action.

By proposing an initial set of financing approaches and de-risking solutions, this report seeks to initiate an important discussion on how to rapidly accelerate the deployment of capital towards breakthrough technologies.

The report launched at the Mission Possible Partnership event Supercharging Industrial Decarbonisation. It brought together public and private sectors from shipping, aviation, and steel.

The Mission Possible Partnership will share learnings across these critical industrial sectors and present sector-specific blueprints for industrial decarbonisation.

Steel sector and technology overview

Steel is responsible for about 7% of GHG emissions,27 with emissions estimated to increase by 43% given likely production growth by 2050. Deploying zero-carbon primary production processes at scale is the only viable route to achieve net zero.

These production processes, however, require scaling and are still in the initial stages of commercial validation and deployment. In the meantime, CCS can support emissions reduction. This breakthrough technology has the potential to reduce over 80% of CO2 emissions and can be appended to various industrial processes. It is potentially easier to deploy than alternative decarbonization technologies, given that it can be retrofitted on existing production processes, requiring minimal changes to equipment and assets.

CCS' technology readiness level is approximately 7-8 (on a scale of 1 to 9) and is ready for market-wide deployment from a technological perspective, though it requires development of a carbon transport and storage infrastructure network, which is currently being developed.

CCS requires financing across its value chain (i.e. capture, transportation, storage infrastructure), increasing the risks across the project, since the transportation and storage infrastructures are still being established.

For non-recourse projects, the risks are significant, especially since the supply of CO2 to the CCS modules is key to the viability of business models of ring-fenced CCS entities.

More information

Download the full report at:

www.weforum.org

www.oliverwyman.com

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Front cover: In LEILAC Phase 1 a CO2 separation pilot plant was constructed at the HeidelbergCement plant in Lixhe, Belgium (pg. 18)

Back cover: The East Coast Cluster is one of two selected by the UK as a 'Track 1' cluster putting it on course for deployment by the mid-2020s (pg. 21)

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Leaders - Global Status 2021 and CCUS in Asia

Projects and policy

Capture and utilisation

Transport and storage

Global Status of CCS 2021: projects accelerating but vastly more required

The Global CCS Institute's flagship report finds that the CCS project pipeline is growing more robustly than ever but deployment needs to be rapidly accelerated enormously further.

"This year's Global Status of CCS Report reveals that just as the acceleration in climate action commitment is unprecedented, so too is the growth in the CCS facility and project catalogue," said Brad Page, Former CEO, Global CCS Institute, in the introduction to the report.

From 73 million tonnes a year (Mtpa) at the end of 2020, the capacity of projects in development grew to 111 Mtpa in September 2021 – a 48 per cent increase.

"In all the years that the Institute has been recording and publishing the data on CCS facilities and projects, never before has such a big single year increase in the project pipeline been recorded," he said. "This is the natural outworking of the commitments being made to address emissions and achieve NZE. It confirms the findings of modelling undertaken by a variety of different, independent agencies: CCS is a necessary element of the technology suite that must be deployed if the world is to achieve the Paris Objectives."

"As impressive as the past year's progress with accelerating the CCS project pipeline is, the stark reality is that enormously more CCS facilities are required – at least a 100-fold increase over the 27 in operation today – by 2050. Without this, the world is extremely unlikely to achieve the key targets in the Paris Agreement with the well documented serious consequences of such an outcome."

"Increasingly the focus for the application of CCS is in the industrial or 'difficult to decarbonise' sectors. For the most part CCS is the 'go-to' solution where electrification is not a viable solution, often when high heat or chemical reactions dependent on the presence of carbon are required. In other instances, CCS has very low cost and demonstrated mature technology strongly in its favour. And because these heavy industries often congregate together, CO2 networks have quickly become a significant element in CCS deployment."

"While we reported similarly in 2020, this year has seen significant strides taken in progressing many of these CCS network projects and new ones, like the Houston Ship Channel project, being announced. The world continues to employ fossil fuel-based electricity generation plants at enormous scale. While in some countries these are declining, in other parts of the world coal and gas fired power plants remain a central, and in some cases growing, part of electricity systems."

"While power generation did not feature significantly in our reports for some years, this changed in 2020 and further new projects have been announced that are included in this report. This is good news as there will be a large and increasingly urgent need to address power sector emissions in, for example, much of Asia where early retirement of relatively young coal and gas plants is unlikely. Technology deployment in developed nations will make for lower cost application elsewhere."

"We know based on reputable analysis, including from the IPCC, that carbon dioxide removal will be required to meet the Paris targets. We also know that nature-based solutions alone will not be enough. Bioenergy with CCS – BECCS – has long been understood to be an important element of this. It is also increasingly apparent that direct air capture will need to play a significant role."

"Pleasingly, the development and deployment of direct air capture of CO2 is gaining momentum, albeit off a small base. Significant capital investment in nascent direct air capture developers is being seen and substantial new projects are being progressed. The decreasing cost curve for direct air capture is notable and important."

"As I sign off from my final edition of the Global Status of CCS Report, I am hugely encouraged that CCS is now on a strong growth trajectory after enduring some very difficult years. Over the past decade I have seen CCS move from being falsely identified only as a coal fired power generation technology to being increasingly embraced as a vital element of meeting the climate challenge due to its versatility of application, demonstrated effectiveness and ability to deal with enormous volumes of emissions."

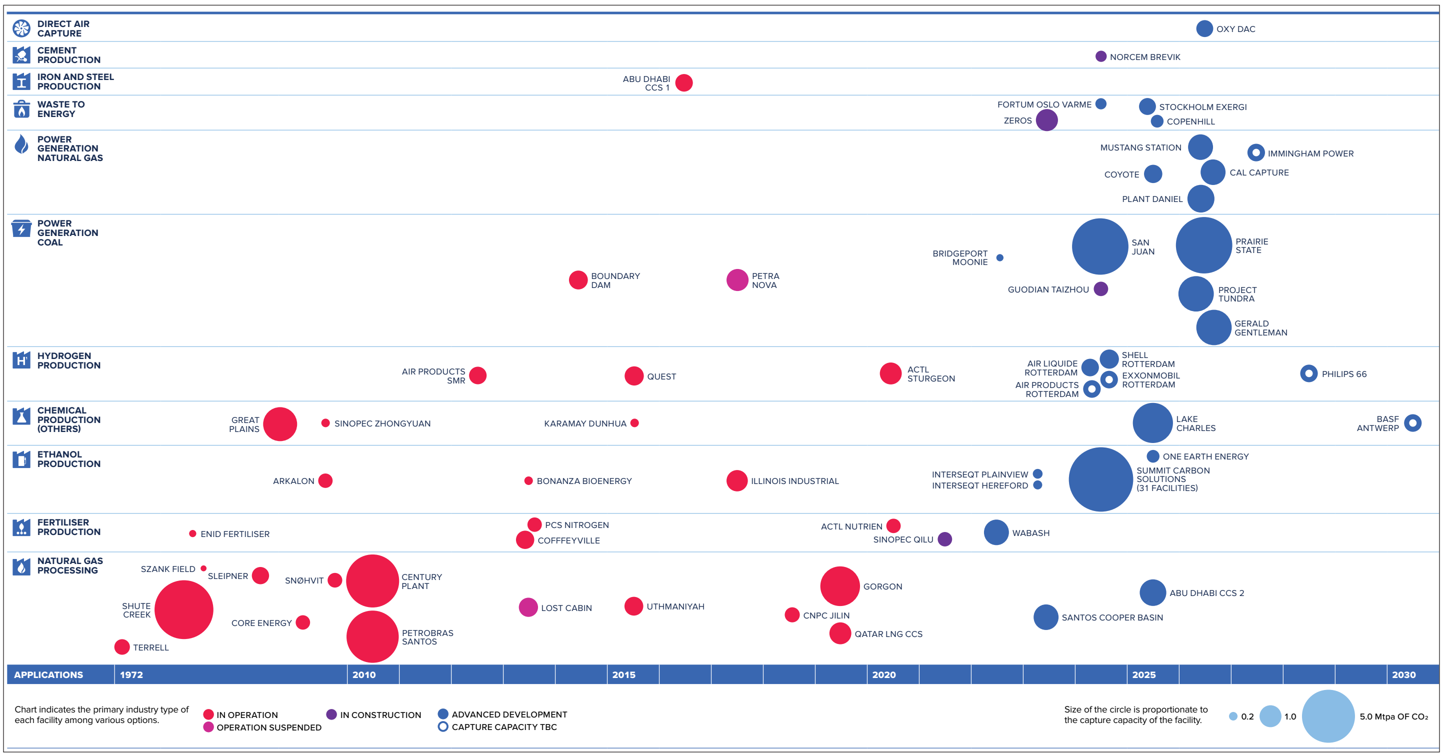
"Recently, its role in removing CO2 from the atmosphere has added yet another string to its bow. Time is not on anyone's side. We must press on with vigour in rapidly accelerating still further the deployment of CCS."

Net zero by 2050 requires strong action by 2030

Despite unprecedented growth in the CCS project pipeline for the last 12 months, there remains a massive gap between today's CCS fleet and what is required to reduce global anthropogenic emissions to net zero, says the report. Limiting global warming to 2°C requires installed CCS capacity to increase from around 40 Mtpa today to over 5,600 Mtpa by 2050. Between USD$655 billion and USD$1,280 billion in capital investment is needed to 2050.

This figure may appear daunting but investing around one trillion dollars over almost 30 years is well within the capacity of the private sector – in 2018, it invested approximately US$1.85 trillion in just the energy sector. In addition to enormous financial resources, the private sector has the expertise and experience to develop projects. In the face of rising expectations from stakeholders and shareholders to invest in assets that aid climate mitigation, the private sector is also actively seeking opportunities.

All that's needed is a business case. If we assume there is a business case for investment, and that capital is not a big constraint, the largest barrier to meeting climate targets is time. Rapid growth of supporting infrastructure is required by 2030 to bring more projects into the development pipeline and get



CCS projects by sector and scale (by CO2 capture capacity) over time (Source: Global Status of CCS 2021)

them operating by 2050. In many cases, supporting infrastructure is an investment prerequisite – not only for CCS but other essential parts of any net zero strategy.

For example, investing in new renewable power generation means more electricity transmission lines, while ramping up clean hydrogen production and use requires new storage, transportation and distribution infrastructure. Faster rates of CCS facility development demand additional CO2 transport and storage facilities.

North America's CO2 transport pipeline network is estimated to need to grow from around 8,000 km today to 43,000 km by 2050. This scale is definitely achievable, being only slightly larger than Australia's natural gas transmission network, which has over 39,000 km of pipelines.

Driving infrastructure development to support a net zero economy should be a priority of governments everywhere. There are many examples where their support or direct investment was required to de-risk and initiate industries, including road, rail, telecommunications, electricity generation and distribution, space exploitation and more recently, renewable energy. As these industries matured and became commercial, government intervention was replaced by increased private sector investment. Governments could similarly support the establishment of CO2 transport and storage networks to service industrial CCS hubs.

A CCS network requires geological storage for CO2. Identifying and characterising a storage resource requires tens to hundreds of millions of investment dollars. All funds are at risk as there is no guarantee of success. Unlike mineral or hydrocarbon exploration, exploring for pore space does not yet generally justify risking tens of millions of dollars. Government can assist by supporting the collection of geological data and making it available.

Today's CCS facilities benefited from geological data collected during oil or gas exploration and/or from government funded programs. Large infrastructure projects like CCS facilities or pipeline networks, usually take seven to 10 years from concept study through feasibility, to design, construction then operation.

There is no time to waste. Creating an enabling environment for investment in CCS facilities and other net zero aligned assets – particularly in supporting infrastructure – through both policy and funding, should be a high priority for governments between now and 2030.

CCS projects are becoming more diverse

As new projects are announced and developed, the range in the scale of facilities is becoming broader. Individual capture plants are larger, with facilities like Shell's Rotterdam hydrogen project developing in the megatonne range.

At the same time, networks like the US's Summit Carbon Solutions are making smaller capture viable – their smallest capture plant has a capacity of just 90,000 tonnes a year. Capacities this small would be difficult to justify without supporting network infrastructure.

The recently approved Norcem Brevik project, part of the Langskip network in Norway, has CCS expanding into a new sector – cement manufacturing. As a significant global emitter with limited decarbonisation options, the cement sector's use of CCS is an essential step towards net zero. The Norcem project is expected to provide valuable CCS learning and insights.

More information

www.globalccsinstitute.com

CCUS in China - value and opportunities for deployment

CCUS will be essential for China to achieve its target of carbon neutrality by 2060, providing up to 2.7Gt of emissions reductions annually by 2050, finds a report from the Oil and Gas Climate Initiative.

OGCI's report looks at the value and opportunities for deployment of carbon capture, use and storage as China works towards carbon neutrality by 2060.

This report is based on OGCI's analysis and engagement in China, working with member company CNPC and leading Chinese experts.

China currently has 16 large-scale CCUS projects in the pipeline, with one in operation and five scheduled for completion this year.

Key findings

• CCUS will be essential for China to achieve its target of carbon neutrality by 2060, providing between 1.5 Gt and 2.7 Gt of emissions reductions annually by 2050.

• In addition to climate benefits, CCUS will also create social and economic benefits, helping China to maintain economic growth, strengthen its market position in low carbon energy and secure energy supply.

• Deploying CCUS on this scale will require a range of new policies to commercialize CCS and help a CCUS industry to emerge. China can draw on early experience in other countries to define appropriate market incentives, subsidies and mandates.

• CCUS hubs, providing collective transport and storage infrastructure for carbon dioxide captured from different industrial and power sources, will facilitate China's CCUS scale up. CNPC's China Northwest hub, part of OGCI's hub initiative, aims to lead the way for other hubs to emerge.

• If China can accelerate CCUS deployment at the scale needed to achieve carbon neutrality, it would catalyze the global CCUS industry.

Getting to scale

Getting CCUS to scale is a huge task, however – both globally and in China. The International Energy Agency's latest scenario estimates that over 7 Gt of carbon dioxide will need to be captured by 2050 to achieve net zero, with most of that permanently stored. Currently, some 20 large-scale CCUS projects store around 45 Mt globally per year.

According to IEA's net zero scenario, from 2030 onwards, 10 heavy industrial plants need to be equipped with carbon capture technology every month in order to achieve the 2050 target.

In China that scale-up will need to be even faster. China is proposing to get from carbon peak to carbon neutrality in just 30 years – significantly shorter than in Europe and North America which have peak to neutrality time spans of about 70 and 50 years, respectively, according to Tsinghua University Low Carbon Economic Research Institute.

CCUS will be a crucial technology for China to rapidly reduce absolute emissions from its use of fossil fuels so that they peak before 2030. Such a scale-up would also directly enhance the future competitiveness of Chinese industry – supporting the low-carbon transformation of both the energy sector and high-emission industries. That would preserve and create jobs, stabilize and boost foreign trade, secure energy supply and bring economic value far greater than the the cost of supporting deployment.

If China can accelerate CCUS deployment in the power, steel, cement, chemicals, hydrogen and fertilizer sectors as needed to achieve carbon neutrality, it would catalyze the global CCUS industry – bringing down costs while demonstrating its potential, as happened with solar power.

Experience to date

China has completed 35 CCUS projects, but most are on a demonstration-scale and largely implemented by state-owned enterprises under the government's guidance, rather than as a commercial project.

One large-scale CCUS project is already in operation at CNPC's Jilin oilfield, five are due to start operation in 2021, and 10 are currently under consideration or in development, including China's first CCUS hub, part of OGCI's KickStarter initiative and three other CNPC-led hubs. Together, these projects have the capacity to capture and store over 19 million tonnes of carbon dioxide per year.

Led by large energy enterprises, these projects and pilots have provided valuable experience in the integrated design, construction and operation of CCUS. Carbon capture demonstration units are using a variety of capture technologies from pre-combustion, post-combustion and oxy-combustion of coal-fired power plants, post-combustion capture technologies for gas-fired power plants, and post-combustion exhaust capture technology for cement kilns.

Meanwhile, the first carbon capture technology testing platform in Asia was established at the China Resources Power Haifeng power plant in Guangdong province.

More information

Download the full report:
www.ogci.com

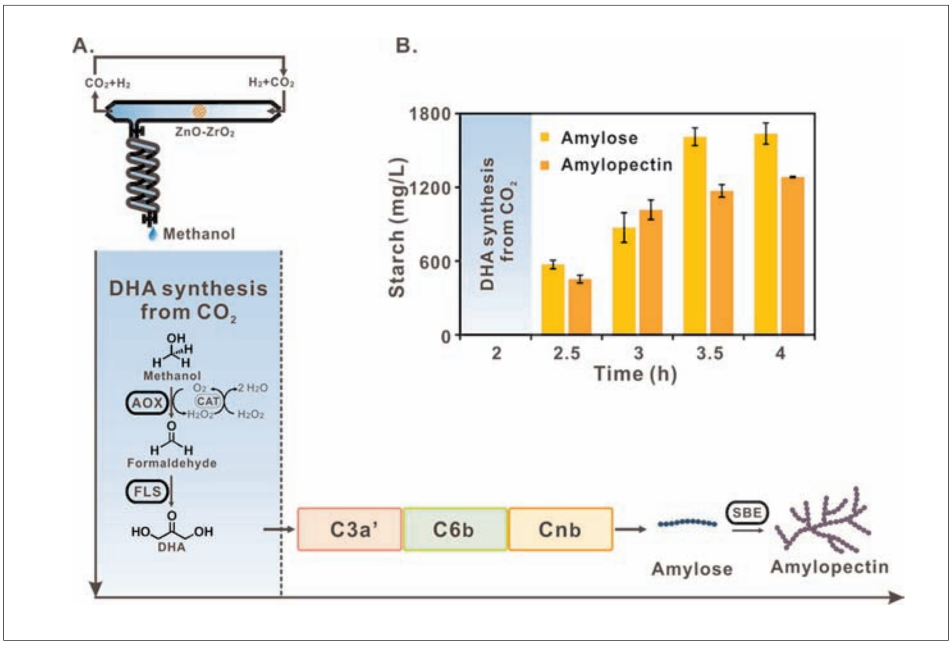
Chinese scientists report starch synthesis from carbon dioxide

The new route makes it possible to shift the mode of starch production from traditional agricultural planting to industrial manufacturing, and opens up a new technical route for synthesizing complex molecules from CO2.

Starch is the major component of grain as well as an important industrial raw material. At present, it is mainly produced by crops such as maize by fixing CO2 through photosynthesis. This process involves about 60 biochemical reactions as well as complex physiological regulation. The theoretical energy conversion efficiency of this process is only about 2%.

Strategies for the sustainable supply of starch and use of CO2 are urgently needed to overcome major challenges of mankind, such as the food crisis and climate change. Designing novel routes other than plant photosynthesis for converting CO2 to starch is an important and innovative S&T mission and will be a significant disruptive technology in today's world.

To address this issue, scientists at the Tianjin Institute of Industrial Biotechnology (TIB) of the Chinese Academy of Sciences (CAS) designed a chemoenzymatic system as well as an artificial starch anabolic route consisting of only 11 core reactions to convert CO2 into starch.



Starch synthesis via artificial starch anabolic pathway (ASAP) from CO2. (Image by TIBCAS)

This route was established by a "building block" strategy, in which the researchers integrated chemical and biological catalytic modules to utilize high-density energy and high-concentration CO2 in a biotechnologically innovative way.

The researchers systematically optimized this hybrid system using spatial and temporal segregation by addressing issues such as substrate competition, product inhibition, and thermodynamical adaptation.

The artificial route can produce starch from CO2 with an efficiency 8.5-fold higher than starch biosynthesis in maize, suggesting a big step towards going beyond nature. It provides a new scientific basis for creating biological systems with unprecedented functions.

"According to the current technical parameters, the annual production of starch in a one-cubic-meter bioreactor theoretically equates with the starch annual yield from growing 1/3 hectare of maize without considering the energy input," said CAI Tao, lead author of the study.

This work would open a window for industrial manufacturing of starch from CO2.

"If the overall cost of the process can be reduced to a level economically comparable with agricultural planting in the future, it is expected to save more than 90% of cultivated land and freshwater resources," said MA Yanhe, corresponding author of the study.

In addition, it would also help to avoid the negative environmental impact of using pesticides and fertilizers, improve human food security, facilitate a carbon-neutral bioeconomy, and eventually promote the formation of a sustainable bio-based society.

TIB has focused on artificial starch biosynthesis and CO2 utilization since 2015. To carry out such demand-oriented S&T research, all kinds of resources for innovation have been gathered together and the integration of "discipline, task and platform" has been strengthened to achieve efficient coordination of research efforts.

This study was supported by the Key Research Program of CAS and the Tianjin Synthetic Biotechnology Innovation Capacity Improvement Project.

More information

english.cas.cn

www.science.org

RMI report shows path to zero carbon steel in China

The report from RMI finds that it is technically and economically feasible for the steel industry to decarbonize through demand reduction, steel recycling and switching to green routes.

China produces and consumes more than half of the world's steel, accounting for about 17 percent of the country's carbon emissions. This makes the steel industry the country's second largest carbon emitting sector. The decarbonization of China's steel industry will be a significant contribution to the country's dual-carbon goals and the world's carbon reduction goal.

The report, "Pursuing Zero-Carbon Steel in China - A Critical Pillar to Reach Carbon Neutrality", is one of the first in China to provide a decarbonization roadmap of the steel industry, and makes a preliminary analysis of the energy consumption structure of China's steel industry.

It estimates that under the zero-carbon scenario, China's steel demand will accelerate to peak and decline rapidly, and the product structure, energy consumption structure, and production process will undergo great changes. The report maps out three steps for the industry's decarbonization.

• Demand reduction: Under the zero-carbon scenario, China's steel production will peak in 2024 and decline to 621 million tons per year in 2050—40 percent lower than the 2020 level. The main reasons for the decline are new phases of industrialization and urbanization. The peaking and declining of the steel industry are further accelerated by the carbon emissions reduction target, which is a new constraint.

• Steel recycling: China's secondary steel production will change from a supporting role to a mainstay, accounting for up to 60 percent of total steel production by 2050. The transformation of secondary steel from a supporting role is driven by China's steel stock and scrap resources security, as well as potential favorable costs in the future through supportive policies as the scrap recycling market gradually matures.

• Switching to low-carbon alternatives: Hydrogen direct reduced iron, smelting reduction with coal or hydrogen, and carbon capture and storage will all be important green steelmaking routes to China. These methods will produce 250 million tons in total by 2050, resulting in a significant decrease in fossil-fuel-based steel production, from 90 to 20 percent.

	Routes	Mitigation potential	TRL	Resource capacity	Economics	Easiness of implementation	Potential
Incremental technology	Energy efficiency	15%-20%	●	●	●	●	• microwave sintering, heat recovery, etc. • Digitalization could bring 10%-15% energy saving
	Oxygen blast furnace (OBF)	30%	◔	◔	◔	◑	• Under experiment in China • Could leverage BF facility and operation knowledge
	Hydrogen blending in BF	10%-20%	◕	◕	◕	◕	• Transitional technology with coke oven gas • Piloting in China
	Biomass	30% (95% with CCS)	◔	◔	◔	◕	• Limited biomass resource in China
	CCS	60%	◕	◑	◔	◑	• Limited application in steel sector in China
	Smelt reduction (HIsarna, HIsmelt, COREX, FINEX, etc.)	20% (80% with CCS)	◑	◑	◔	◑	• Several projects running in China • Supported by MII T policy
Fully decarbonized primary steel	Hydrogen DRI	95%	◕	◑	◔	◔	• Piloting in China and supported by MIIT policy • Need green hydrogen cost reduction
	Hydrogen plasma smelting reduction (HPSR)	95%	◔	◑	◔	◔	• Final stage of Jianlong Steel pilot project (CISP) • Gradually transition from coal-based to hydrogen -based
	Direct electrolysis	95%	◔	◔	◔	◔	• Still in development by Boston Metal, etc.

* The mitigation potential can be fully captured by using zero-carbon electricity. We assume EAF as the steelmaking process after DRI and BOF after smelting reduction.

Technology options for steel decarbonization

"Compared with other major steel-making countries, China's steel industry is perhaps facing bigger challenge in terms of decarbonization for at least three reasons: much deeper reliance on coal as fuel and feedstock, much younger operating assets and a much larger portion of primary steel production," said Ji Chen, principal of RMI, main author of the report.

"It therefore requires much greater efforts to achieve net zero in the next 30–40 years for the country. Nevertheless, as our report clearly shows, it is technically and economically possible to overcome these challenges and reach full decarbonization at the pace that China's carbon neutrality goal requires."

"The decarbonization of the steel industry will make an important contribution to China's goal of achieving carbon neutrality by 2060," notes Ting Li, regional managing director and chief representative of RMI's Beijing office. "The low-carbon transformation of the industry will be driven by emerging new technologies and market changes. RMI hopes to collaborate with partners to help scale up new solutions to accelerate the decarbonization of the steel industry."

The in-depth exploration of the steel industry builds on RMI and Energy Transitions Commission's 2019 report China 2050: A Fully Developed Rich Zero-Carbon Economy, which provides a comprehensive vision of a zero-carbon scenario for China's entire economy.

RMI released the report at China's Steel Industry Zero-Carbon Transformation Forum held in Beijing by RMI.

More information

Download the full report:

rmi.org

www.energy-transitions.org

IEA report: An Energy Sector Roadmap to Carbon Neutrality in China

The China Roadmap sets out a pathway consistent with the enhanced ambitions that China announced last year in which CO2 emissions reach a peak before 2030 and carbon neutrality is achieved before 2060 and shows that the required investments are well within China's capacities.

By accelerating its clean energy transition, China can secure major economic, innovation and employment benefits while helping the world move nearer to achieving shared climate goals finds the International Energy Agency report, "An Energy Sector Roadmap to Carbon Neutrality in China."

China's remarkable economic growth over the past four decades has lifted hundreds of millions of people out of poverty, turning the country into a leader in many industries but also the world's largest carbon emitter, accounting for one-third of global carbon dioxide (CO2) emissions. China provides more than half of the world's steel and cement, but the CO2 emissions from just those two sectors in China are higher than the European Union's total CO2 emissions.

China is aiming to reach a peak in its CO2 emissions before 2030 and carbon neutrality before 2060. The energy sector is the source of almost 90% of China's greenhouse gas emissions, putting energy policies at the heart of the country's transition to carbon neutrality. The report explores how China can reach its objectives while ensuring energy security and affordability for its citizens. It shows that the required investments are well within China's capacities, given the size and dynamism of its economy. The report responds to the Chinese government's invitation to the IEA to cooperate on long-term strategies.

"China is a clean energy powerhouse and has played a leading role in many of the world's success stories to date, from solar power to electric vehicles," said Fatih Birol, the IEA Executive Director. "China's efforts to achieve its ambition of carbon neutrality will result in even greater flourishing across a wider array of low-carbon technologies and a significant decline in fossil fuel use in the coming decades."

"However, the really uplifting news is that our new Roadmap shows China has the means and capabilities to accomplish an even faster clean energy transition that would result in greater social and economic benefits for the Chinese people and also increase the world's chances of limiting the rise in global temperatures to 1.5 °C," Dr Birol added. "This accelerated transition would put China's CO2 emissions into marked decline after 2025, opening up the possibility of China reaching carbon neutrality well before 2060. This would be both good for China and good for the world."

China has made notable progress in its clean energy transition, but it still faces some significant challenges. Coal accounts for over 60% of electricity generation, and China continues to build new coal power plants domestically. At the same time, China has added more solar power capacity than any other country year after year. It is the second largest oil consumer in the world, but it also home to 70% of global manufacturing capacity for electric vehicle batteries.

At the same time, reaching China's climate targets cannot rely solely on the rollout of renewables and electric vehicles. It will need to involve solutions to tackle emissions from its huge existing fleet of fossil fuel-based power plants, steel mills, cement kilns and other industrial facilities. If the existing emissions-intensive energy infrastructure in China contin-

CCUS deployment targets and policies

Policy and regulatory developments over the last decade signal that CCUS is gaining traction in China. Since the 12th FYP (2011-2015), China has included CCUS in its national carbon mitigation strategies and in its nationally determined contribution. The development of large-scale CCUS demonstration projects was included for the first time in the 14th FYP (2021-2025). Several ministries have issued guidance documents to support the development of CCUS technologies through research, development and demonstration (RD&D), such as the 13th Five-Year Special Plan for Climate Change Science and Technology Innovation. Interest for CCUS is also growing at the regional level, with 29 of the country's 34 administrative divisions issuing CCUS-related policies (Xian, 2021).

In 2019, the Department of Social Development of the Ministry of Science and Technology and the Administrative Centre for China's Agenda 21 (ACCA21) jointly released a roadmap for the development of CCUS technology in China (ACCA21, 2019). It defines several goals in five-year increments to 2050. By 2030, CCUS should be ready for industrial applications, while long-distance onshore CO2 pipelines with capacities of up to 2 Mt/year should be available. It also aims to reduce the cost and energy consumption of CO2 capture by 10-15% by 2030 and 40-50% by 2040. By 2050, CCUS technology is to be deployed extensively, supported by multiple industrial CCUS hubs across the country.

China's CCUS policies have so far focused mainly on the science and innovation, leading to major advances in all aspects of the technology. China has not yet enacted any specific laws to encourage the deployment of CCUS and overcome barriers to new projects. That will require the introduction of a legal and policy framework, market incentives including CO2 pricing and subsidies to address the high capital and operating costs of large-scale projects (Jiang et al., 2020).

ues to operate in the same way as it does today, its CO2 output between now and 2060 would amount to one-third of the global carbon budget for limiting the global temperature rise to 1.5 °C. This is aside from any new plants that may be built to meet growing demand.

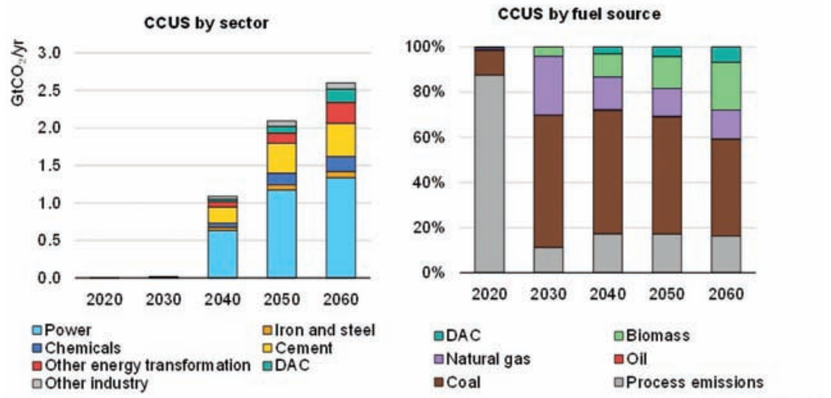
The China Roadmap sets out a pathway consistent with the enhanced ambitions that China announced last year in which CO2 emissions reach a peak before 2030 and carbon neutrality is achieved before 2060. The main drivers of emissions reductions between now and 2030 in this pathway are energy efficiency improvements, expansion of renewables and a reduction in coal use.

Electricity generation from renewables, mainly wind and solar PV, increases sevenfold between 2020 and 2060, accounting for almost 80% of China's power mix by then. Industrial CO2 emissions decline by nearly 95% by 2060, with the role of emerging innovative technologies, such as hydrogen and carbon capture, growing strongly after 2030. These changes will boost China's labour market, with more new jobs created in growing low-carbon energy technologies than are lost in declining fossil fuel industries.

The Roadmap also explores the opportunities for China to pursue – and benefit from – an even faster clean energy transition, which would result in China's CO2 emissions declining to almost 20% below their current level by 2030. On top of the major advantages that come from reducing the impact of climate change, the social and economic benefits include greater prosperity for regions that have not yet fully benefited from China's economic development and a bigger net gain in job creation nationwide. And investment needs are not a barrier for the faster transition, since the cumulative investments are similar to those in the slower one.

"This Roadmap shows what is possible: China has a clear pathway to build a more sustainable, secure and inclusive energy future," Dr Birol said.

"As China makes some important decisions in the coming weeks and months, the IEA is pleased to share our analysis and global expertise with Chinese policy makers so that together we can help build a brighter future. I also welcome President Xi Jinping's announcement last week that China will stop building coal power plants overseas as a further positive step towards curbing global emissions."



IEA, 2021.

Notes: Other energy transformation includes fuel transformation, extraction of fossil fuels, and mining. DAC = direct air capture; CCUS = carbon capture, utilisation and storage. CCUS capacity excludes internal use of captured CO_2 for chemical production.

CCUS deployment by sector and source of emissions in China in the Announced Pledges Scenario (APS)

CCUS - Role in the energy transition

China has made significant progress in the development of CCUS over the past decade, which could provide the basis for a rapid acceleration in deployment. A growing number of CCUS projects are operating or planned. There are currently at least 21 pilot, demonstration, or commercial projects in operation in China with a combined capture capacity of over 2 Mt of CO2 per year – many of which are associated with enhanced oil recovery involving (EOR) the injection of CO2 to boost oil production (CO2-EOR).

CCUS is set to play an important role in China's transition to carbon neutrality in the Announced Pledges Scenario (APS), in large part because of the composition of its existing energy infrastructure and large role of coal in the energy mix today. CO2 capture is deployed in industry, fuel transformation and power generation, with the CO2 either permanently stored or used in various ways.

Many of the country's existing power and industrial plants have been built relatively recently and could continue operation with CCUS retrofits, avoiding potentially costly early retirements. CCUS also provides a means of generating negative emissions via bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) with CO2 storage, both of which are technologies that can remove CO2 from the atmosphere on a net basis.

In total, CCUS contributes 8% of the cumulative reduction in China's CO2 emissions between now and 2060 with its contribution growing over time. In the APS only small increases in the total volume of CO2 captured from 2020 to 2030 are needed to support China's enhanced near-term targets declared in 2020 related to its nationally determined contribution under the Paris Agreement. That period is used to ensure that the necessary enabling environment, including advanced regulatory frameworks and transport and storage infrastructure, is in place for widespread deployment.

Deployment of CCUS technologies ramps up after 2030 to support deeper emissions reductions in the power, industry and fuel transformation sectors, reaching 2.6 Gt in 2060. Around 620 Mt of CO2 are removed via BECCS and DAC with CO2 storage in 2060, 25% of total CO2 capture, entirely offsetting residual emissions in industry and transport.

The contribution of CCUS to China's pathway to carbon neutrality hinges on the rapid development and commercialisation of capture technologies in each sector and the expansion of CO2 transport and storage networks. The maturity of CCUS in China today varies considerably by technology type and application.

More information

Download the full report:

www.iea.org

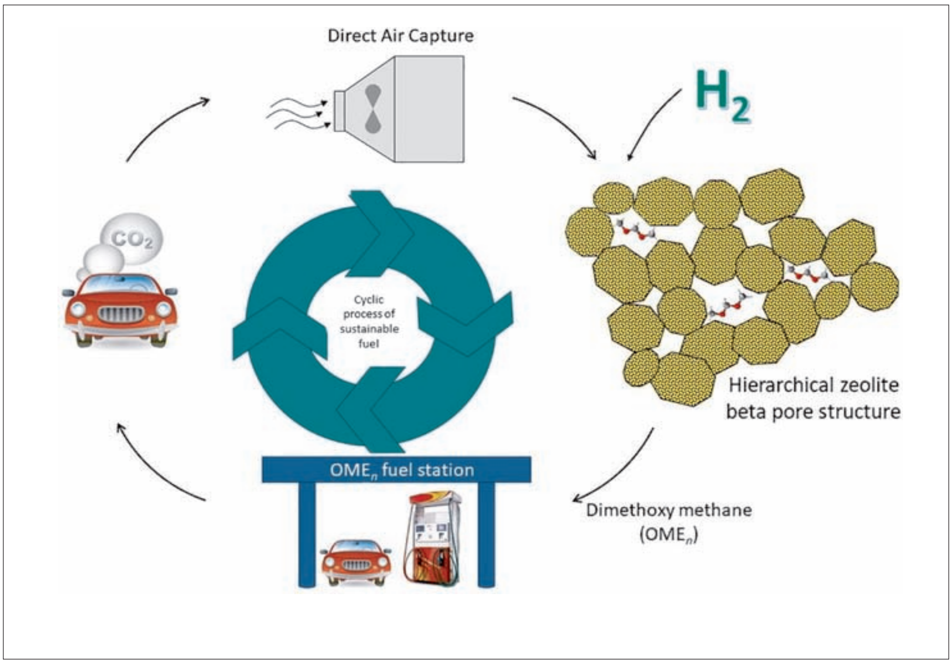
The path to net-zero liquid fuel

Researchers from Monash University and Hokkaido University have developed a method that converts carbon dioxide into a diesel-range fuel.

When carbon dioxide is added to the manufacturing process of fuel production, it has the capability to produce fuels that reduce or reverse the net CO2 emissions. When the hydrogen required for this process is supplied via solar powered water electrolysis, the entire process becomes completely renewable. The end result is a net-zero carbon emitting fuel product.

The research, which was recently published in the Journal of Energy Chemistry, offers a diesel-range fuel alternative which has the capability to be applied anywhere in the world.

Associate Professor Akshat Tanksale, from the Department of Chemical and Biological Engineering at Monash University, says OME (oxymethylene ethers), are among a number of fuel alternatives that are attracting increasing attention for their net-zero carbon emitting properties.



A graphical representation of how carbon dioxide can be converted into a diesel-range fuel

"OME is a diesel blend or substitute fuel for which we are reporting the best yield to the best of our knowledge anywhere in the world, and when coupled with green hydrogen, the manufacturing method we're proposing can provide net-zero liquid fuel," said Associate Professor Tanksale, lead author of this study.

Dimethoxymethane (DMM), which is a diesel blend fuel and the simplest form of an OME, is currently being researched with high interest due to its unique fuel properties. Commercially, it can be produced via a two step-process of methanol oxidation to make formaldehyde, followed by coupling with methanol. However, currently, both methanol and formaldehyde are produced from natural gas.

In the method developed by Monash, carbon dioxide, hydrogen and methanol are used as a feedstock for producing DMM in a single reactor. The team developed a novel catalyst based on ruthenium nanoparticles which make this reaction possible. An added advantage is that this reaction takes place at much lower temperatures than conventional methanol and formaldehyde production methods, making it significantly more energy efficient.

Monash engineers are also working on a methanol synthesis method from carbon dioxide and hydrogen, closing the carbon loop to renewables only.

"Recycling waste carbon dioxide to OME is a promising way to produce fuel with a significantly lower carbon footprint. We are glad we could collaborate with the team at Monash to further understand the role of catalysts in this state-of-the-art work," said Dr Abhijit Shrotri, Institute for Catalysis, Hokkaido University.

The project has recently received funding for further research into the industrialisation and scale-up of this state-of-the-art catalyst and process by the Hindustan Petroleum Corporation Limited (HPCL), India.

"CO2 valorization to fuels is one of the prominent pathways to achieving net-zero in the future and researchers are exploring efficient processes for this conversion. We're currently focusing on several CO2 conversion technologies for the development of industrially scalable catalysts and processes. Our collaboration with Monash University to develop and scale-up OME production from CO2 will certainly contribute to the development of a process for CO2 conversion into fuels which is proving necessary in the current climate," said Dr G Valavarasu from HPCL.

"In this study, we developed a unique pore structure that could synthesise large molecules like DMM. The particle size of ruthenium, along with the pore size and acidity of the catalyst, is extremely important for this reaction to take place. By precisely controlling these parameters we were able to achieve the highest yield of DMM reported in the literature," said Dr Waqar Ahmad, who recently completed his PhD on this project.

More information

www.monash.edu
www.global.hokudai.ac.jp

Unlocking the potential for CCUS in Vietnam

There is excellent potential for CCUS in Vietnam and the government could play a key role through subsidies for demonstration projects and regulatory changes to incentivise the industry.
By Stephen B. Harrison and S. Hamidreza Yousefi, sbh4 consulting.

Vietnam is a highly populated country, of close to 100 million inhabitants, located in Southeast Asia. Its economic growth rate has remained consistently high during recent decades, with an average annual GDP growth of around 7%.

This pace of development is likely to continue in the coming years, which means that investment in heavy industry will increase, leading to higher annual carbon dioxide emissions. There are also significant plans to increase natural gas and coal-fired power generation to support the expected industrial development, further increasing CO2 emissions.

Furthermore, Vietnam's proximity to highly industrialised countries in North Asia, such as Japan and South Korea, makes it an attractive location as a regional CCUS hub. Japan and South Korea are targeting CO2 emission reductions based on The Paris Agreement and are considering exporting CO2 on tankers for permanent underground storage in Indonesia and Australia.

These countries are much further away than Vietnam, potentially making Vietnam a more cost-effective and attractive option for a regional North Asian CCS hub.

CO2 emissions sources in Vietnam

Currently, the main source of CO2 emissions in Vietnam are thermal power stations, including coal, gas, and fuel oil fired plants. Refineries, steelworks, and cement plants also contribute to a strong industrial base. Annual CO2 emissions in Vietnam have increased from 13 million tonnes in 1990, to 253 million tonnes in 2018. It is expected that this could increase to 830 million tonnes in 2030.

This is mainly due to high number of coal-fired power stations that have been installed in recent years, as well as a coal fired power generation ramp up to 37 GW of power generation in 2030 to meet the growing national demand [1].

To meet the worldwide need to mitigate climate change in the coming years, it is likely that CCS technology will be used in many countries to capture CO2 from main emissions sources and inject it into underground reservoirs, instead of releasing it into the atmosphere.

CCS is a viable option that could play an important role in the future CO2-neutral energy system. Beyond that, CCUS can be more economically attractive than CCS when the CO2 is used for Enhanced Oil Recovery (EOR) for depleted oil fields, or CO2 Enhanced Coal Bed Methane Recovery (CO2-ECBM) for Coal Bed Methane (CBM) resources.

CCS must become integrated into future energy sector infrastructure plans to ensure cost-effective decarbonisation. The combination of natural gas reforming with CCS to make blue hydrogen is one possible example. Gasification of coal with integrated CCS to make purple hydrogen is an alternative.

The ideal geological structures for CCUS

Saline aquifer and depleted oil and gas fields are two main options for CO2 storage. Depleted oil and gas fields often have legacy surface and subsurface facilities from previous hydrocarbon production and the possibility of EOR may also exist. Therefore, they can be less expensive to use for CCS than aquifers.

However, aquifers have much larger storage volume and are more ubiquitous worldwide. They are also plentiful in and around Vietnam and could therefore play a significant role in CO2 emissions reduction for the nation and broader region.

One of largest CCS projects in development globally is the Gorgon project in Western Australia. It has faced several issues regarding equipment specifications and the challenges of saline aquifer water removal from the sandstone rocks that cap the carbon dioxide storage field. The problems are not related to fundamental issues of using saline aquifers for CCS but are specific to the way the project has been engineered and executed.

To demonstrate that aquifers can successfully be used for CCS; the Utsira saline aquifer in the North Sea has been used for permanent underground CO2 storage by Equinor (previously Statoil) for over 20 years. Sleipner West, Gorgon and more than 20 other CCUS projects can offer many lessons for subsequent projects in Vietnam and other high-potential regions of the world.

The third underground CO2 utilisation and storage option is CO2-ECBM. Although CO2-ECBM has not been developed in Vietnam, there may be a significant opportunity to use this technology with several coal reserves, located in the northern part of the. CBM is an unconventional natural gas resource in which gas is generated in coal deposits and is recovered by conventional well drilling methods.

CCUS operation for CO2-ECBM in CBM deposits is an appropriate solution not only for CO2 storage, but also for enhanced natural gas recovery from these sources. It can be a complimentary mix to the range of CCUS technologies in locations where saline aquifer and depleted fields are not available.

From a technical point of view, Vietnam has an attractive geological structure for underground CO2 storage and injection. Most of these geological structures are offshore sedimentary basins.

Based on conservative initial estimates, 12.2 billion tonnes of CO2 could be injected into the subsurface, including 10.4 in saline aquifers, 0.6 in depleted oil fields, 0.7 in depleted gas fields and 0.5 in CBM [2].

More than thirty hydrocarbon fields are producing oil and gas in the offshore regions around Vietnam. It is estimated that the top 14 oil and gas fields could have the capacity of 900 million tonnes for CO2 Storage.

During every underground CCS project, there is a risk of leakage for CO2 storage that should be considered during the design and pilot phase of the project. No CCS pilot has yet taken place in Vietnam, but a recent feasibility study by the Asian Development Bank (ADB) [3] showed that Cuu Long Basin in the southern part of the country could be the best location for CCS due to availability of high numbers of oil and gas fields, as well as its proximity to CO2 resources particularly coal power plants.

The CO2 could be transported from emissions sources via onshore pipeline followed by offshore pipeline or ship to the offshore CCS location.

In the White Tiger oil field of the Cuu Long Basin, the ADB feasibility study estimated an annual CO2 storage capacity of 4.6 million tonnes could be achieved and the oil recovery rate could be enhanced by 45,000 bbl/day.

Industrialisation and power generation investments are set to continue in Vietnam

Unlocking the potential for CCUS in Vietnam

The estimated CCS costs in Vietnam are 43-52 €/tonnes CO2 (85% capture, 4% transportation and 11% storage). High carbon prices would encourage private sector investment in CCS and lead to a CO2 emissions reduction.

Although technical evaluations point to the high potential of CCS in Vietnam, regulatory changes would support deployment of this technology. Whilst energy policy is developing and the use of renewables is increasing, currently, there is no clear plan to reduce CO2 emissions from the installed base of fossil fuel power plants and new coal and LNG fired capacity is being planned.

The government could play a catalytic role in unlocking the potential for CCS with carbon taxes, subsidies for demonstration projects and R&D support to enable change and to motivate industry in Vietnam to decarbonise. A holistic review of energy policy, to focus on low carbon solutions, for example turquoise or blue hydrogen production, could also unlock the potential for CCS.

In the power sector, Vietnam Electricity of (EVN) could be a highly influential stakeholder for CCS. EVN controls power generation and the power grid in Vietnam and its ambition and vision impact CO2 emissions and the potential for post-combustion CCS deployment.

Another key to unlock the potential could be for companies such as Petro Vietnam, the national Oil and Gas group, to cooperate with operators in countries that have experience of CCS such as China, Kazakhstan, Australia, Canada, US, and Norway, to develop economical and safe CCS schemes and system designs.

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More information

www.sbh4.de

Can Carbon Capture Utilisation and Storage be profitable?

Max Richards, Energy Transition Services Lead, OPC, outlines the realities of commercialising CCS from the perspective of an independent operator and provides some insights from a non-early mover.

Oilfield Production Consultants (OPC) is a subsurface consultancy headquartered in London, with offices around the world, including in Houston, Kazakhstan, and the Middle East. The majority of our major clients are small- to medium-sized independent oil and gas companies centred on one or two major assets. Our focus in supporting our clients is usually on two key objectives: maximising value, and developing technical expertise.

Achieving these goals means aligning to key principles; positive cash flow, realistic long-term objectives, and focusing on core business activities. This is where the first obstacles to Carbon Capture and Storage (CCS) appear. Our experience working alongside our clients is that there is a large amount of ambiguity in addressing the above and key questions always arise.

How do you make money from CCS? Will CCS be supported by the regulator and the governments over the lifecycle of our assets? How can I get involved? There are a number of anxieties our clients have - as well as a desire not to be left out given the quickly-evolving future of CCS and that information is hard to discern.

In our most recent CCS project as a part of a larger technical study examining a client's reservoir storage capacity, injection profiles, and geomechanics we sought to understand what modifications would be needed to inject CO2 at a sustained rate (1Mt, 3MT and 5MT/PA). This included the facility modifications and the associated CAPEX and OPEX costs.

In conjunction with well-developed theoretical and practical CO2 storage capacity calculations, we were able to accurately estimate the cost per tonne of CO2 injected and stored into the reservoir over 50 years. Armed with our injection costs OPC ran a number of economic projection scenarios to estimate the price to charge potential customers for using our client's reservoir. Job done!

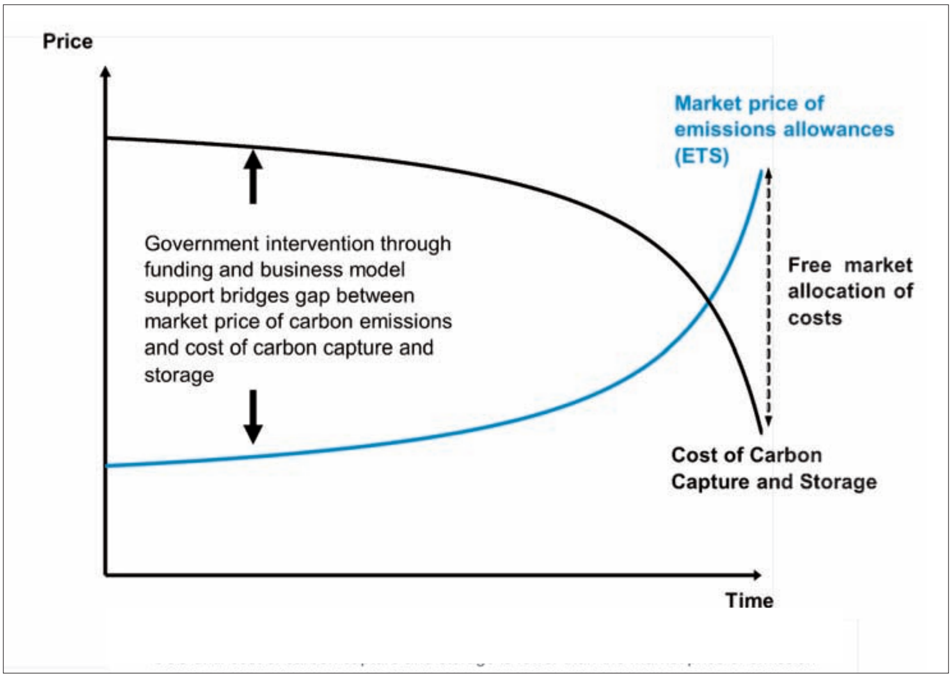

Figure 1 – Illustrative example of how government intervention will underpin market failings of CCS until cost of carbon capture and storage is lower than the market price of emission allowances. Adapted from Industrial Decarbonisation Strategy (BEIS; March 2021)

The more seasoned amongst us will know that is it unfortunately not as simple or straightforward as that. There are several moving parts that need to be constrained and understood before going to market. The Energy Transition team at OPC made the client aware of this, with further research and conceptualisation required.

This was a journey that we undertook together; to translate business models and regulatory dependence into easily digestible concepts, demystifying commercialisation routes, and discerning 'what slice of the pie' each stakeholder in the CCS value chain will receive (capture, dehydration, compression, transport, utilisation, and storage).

In this article we will outline the realities of how to commercialise CCS from the perspective of an independent operator whilst remaining true to our principles of maintaining positive cash flow and aligning to long term objectives of relevance and remaining in touch with reality. It must be stressed that this article is a reflection of our interpretation of government policy and market.

It should not be taken without a pinch of salt. Of note is that the work that was completed was an initial study to understand key concepts, constraints, and opportunities. OPC focuses on developing the knowledge and technical expertise to enable our clients to control and understand the narratives of the energy transition running through the global oil and gas industry for their advantage.

The Cost of CO2

In January 2021, the UK Emissions Trading Scheme (UK ETS) replaced the EU ETS, placing a cost on greenhouse gas (GHG) emissions across energy-intensive industries. These markets seek to price the externalities of polluting CO2 more accurately by forcing energy-intensive industries to purchase emissions allowances (1 ETS = 1 tonne of CO2e) from the ETS.

The ultimate objective is to bridge the gap between the cost of emission reduction and the market price of emissions allowances so that a free market can then determine the most efficient pathways to decarbonisation. The development of a free market is inherently reliant on the price of polluting CO2 being sufficient to drive polluters to invest in CCS and emissions reduction technology.

In October 2021 the current price for one EUA (allowance) is hovering around €58 and in the UK £58, lower than the cost of CCS. Many believe this price is still too low to reach 2030 and subsequent targets across the Europe as solutions such as CCS are still in the €100 to €200 per tonne range. Uptake of CCS will depend on the carbon price and the price of source-to-sink technologies. If the price per tonne of CO2-avoided by CCS is lower than the carbon price, then CCS may begin to be commercially attractive.

In the immediate future, the carbon price is not sufficient to drive markets to begin capturing and storing CO2 without market intervention by governments. Many of the industries seriously considering CCS such as steel and cement are 'hard to abate,' meaning pathways to reduce emissions through electrification and use of low-carbon fuels are particularly challenging. In order to support these essential industries and prevent the acceleration of emissions costs, CCS can be deployed to keep industry competitive whilst minimising emissions. But as the price of polluting remains too low, government intervention is required (see Figure 1).

Carbon Capture and Storage Clusters

In December 2020 the Department for Business Energy and Industrial Strategy (BEIS) outlined their position on the commercial business model describing CCS cluster sequencing and Transport & Storage (T&S) business models. These were designed to incentivise deployment of carbon capture technology for industry to help overcome a number of different market failures and barriers to entry that prevent industry from securing investment needed to start the low carbon transition. For 'first of a kind' projects, BEIS expect the model to cover operational costs, T&S fees and a rate of return on capital investment, with an element of capital co-funding for initial projects.

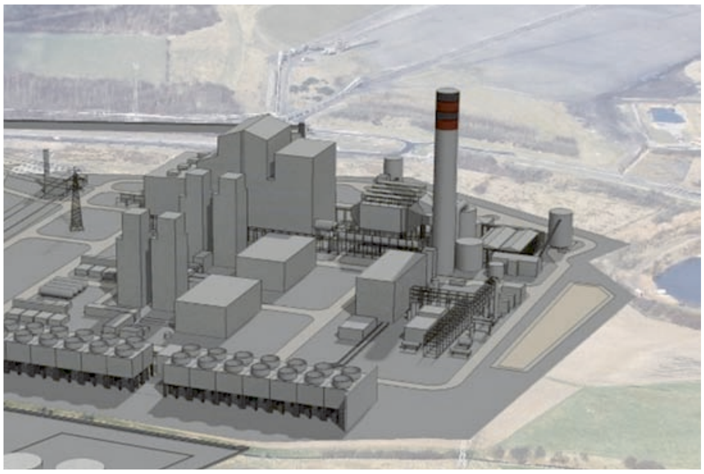

Figure 2 – The White Rose CCS Project (2014) would have been the first coal-fired power plant to demonstrate the use of CCS. OPC provided support in reservoir simulation and modelling for long term carbon injection and storage project

In October 2021 it was announced that the government would be spending £1 billion to support the development of two CCS clusters and T&S networks, East Coast & HyNet. Industrial hubs and CCS clusters are the preferred business model being adopted worldwide through the utilisation of a Transport & Storage (T&S) network. In this business model, heavy industries such as cement, steel, and fertiliser production which exist in industrial clusters are connected to a T&S network.

This allows multiple sources of CO2 to access a common CO2 T&S infrastructure. This significantly reduces the unit cost of CO2 storage through economies of scales and offer commercial synergies that reduce investment risk. T&S networks also reduce cross-chain risk by creating multiple customers for the operators of CO2 T&S networks, including CO2 arriving from outside the local cluster such as via ship. Under this model 'users' of the T&S network will pay a fee. As these networks will be inherently monopolistic, they would be heavily regulated by governments like other monopolistic networks such as rail, water, and gas. We will go into this in further detail in the next section - bear with us, it gets quite complicated.

The reason 'clusters and hubs' are being developed is that they over come one of the key risks associated with CCS projects – cross-chain risk. Previously projects such as the UK's CCS competition (White Rose, which OPC worked on; Figure 2) attempts were made to capture CO2 from a single source and inject and store into a single sink. This is referred to as a disaggregated business model such as Sleipner and Gorgon. This model ultimately led to higher costs of capital and higher project costs.

So far, I've tried my best to give a good overview of the main commercial levers incentivising CCS, the avoidance of an emissions bill and to keep industries competitive. We roughly understand the drivers of market intervention and what is expected from policy makers, what do the proposed state supported business models look like?

Transport & Storage Business Models

Supporting the development of the two CCS clusters BEIS has outlined the proposed business models for the provision of Transport and Storage companies, referred to as 'TS&Co'. These commercial entities are joint ventures (JV) which will construct, manage, and decommission the transport of CO2 from 'users' to an appropriate storage reservoir via a network.

The TS&Co will be the asset owner and the system operator. The aim of the TS&Co business model is to support the development of CCS clusters while managing the key risks associated with large infrastructure projects which are naturally monopolistic. BEIS guidance to date on how these business models are designed is constantly changing, and certain aspects remain ambiguous.

To simplify as much as possible, the revenue generation of the TS&Co will be set by strict government policy through defined phases.

Essentially government support will be greatest during the first phases of deployment and will taper away as clusters are anticipated to become independent from support. In the subsequent regulatory periods, the regulator (the government) would design the Economic Regulatory Regime (ERR), covering allowed revenues and any other incentives/penalties. In effect the regulator would be similar to that in sectors currently subject to independent economic regulation such as electricity, gas, water, telecoms, and transport. The business model does not cover the supply of CO2 via non-pipeline transportation, though it does indicate that this subject will be dealt with in subsequent policy updates. To summarise, the CCS business will be treated like a waste disposal with dictated utility-esque margins.

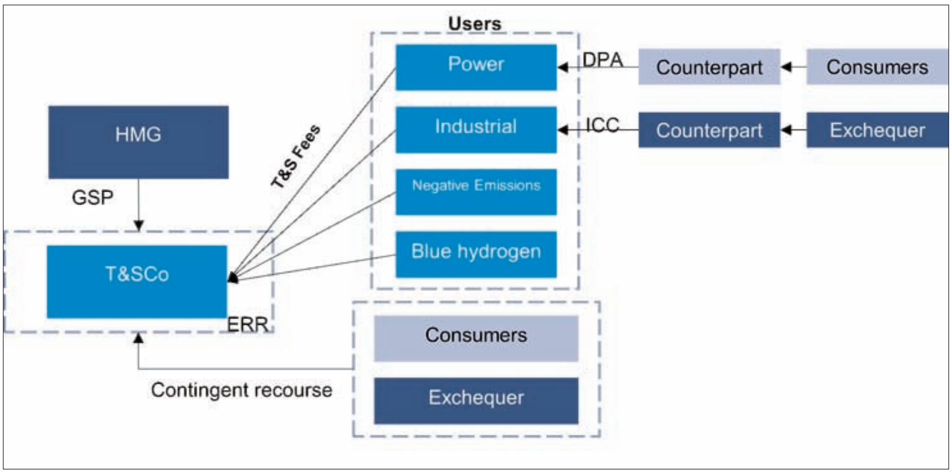

Figure 3 – Diagram of revenue stream model for the TS&Co. HMG will support the development of the T&SCo via Government Support Packages (GSP). The T&SCo will be governed by an Economic Regulatory Regime (ERR). T&S fees will be generated from expected users of the network – power stations, industrial facilities, negative emissions technologies, and blue hydrogen. Power users will be subsidised by Dispatchable Power Agreements (DPA), industrial users via Industrial Carbon Capture (ICC) agreements

So, who's paying for it?

Whilst the BEIS T&S business model covers the organisational structure by which the T&SCo will be regulated it does not cover the revenue sources. Under the T&SCo revenue model, revenue will be generated by users under a 'Users Pays' model. Within this agreement users of the T&S network will pay fees reflecting the magnitude of their use of the network. Elements of fees would be connection, capacity, and volumetric fees. Under this agreement the T&SCo would also have 'contingent recourse' to consumers and/or taxpayer support to ensure the revenue stream from users is predictable and robust from a financial perspective. It is outlined in Figure 3.

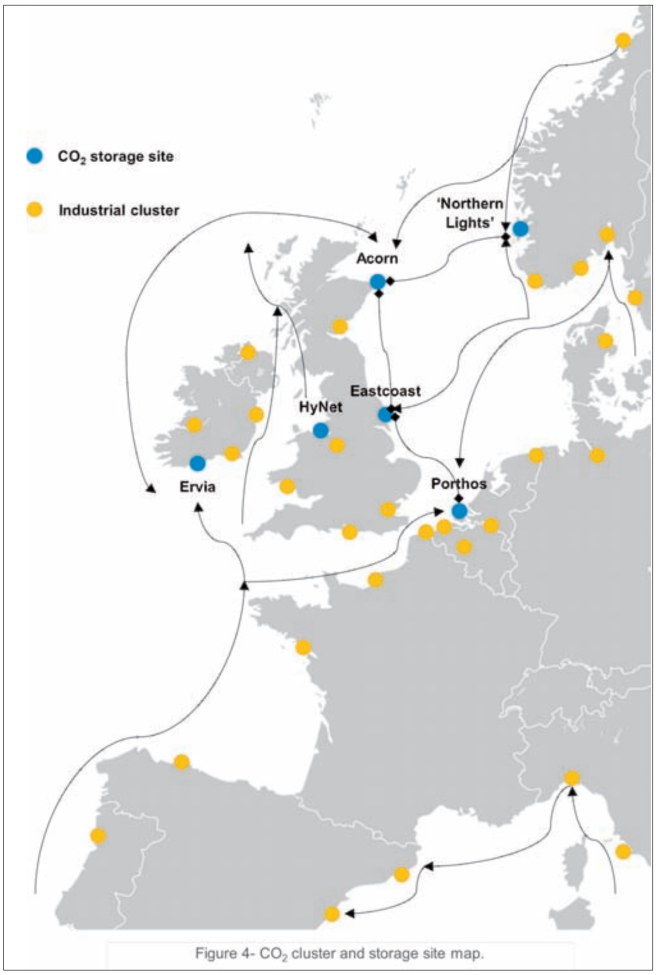

Figure 4 - CO2 cluster and storage site map

What does it all mean for me?

One thing is for sure, the economics of CCS are nowhere near as glamorous to that of Oil and Gas. Returns are as a utility and it at this current point in time seems like a risky business to be in, subject to the discretion of governments for financial support. Costs along the chain are highest when capturing CO2 and often are as much as 90% of total costs.

Dehydration and compression of CO2 costs around 5-15%, transport depending on pipeline, shipping, and length can be as low as 5% and up to 20%. Storage incidentally, and the bit that the upstream oil and gas industry will likely be most involved can be very cheap, as low as 2.5% of costs. Costs change by a large margin depending on the specific case being examined.

CCS projects globally are focusing on developing 'low hanging fruit', clusters optimally aligning a combination of CO2 source and transport network scalability, and access to optimum storage sites (see Figure 4). When those storage sites are filled with CO2 the next best reservoir will be utilised. This will be the opportunity for new parties to enter the market, subject to the success of current projects and net-zero goals.

If you own and operate an asset in the North Sea and you repurpose as a storage site, decommissioning and abandonment costs will be significantly less. And you may be able to generate revenue for another 50 years. For independent oil and gas companies who may not have a 50-man strategy team trying to predict the future, CCS may seem a bit a long shot. But it also may be an opportunity to safeguard revenues and prevent stranded assets.

More information

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Energy Efficiency/CO2 Mitigation in the Allied Industries

The latest techno-economic report from the Carbon Dioxide Capture and Conversion (CO2CC) Program looks at Greenhouse Gas reduction technologies and activities in three key industries: cement, iron and steel and mining.

The report, "Energy Efficiency/CO2 Mitigation Case Study Series – Vol. 3: Allied Industries," highlights the positive news that there are many approaches which can be used to lower industrial emissions. Methods broadly break down to: preventing emissions through energy and process efficiency improvements, recycling of waste materials back into the process, carbon capture and utilization (CCU), carbon capture and storage (CCS), and a combination of the latter two (CCUS).

The allied industries including cement, iron and steel production, as well as mining are high profile greenhouse gas (GHG) emitters and are under increasing pressure to decarbonise their operations. Each of the report's chapters sets out an introduction to the industry and its decarbonisation challenges, then goes on to profile the technologies which can be employed and the progress made to date.

Industry characteristics and landscape, sources of GHG emissions and relevant GHG mitigation techniques are set out with a view to profiling each industry's progress and plans for further decarbonisation. A selection of high-profile projects and company activities are presented as individual case studies. Comments on the remaining hurdles, challenges, and outlook are provided in each of the chapters.

Table 1. Case Studies for Decarbonisation in the Cement Sector

Company/Project	Technology/ Project Name	Decarbonisation Approach
CNBM		Waste heat recovery, energy from waste, low clinker content
Cemex	Climafuel	Waste fuel
Lafarge	Cement2020 Geocycle	Biomass Waste fuel
Siemens	Sciement	Digitalisation
Schneider Electric	Ecostruxure	Digitalisation
LEILAC	Direct Separation Reactor	New calciner with integrated CO_2 separation
Hanson	EcoPlus	Clinker substitution
CarbonCure	CarbonCure	CO_2 curing
Heidelberg	Brevik	Variety of CCS technologies

Cement

In the cement sector, much has been achieved already for decarbonisation. Especially in the area of energy efficiency, improvements have been made through approaches such as those which utilise waste heat and optimise steam usage and those which reduce raw material requirements – e.g. CO2 curing and lower clinker cement options including partial replacement with supplementary cementitious materials (SCMs) and alternate cement chemistries.

The direct separation reactor (DSR) is also very rapidly being proven and there are significant industry backers for two European Union consortium projects utilising this type of approach - LEILAC and its successor LEILAC II.

Table 1 summarises the case studies in the cement sector included in the report. The main difficulty of CCS is cost, as it incurs an energy penalty on the plant – in particular if a more commercialised amine technology is adopted. Membranes are also being considered, however there are many technical hurdles to overcome and these are unlikely to have much impact in the short-medium term. Other technologies such as calcium looping, and the aforementioned DSR have more potential.

Switching to hydrogen or biomass fuel are approaches which have been popular for study in the cement sector – however their impacts are limited as they do not address the majority of GHG emissions and would need to be combined with carbon capture. In fact, the necessity of CCS for the cement sector is becoming clear if carbon penalties and a continued negative public image are to be avoided.

China is showing a stronger interest in CCUS approaches, however and it may decide to advance this more rapidly. In the meantime, regulators will continue to have a tough balancing act when setting regulations which would enforce carbon capture, as they must also consider border tax measures to avoid risking damage to the competitiveness of the domestic industry. Thus far such border measures have not met with the approval of the European Parliament.

Monetization of the captured carbon i.e. CCUS may be a possibility for overcoming cost hurdles – and one where industrial emitters are investing significant time and resources. Combinatorial approaches with process, formulations and CCUS are likely to be adopted going forward.

Case Study: LEILAC

The LEILAC project (LEILAC Consortium, 2020) is aiming help the company Calix to commercialize their "Direct Separation Reactor" (DSR), the design of which inherently captures a stream of high purity CO2 (~95 %) by physically isolating the calcination reaction from the combustion processes used for heating.

Overall, the DSR is claimed to be able to capture the majority (~60%) of total CO_2 emissions during manufacturing without large additional financial or energetic costs.

The technology has been successfully demonstrated with a magnesite feed on a commercial plant (Bacchus Marsh, Australia), from which a working model was developed (i.e. heat transfer, mass transfer, reaction kinetics) and validated against plant data.

Future iterations of the DSR technology could realize additional reductions in emissions. For instance, coupling the technology with an ASU such that heating occurs by oxyfuel combustion would mean the gases generated in the outer furnace were of similarly high purity (~90 %).

Case Study: CarbonCure

CarbonCure Technologies was founded in 2007 in Halifax, Canada. The company's key activities are in producing mineral carbonation equipment for sequestering CO_2 in the form of nanosized calcium carbonate particles into otherwise conventionally produced concrete. CO_2 is added to enhance the curing of concrete.

The CarbonCure website states that there is a reduction of around 15 kg of CO_2 per m3 of cement (around 47 kg/ton, depending on the exact composition) produced from the use of Carbon Cure technology.

In the CarbonCure system, waste CO_2 is collected from local cement facilities, purified and delivered in bottles by local gas suppliers to concrete producers where it is precisely injected into the concrete mixers during the production stage using CarbonCure's proprietary injection and delivery system. CO_2 is delivered to the equipment as a gas in one stream and separately as a liquid, which phase changes into solid and gas within the mixing zone.

Initially the technology was for the pre-cast market (Carboncure, 2017). However, ready-mix concrete technology is now available. The company now claims to have treated "more than 1 million cubic yards" of cement.

Iron and Steel

The iron and steel sector has many synergies with that of cement in terms of making efficiency improvements. Similar approaches such as use of biomass- and waste-derived fuels, hydrogen, renewable electricity, plant design and digitization are all in development and could be short-medium term approaches.

Table 2. Case Studies for Decarbonisation in the Iron & Steel Sector

Company	Process/ Technology	Improvement
ArcelorMittal	Siderwin	Raw materials – Process using electrowinning of iron ore with renewable energy
ArcelorMittal	Carbon2Value	CCU – Separation of off gases for production of several value-added chemicals
ArcelorMittal	TORERO Biocoal	Raw materials – Use of biomass-derived fuel within blast furnaces
Baowu/Rio Tinto/Tsinghua	Various Innovations	Energy efficiency – Improved technical performance of conventional blast furnaces
LKAB-SSAB-Vattenfall	HYBRIT	Raw materials – Direct reduction of iron using renewable-derived hydrogen
Tata Steel	Combined Heat & Power	Energy efficiency – Recovery of waste heat for generation of low-grade heat and power
Lanzatech	Steelanol	CCU – Use of off gases for production of bioethanol
ULCOS Consortium	HIsarna	Energy efficiency – Modern furnace design that avoids shortcomings of conventional blast furnace
MIDREX	Al-Reyadah Plant	CCS – Direct reduction of iron using fossil-derived hydrogen with downstream storage
STEPWISE Consortium	SEWGS	CCU – Use of off gases toward production of a syngas or hydrogen.

In modern iron and steel plants, energy in the integrated flowsheet of a steel plant is based on coke oven gas (COG), blast furnace gas (BF gas) and basic oxygen furnace gas (BOF gas). The heat management is optimised through exchange of these gases, and in addition there is the possibility to capture CO_2 and to reuse it or capture and store it underground. Lanzatech for instance has been very successful in working with steel companies to implement its Steelanol gas fermentation technology for production of alcohols and aviation fuels.

Table 2 summarises the approaches of companies with technologies for decarbonising iron and steel included in the case studies for the report. CCUS approaches are particularly popular and several of the projects in the list are in this category.

Case Study: ArcelorMittal–Carbon2Value

The Carbon2Value project is an ongoing collaboration being principally led by ArcelorMittal and Dow Benelux as part of the EU's Interreg2Seas programme. The project began in January 2017 and has received around €10.4 million in direct funding for research to be conducted through January 2021.

The aims of the project generally include to reduce emissions by 30-45% across the steel industry, to be achieved by initial separation of the CO/CO_2 content within off gases, then allowing their conversion by CCU into valuable chemical products. The two candidate valued-added routes primarily studied by Carbon2Value include fermentation to ethanol (i.e. a drop-in transportation fuel) and Fischer-Tropsch synthesis of naphtha (i.e. an existing chemical building block).

Techno-economic analyses examining methanol synthesis report production costs between \$0.29-0.57/kg, averaging somewhat higher than the market price (between \$0.29-0.31/kg in April 2020).

Mining

Mining has not had the same level of focus on GHG emissions as have iron and steel, or cement.

The mining industry is so expansive –with over 700 companies globally covering production of fossil fuels as well as ferrous and non-ferrous ores. It has a high electricity burden, emits both CO_2 and the more potent GHG methane.

At the heart of decarbonizing the mining sector is the production of low-carbon electricity. Ironically, the move to renewables in itself has the effect of reducing the amount fossil fuel mined/extracted, but this is happening slowly, and, in the meantime, strategies are needed to decarbonise mining operations. Improving energy efficiency of mining processes, electrification of plant operations, reducing waste, capturing both methane and CO_2 where possible and optimizing heat recovery and transportation are all essential approaches.

Reductions in the industry's carbon footprint have thus far largely been realised as a result of the economic and competitive benefits that come with adoption of best available techniques (BAT). Methane abatement has been a relatively low-hanging fruit for the industry and the payback on recovered heat and power has provided good techno-economics, in particular for the more concentrated coal mine methane (CMM) and coal-bed methane (CBM) streams.

The industry faces many challenges to improve including slow renewable energy deployment, the lack of a sectoral analysis on strategies for holistic decarbonisation across the sector and insufficient government funding and policies to support sustainable mining projects. Despite this, several excellent decarbonization approaches are ongoing (Table 3).

Table 3. Case Studies for Decarbonisation in the Mining Sector

Company/ Project	Process/ Technology	Improvement
AngloAmerican	Mechanical/Advanced Fragmentation	Improvement to mechanical treatment for higher operations efficiency
Goldfields	PV Solar	Integration of renewable electricity
Rio Tinto	Aluminium Smelter	Direct GHG replacement and integration of renewable energy
JX Nippon	Biomining	Switching from conventional to biomining
Goldcorp's Borden Lake	Electrification	Electrification of plant operations
MEG Energy	SAGD	Increase in material efficiency
Anglocoal	Methane Abatement	CCUS
BHP Billiton	Methane Abatement	CCUS

Case Study: Rio Tinto Aluminum Smelter

The aluminium industry accounts for as much as 1 % of global GHG emissions and processing alumina into aluminium is a highly energy and carbon-intensive process, especially at smelters that source power from coal.

Rio Tinto developed a more efficient aluminium smelter that lowered its costs and emissions while improving productivity by 40%. In Canada, if fully implemented at existing aluminium smelters in the country, the technology could eliminate the equivalent of 6.5 million metric ton of GHG emissions.

Economics (costs) remain a driver in the decision to include renewable energy projects into mine development, and for energy efficiency projects to appeal to the mining industry, the total financial benefit need to be monetised.

Outlook

There are many challenges to consider when it comes to the possible technology changes in the Allied Industries:

In some ways (formulations, application of CCS), the industry is conservative, but in others (waste fuel burning, digitalization, heat recovery), the industry is quite rapidly developing. To reduce the emissions to near zero, it will be necessary to use CCS, likely in combination with the combustion of biomass; this will necessitate a significant increase in cost for cement.

Cost is also very important in a commodity product that can be traded globally, and a key issue is in common for low-carbon cement and low-carbon steel is to ensure that any competitors in a market facing penalties for CO2 emission are protected from competition from materials with high embedded CO2 emissions.

Although an important milestone for the iron and steel sector, the financial costs of mature capture technologies (i.e. amine scrubbing) are currently very high. Further development is required to improve the technoeconomic performance of capture processes and thereby the economic viability of CCS. Likewise, utilisation of off gases produced within the steel industry toward valuable chemical products is similarly economically challenged.

There is strong motivation to decarbonise the steel industry with a wide variety of emergent technologies currently in development. However, none of these technologies currently offers a definitive solution for complete decarbonisation of the steel industry.

Decarbonisation of the mining sector would trickle down to other industrial sectors since mining is the supply foundation of the entirety of industrial production. The mining sector stands at the start of most value chains, making the sector a critical supplier of essential products and raw materials

The pace and scale of renewable energy deployment in the mining sector is slower than the business case requires. Causes include: (1) Lack of clear strategic plans to integrate renewable energy, (2) third parties not used to develop, fund and deliver renewable energy assets, (3) Renewables seen as "non-core," with significant opportunity cost.

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Carboncure (2017 11 14). Overview of CarbonCure's ready mixed technology system and plant integration.

LEILAC Consortium (2020), Leilac Consortium Website. Retrieved from https://www.project-leilac.eu.

Other articles

This is the second in a series of articles summarising recent key reports from The Catalyst Group Resources Carbon Dioxide Capture and Conversion (CO2CC) Program. The previous issue featured, "Assessing the sustainability of chemical and polymer production" and the next issue will feature, "The Role of CO2 Emissions Reduction in Overall Corporate Sustainability Initiatives."

More information

More information about this report and other services of the CO2CC Program can be found at:
www.catalystgrp.com/tcg-resources/member-programs/co2-capture-conversion-co2cc-program

www.catalystgrp.com/php/tcgr_CO2cc.php

LEILAC Technology Roadmap to 2050

LEILAC (Low Emissions Intensity Lime and Cement) is a high potential cost-effective path to zero and negative carbon emissions lime and cement production.

LEILAC projects aim to apply a breakthrough in low-cost carbon capture technology that will enable Europe's cement and lime industries to reduce their emissions dramatically, while retaining their international competitiveness.

Focused on addressing these industries' unavoidable process emissions using Calix's novel carbon capture technology – and supported by leading industrial players – the LEILAC projects are on track to deliver commercially relevant solutions by 2024.

The LEILAC Technology Roadmap finds that the techno-economic forecast for the technology is very promising. It is feasible that the LEILAC process can be applied to a cement and lime plant in the near future at full scale, capturing their unavoidable process emissions for minimal cost.

Comprehensive life-cycle analysis studies have been carried out on a wide range scenarios and options, illustrating that dramatic emissions cuts in cement and lime production are possible using the low-cost LEILAC process.

There is an enormous drive, and support, for addressing unavoidable process emissions derived from the production of cement and lime, says the Roadmap. Until very recently, there were not the technologies nor policy mechanism available to support wholesale decarbonisation efforts globally – but that has changed. Today the global cement and lime industries are both committed, and are developing the tools, to take dramatic steps in achieving net zero production.

Highlights of the Roadmap

The Cement and Lime industries play a vital role in our society

Cement is used in our roads, buildings, homes, offices and almost all our infrastructure. Lime is used in a variety of applications including in the iron & steel, chemical, paper, pharmaceutical, drinking water, food, and farming industries. EU recognised these sectors as being 'indispensable' to the economy. Responsible for 8% of global CO2 emissions, global cement and lime demand will increase due to the global population growth and the trend of further urbanisation. They play a vital part of our society and economy.

The Cement and Lime industries are dedicated to decarbonising

Cement and lime industries, both through their associations and individual corporate pledges, have made clear commitments to carbon neutral emissions production by 2050.

The LEILAC process (Direct Separation) represents a low cost, eco-efficient means of capturing process CO2, and can be run on renewable energy

A variety of approaches and technologies are being developed to capture the CO2 emissions from the cement industry, and they all need to be urgently developed and scaled up. Supported by industry and the EU, the proven LEILAC technology captures unavoidable process CO2 emissions for minimal expense, as it as it does not need additional processes or chemicals. It can work in synergy with other technologies and approaches. It can also be fully powered by renewable energy and/or hydrogen, and all units will be 'electrification' ready.

These industries recognise that reaching carbon neutrality requires the use of carbon capture, utilisation and storage (CCUS)

Two-thirds of emissions from the production of cement and lime are unavoidable 'process emissions'. While several approaches can be taken to reduce the volumes of CO2 generated – and these should be pursued strongly – the most viable means of ensuring process emissions do not reach the atmosphere is by capturing and permanently safely storing the CO2 typically in minerals or by sequestration. Using the CO2, for example in the chemical industry and for creating synthetic fuels, may be an important enabler for capturing CO2 from the cement and lime industry.

The LEILAC process is being designed for efficient, global roll out

A LEILAC module addressing 20% of a cement plant's emission will begin constructed in 2022. The intent behind the commercial, global rollout of the technology is for the modular, scalable design to capture the process emissions from a plant of any size. The designs will eventually be 'blueprinted' and applied by engineering firms on a global basis to cement and lime plants, enabling localised expertise to be developed and used.

Appropriate long-term incentive frameworks and public financing for early movers are critical

Effective policy environments and incentive mechanisms are required globally to ensure that vital industries can continue to operate, while taking necessary decarbonisation steps. Public subsidies and investments are required to allow these technologies to continue to be quickly developed and installed globally. Support is required to enable and widely deploy transport and storage infrastructure, ensuring the captured CO2 does not reach the atmosphere.

CO2 transport and storage availability is vital to enable industrial decarbonisation, and without it the ability for our society to reach it climate change ambitions will be limited

The consortium considers the development and availability of transport and storage infrastructure to be vital for decarbonising the cement and lime industries. Unlike examples in the power and refining sector, the volume of CO2 to be stored per plant is less. This opens local storage opportunities and industries. Given the very small size of most of the cement and lime players, steps must be taken to quickly develop storage sites of all sizes; ensure larger storage developments are appropriately sized for 2050 (particularly if using public money and only facilitating bigger players); and enable fair access.

Societal acceptance and Government support are essential

While pursuing every option available to decarbonise, the cement and lime sector needs the help and assistance of our society (as both project stakeholders and product consumers)as it decarbonises. On a local level, that can range from small increases in prices of cement, through to active support of decarbonisation projects so they remain competitive.

Techno-economic summary

A detailed technoeconomic model has been developed as part of the LEILAC project, aiming to provide a verified, integrated process and economic model that provides insight into the CAPEX and OPEX costs of the LEILAC technology at full scale, in a range of scenarios.

The model allows for the identification of the optimal trade-off between energetic, economic and environmental performances and greatly de-risks the investment decisions needed to pursue the full-scale plant, as it provides accurate predictions of costs before plant construction, lessening investor risk.

The model is verified through the existing LEILAC pilot development and establishes a basis for objective, informed analysis and decisions.

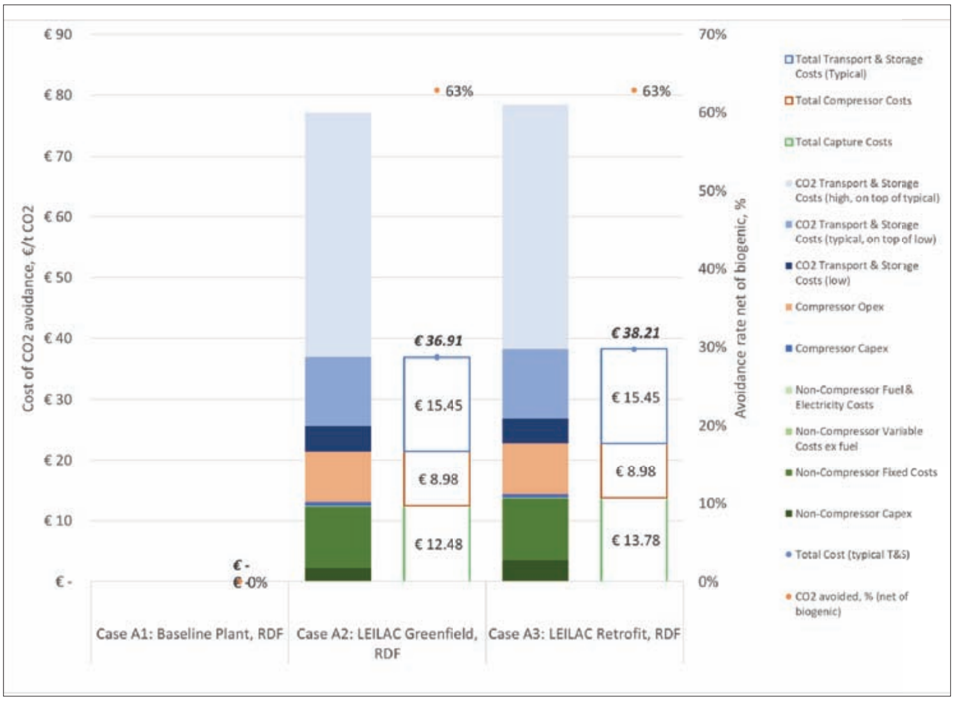
Key Findings of the technoeconomic model confirm: The LEILAC process represents a very low cost, efficient means of capturing process CO2

• Low operating costs:

- The technoeconomic model shows expected full chain CCS abatement costs (capture, transport, storage, including capex costs) for a future, full scale retrofit of a LEILAC installation, of around €38 per tonne of CO2 avoided . Almost half of these costs relate to transporting and storing the CO2.

- LEILAC's Energy and Mass Balance (EMB) for an nth-ofa- kind full scale retrofit using alternative fuels indicates a possible efficiency penalty of 0.6 GJ/t CO2 – with options for near zero penalty (the model does not assume energy is recovered from the CO2, and the degree of heat integration with the host plant that could be increased). With an electrically powered LEILAC, there could be an improvement of 0.7 GJ/t CO2.

- The resulting thermal fuel costs are low when RDF is used; indeed, given similar energy consumption (+2–3%) and the same fuel



It is expected that a future, full scale retrofit of a LEILAC installation may have a full chain CCS abatement cost (capture, transport, storage, including capex costs) of around €38 per tonne of CO2 avoided. 40% of these costs relate to transporting and storing the CO2

as the baseline plant, this has little contribution to the cost of capture. If coal or other more expensive fuel is required, this raises the fuel OPEX, depending upon the level of heat integration able to be achieved in a retrofit

• Low capital costs:

- The capital cost of the LEILAC plant is considerably lower than other technologies, with the gross costs for a full scale plant in the range of 58–64 M€ for greenfield projects, and retrofit projects costing around 66–74 M€.

- When offset against the costs associated with conventional pre-calciners and pre-heaters but including the cost of CO2 compressors, the project net additional CAPEX above an unabated reference plant is around 27–34 M€ for a greenfield plant, and 34–44 M€ for a retrofit.

- This range is based upon the LEILAC1 completed installation, current basis-of-design costs of the LEILAC2 installation, and industry-standard escalation from first-of-a-kind to nth-of-a-kind costs. These capital costs are comparative, if not lower than, other technologies targeting CO2 mitigation in lime and cement. The majority of the costs relate to the structural steel, foundations, and installation, as the technology is mechanically relatively simple.

• Low, fair cost CO2 transport and storage is required:

- While a baseline case of around €15 per tonne of CO2 is used for transport and storage costs, this is a major variable. This represents a 'low cost transport and storage scenario', (excluding initial compression). However, it is expected that for first movers, or areas with transport/ storage operators with limited capacity, the costs may be much higher. For this reason, within the 'high cost transport and storage scenario', a transport and storage estimate has been made of €50/tonne of CO2 (excluding initial compression).

- The significant variance in these transport and storage costs illustrate the need for low-cost solutions, and governmental assistance in developing solutions at large scale – ensuring free and fair access to smaller players.

More information

Download the full reports:

www.calix.global

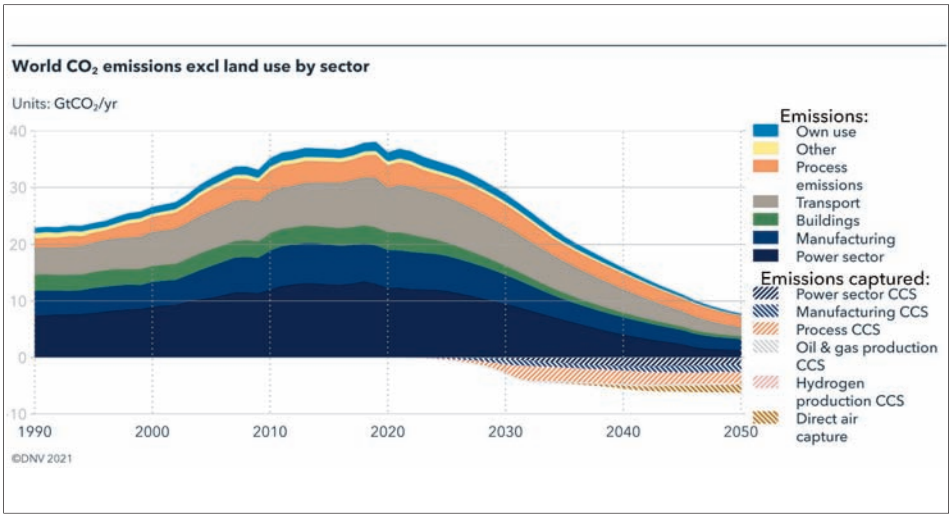
www.project-leilac.eu

DNV: Zero emissions by 2050 is not enough

DNV's new report "Pathway to Net Zero Emissions" describes a feasible way to limit global warming to 1.5°C and CCUS is required.

A feasible path to limit warming to 1.5°C requires certain countries and sectors to go below net zero and to do so well before the middle of the century, according to new analysis from the authors of the Energy Transition Outlook. Policy makers are set to meet in Glasgow for the COP 26 summit with an eye on achieving zero emissions by 2050.

For this to happen, North America and Europe must be carbon neutral by 2042 and then carbon negative thereafter, according to DNV's pathway to net zero. The pathway also finds that Greater China must reduce emissions by 98% from 2019 levels by 2050. There are regions that cannot realistically transition completely away from fossil fuels in the same timeframe, such as the Indian Subcontinent, which will reduce emissions by 64%.



In order to achieve net zero emissions in 2050, fossil fuel use is reduced about 80% from today, and carbon capture and removal removes a further 8 Gt of CO2 emissions

Pathway to Net Zero Emissions also lays out the pace at which different industry sectors need to decarbonize. The so-called hard-to-abate sectors will take longer to decarbonize and even if sectors like maritime (-90% CO2 emissions in 2050) and iron and steel production (-82%) scale up the introduction of greener technologies, they will still be net emitters by 2050.

Whilst the DNV Energy Transition Outlook forecasts the most likely energy future through to 2050, the Pathway to Net Zero Emissions offers a feasible way to limit global warming to 1.5°C. The report stands out amongst its peers as it is the only one that starts from the point of where we most likely will be in 2050 and then seeks to close this gap.

"Zero is not enough. That is because, try as they might, many developing nations and hard-to-abate sectors will not be able to achieve zero emissions by 2050 – the critical threshold for the world to stay within 1.5°C of warming," said Remi Eriksen, Group President and CEO of DNV. "Developed nations, leading companies and easy-to-electrify sectors are therefore going to have to go below zero before 2050."

The primary energy mix laid out in the net zero report is radically different from the current trajectory. Electricity meets just above half (51%) of the energy demand with wind and solar supplying 86% of electricity. Hydrogen, which is vital to decarbonize the hard-to-abate sectors, has a 13% share. Fossil fuels will still be required by countries and industries that are unable to decarbonize completely by 2050.

21% of the energy mix is derived from fossil fuels (8% oil, 10% natural gas and 3% coal), although there will be no need for new oil and gas fields after 2028 in this pathway. Carbon capture and removal technologies are a must according to the net zero report to remove the final 20% of emissions. Nuclear does not feature prominently because it is too costly compared to renewable energy.

The mid-term aim of the Paris Agreement to halve emissions compared to 2017 levels by 2030 is out of reach and the net zero report puts emission reduction at 30% at this point. However, for technologies to become scalable further down the line – such as hydrogen and CCS – investments and reshaping of policies must start now. Simultaneously, a massive ramping up of solar and wind needs to start immediately to accelerate the green electrification of the energy system beyond the current fast pace of change.

Time is the key restraint to realizing the Pathway to Net Zero Emissions, rather than money. Even with very large investments required, particularly in the short term, (cumulatively USD 55trn in renewables and USD 35trn in grids over 30 years) the additional costs of reaching 1.5°C are less than 1% of global GDP the next 30 years.

More information

Download the full report:
www.dnv.com

Projects and policy news

Significant milestone for Net Zero as UK announces first CCUS clusters

www.ccsassociation.org

The Carbon Capture and Storage Association (CCSA) has welcomed the announcement of the first successful CCUS clusters that will be taken forward following the Government's Cluster Sequencing competition.

The successful clusters are:

• The East Coast Cluster – a collaboration between Zero Carbon Humber, Net Zero Teesside and Northern Endurance Partnership, deploying CCUS across Humber and Teesside.

• HyNet North West – a CCUS and hydrogen energy project which will deliver low carbon hydrogen and CCUS in the North West of England and North Wales.

In addition, the Scottish Cluster – which is centred around the Acorn CCS project based in the North East of Scotland – was announced as a reserve cluster.

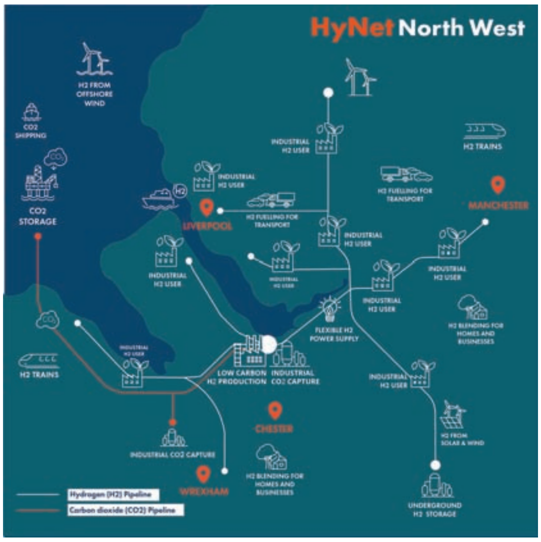
Ruth Herbert, Chief Executive of the CCSA said, "The UK has today taken a significant step towards meeting its net zero target, by selecting the first projects that will start capturing and storing carbon dioxide in the mid-2020s. These first clusters will showcase the breadth of applications for CCUS; including industrial decarbonisation, clean hydrogen production and greenhouse gas removal – and will make a significant contribution to regional growth and levelling up in some of the UK's key industrial heartlands."

"It is now absolutely critical that the industry has clarity over the long-term rollout of CCUS. If we are to achieve our climate goals, and the Climate Change Committee's target of capturing 22 million tonnes of CO2 per year by 2030, the industry and wider supply chain need a clear line of sight to the future delivery of CCUS across the country. The CCSA looks forward to working with Government to bring forward the next phases of clusters."

"Ahead of next week's Spending Review, we are calling for the Government to introduce a delivery plan for CCUS – setting annual spending budgets over the next decade to give the industry certainty to invest in projects now. As the UK prepares to host COP26 in November, we believe this commitment will send a strong signal that the UK is serious about meeting the Paris Agreement and becoming a global leader in this crucial planet-saving technology."

Nick Cooper (CEO of Storegga) on behalf of the Scottish Cluster said, "Whilst we are disappointed of the outcome of the sequencing bid, we remain convinced of the potential and significant advantages of the Scottish Cluster and are committed to the development of CCS to support decarbonisation of UK industry and power."

"We have been very clear that all of the current clusters need to be operating to meet UK net zero targets and will be seeking support to progress as soon as possible. The Scottish Cluster has been selected as a reserve project and we will continue engaging with Government to progress its development and planning. The Acorn project will play a significant role in achieving UK Net Zero and will be developed."



The HyNet project has been selected by the UK Government as a 'Track 1' cluster paving the way for deployment by the mid 2020s

Large-scale direct air capture to fuel plant planned for British Columbia

www.huroncleanenergy.com

The facility will capture carbon dioxide from the atmosphere and is expected to produce up to 100 million litres of ultra-low carbon fuel each year.

Huron Clean Energy with its partners, The Upper Nicola Band, Oxy Low Carbon Ventures and Carbon Engineering have begun preliminary engineering and design on a large-scale, commercial facility in British Columbia that would produce transportation fuel out of atmospheric carbon dioxide.

The proposed facility is being designed to use CE's Direct Air Capture and AIR TO FUELS™ technologies to capture carbon dioxide out of the air and deliver up to 100 million litres of ultra-low carbon fuel each year.

Powered by B.C.'s clean hydroelectricity, the plant will combine atmospheric carbon dioxide with hydrogen to produce renewable fuel, such as gasoline, diesel, and jet fuel. These fuels create up to 90 per cent fewer emissions than conventional hydrocarbons and work in existing airplanes, ships, trucks and cars without the need to modify the vehicles.

Huron intends to partner with Oxy Low Carbon Ventures, a subsidiary of Occidental, as Huron's execution and operations partner on the project. Construction is expected to begin in 2023 with operations targeted to commence approximately three years after that.

The partners have commenced a preliminary feasibility engineering and design study on the AIR TO FUELSTM facility. The B.C. Government's Innovative Clean Energy Fund is contributing $2 million in funding to the initial design work, demonstrating the Province's continuing support for home-grown cleantech innovations.

With a target production capability of up to 100 million litres of fuel each year, the project is expected to make a significant contribution to the B.C. Government's CleanBC target of 650 million litres of renewable and low-carbon fuel production by 2030. The project is also expected to create demand for up to 25,000 tonnes of green hydrogen annually, representing Canada's largest green hydrogen project announced to date – a clear demonstration of B.C.'s Hydrogen Strategy in action.

$4.5 Billion blue hydrogen clean energy complex in Louisiana

www.airproducts.com/LAblueH2

Air Products will build, own and operate the project, which will produce over 750 million standard cubic feet per day of blue hydrogen in Ascension Parish, Louisiana.

"Blue" products are produced using hydrocarbons as a feedstock, with the carbon dioxide in the production process captured for permanent sequestration. The project will create 170 permanent jobs with a total annual payroll of $15.9 million and more than 2,000 construction jobs over three years. It represents Air Products' largest-ever investment in the U.S.

A portion of the blue hydrogen will be compressed and supplied to customers by Air Products' extensive U.S. Gulf Coast hydrogen pipeline network. The network is the largest hydrogen pipeline system in the world, stretching more than 700-miles from Galveston Bay in Texas to New Orleans, Louisiana.

The balance of the blue hydrogen from the new Ascension Parish facility will be used to make blue ammonia that will be transported around the world and converted back to blue hydrogen for transportation and other markets.

The innovative megaproject will also feature the world's largest instance of CO2 capture for permanent sequestration and produce only environmentally friendly blue products. The megaproject is expected to be operational in 2026.

"This is a major industrial investment that will create quality manufacturing jobs while limiting environmental impacts, a goal envisioned by my Climate Initiatives Task Force," Gov. Edwards said.

Approximately 95 percent of the CO2 generated at the facility will be captured, compressed and transported by pipeline to multiple inland sequestration sites located along a pipeline corridor extending up to 35 miles to the east of the new production facility. Over five million metric tons per year (MTPY) of CO2 will be permanently sequestered in geologic pore space secured from the State of Louisiana approximately one mile beneath the surface. Air Products has already received approval from the State Mineral and Energy Board for the permanent sequestration of the CO2.

Climeworks and CarbFix begin operation of Orca

www.climeworks.com

www.carbfix.com

The world's first and largest direct air capture and storage plant has begun operation in Iceland capturing 4,000 tons of CO2 per year.

Orca, the world's first direct air capture and storage plant, began operation in Iceland (Image: ©Climeworks)

Orca delivers permanent, metered carbon dioxide removal and sets the precedent for a high-quality, verifiable carbon removal market by being the first direct air capture and storage service with a validated process - awarded mid-June 2021 by independent third-party DNV.

ON Power, the Icelandic geothermal energy provider, supplies clean renewable energy to power the Orca plant. Partners Carbfix, experts in rapid underground mineralization mix the air-captured CO2 with water and pump it deep underground, where it is trapped in stone through a natural mineralization process that takes under two years.

The construction of Orca started in May 2020 and is based on modular technology in the form of innovative stackable container-size collector units. These units are powerful and compact with minimal physical footprint. This has made it possible for Orca to be operational in under 15 months. Compared to the previous technology generation, the use of steel in the collector units has roughly been reduced by half per output unit.

Orca also supports the expansion of Climeworks, as the technology can easily be replicated at different locations worldwide and on ever larger scales, in a flexible manner wherever ample renewable energy and storage conditions are available. Strategically located adjacent to ON Power's Hellisheiði Geothermal Power Plant, Orca runs fully on renewable energy.

Orca is the first-of-its-kind plant that translates the vision of industrial-scale direct air capture and storage into reality. Climeworks has been able to intensify the process leading to increased CO2 capture capacity per module. This optimized process means that more carbon dioxide can be captured and stored than before.

Dow to build first ethylene and derivatives complex with CCS

www.dow.com

The Fort Saskatchewan site was selected due to availability of carbon capture infrastructure, competitive feedstocks and attractive government partnerships.

Dow has announced plans to build the world's first net-zero carbon emissions integrated ethylene cracker and derivatives site with respect to scope 1 and 2 carbon dioxide emissions. The project would more than triple Dow's ethylene and polyethylene capacity from its Fort Saskatchewan, Alberta site, while retrofitting the site's existing assets to net-zero carbon emissions.

The Company expects to allocate approximately $1 billion of capex annually to decarbonize its global asset base in a phased, site-by-site approach.

Dow expects the new brownfield ethylene cracker to add approximately 1.8 million metric tons of capacity in a phased manner through 2030, and along with derivatives capacity and site retrofit investments, will enable the Company to produce and supply approximately 3.2 million metric tons of certified low- to zero-carbon emissions polyethylene and ethylene derivatives for customers and joint venture partners around the globe.

The investment, which is subject to approval by Dow's Board of Directors and various regulatory agencies, would decarbonize approximately 20 percent of Dow's global ethylene capacity while growing polyethylene supply.

ION solvent meets the grade for post-combustion CO2 capture

ION Clean Energy successfully completes six-month CO2 Capture campaign demonstrating >98% capture rate at industry-leading energy requirements on post-combustion natural gas.

ION Clean Energy (ION) has successfully completed a six-month testing campaign for its third-generation solvent technology, ICE-31, at the National Carbon Capture Center (NCCC) in Wilsonville, Alabama, which was developed in partnership with the Department of Energy's National Energy Technology Laboratory and Southern Company.

ION is the first technology developer to test post-combustion CO2 capture from natural gas flue gas at the NCCC's Pilot Solvent Test Unit (PSTU) using the neutral test facility's newly configured natural gas-fired infrastructure. This work has been supported as part of its DOE-NETL project (DE-FE0031727).

ION and collaborators have previously conducted lab and small pilot studies with ICE31 demonstrating its unique physical and chemical properties that result in low energy requirements and exceptional solvent stability for post combustion CO2 capture. The ICE-31 campaign at NCCC operated for over 4,000 hours between March and September of this year that included parametric and long-term steady-state testing using multiple flue gases including natural gas combined-cycle (NGCC) surrogate flue gas (4% CO2), real gas-fired boiler gas (8% CO2), and real coal-fired flue gas (13% CO2).

ION would like to spotlight the following key results from its successful ICE-31 campaign:

1. 95%+ CO2 Capture for NGCC Flue Gas Conditions

• Continuous steady-state capture operation at the NCCC PSTU for more than 1,500 hours capturing 95%+ CO2 using natural gas boiler flue gas at 4% CO2 and 14% O2

• CO2 Capture efficiency of 98% demonstrated with only 2-3% more specific energy for 4% CO2 flue gas (relative to 95% capture)

• ICE-31 demonstrated CO2 capture ramp rates to 98%+ within minutes from warm start-up, indicating flexibility for dynamic operations necessary in load-following commercial environments

2. Industry-Leading CO2 Capture Energy Requirements

• Demonstrated specific energy of 3.0 GJ/tCO2 on 4% CO2 natural gas-fired flue gas at 95% capture, and 2.5 GJ/tCO2 on 13% CO2 for coal-fired flue gas at 91% CO2 capture

• ProTreat® modeling for typical U.S. facilities using ICE-31 at 95% CO2 capture indicate specific energy of 2.6 GJ/tCO2 for natural gas flue gas conditions and 2.4 GJ/tCO2 for coal-fired flue gas conditions

3. Stable and Environmentally Advantageous for Post Combustion CO2 Capture

• The campaign demonstrated ICE-31's exceptional solvent stability and extremely low emissions

4. ProTreat® Predictive Modeling Validated with Empirical Results from ICE-31 CO2 Capture Campaign at the NGCC

• ION used its proprietary module within the Optimized Gas Treating's software ProTreat®, where parametric predicted specific energies have an average error of 1% when compared with the empirically measured results from the NCCC campaign

These results confirm and expand ION's expectations that ICE-31 is an exceptional solvent for natural gas and other flue gases having low CO2 and high O2 concentrations such as in NGCC facilities.

ION will continue to advance commercial readiness of ICE-31 at the new 10 tonnes-per-day pilot facility being constructed at Calpine's Los Medanos Energy Center in Pittsburg, California. This facility is specifically designed to optimize capture at an operating NGCC power plant and is expected to begin operations in late 2022.

"We are extremely pleased to have had the opportunity to demonstrate the exceptional qualities of ICE-31 at NCCC. We believe the results obtained here strongly support the advancement of ICE-31 for capturing carbon from point source emissions with low CO2 concentrations," said Buz Brown, CEO.

"Furthermore, the rigorous test campaigns that we've completed over the past seven years with ICE-21, and now with ICE-31, have allowed us to validate our solvent specific modules in ProTreat® with an extremely high degree of accuracy. This underpins our confidence in translating the large pilot testing to commercial-scale application, with minimal process risks. With the additional work currently ongoing and planned in 2022, we are hopeful that ICE-31 will soon complement ICE-21 in ION's commercial portfolio for deployment in post-combustion flue gas applications."

ION is commercializing proprietary solvent and process technologies that are more cost efficient than current commercial solutions for use by point sources of CO2 emissions including natural gas and coal-fired power generators, and industrial emitters such as cement, petrochemical, steel, and mining operations. ION is currently working with domestic and global partners to deploy its carbon capture technology in commercial settings.

More information

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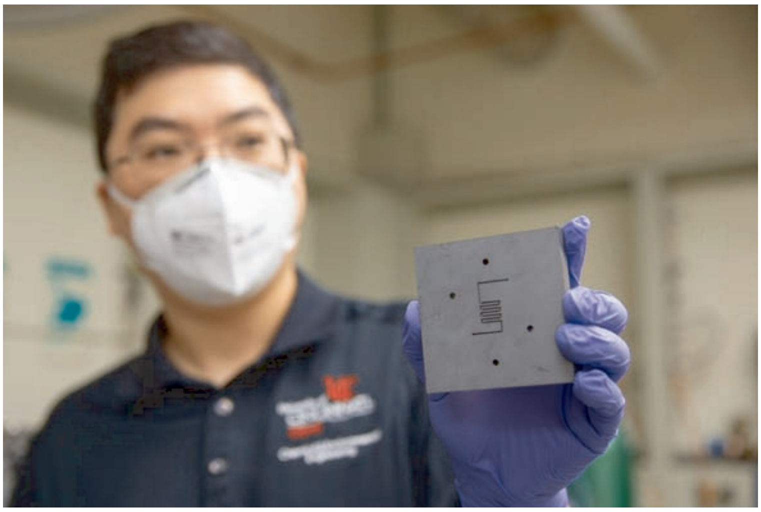
CO2 reactor makes Martian fuel

Engineers at the University of Cincinnati are developing new ways to convert greenhouse gases to fuel to address climate change and get astronauts home from Mars.



UC chemical engineer Jingjie Wu holds up the reactor where a catalyst converts carbon dioxide into methane. UC's research makes him optimistic that scientists will be able to remove carbon dioxide from the atmosphere. Photo/Andrew Higley/UC Creative + Brand

UC College of Engineering and Applied Science assistant professor Jingjie Wu and his students used a carbon catalyst in a reactor to convert carbon dioxide into methane. Known as the "Sabatier reaction" from the late French chemist Paul Sabatier, it's a process the International Space Station uses to scrub the carbon dioxide from air the astronauts breathe and generate rocket fuel to keep the station in high orbit.

But Wu is thinking much bigger.

The Martian atmosphere is composed almost entirely of carbon dioxide. Astronauts could save half the fuel they need for a return trip home by making what they need on the red planet once they arrive, Wu said.

"It's like a gas station on Mars. You could easily pump carbon dioxide through this reactor and produce methane for a rocket," Wu said.

UC's study was published in the journal Nature Communications with collaborators from Rice University, Shanghai University and East China University of Science and Technology.

Wu began his career in chemical engineering by studying fuel cells for electric vehicles but began looking at carbon dioxide conversion in his chemical engineering lab about 10 years ago.

"I realized that greenhouse gases were going to be a big issue in society," Wu said. "A lot of countries realized that carbon dioxide is a big issue for the sustainable development of our society. That's why I think we need to achieve carbon neutrality."

The Biden Administration has set a goal of achieving a 50% reduction in greenhouse gas pollutants by 2030 and an economy that relies on renewable energy by 2050.

"That means we'll have to recycle carbon dioxide," Wu said.

Wu and his students, including lead author and UC doctoral candidate Tianyu Zhang, are experimenting with different catalysts such as graphene quantum dots — layers of carbon just nanometers big — that can increase the yield of methane.

Wu said the process holds promise to help mitigate climate change. But it also has a big commercial advantage in producing fuel as a byproduct.

"The process is 100 times more productive than it was just 10 years ago. So you can imagine that progress will come faster and faster," Wu said. "In the next 10 years, we'll have a lot of startup companies to commercialize this technique."

Wu's students are using different catalysts to produce not only methane but ethylene. Called the world's most important chemical, ethylene is used in the manufacture of plastics, rubber, synthetic clothing and other products.

"In the future we'll develop other catalysts that can produce more products," said Zhang, a doctoral student in chemical engineering.

Like his professor, Zhang said he sees a bright future for green energy.

"Green energy will be very important. In the future, it will represent a huge market. So I wanted to work on it," Zhang said.

Synthesizing fuel from carbon dioxide becomes even more commercially viable when coupled with renewable energy such as solar or wind power, Wu said.

"Right now we have excess green energy that we just throw away. We can store this excess renewable energy in chemicals," he said.

The process is scalable for use in power plants that can generate tons of carbon dioxide. And it's efficient since the conversion can take place right where excess carbon dioxide is produced.

Wu said advances in fuel production from carbon dioxide make him more confident that humans will set foot on Mars in his lifetime.

"Right now if you want to come back from Mars, you would need to bring twice as much fuel, which is very heavy," he said. "And in the future, you'll need other fuels. So we can produce methanol from carbon dioxide and use them to produce other downstream materials. Then maybe one day we could live on Mars."

More information

www.uc.edu

Capture and utilisation news

Carbon Clean launches 'smallest' industrial carbon capture solution

www.carbonclean.com

The prefabricated, modular solution will make carbon capture simple, affordable, and scalable said the company.

The world's smallest industrial carbon capture solution – CycloneCC – has been launched by Carbon Clean, bringing the technology within reach of many more industrial emitters and shifting the economics of carbon capture.

The technology has been successfully pilot tested at 1 TPD in the UK and US and is currently being commercialised at 10 TPD and 100 TPD with select partners, including CEMEX and Veolia, for final product roll out by summer 2022 and market roll out in 2023.

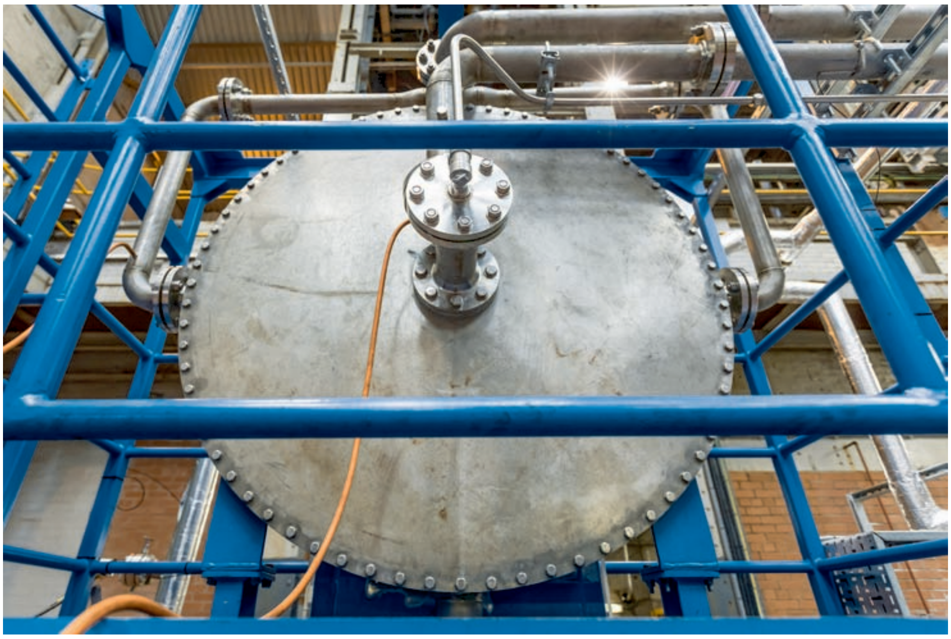
The project is backed by £5 million of UK Government funding.

The size of carbon capture technology has been a significant barrier to adoption. Earlier this month, a Decarb Connect survey of hard-to-abate industries – Scaling up CCUS - market insights – found that space remains a major concern and that industries need to be able to integrate carbon capture solutions within their existing footprint.

CycloneCC has a footprint that will be ten times smaller than conventional carbon capture, making it easily deployable in less than 8 weeks. The solution will also reduce capex and opex by up to 50%, driving down the cost of carbon capture to $30/tonne on average – a cost that is well below the current EU carbon price and makes the economic case for carbon capture, utilisation and storage undeniable.

"With many industrial plants having limited space, the biggest barriers to widespread CCUS adoption have been the size and cost of existing technology," said Co-founder & CEO of Carbon Clean, Aniruddha Sharma.

"Carbon Clean is breaking down these barriers with the world's smallest industrial carbon capture solution. CycloneCC is the next generation of technology that will make carbon capture simple, affordable, and scalable – bringing it within reach of a huge number of industrial emitters, especially those with small to mid-size emission point sources."



Built on an easy-to-transport skid mount, each CycloneCC unit can be delivered ready to install and fully operational in less than eight weeks

Elkem to test first carbon capture pilot for smelters

www.elkem.com

Elkem will test the world's first carbon capture pilot for silicon smelters at its plant in Rana, Norway.

The project has received financial support from Gassnova CLIMIT and is a follow-up to the company's recently launched climate roadmap to reduce emissions towards net zero while growing supplies to the green transition.

The carbon capture pilot is a collaboration between Elkem and Mo Industripark, SINTEF, Alcoa, Celsa, Ferroglobe, SMA Mineral, Norcem, Norfrakalk, Arctic Cluster Team and Aker Carbon Capture.

The test unit will be installed at Elkem's plant in Rana, which produces high purity ferrosilicon and Microsilica. In addition, emissions from SMA Mineral will also gradually enter the treatment plant. Aker Carbon Capture delivers the test unit, which is the only one of its kind in Norway.

The main goal of the project is to verify the technology on real industrial exhaust gases from smelters, in order to prepare a full-scale plant for industrial carbon capture.

Aker Carbon Capture selected by Viridor for energy from waste plants

akercarboncapture.com

www.viridor.co.uk

The companies are partnering on the installation of modular CCUS plants on five Viridor waste-to-energy sites across the UK.

To support the delivery of CCUS, Viridor has unveiled plans to invest up to £1bn into the UK. It has now partnered with Aker Carbon Capture for the delivery of five modular plants which it says could accelerate Viridor's net zero plans by a decade to 2030.

Aker Carbon Capture's Just Catch™ modular carbon capture plant is based on the company's proprietary and HSE-friendly carbon capture technology, which it has developed over the past two decades. The modular carbon capture plants will allow the technology to be deployed within fifteen months of planning and permitting, reducing fossil emissions at these sites by up to 90 percent.

Developing the modular CCUS plants on the five waste-to-energy sites combined with two planned bespoke CCUS plants, would deliver about 1.5 million tonnes CO2 savings a year, meeting 15 percent of the UK government's 2030 emissions reduction target.

Sleipner - lessons from 25 years of CO2 storage

Behzad Nobakht, Data Scientist at TÜV SÜD National Engineering Laboratory, provides an overview of the first evaluation of the joint effect of uncertain parameters in CO2 storage in the Sleipner project.

Carbon capture and storage (CCS) has the potential to reduce greenhouse emissions by up to 32 % by 2050. The best formations for the safe long-term storage of CO2 are usually sedimentary rocks with the appropriate porosity and permeability to prevent the gas from escaping.

However, other selection process parameters in any storage site should also be considered, such as volume, temperature and pressure, heterogeneity, caprock permeability, formation thickness, the presence of reactive minerals, CO2 solubility in brine, seismic fault potential, stress regime, injectivity and fracture formation.

Although the industry has learnt a lot from different storage pilot projects worldwide, the reality is that geological formations are heterogeneous, and their properties vary significantly with location. This creates difficulties in understanding the flow behaviour when CO2 and brine are injected into deep storage reservoirs.

The Sleipner CCS project was the first storage project on a commercial scale. About three years after the start of the project, the plume migrated through thin layers of shale and stopped beneath the caprock. Nearly 25 years after the first CO2 was injected at this storage site, although nothing suggests any of the CO2 has escaped to the atmosphere, it is essential to manage the risk of leakage through all stages of the storage process for any CCS programme. Also, a reliable estimation of storage capacity and plume dynamic behaviour is required to make better decisions. It is therefore necessary to quantify any uncertainties in the storage site.

Several researchers have therefore studied the Sleipner model to understand the inherent flow physics better, in order to find a satisfactory match between the CO2 plume outline from simulation and seismic data. Consequently, various sources of uncertainty in the geological model and the fluid have been investigated.

While some studies considered a limited number of parameters in their sensitivity analyses, most of the previous Sleipner models took one factor at a time (OFAT). This is where the response to one parameter is investigated and the rest are kept at their initial value. However, it has been proven that the effect of a parameter on the CO2 plume outline can be different in the presence of another parameter.

TÜV SÜD National Engineering Laboratory was therefore part of a research group* that, for the first time, investigated the joint effect of six important parameters – temperature, pressure, injection rate, porosity, permeability and caprock elevation. This has revealed their impact on the overall CO2 migration and trapping in Sleipner and identifies which parameters should be prioritised and calibrated more carefully. The research performed ten thousand forward simulations to analyse the importance of porosity and permeability heterogeneity, reservoir temperature and pressure, and caprock elevation to the plume outline.

Temperature and pressure

One source of uncertainty addressed in previous studies of the Sleipner model is CO2 density, a function of pressure and temperature, which was considered as one of the uncertain parameters in this most recent study.

The Sleipner aquifer is characterised with high porosity, permeability and lateral extension. As this is a suitable combination for CCS, there has been negligible pressure build-up since the beginning of the injection phase. This research assumed the reservoir pressure to be initially hydrostatic, and its uncertainty was addressed within the range of -4 to 4 bar.

In terms of temperature uncertainty, temperature changes would primarily affect the CO2 density and viscosity, and therefore its buoyancy and mobility. As Sleipner has no down-

Behzad Nobakht, Data Scientist at TÜV SÜD

hole gauge it has no accurate temperature data. However, the Volve field, 10 km north of the Sleipner injection well, provides one of the most precise options for a source of temperature data, and the average temperature in Sleipner has therefore been calculated at around 31 °C.

In this study, changing temperature and pressure was shown to have an impact on CO2 dissolution. When the temperature increased by 4 °C in the base case model (at constant pressure condition), CO2 solubility was reduced by around 1.1 %. On the other hand, decreasing pressure by 4 bars at isothermal conditions dropped solubility by about 0.2 %.

Injection rate

The original Sleipner model is made up of nine layers, each separated with a thin shale layer (Fig. 1), and the plume is injected at a depth of 1010.5 m into Layer 1 below sea level. In this study, we disregarded internal layers and modelled the whole thickness of the aquifer as one layer in a single model, only modelling Layer 9.

In a real case storage process, once injected, the plume encounters and passes through eight intra-formational shale layers before

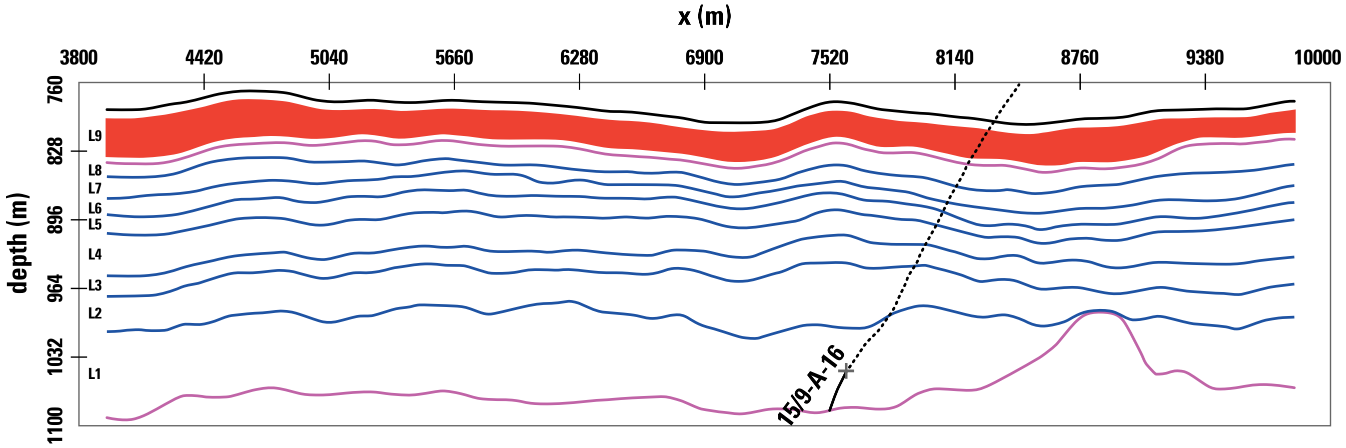


Fig. 1. Cross-sectional model for the Sleipner saline aquifer. Purple line: bottom of the reservoir; blue lines: intra-formational shale layers; red zone: the only sand layer considered in this study (L9); dotted line: injection well in the original model; 15/9-A-16: injection well.

reaching Layer 9. Of course, its flow behaviour is still subject to uncertainties and the mechanisms of vertical migration (diffusion, migration points or both). The number and location of vertical migration points are also uncertain. The volume entry rate into Layer 9 used in this study is taken from previous works (Nilsen et al., 2017) and ten thousand random rate multipliers (RM) between 0.7–1.3 are applied to the benchmark's volumetric rate to include the uncertainty of the entry rate into Layer 9.

Porosity, permeability and caprock elevation

The reported ranges for porosity and permeability data of Sleipner Layer 9 are 0.27-0.4 and 1100-5000 mD. This study generated ten thousand permeability realisations using a lognormal distribution approach within the reported range. Porosity realisations were then generated from permeability data using the Kozeny-Carman Correlation.

The typical seismic resolution is around 10 m, and the reported seismic vertical resolution for the Sleipner model is 8 m. In order to investigate the importance of the topography variations below the seismic detection range, ten thousand realisations of top surface elevations within the range of ± 5 m were considered in this study, using Gaussian random fields.

Simulation approach

This study ran ten thousand sets of simulations with two phases: CO2 and formation brine. The simulations were performed using the VE modelling approach, implemented in MATLAB Reservoir Simulation Toolbox's (MRST) co2lab module to make the study computationally feasible. The impact of uncertainty in caprock topography, reservoir pressure, reservoir temperature, porosity and permeability heterogeneity and volume entry rate into Layer 9 were studied for plume migration and structural trapping to analyse the importance of uncertain parameters on the CO2 migration and trapping process.

To provide the simulation inputs and treat the parameters equally for each of the ten thousand simulation runs, six parameters were randomly selected. Two base assumptions of VE modelling were also followed. First, the hydrostatic equilibrium between brine and CO2 is pre-assumed throughout the simulation. Secondly, the vertical flow migration can be considered negligible compared with the horizontal one.

The Sleipner condition is close to the critical point (30.4 °C and 73.8 bar), and CO2 has a gas-like behaviour in a supercritical condition. Therefore, increasing the temperature results in a significantly lower density and consequently a higher buoyancy force. Moreover, a higher temperature at pressures close to the average pressure of 83 bar in Layer 9 results in lower viscosity and consequently higher mobility.

In high temperature conditions, the CO2 plume conforms more accurately to the caprock morphology. Previous research had suggested that increasing the temperature would improve the match between simulation and seismic surveys results. However, our study shows that an RM of 0.86 results in the best average plume match.

Note that the results presented here are just one of the many possible "acceptable" results. Since the parameters are not entirely independent, a different set of input parameters might potentially lead to the same if not better results. The problem we are dealing with in the Sleipner is complex, so a different set of parameters might account for the best match in each time step. Therefore, a data-driven modelling approach was used to identify the contribution of each parameter in CO2 plume migration more precisely.

The joint effect of parameters

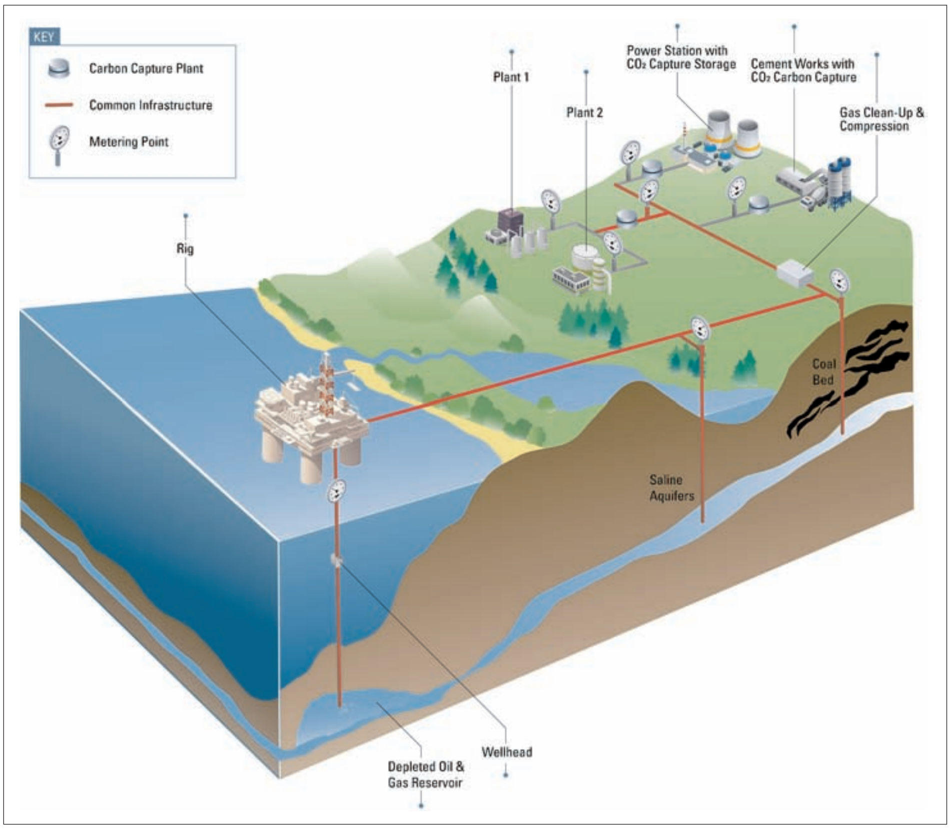
Results clearly show that the impact of each parameter might change throughout the simulation. For instance, while the elevation is shown to be the dominant factor in 2001 (38.00 %), its impact becomes less significant later in 2010 (14.43 %). Meanwhile, the importance of injection rate seems to increase with time and its percentage predictor importance changes from 17.83 % in 2001 to 32.40 % in 2010.

One justification is that the injection rate is overshadowing the impact of other uncertain parameters in later years. This happens because the volume entry rate into Layer 9 is not constant and increases with time. The injection rate is the only parameter that impacts the mass flow rate in the aquifer directly.

Since we were using multipliers for this parameter, a constant amount was not applied throughout the simulation. As the injection rate in the model increases, its impact becomes more significant as well. The results indicate the caprock elevation as the most important parameter in controlling the plume outline in the Sleipner model.

Although there have been several sources of uncertainties reported in the research literature for determining the best plume match, the impact of caprock morphology seems to be underestimated as it has an average importance of about 26 %.

This study also shows that permeability and porosity contribute to changing the shape of the plume outline, with an overall percentage importance of around 13 % and 6 %, respectively. Uncertainty in pressure has an overall percentage importance of around 9 %. Pressure and temperature both have an impact on viscosity and density. As expected, a larger and positive caprock elevation change and porosity increase the structural trapping.



CCS has the potential to reduce greenhouse emissions by up to 32% by 2050

Conclusions

For this study, the upwards migration of CO2 through internal layers was implicitly modelled by rate multipliers. A more detailed study would involve applying a VE model to each internal layer, which we consider worthy of future work.

The results showed that CO2 density values of around 390 kg/m3 improve the plume match in the Sleipner model. The caprock morphology was also shown to be the most critical parameter in controlling the plume migration, with an overall importance of 26 %, followed by the injection rate (24 %), temperature (22 %), heterogeneity in permeability (13 %), pressure (9 %) and porosity (6 %).

As was shown in the results of previous studies using the OFAT approach, the effect of a parameter on the plume outline can be different in the presence of another parameter, which could be considered as one of the limitations of the OFAT approach. For example, while previous studies showed that increasing temperature would result in a better match in the Sleipner model, our results showed that this statement is not always valid and depends on the realisations used for caprock, porosity and permeability.

However, there are not any fixed correct sets of realisations for these data. Any distribution of porosity and permeability within the reported range, and any elevation variations within the ranges lower than the seismic detection limit, can be considered as a valid answer. Therefore, this study cannot make a general statement on the impact of a parameter on the plume match in Sleipner, based on the results from the OFAT approach.

This current work also helps us understand which of the addressed uncertain parameters for the Sleipner model in literature should be prioritised and calibrated more carefully to improve the match. A similar study could be performed on any CO2 storage or oil and gas site to find the importance of uncertain parameters before performing a history matching. After which, it is possible to minimise the mismatch between simulation and observed data more efficiently by improving the geological, operational and fluid properties.

Carbon capture and storage can play a significant role in reducing global CO2 emissions and reaching the net-zero target. The majority of saline aquifers are sparsely drilled with minimal dynamic data and are subjected to substantial uncertainty.

We have used data-driven models to comprehensively analyse the joint-effect of fluid and model uncertainties on CO2 plume migration and trapping mechanisms. The current research improves our understanding of the CO2 storage process in large storage sites, which helps to have a more secure long-term storage plan.

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TÜV SÜD is a global centre of excellence for flow measurement and fluid flow systems and is the UK's Designated Institute for Flow and Density Measurement, with responsibility for providing the UK's physical flow and density measurement standards.

More information

www.tuvsud.com

Transport and storage news

Urgent action needed to reduce uncertainty on CO2 storage prospects

www.uq.edu.au

An urgent increase in policy support and investment would be needed for CCS to achieve the scale needed to meet global decarbonisation goals, according to University of Queensland and Princeton University researchers.

The study's lead author, Dr Joe Lane, said CCS was regarded as a key technology for reducing energy and industrial sector emissions and for achieving negative emissions when coupled with bioenergy or direct air capture of carbon dioxide.

"Most scenarios for deep decarbonization of the global economy rely on massive scale CCS to be compliant with the Paris Agreement - from three to more than 20 gigatonnes of CO2 per year being captured and stored, worldwide by 2050," Dr Lane said.

"Even the lower targets imply an extremely challenging pace and scale of CCS deployment across all major economies."

UQ Centre for Natural Gas Director Professor Andrew Garnett said more information is needed globally to support such high expectations.

"Those scenarios typically assume that there is more than enough storage volume available in porous geological reservoirs around the world," Professor Garnett said.

"But the essence of our abatement challenge is not the volume of storage available, it's the rate at which CO2 can be safely injected and permanently contained that counts.

"We have a poor understanding of injection rates that can be sustained in key regions and in aggregate - there is simply not enough key data available."

Princeton University Senior Research Scientist from the Andlinger Center for Energy and Environment, Dr Chris Greig, said the storage uncertainty created a "chicken and egg" problem for CCS ambitions.

"The characterisation work required to build confidence in our storage capacity relies on mobilising tens of billions of dollars in risk capital over the next decade," Dr Greig said.

"Currently, these capabilities are in the Oil and Gas sector. For the necessary investment to happen, storage developers need to be confident that the capture projects will actually be built before they enter into long term storage contracts."

"At the same time, investors will remain cautious until there's a high level of confidence that cost-effective storage capacity will be available."

Dr Lane said strategic planning is needed now if carbon dioxide storage is to play a major role for decarbonising crucial industries and the developing world. The study is published in Nature Climate Change

Wärtsilä and Solvang retrofit CCS system

www.wartsila.com

solvangship.no

Wärtsilä Exhaust Treatment will retrofit a full-scale pilot installation of a CCS system on one of Solvang's ethylene carriers, the 21,000-cbm Clipper Eos.

Wärtsilä Exhaust Treatment will design the retrofitted unit while it also completes a land-based 1MW test system at its Moss headquarters in Norway. The land-based unit will be completed in autumn 2021, and the companies expect to retrofit the pilot CCS system on the Clipper Eos by 2023.

The agreement reinforces Wärtsilä's continued research and development into carbon capture at the point of exhaust to support the shipping industry's decarbonisation pathway.

The project will enable both Wärtsilä and Solvang to strengthen their position at the cutting edge of sustainable technology development in shipping. To remain in line with the IMO's decarbonisation targets, Wärtsilä is initially aiming for a 70% reduction in CO2 emissions at the point of exhaust with its pilot unit.

Commenting on the announcement, Sigurd Jenssen, Director at Wärtsilä Exhaust Treatment, said, "Joining forces with Solvang to build and retrofit a commercially viable CCS technology demonstrates to the industry that we are only two or three years away from bringing to market another vital tool in shipping's decarbonisation toolkit. Our land-based test unit is nearing completion, and we will then move to making it a reality on the Clipper Eos, ensuring that both Wärtsilä and Solvang remain at the forefront of maritime sustainability technology advancement."

Northern Lights awards CO2 carrier ship contract

northernlightsccs.com

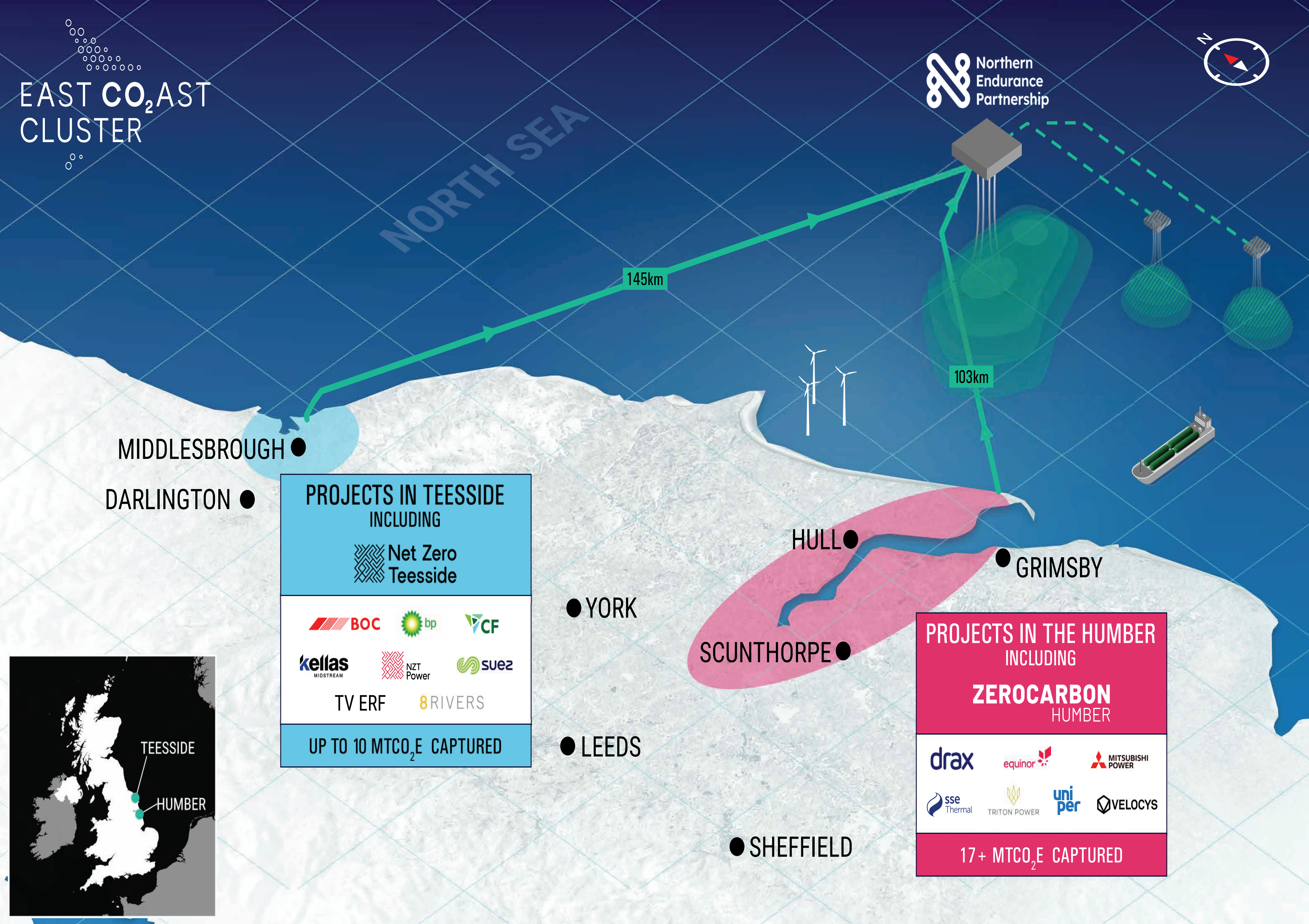
Northern Lights has awarded contracts for building of two dedicated CO2 carriers to Dalian Shipbuilding Industry.

As part of the first phase of its CO2 transport and storage infrastructure development, Northern Lights is building two dedicated CO2 carriers, each with a cargo size of 7,500 m3 and a length of 130m. The ships will be built by Dalian Shipbuilding Industry Co., Ltd. (DSIC) and will be ready for delivery by mid-2024.

The vessels are designed to transport liquid CO2 with purpose-built pressurised cargo tanks. The primary fuel for the ships will be LNG, keeping emissions low. Other innovative technologies, such as a wind assisted propulsion system and air lubrication will be installed to reduce carbon intensity by around 34% compared to conventional systems. The ships are the first of its kind and will potentially set a new standard for CO2 shipping on coastal trading routes.

"The award of these contracts is a significant milestone for Northern Lights. The use of ships will enable the development of a flexible and efficient European infrastructure network for transport of CO2 captured by our industrial customers, keeping costs as low as possible to help decarbonisation scale up. I am also very pleased that these ships will be built to keep their own emissions to a minimum through use of innovative technology", says Børre Jacobsen, Managing Director of Northern Lights JV.

Once in operation, the ships will load captured and liquefied CO2 from European emitters and transport it to the Northern Lights receiving terminal in Øygarden in western Norway.



EAST CO_2AST CLUSTER
Northern Endurance Partnership
NORTH SEA
145km
103km
MIDDLESBROUGH
DARLINGTON
PROJECTS IN TEESSIDE
INCLUDING
Net Zero Teesside
BOC
bp
CF
kellas MIDSTREAM
NZT Power
suez
TV ERF
8RIVERS
UP TO 10 $MTCO_2E$ CAPTURED
YORK
LEEDS
HULL
SCUNTHORPE
GRIMSBY
SHEFFIELD
PROJECTS IN THE HUMBER
INCLUDING
ZEROCARBON HUMBER
drax
equinor
MITSUBISHI POWER
sse Thermal
TRITON POWER
uniper
VELOCYS
17+ $MTCO_2E$ CAPTURED
TEESSIDE
HUMBER