THE CCUS HUB

THE CCUS HUB PLAYBOOK

A guide for regulators, industrial emitters and hub developers

FOREWORD

It's long been clear that we need CCUS to help achieve Paris Agreement climate goals. However, even though the math is compelling, broad deployment of CCUS has remained challenging.

The good news is that this is changing rapidly. The lack of alternatives for decarbonizing heavy industry has brought a growing recognition that CCUS offers governments and industry significant opportunities as an integral part of their decarbonization strategies. Reflecting the maturing policy support provided by several countries, dozens of new CCUS projects are being announced.

Policy-driven CCUS deployment will enable projects to get started in many countries and grow the few dozen carbon capture facilities operating today into a true CCUS industry. Part of an efficient policy solution is to support formation of CCUS networks and hubs, where groups of emitters collaborate with regulators and hub developers to build shared infrastructure, achieve economies of scale, and develop practical business models within a new industrial value chain. As these hubs develop, they are turning a growing number of projects into a scalable reality.

That's why we welcome this initiative by OGCI to share lessons from the most advanced CCUS hubs under development globally, helping to create a new mindset for CCUS developers and a culture of knowledge sharing. We look forward to partnering with OGCI and others to evolve The CCUS Hub platform into a shared resource and global community. If there is one lesson that is already clear, it is that CCUS will only get close to achieving its potential if we collaborate.

Jarad Daniels
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1. CCUS BASICS

1.1 UNDERSTANDING CCUS

WHAT IS CCUS?

Carbon capture, utilization and storage (CCUS) is a set of methods to stop carbon dioxide reaching the atmosphere.

The combustion of fossil fuels, and some industrial processes such as cement or steel making, emit carbon dioxide that is mixed in with other gases in various concentrations. A range of capture technologies are used to extract it in concentrated form. The carbon dioxide can then either be stored or used.

In carbon capture and storage (CCS), the captured carbon dioxide is transported predominantly by pipeline or ship to an offshore or underground storage site and pumped into a suitable storage reservoir such as a deep saline aquifer or depleted oil or gas field.

In carbon capture and utilization (CCU), the captured carbon dioxide is put to use. The carbon dioxide can be permanently locked up in a product (in construction materials, for example) or go into a process (such as enhanced oil recovery, EOR). It can also be used and then emitted – for example through chemical conversion to make synthetic fuels, displacing fossil-fuel use.

Today, CCUS projects around the world are storing millions of tonnes of carbon dioxide each year. We now need to turn millions into billions. One way to accelerate that scale-up is to focus on CCUS hubs, which take carbon dioxide from several sources and then transport and store it using common infrastructure.

WHY IS CCUS IMPORTANT FOR THE ENERGY TRANSITION?

CCUS can clean up the stubborn emissions that renewables struggle to reach. According to the International Energy Agency, "reaching net zero will be virtually impossible without CCUS".

Industrial cleaner. Industry accounts for about 30% of global greenhouse gas emissions, mostly in the form of carbon dioxide. Some can be cut out easily using renewable electricity, but much cannot. For example, carbon dioxide is a by-product of some chemical processes, such as making the most common type of cement using limestone. CCUS may be the most realistic way to tackle those emissions. Many industrial processes also need intense heat, which is difficult or expensive to provide with electricity, so it usually comes from burning fossil fuels. CCUS could be the most cost-effective way to cut those emissions.

Power supporter. Future electricity generation is likely to be dominated by solar and wind power, with output that depends on the weather rather than tracking demand. On a still, grey day, we will need backup power. In many countries, backup will be provided by natural gas – which could supply low-carbon electricity with the help of CCUS.

Hydrogen launcher. Hydrogen will be an essential part of a net-zero world. It can be used to power heavy industry and long-range transport in a low-carbon way. It can also replace natural gas in providing heat. It is becoming an important part of Europe's decarbonization plans. Eventually, most hydrogen will be made using surplus renewable power; in the meantime, gas-rich countries can drive the clean hydrogen market by making it from natural gas. This process generates carbon dioxide, so CCUS is needed to clean it up.

Air purifier. Just cutting down on emissions won't be enough to prevent dangerous climate change. Some carbon dioxide will need to be taken out of the air, both to balance any remaining greenhouse gas emissions and to compensate for emissions in the past. This is known as carbon removal. The storage element of CCUS will be vital in ensuring the removed carbon does not return to the atmosphere.

HOW MUCH CCUS IS NEEDED TO REACH NET ZERO EMISSIONS?

The International Energy Agency recently developed a scenario to show what technologies must be deployed to reach net zero emissions from the energy sector. It sees carbon capture reaching 1.6 billion tonnes (gigatonnes) by 2030 and 7.6 gigatonnes per year by 2050. To put that into perspective, stand-alone CCUS facilities can capture around 1-2 million tonnes of carbon dioxide per year. CCUS hubs will be able to store 5-10 million tonnes of carbon dioxide per year by 2030, so around two hubs a month would need to be built every year until 2030 to get on track.

In the IPCC Special Report on Global Warming of 1.5°C, nearly all of the 90 scenarios include CCS in some form. Across all scenarios, the average volume of CCUS in 2050 is 10 gigatonnes per year.

LEARN MORE

- CCUS: Barriers, enabling frameworks and prospects for climate change mitigation, The Oxford Institute for Energy Studies (January 2022)

HOW CCUS CAN SUPPORT INDUSTRIAL REGIONS AND JOBS

Renewable electricity and efficiency measures can only go part way to decarbonizing heavy industry. The main barriers are access to enough on-demand renewable power, the need for intense heat, and the carbon dioxide produced in some common chemical processes.

CCUS is currently the most promising and in some cases the only viable way to remove the remaining emissions from making cement, steel, chemicals and fertilizers.

Without CCUS, rising carbon prices in some countries are liable to make their heavy industries uncompetitive, pushing production into countries where emissions are not regulated. Then, as countries introduce carbon border taxes to re-level the playing field, exporters will need to introduce CCUS or other decarbonization solutions to remain competitive. In July 2021, the European Commission announced plans for such a carbon border tax, to be phased in from 2026.

With CCUS to lift the carbon burden, industrial regions can survive and flourish while moving to low-carbon production. As well as preserving traditional industries and all the jobs that go with them, it promises to minimize disruption to society and economy by making use of existing infrastructure. The CCUS industry itself will bring new jobs and income. It can also enable industrial regions to reinvent themselves as low-carbon technology hubs, attracting new green businesses.

WHAT ARE THE ALTERNATIVES TO CCUS?

Low-carbon hydrogen is likely to be a friendly rival to CCUS in decarbonizing some areas of industry, and for backup power. When made using renewable power to split water, it is known as green hydrogen. This can be burned instead of natural gas in backup powerplants; it can replace the fossil fuels used in steelmaking; and it can provide high temperatures for some other industrial processes.

Green hydrogen is expensive today and will take several years at least to scale up. Until then CCUS could give the hydrogen economy a boost, by enabling a different kind of clean hydrogen – blue hydrogen – made from natural gas with carbon dioxide captured and stored. That would scale up the market for clean hydrogen and pave the way for more green hydrogen in the future.

There are some industries where hydrogen is not a decarbonization solution. For example, it cannot decarbonize cement manufacturing, the source of over 5% of manmade global greenhouse gas emissions, which releases carbon dioxide from limestone used in the process. Alternative building materials are being explored that could eventually do away with the need for cement, but for the foreseeable future CCUS is the only way to cut emissions.

In the IPCC's Fifth Assessment Report, excluding CCS from the portfolio of technologies was found to double the cost of remaining within 2°C, the largest cost increase from the exclusion of any technology. Now that policymakers are exploring how to decarbonize industry in the next few decades, they are starting to see CCUS – as hard as it is – as faster, cheaper and more scalable than available alternatives.

IS CCUS NECESSARY FOR CARBON REMOVAL?

To meet the Paris goal of limiting global warming to 1.5°C, the world will almost certainly have to go carbon negative, taking a lot more carbon dioxide out of the air than is put into it. Nature-based solutions like planting trees and other land-use change can address part of the challenge, but the required quantities are so vast and the need for more durable solutions so crucial that technological solutions will be unavoidable.

Some emerging solutions, such as biochar and enhanced weathering, use technology to support and enhance natural solutions. The IPCC estimates that each of these could remove up to a few gigatonnes of carbon dioxide per year in 2050, but uncertainties are large.

The leading technological carbon removal options involve CCS. Bioenergy with carbon capture and storage (BECCS) bolts CCS onto power plants that burn biomass – so plants suck carbon out of the air, which is then buried via CCS. Direct air capture and storage (DACS) captures carbon dioxide directly from the atmosphere. These technologies are certainly not perfect. DACS is expensive and requires large amounts of energy, while BECCS will require a source of sustainable biomass in vast quantities, without competing for agricultural land. They are, however, crucial options to develop as part of net zero strategies.

By scaling up CCUS now, the world will make a vital start on building the infrastructure needed for this negative carbon effort.

HOW MATURE IS CCUS TECHNOLOGY?

Carbon capture has been in use since the late 1930s, using carbon dioxide as an ingredient for carbonated drinks and other industrial purposes. The storage part began in 1972, when a plant in Texas started injecting captured carbon dioxide into an oilfield, in order to force more oil out of the wells – a process known as enhanced oil recovery (EOR). Pure geological carbon storage, without EOR, goes back to 1996, when Norway started pumping carbon dioxide captured from natural gas production into a saline aquifer under the North Sea at its Sleipner facility.

These two uses – EOR and natural gas processing – still account for most of the 40 million tonnes of carbon dioxide captured globally each year. While these uses will continue and can support CCUS business models, the scale-up of CCUS needs to focus on abating industrial and backup power emissions, as well as negative emissions.

HOW DOES CARBON CAPTURE WORK?

In the exhaust from industrial processes and fossil fuel powerplants, carbon dioxide is mixed in with nitrogen, oxygen and other gases. So CCUS first separates out the carbon dioxid.. The main method currently used to do this is amine scrubbing. Flue gas is piped into the bottom of a vertical reactor vessel, where it rises up through a mist of a carbon dioxide absorbing liquid (usually an amine solution). The scrubbed gas is released at the top, with typically 90% or more of its carbon dioxide removed. The amine then goes to another vessel where high-temperature steam takes out the carbon dioxide. Finally, the near-pure carbon dioxide is compressed ready for transport.

Other approaches are being pursued to reduce costs and improve efficiency. One option is to use solid calcium oxide that reacts with carbon dioxide in flue gas to become calcium carbonate, which is then heated to reverse the reaction and generate concentrated carbon dioxide. Then there are polymer membranes that can separate gases, as well as adsorption onto the surface of porous structures such as metal-organic frameworks.

Instead of catching the carbon dioxide after combustion, fuel can be pre-treated at high temperature to turn it into a mixture of carbon dioxide and hydrogen. One of the capture technologies is to separate out the carbon dioxide, keaving hydrogen that is burnt as low carbon fuel. It is also possible to burn fuel in pure oxygen to generate a stream of concentrated carbon dioxide, doing away with the need for any gas-separation technology. This technology is, however, still in development.

HOW DOES CARBON TRANSPORT WORK?

The main options are pipelines, ships and tanker trucks. For pipeline transport, the carbon dioxide gas is usually compressed. At a pressure of more than 74 atmospheres it enters what's known as densephase: dense like a liquid, but highly compressible and low viscosity like a gas. Pipeline transport is the lowest-cost option for large volumes of carbon dioxide or where pipeline infrastructure already exists. This is the solution being used by Net Zero Teesside in the UK and Port of Rotterdam in the Netherlands, for example.

Where stores or pipelines are not readily available or volumes are smaller, carbon dioxide can be chilled into a liquid state to go on ships and/or tanker trucks for transport to the injection location. The transport cost per tonne is higher, but the solution offers greater flexibility for collecting multiple sources, requires less capital expenditure upfront and is lower risk in built-up areas. Northern Lights in Norway is developing an innovative solution to allow emissions to be collected by truck from emitters from across Europe, brought to ports where it is shipped to Norway and stored in a saline aquifer in the North Sea.

HOW DOES CARBON STORAGE WORK?

The aim of CCUS is to keep carbon dioxide permanently out of the atmosphere. The favoured method is geological carbon storage – injecting carbon dioxide into deeply buried rocks. It is injected at high pressure, in a state that is both dense like a liquid and low viscosity like a gas.

Before injection can take place, the subsurface is studied and tested with seismic analysis to verify that the site is suitable for storage. Suitable rock formations are porous, to accommodate the carbon dioxide, and sealed off by impermeable layers of rock above.

Depleted oil and gas fields fit the bill, as the geology is well known and has demonstrated ability to hold oil and gas and natural carbon dioxide underground for millions of years, trapped in microscopic rock pores and under impermeable cap rocks. Old wells are potential leakage sites, so they need to be plugged with cement and monitored to ensure the storage is secure. The Porthos CCUS hub in Rotterdam plans to use a depleted gas field in its first phase.

Carbon dioxide can also be injected into large saline aquifers, where brine is held within porous rocks. Some carbon dioxide gets trapped in small pores, while the majority flows upwards to be trapped under the impermeable caprock. Over hundreds to thousands of years it dissolves in the brine, eventually combining chemically with the rock. This last process, mineralisation, ensures storage for thousands of years, and also occurs in depleted oil and gas fields. (For more detail on trapping mechanisms see this 2019 review article.)

Saline aquifers have more potential capacity than depleted oil and gas fields, but they are less well studied and therefore require more appraisal work upfront to support carbon dioxide storage on a huge scale. Northern Lights in Norway and the Net Zero Teesside and Humber CCUS hubs in the UK are using saline aquifers for storage.

Close monitoring using seismic data, helps to confirm that the carbon dioxide is migrating within the rock space as expected. If it does not, the operator can change the injection pressure or sites to manage its behaviour.

Another option is mineral storage: chemically reacting carbon dioxide with calcium or magnesium-based minerals to form stable carbonates. This is currently much more expensive than geological storage and uses a lot of energy. Mineralization is being used on a small scale in Iceland to store carbon dioxide from direct air capture. Research is underway in several countries to test its potential for large-scale storage.

HOW MUCH GEOLOGICAL STORAGE SPACE IS AVAILABLE?

The Oil and Gas Climate Initiative has put together a CO_2 storage resource catalogue covering more than 700 potential geological sites in 18 countries. The catalogue estimates potential global carbon dioxide storage capacity at roughly 13,000 gigatonnes – more than enough to meet projected needs for CCUS over the coming century. Around 550 gigatonnes is identified as 'discovered capacity' – sites where at least one well has been drilled to establish the potential for carbon dioxide storage. Further exploration is expected to reveal many more such sites.

HOW MUCH DOES CCUS COST?

CCUS is costly, but both scientists and politicians have calculated that it is the most cost-effective way to decarbonize industry. The IPCC's Fifth Assessment Report found that excluding CCS from the portfolio of technologies doubled the cost of remaining within 2°C, the largest cost increase from the exclusion of any technology.

More recently, politicians in the Netherlands and Norway have determined that CCS is the cheapest way to remove carbon dioxide emissions at scale. In the Netherlands, the government held an auction in 2021 to identify the cheapest price per tonne of industrial carbon dioxide reduction. CCS solutions were the most cost-effective by far, taking 40% of the available subsidy budget to achieve 60% of the government's targeted emission reductions. In Oslo, the City Council identified CCS on waste-to-energy as the most cost-effective option for decarbonizing these hard-to-abate facilities, and cities across Europe are now working on this solution..

The exact cost of CCUS depends to a great extent on the mixture of gases it has to deal with. If there is a high proportion of carbon dioxide, at high pressure and on a large scale, it is relatively easy to capture, making costs lower than for dilute or low-pressure exhaust gases. A 2021 Global CCS Institute report showed that for industries making fertilizers or ethanol, capture cost is well below $50 per tonne; for steel it can be around $100 per tonne, rising up to around $250 per tonne for aluminium. In 2017 the Institute calculated the cost of pipeline transport and storage to be $7 to $12 per tonne for onshore, and $16 to $37 per tonne for offshore.

Overall, CCUS costs are expected to fall rapidly as the industry grows and more cost-effective capture technologies mature. CCUS hubs are expected to accelerate this process through economies of scale on transport and storage, as well as standardization effects as new industries deploy and develop new capture technologies.

HOW SECURE IS CCUS?

It is vital that stored carbon dioxide stays stored, rather than leaking into the atmosphere. Leakage risk is extremely low in a well-managed reservoir, but can occur in small volumes through ill-maintained abandoned wells or rock fractures. The risk of carbon dioxide leaks decreases significantly once the injection stops, wells are sealed and longer-term trapping mechanisms lock in a growing proportion of the carbon dioxide.

A 2012 report for the UK's Department of Energy and Climate Change looked at the risks of carbon leakage from sites in the North Sea. The report acknowledged that there is considerable uncertainty over some of the risks, notably from faulting. But even the upper end of their assessments saw only a very small percentage of carbon dioxide leaking out. The report concludes: "Overall, the risk of experiencing a leak over the anticipated lifetime of a storage site is considered to be very low and the magnitude of any associated carbon dioxide loss is estimated to be low and manageable through existing and proven corrective measures."

WHAT IS THE RISK OF INDUSTRIAL ACCIDENTS?

Transporting large amounts of any gas holds the potential for accidents. A sudden pipeline failure could release a cloud of gas, and because carbon dioxide is denser than air it would stay close to the ground and settle in any depressions, with potential for asphyxiation. But risk assessment and safety measures deployed by the industry are well developed, with CCUS projects running safely for decades. Where there are innovations such as carbon dioxide shipping, engineers have developed tanks with thick walls made of special high-tensile nickel steel alloy to cope with the high pressure and density.

A 2009 IEA study concluded that "the industry has sufficient experience…to conduct CCS operations safely". The UK's Health and Safety Executive comes to a similar conclusion: "where the risks are properly controlled the likelihood of a major hazard incident is expected to be very low, as in other similar processes in the energy, chemical and pipeline industries." As the industry scales up, there stakeholders will conduct further research into safety.

1.2 THE ROLE OF CCUS HUBS

WHAT IS A CCUS HUB?

A CCUS hub takes carbon dioxide from several emitting sources, such as heavy industries and power, and then transports and stores it using common infrastructure. A CCUS hub can be more complex to establish than a CCUS value chain on a single point source, managed by one company; but CCUS hubs bring many benefits, including lower unit costs, reduced risk and the ability to standardize and scale up quickly. For emitters, the hub offering opens up CCUS as a decarbonization option without them having to take responsibility for building pipelines and drilling storage wells and without long-term liability for the stored carbon dioxide.

Most CCUS hubs will be based around industrial clusters, where emission sources are close together, as in Net Zero Teesside, Rotterdam or China Northwest. But some will be geographically scattered, collecting emissions sources by pipeline or ship, as in Northern Lights in Norway.

WHAT ARE THE ADVANTAGES AND DISADVANTAGES OF A CCUS HUB OVER A SINGLE PROJECT?

- ✔ **Faster scale up.** CCUS must expand rapidly to play a role in reaching climate goals. At present, the average large-scale CCUS project captures and stores around 1 Mt of carbon dioxide per year. Early CCUS hubs are aiming to capture around 5-10 Mt a year or more by 2030 and expect exponential growth. Future hubs are likely to be even larger.
- ✔ **Lower costs and investment risks.** Collective transport and storage infrastructure bring economies of scale in construction and operations, specifically in compression, dehydration, pipeline and storage. At the same time, shared lessons and standardization will bring down the costs of carbon capture and reduce risk. In the early stages of appraising potential new storage sites for hubs, sharing costs and risks make it simpler to get started in areas that have not been developed.
- ✔ **More government support.** A hub can decarbonize an entire industrial region, saving jobs and attracting clean new industries. With such social and economic benefits, on top of its contribution to meeting climate goals, a hub is much more likely than an individual project to gain government support. Efforts to create hubs in the UK, for example, have ensured that the government develops policy incentives for emitters and operators. The Norwegian and Dutch governments worked to change European regulations on the cross-border export of carbon dioxide, and both Northern Lights and Porthos attracted large-scale EU funding. The Northern Lights JV has gained support from standard setter Verra and emitting industries to take a new look at carbon accounting for CCUS. The four CCUS projects that received support from the EU Innovation Fund in 2021 are all connected to a hub.
- ✖ **Complexity.** This is the main disadvantage – and the reason we have set up this platform. A CCUS hub is a multi-stakeholder undertaking, which magnifies the need for careful communication and alignment between partners. Decisions on commercial relations, risk management and long-term investments must all be agreed between emitters, operators and government – who are all acting with different drivers and timescales. Countries that are pioneering hubs, such as the UK, Norway and the Netherlands, are building on years of frustrating attempts to get large-scale CCUS off the ground. They have learned lessons from these failures and are now applying them to make CCUS hubs a reality.

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› Getting started

WHAT CONDITIONS HAVE DRIVEN HUB DEVELOPMENT SO FAR?

Three conditions have come together to enable the development of the three most advanced CCUS hubs around the North Sea in Europe.

1. **Confidence that storage capacity exists,** due to previous work on CCUS and the involvement of companies with subsurface and transportation experience.

    - Northern Lights/Longship in Norway built on lessons learnt from over 20 years of experience storing carbon dioxide under the North Sea.
    - Net Zero Teesside in the UK built on the White Rose projectwhich focused on the Endurance reservoir that is now being used by the hub's transport & storage operator, Northern Endurance Partnership.
    - Porthos in the Netherlands is based on the ROAD project in the Port of Rotterdam, and carbon dioxide suppliers suppliers Shell and ExxonMobil have engaged their upstream subsurface engineers to build confidence in storage capacity.

2. **National and regional support** to incentivize and build confidence for the large, high risk capital investments initially required.

    - In Northern Lights/Longship, the Norwegian government has committed to national political objectives for CCUS and, in the first phase, is subsidizing 80% of investment costs for both emitters and transport and storage infrastructure.
    - In Net Zero Teesside, both regional and national authorities are politically committed to supporting the region and its industry base through the energy transition.
    - In Porthos, the Port of Rotterdam wants to position itself as a clean industrial hub and national authorities are committed to industrial decarbonization.

3. **Understanding of the CCUS hub value proposition** by a group of stakeholders involved in knowledge building and lobbying – smoothing the pathway and creating a broader ecosystem.

    - Knowledgeable ministers have driven support at the top of the house. In Norway, governments and industry learned how they needed to work together from failed attempts to start CCUS facilities in the 1990s.
    - Industry associations have brought things together at lower levels – such as the Energy Technologies Institute (ETI) and the Carbon Capture and Storage Association (CCSA) in the case of Net Zero Teesside.
    - Cross-national engagement between ministers and policy makers from Norway, the UK and the Netherlands who talk frequently to exchange information, provide support and explore how a potential network of linked projects can be created to reduce costs and risks.

In **North America,** CCUS ecosystems have also developed in areas such as the US Gulf Coast and Alberta, where the Quest CCS facility has operated for over six years. In the US, CCUS evolved initially in relation to enhanced oil recovery projects but is increasingly being seen as part of low carbon business transformation.

- Multi-stakeholder coalitions have been responsible for developing and shepherding the 45Q carbon storage tax credit legislation through the US Federal Government legislative process and building knowledge among policy-makers.
- Knowledge sharing by groups of emitters and potential hub developers, including OGCI, has been crucial to get state-level support and regulations in place and to help industrial emitters understand the options.

WHERE IN THE WORLD ARE CCUS HUBS POSSIBLE?

OGCI is analyzing the global potential for CCUS hubs as part of the Global Hub Search tool. We have reviewed the potential for CCUS hubs in 52 countries, focusing on how much carbon dioxide can be captured and stored, and at what cost (techno-economic potential), as well as the environment for policy, regulation and commercial readiness.

Most of the 52 countries have potential CCUS hubs that cost below $100/tonne for capture, transport and storage, assuming existing technology costs. These span all world regions and add up to 933 Mt of abatable annual emissions or, equivalent to around 2% of total emissions.

The most promising near-term opportunities are in regions where high techno-economic potential meets a supportive environment. The project identifies 23 such potential CCUS hubs, representing 319 Mt of annual emissions that could be abated.

CAN CCUS HUBS BE SET UP EVEN WHERE THERE ARE NO GOOD LOCAL STORAGE OPTIONS?

Yes. Where there is no convenient storage site, it is possible to create a geographically distributed CCUS hub, with ships or a pipeline carrying carbon dioxide to a distant storage site. The cost of using ships for transport is more expensive on a large scale than a localized hub based on pipelines, but a shipping solution has two advantages: it supports the gradual development of a CCUS hub, and allows one storage facility to serve several smaller CCUS emission clusters.

The Northern Lights project in the North Sea is the most advanced example of a distributed hub and is already building ships to safely carry large volumes of carbon dioxide. Several projects in Europe are looking at the potential of using ships as part of their development strategies, expanding beyond pipelines to offer services to new emissions clusters. Projects in Singapore and Japan are investigating distributed hubs to overcome their lack of suitable storage sites. Several countries, including China and Saudi Arabia, are exploring the possibility of providing storage services to the world.

CAN A CCUS HUB SUPPORT CARBON REMOVALS?

Yes, depending on the sources of carbon dioxide included. Negative emissions, also known as carbon dioxide removal, require carbon dioxide to be taken out of the atmosphere and then stored. This is possible through various natural and engineered approaches, and some of the most promising involve CCUS technology.

Removals are already being built into hub concepts. At the Net Zero Teesside hub, one power station will burn biomass, in a process known as bioenergy with carbon capture and storage (BECCS). Northern Lights is collaborating with Climeworks, one of the leaders in direct air capture (DAC) technology, to explore the potential of locating a facility close to the collection point for storage under the sea.

Even CCUS hubs that don't include carbon removal technologies will help indirectly, doing their bit to drive a massive scale-up of CCUS infrastructure. This will enable the kind of multi-gigatonne negative emissions that will be needed in the next few decades.

1.3 STATE OF PLAY

WHAT IS THE CURRENT STATUS OF CCUS AND CCUS HUBS?

The CCUS project pipeline is growing more robustly than ever, according to the 2021 report from the Global CCS Institute. It identifies 27 commercial CCUS facilities operating around the world as of September 2021, with a total capture capacity of about 40 million tonnes of carbon dioxide per year. Capacity in the pipeline, however, has risen by 46% in the first nine months of 2021 and now totals 111 million tonnes per year.

According to the IEA, more than 100 new CCUS facilities were announced in 2021. There are CCUS projects or planned developments in 25 countries around the world, with three-quarters in the US and Europe.

Global capacity under development declined in the early 2010s, in part owing to the financial crisis, but it rebounded in 2018. Growth is accelerating as governments and companies focus on how to implement net zero targets, interest in low carbon hydrogen grows and CCUS hubs open up scalable options for industrial decarbonization.

There are currently around 40 CCUS hubs in development around the world. Over half of these – and the most advanced – are in Europe, where a combination of rising carbon prices and net zero commitments are driving the search for large-scale industrial decarbonization. There is a growing tendency for consolidation and collaboration among these emerging hubs.

In North America, the model has tended to be different, with single source-to-sink projects set up with overcapacity in transport and storage, so that other emitters can feed in later. The 45Q tax credit and low fuel standards in the USA are incentivizing many single point source CCUS projects and these could provide a basis for more hubs in future. A number of Asian countries are looking closely at CCUS hub options, with China planning three new hubs, following the example of the China NorthWest hub.

WHY SHOULD CCUS TAKE OFF NOW AFTER SO LONG?

Governments and businesses are now realizing that climate action is urgent, spurred in part by recent IPCC reports. Ambitious targets, aiming for net-zero and net-negative emissions within a few decades, require solutions for decarbonizing hard-to-abate sectors such as steel, cement and chemicals. CCUS is a ready solution.

In the past, CCUS tended to be viewed primarily as a way to decarbonize power and therefore its cost was seen in relation to renewables – but both governments and businesses are now starting to view its value relative to industrial decarbonization strategies. Policy-makers are realising that carbon capture can be the cheapest way to achieve rapid decarbonization while sustaining an industrial base and jobs. Higher carbon prices, particularly in Europe, are driving emitters to look for new low-carbon strategies. The emergence of CCUS hubs provides emitters with an affordable way to abate their carbon dioxide emissions.

Policy incentives and regulations for CCUS are maturing, particularly in Europe and North America. Some of the world's biggest financiers are now seeking ethical investments, with environmental, social and governance assets projected to reach $53 trillion by 2025.

This new momentum is just beginning to be visible, with the number of new CCUS projects accelerating.

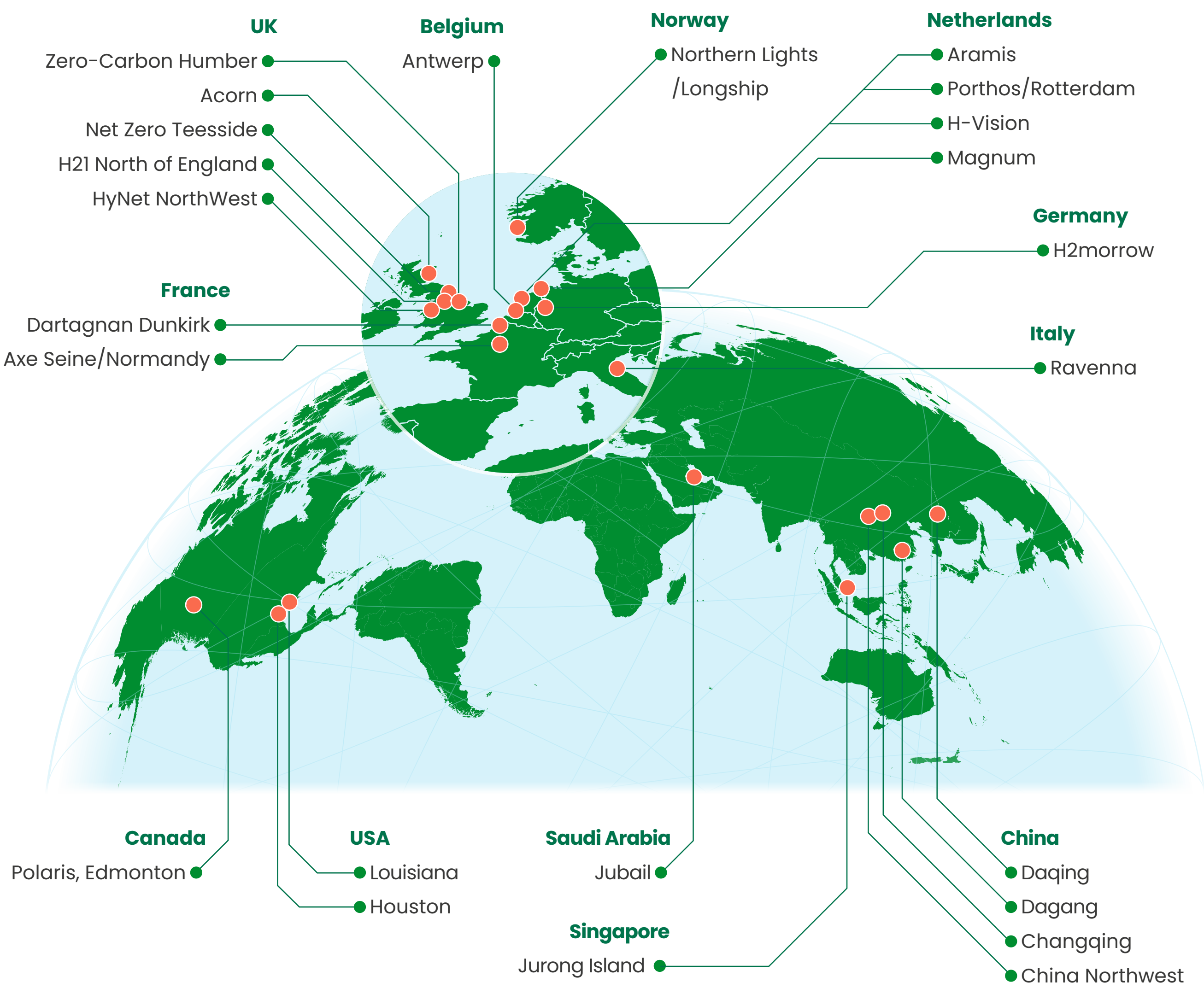
LEARN MORE

- Carbon capture in 2021: Off and running or another false start?

DOES CCUS FEATURE IN NDCS AND LONG-TERM LOW EMISSIONS STRATEGIES?

Nationally Determined Contributions (NDCs) are non-binding pledges to mitigate climate change, made as part of the Paris Agreement. They include emissions reduction targets for 2030 and some details on how to achieve those targets. As of January 2022, 21 countries (including the EU as one country) mention CCUS specifically as a decarbonization tool in their NDCs. Australia, Iceland, France, USA, Canada, Malawi, Qatar, China, Saudi Arabia, Bahrain, Kuwait and Japan have so far mentioned CCUS in their most recent updates. CCUS appeared in 24 out of 29 Long Term Low Emissions and Developments Strategies submitted under Article 4 of the Paris Agreement.

Emerging CCUS hubs with OGCI member company involvement (end-2021)



2. HUBS IN ACTION – LESSONS FROM OGCI'S KICKSTARTER HUBS

NET ZERO TEESSIDE

Aiming to create the UK's first decarbonized industrial cluster, this hub will provide offshore carbon storage to industries in the northeast of England.

Net Zero Teesside will capture and store carbon dioxide from industries near the mouth of the River Tees in north-east England. Teesside is an attractive site for a CCUS hub, with 5.6% of the UK's industrial emissions concentrated in a compact area and plenty of brownfield land for redevelopment, all close to suitable storage sites under the North Sea.

Location
northeast England

Potential impact by 2030
10 $MtCO_2$/year

Hub developer
bp, Equinor, TotalEnergies

CO_2 sources
gas power plant, biomass power station, hydrogen production facility, fertilizer

Transport
pipeline

Storage site
Endurance

Reservoir

Status
final, investment decision expected in 2022

In operation
2026

Website
https://www.netzeroteesside.co.uk/

OGCI Climate Investments acquired the original government-funded concept and developed it into a commercial project, working with industries, interest groups, and local and national government. The project is now being developed by a consortium of OGCI member companies, led by bp.

To anchor the project, the consortium will commission a natural gas power plant with post-combustion carbon capture. This will be linked to a large pipeline with the spare capacity to transport carbon dioxide from other sources, likely including a biomass powerplant, a hydrogen plant and a fertilizer plant, and potentially carbon dioxide imports. By 2030 the project plans to capture up to 10 million tonnes of carbon dioxide per year from the Teesside industrial area.

This carbon dioxide will be stored in a saline aquifer called the Endurance Reservoir, 145 km offshore and about 1.6 km below the bed of the North Sea. Geological assessments indicate that Endurance can safely store 450 million tonnes of carbon dioxide, and other nearby storage sites have the potential to boost that to a billion tonnes.

Another CCUS hub project, Zero Carbon Humber, plans to use the same reservoir to store up to 17 million tonnes of carbon dioxide per year, further sharing infrastructure costs and creating other economies of scale. The two hubs successfully bid jointly for government funding as the East Coast Cluster. Storage will be managed by the Northern Endurance Partnership, a collaboration between bp, Eni, Equinor, National Grid, Shell and TotalEnergies, formed in 2020.

As well as capturing and storing carbon dioxide, Net Zero Teesside will provide infrastructure to regenerate the region – attracting companies that use carbon dioxide or want to cut their emissions. That should enable exports of low-carbon industrial products and build a world-leading skill base in CCUS. An assessment of the project's construction phase estimates it will directly create 5,500 jobs in construction. Beyond that, it should safeguard existing local industries and employment, and help create at least 7,000 additional jobs.

LEARN MORE

- NYT (March 2021): Oil giants prepare to put carbon back in the ground

NORTHERN LIGHTS

This pioneering public-private partnership in Norway uses ships to transport carbon dioxide from around Europe and store it in a collective reservoir under the North Sea.

Location
Norway

Potential impact by 2030
well over 5 $MtCO_2$/year

Hub developer
Gassnova (phase 1); Northern Lights JV (phase 2)

Initial CO_2 sources
cement, waste incineration

Potential CO_2 sources
hydrogen, biomass, steel, refineries

T&S company
Northern Lights JV (Equinor, Shell, TotalEnergies)

Transport
ships

Storage site
Aurora reservoir

Status
under construction

In operation
2024

Website
https://northernlightsccs.com/

Northern Lights is not a physically localized hub, but a distributed one. While other hubs are based on compact industrial clusters linked by pipeline, this Norwegian hub will use ships to connect geographically distant carbon dioxide sources from around Europe. The investment was approved in late 2020 and the facilities are now under construction.

In its first phase, 80% subsidized by the Norwegian government and known as Longship, the project aims to store emissions from two sites in eastern Norway: the Fortum waste-to energy plant in Oslo and the Norcem cement factory in Brevik. Between them, they will capture about 800,000 tonnes of carbon dioxide per year. Norcem is under construction; Fortum is seeking full financing.

The captured carbon dioxide will be compressed and liquefied at each site. Specially designed ships will then take it to a temporary storage site in Øygarden in western Norway, from where it will be piped for permanent storage to the Aurora reservoir, a saline aquifer about 110 km from shore and 2.6 km under the seabed. Its storage capacity is expected to be at least 100 million tonnes.

Transport and storage will be handled by the Northern Lights joint venture, owned by three OGCI members: Equinor, Shell and TotalEnergies. Gassnova is overseeing the project for the government, ensuring that the value chain from emitters to storage is properly regulated and managed.

For the second phase, Northern Lights is offering commercial carbon storage services to companies across Europe. The receiving terminal, offshore pipeline and injection infrastructure are designed to be extended to accommodate over 5 million tonnes of carbon dioxide per year, depending on demand. Northern Lights has identified over 90 suitable capture sites, and there is already interest from industrial sites in eight countries, in sectors including steel, biomass and hydrogen. Four of these sites – a hydrogen refinery in Finland, hydrogen and chemicals manufacturers in Antwerp, a cement plant in France and a biomass with CCS plant in Sweden – have received investment from the EU's Innovation Fund to support large-scale capture of carbon dioxide. Northern Lights is also collaborating with Swiss direct air capture company Climeworks to look at the potential of storing carbon dioxide captured directly from the atmosphere.

The project's construction phase will bring between 1,500 and 3,000 jobs, with around 170 jobs created directly during operation, alongside many thousands of jobs created and safeguarded in industries that decarbonize through CCS or participate in carbon removals.

PORTHOS/ROTTERDAM

A project led by the Dutch Government will capture carbon dioxide from industry in the Rotterdam port area and supply it to the Porthos transport and storage organization.

Industries around Rotterdam emit around 25 million tonnes of carbon dioxide per year, some 20% of the Dutch total. With the Netherlands targeting a 49% reduction in emissions by 2030, and carbon prices rising, the Port of Rotterdam authority looked for a way to retain carbon-intensive industries and become an attractive site for new industries that want to operate with a low carbon footprint.

Location
Rotterdam, Netherlands

Potential impact by 2030
10 $MtCO_2$/year

Hub developer/T&S
Porthos (Port of Rotterdam, Gasunie, EBN)

Initial CO_2 sources
refineries, hydrogen production

Potential CO_2 sources
imports from Antwerp and the Rhine Valley

Transport
pipeline, potentially ship and truck later

Storage site
offshore depleted gas fields

Status
investment decision expected in 2022

In operation
2024

Website
https://www.porthosco2.nl/en/

Despite popular unease over CCUS in the Netherlands, the Port and state-owned energy companies Gasunie and EBN joined forces to set up a carbon transport and storage project, Porthos, supported by EU funding. Porthos is currently the most advanced CCUS hub within the EU.

Porthos builds on the ROAD project, an earlier attempt to provide CCS for coal power stations in the area. It will act as an open-access utility for industries that have no viable decarbonization alternatives, such as refineries and the chemical sector. In the early stage, four companies in the port area – Air Liquide, Air Products, ExxonMobil and Shell – will capture 2.5 million tonnes of carbon dioxide per year. These companies successfully competed for financial support through a government auction, SDE++, designed to support the most cost-efficient industrial carbon dioxide reductions.

In 2022–2023, Porthos aims to build the infrastructure that will pipe carbon dioxide from these companies to the North Sea. The initial storage site, a depleted gas field designated P18, is 20 km offshore and more than 3 km beneath the seabed. It has a capacity of 37 million tonnes; other gas fields nearby have potential capacity of up to 1.6 billion tonnes.

Porthos plans to increase storage to at least 10 million tonnes per year, potentially by importing carbon dioxide from other Dutch regions, Germany and Belgium, through pipelines, ship and truck.

CHINA NORTH-WEST

China's first CCUS hub, led by CNPC, is designed to capture and store carbon dioxide from the hydrogen production units of refineries.

Location
northwest China

Potential impact by 2030
3 $MtCO_2$/year

Hub developer/T&S
CNPC

Initial CO_2 sources
refineries

Potential CO_2 sources
cement, chemicals, power

Transport
trucks,
pipeline

Storage site
oilfields, active (for EOR) and disused

Status
expected to start construction by 2023

In operation
2025

The China National Petroleum Corporation (CNPC) is setting up the country's first CCUS hub, China North-West, in the Junggar Basin. This area has a high concentration of large-scale emitters with relatively pure carbon dioxide streams.

In the first phase, operating by 2025, CNPC plans to construct the pipelines and storage systems, and capture 1.5 million tonnes of carbon dioxide each year from one of its own refinery facilities. In the second phase, expected to capture 3 million tonnes of carbon dioxide per year by 2030, the hub will expand its transport infrastructure, taking carbon dioxide from hydrogen production, as well as from other potential customers including cement, steel and power plants. The aim is to expand to 10 million tonnes per year by 2040.

CNPC's oilfield subsidiary will inject the carbon dioxide. Initially this will be used for enhanced oil recovery to provide a commercial impetus, to develop the technology, but the plan is to move towards long-term geological storage. Transport may start using tanker trucks, to be replaced with pipelines as the project scales up.

Interest from industrial emitters is growing. China announced in 2020 that it was targeting carbon neutrality by 2060, and a national emissions trading scheme started operating in July 2021. Although carbon prices on the scheme have started low, at a few dollars per tonne, emitters are anticipating much higher prices by 2030 that will make CCUS a commercial proposition.

Policy support mechanisms for capital expenditure and operating expenses are still under discussion for the transport and storage infrastructure. Negotiations are also in progress with potential emitters to create a commercial foundation for capture. These mechanisms will become clearer when China's National Development and Reform Commission publishes its CCUS plan, expected by early 2022.

CNPC is planning to build three additional hubs in China by 2030.

RAVENNA CCS

Led by Eni, this hub aims to become the reference hub for Italy and the Mediterranean.

Location northwest China	**Transport** trucks, pipeline
Potential impact by 2030 3 $MtCO_2$/year	**Storage site** oilfields, active (for EOR) and disused
Hub developer/T&S CNPC	**Status** expected to start construction by 2023
Initial CO_2 sources refineries	**In operation** 2025
Potential CO_2 sources cement, chemicals, power	

Ravenna CCS aims to become the pioneer hub for Italy and the Mediterranean. Led by Eni, the hub is in early development. The plan is to launch phase 1 in 2023, testing technologies in a full capture, transport and storage chain handling up to 100,000 tonnes per year.

Phase 2, scheduled to start in 2027, will allow storage of 4 million tonnes of carbon dioxide per year, about half of it from three power stations and a hydrogen plant owned by Eni, and the rest from other emitters. Eni is already in talks with hard-to-abate industries in the region (cement, steel, fertilizer, glass etc) in the region, among others. Interest from emitters in Italy and beyond has grown with the increase in European Trading Scheme carbon prices, and the European Commission's 'Fit-for-55' package of climate legislation.

Storage will be in offshore depleted gas reservoirs in the Adriatic Sea. Total storage resource in the Adriatic is estimated at 500 million tonnes, giving the possibility in subsequent development phases to increase storage capacity to more than 10 million tonnes per year, covering the decarbonization needs of additional clusters.

LOUISIANA

Shell is driving the definition and development of this hub in the Mississippi River corridor.

Location
Mississippi River corridor (Baton Rouge to New Orleans)

Potential impact by 2030
NA

Hub developer/T&S
Shell

Initial CO_2 sources
petrochemicals, biofuels

Potential CO_2 sources
biomass, steel, paper, cement, ammonia

Transport
pipeline

Storage site
exploring onshore saline aquifers and offshore oil and gas reservoirs

Status
investment decision expected in 2023

In operation
mid-2020s

Shell is working to create a CCUS hub in Louisiana that would initially focus on decarbonizing Shell's petrochemicals units in the Baton Rouge, New Orleans area, but would be open to a broad range of existing and new industrial companies in the region.

Louisiana already has regulations in place to support CCUS and the state is trying to drive the acceleration of CCUS permitting. Federal and state policies, like 45Q and California Low Carbon Fuel Standards, have opened up potential business models and there is strong competition from potential operators and emitters for projects, supported by a flood of private equity money.

Key challenges include the complexity of land ownership that makes onshore storage difficult, and a lack of clarity on remaining regulatory issues such as transfer of liability over stored carbon dioxide. In addition, there is uncertainty over the longer-term future of federal policies such as 45Q and the evolution of carbon markets.

3. POLICIES & BUSINESS MODELS

3.1 Policies & regulations

WHY SHOULD GOVERNMENTS SUPPORT CCUS HUBS?

CCUS is a cost-effective way to decarbonize heavy industry at scale – and a CCUS hub is designed to leverage the economies of scale for an entire region, while reducing costs by allocating risk management along the entire value chain.

> *Read about how the Dutch government calculated that supporting carbon capture was the cheapest way to meet its industrial decarbonization target.*

CCUS enables a just transition, allowing existing industries to remain competitive, keep and create jobs and continue contributing to local economies while transitioning to a net-zero future. A CCUS hub can help industrial regions to keep existing industrial jobs and attract new ones.

> *Read about job creation in Net Zero Teesside and Northern Lights.*

CCUS hubs accelerate the commercial scale up of CCUS. By splitting the value chain between transport and storage operators and emitters and planning the development, CCUS hubs can involve partners with different risk approaches and also engage multiple emitters – including smaller players and industries that would not have considered CCUS as a solution on their own. As a result, policy support can enable faster decarbonization in the short and medium term, tailormade to the specifics of one or more CCUS hubs, and phase out that support over time as carbon price drive investments in CCUS and create a commercial industry.

> *Read about the Fortum waste-to-energy CCUS project that is a founding partner in Longship/ Northern Lights.*

Flexible power generation capacity that complements renewables can be an integrated part of a CCUS hub – providing reliable low-carbon power for businesses in the hub area.

> *Read about the UK government's contract for back-up electricity in Net Zero Teesside*

Hydrogen is set to play a big role in decarbonizing industry, heating and transport, and the cheapest way to make low-carbon hydrogen today is using natural gas with CCUS. Integrating low-carbon hydrogen production into a hub provides energy for multiple applications in the industrial region.

> *Read about hydrogen at the Humber Zero hub.*

CCUS hubs can also provide opportunities to remove carbon dioxide from the atmosphere at scale, through direct air capture with storage (DACS) and bioenergy with CCS (BECCS).

> *Read about how Norway is enabling industrial scale deployment of carbon removals through its Northern Lights project.*

WHY DO CCUS HUBS NEED GOVERNMENT SUPPORT?

Today's market models make it more favourable for industrial companies to emit carbon dioxide (even where carbon has a cost) than to invest in carbon capture and have the carbon dioxide stored. As carbon prices rise, incentives develop and mandates kick in, CCUS will become cheaper than emitting.

The most advanced CCUS hubs today are supported by government-backed incentives and subsidies that tackle two main challenges:

- How to incentivise emitters to invest in capturing their carbon dioxide emissions so they can maintain competitiveness despite today's market models?
- How to incentivise potential carbon transport and storage operators to invest in infrastructure – providing a business case despite the lack of a sufficiently high and stable carbon price?

In addition, the incentives also need to address challenges throughout the CCUS value chain, like performance risk and counterparty risk.

Policy support is likely to match the dynamics of low-carbon energies such as offshore wind.Early-stage demonstration focuses on proving that a novel technology works in practice. Scale-up develops a few projects near or at full-scale, proving viability and deliverability. In these initial phases, governments are likely to offer some form of development funding, followed by upfront co-funding of capital costs, as well as revenue support.

> See early CCUS projects such as Quest, Gorgon and Boundary Dam.

At roll-out, the objectives are to establish a sustainable industry and to build capacity, via a funnel of projects, multiple developers, and a mature understanding of risks and contracting structures. As risks and costs fall, and the cost of private finance comes down, CCUS hub development could be driven by industry and supported by market-based mechanisms, that are based on giving a value to carbon. Government co-funding of costs could then be phased out as commerciality is reached.

Once established, a mature and stable industry can attract commercial finance on acceptable terms. CCUS hubs will be sustained by an explicit or implicit carbon price, supported by further reductions in the cost of technology applied, and by growing demand for decarbonised industrial products. In this phase, government action would be limited to addressing any remaining market failures and removal of regulatory barriers.

WHAT KIND OF POLICY ENABLERS CAN SUPPORT CCUS HUBS?

Governments are using a range of different policy frameworks to help a CCUS industry get off the ground and scale rapidly. Government support is expected to decrease over time as the industry matures and sufficiently high carbon prices, mandates or market demand for low carbon products create business models.

The tools government are using in different combinations to support CCUS hubs include:

Capital grants for capture and transport and storage facilities including development support. Particularly relevant in early phases of CCUS hub development, these grant schemes can also include support for the operations phase, including minimal performance requirements. *> See Norway.*

Feasibility study grants. These are designed to help emitting companies in industries with tight profit margins to do due diligence on integrating CCUS into their processes. This is particularly important for companies that are pioneering the use of CCUS in their industry, such as waste-to-energy, glass and paper. *> See Fortum in Norway.*

Government-steered model. The government sets up a regulated publicly owned body responsible for delivering and operating the transport and storage infrastructure, with the option of privatisation as the CCUS market matures. *> See Porthos in the Netherlands*

Tax incentives for the capture, storage or utilization of carbon dioxide can take the form of production tax credits and investment tax credits. *> See 45Q storage tax credit in the US.*

Contracts for difference top up carbon market prices where they are still too low to cover the cost of capture for emitters. The government sets a minimum price on stored carbon, paying the difference between the market price and this floor. This provides an incentive for the emitter to invest in capture plant, a clear demand signal to the operator and the prospect of decreasing subsidies to the government. *> See the Netherlands and the UK.*

Regulated asset base. Transport and storage operators receive a licence from the regulator, granting them the right to charge a regulated price to users in exchange for delivering and operating the transport and storage network. The charge is set by an independent regulator who considers allowable expenses, over a set period of time, to ensure costs are necessary and reasonable. For hub development, such schemes require an element of underwriting from the government to manage the counterparty risk. *> See the UK*

Standards that limit the permitted carbon intensity of fuels for transport or other products and create demand. *> See California's Low Carbon Fuel Standard and the European Commission's proposals for a Carbon Border Adjustment Mechanism.*

Public procurement requirements for low or zero-carbon industrial products to stimulate demand. For example, contractors on construction projects would have to include a certain percentage of low-carbon steel and cement. Being considered by some US states. *> See this overview*

Hub alignment and competition. The UK government has successfully accelerated the pace of progress and alignment among hubs by developing support policies step by step and making hub developers compete or align among themselves to get through the next "grant-gate". This is challenging for the hubs, but it has accelerated consolidation among the hubs and highlighted issues that need to be addressed.

Emissions trading linkages that recognize the role of tradeable CCUS credits, or develop a new transferable asset class such as a carbon storage unit (CSU) – a verified tonne of carbon dioxide or carbon securely stored in geological formations. Countries could pledge to buy these units as part of their NDCs; or fossil fuel companies could have a carbon storage obligation.

WHAT ARE THE POLICY SUPPORT MODELS USED IN EARLY HUBS?

CCUS hub	Policy support	
	Transport and storage	Emitters
Northern Lights / Longship, Norway	Phase 1	
	Regulated asset base: investment funding (80%) and operational cost funding (95% decreasing to 80%). Potentially additional EU funding.	Investment funding (80%) and operational cost funding (100% up to a certain level).
	Phase 2	
	None – fees from emitters (reflected in opex cost funding)	Capital grant and opex support from EU Innovation Fund, Connecting Europe Facility
Net Zero Teesside, UK	Regulated asset base: grants for pre-FEED work and FEED	One-off grants through CCS infrastructure fund for initial capture projects; contracts for difference on UK carbon price Modified contract for difference on power price
Porthos/Rotterdam, The Netherlands	Porthos run by three state-owned parties – EBN, Gasunie and Port of Rotterdam; €100 million capital grant from the EU Connecting Europe Facility. Fee from emitters.	Contract for difference on ETS carbon price, known as SDE++
China North-West, China *Under discussion, may include:*	Capital grant (as for other major Chinese infrastructure projects); storage tax credit to offset operating costs	Contract for difference on Chinese carbon market prices
Ravenna, Italy *Under discussion, may include:*	Regulated asset base; possibly some form of capital grants	Contracts for difference on ETS carbon price
Louisiana, US *Under discussion, may include:*	None – fees from emitters	45Q storage tax credit; low-carbon fuel standards

DESIGNING EFFECTIVE POLICIES FOR CCUS HUBS

Identify the potential and the value of CCUS

- Map sources of carbon dioxide, with their concentration and purity – power, industry
- Map storage reservoirs, their type and capacities – saline aquifers, depleted oil & gas reservoirs
- Identify carbon transport options – pipelines, ships, barges, rail, trucks
- Quantify the socio-economic value of CCUS, including its potential for retaining and creating jobs

Set up national CCUS strategy and targets

- Articulate the role CCUS can play versus other levers to accelerate decarbonization in the national context
- Integrate CCUS into industrial, commercial and environmental policy
- Give relevant ministries the resources they need for implementation
- Develop a roadmap laying out targets for captured carbon dioxide
- Ensure a funnel of storage resource options are appraised in a timely manner to match the expected demand from captured carbon dioxide
- Design incentives to ensure industries meet those targets
- Provide support for storage maturation

Provide clarity with regulations

- Clarify issues around carbon dioxide transport, verification of capture and storage, the integrity of storage sites, monitoring, and long-term stewardship.
- Design permitting process to be streamlined across the numerous regulatory actors

Assign roles and responsibilities

- Assign roles and responsibilities to the appropriate authorities for developing policies, incentives, and regulatory frameworks
- Doing so transparently and predictably in the context of a roadmap reduces uncertainties and de-risks capital investments
- In many cases it will be beneficial to assign one party to take the lead role for a CCUS hub development

Work on community acceptance

- Collaborate with local governments, environmental organizations, trade unions, and other industries in the region

LINKS

- Global Hub Search
- CO_2 Storage Resource Catalogue

DEVELOPING EFFECTIVE REGULATIONS FOR CCUS HUBS

Regulations relating to CCUS vary considerably by country. In order for CCUS hubs to scale, consistent regulations across geographies are necessary. Suggested guidelines for developing such regulations are as follows:

- Permit the adaptation of existing pipelines for carbon dioxide transport
- Enable new transport infrastructure such as pipelines, trucks, rail and shipping
- Streamline the process of awarding permits for capture, transport and storage
- Introduce standards for construction, operation and carbon dioxide injection
- Clarify storage liability: who is responsible at each stage of injection, monitoring and long-term stewardship; how risk is shared and eventually transferred to government.
- Introduce monitoring, reporting and verification protocols and processes for injected carbon dioxide to ensure safe, reliable and permanent storage
- Establish provisions for carbon dioxide leakage
- Provide legal certainty on pore-space ownership and how it relates to mineral rights
- Develop rules for joint development of carbon dioxide stores that span land under licence by different companies
- Enable trans-boundary (state and national) movement and storage of carbon dioxide including the delineation of associated risks and liabilities
- Ensure that emitters have access to carbon dioxide transport and storage infrastructure at reasonable rates
- Establish processes for stakeholder consultation

READ MORE

- What questions should policymakers ask themselves when developing policies and regulations for CCUS hubs?
- What are the policy lessons learned from the OGCI KickStarter hubs?

3.2 BUSINESS MODELS

HOW DOES THE CCUS HUB VALUE CHAIN WORK?

The CCUS hub value chain typically consists of a hub developer who initiates and manages the value chain, multiple emitters who guarantee to capture and supply carbon dioxide, and a single transportation and storage company (that could serve several hubs).

A **hub developer** can be:

- One or more companies looking to offer carbon dioxide transport and storage services (as in Net Zero Teesside, China Northwest and Ravenna).
- One or more state-owned entities aiming to develop strategic infrastructure to support industry and jobs in a region (as in Porthos and Longship).
- An infrastructure company, such as a pipeline company, looking to develop new markets.
- An emitter or group of emitters looking for a collective solution to decarbonization.

Each **emitter** is responsible for capturing carbon dioxide from their operations, purifying it to meet specifications and then compressing it. If the carbon dioxide is being transported by ships to storage sites, the emitter may also be responsible for its safe storage in tanks and for the loading infrastructure in ports.

Transport and storage operators are responsible for transporting the carbon dioxide by pipeline, or by ship, from the emitter to the storage site, where they inject it into the subsurface geology.

Public-private partnerships are fundamental at the current stage of CCUS hub development because the cost of emitting carbon dioxide into the atmosphere is still low. Governments need to offer some form of upfront co-funding of capital costs and revenue to attract involvement by emitters and operators – largely motivated by the need to decarbonize heavy industry, maintaining jobs and global competitiveness.

As risks and costs fall, the implicit or explicit carbon price rises and demand for decarbonized industrial products grows, hubs will be driven by industry, supported by market-based mechanisms and commercial financing.

LEARN MORE

- Carbon capture and sequestration - the business, pages 11-16 in The Oxford Institute for Energy Studies (January 2022)

THE BUSINESS MODEL FOR EMITTERS

The business model for emitters depends on them securing revenue streams to cover both their investment in capture, purification and compression facilities (capex) and the transport and storage fees they pay to the operator (opex).

Revenue streams can come from a variety of sources, depending on the regulatory environment and the demand for carbon dioxide and related products from end-use customers. Depending on their location, emitters may be able to secure income from multiple revenue streams (see table).

In the current phase of CCUS hub developments, some governments are looking to provide one-off capital grants to emitters for capture projects, for example through the CCS Infrastructure Fund in the UK and state aid for the Longship projects in Norway.

POTENTIAL EMITTER REVENUE STREAMS

Compliance markets
In a compliance market for carbon dioxide, such as the EU Emissions Trading Scheme (ETS), the emitter realises a value for the emissions reductions represented by the carbon dioxide captured and stored from its operations. For each tonne of carbon dioxide captured and sequestered it does not need to buy an emissions allowance in the emissions trading scheme.

As the carbon dioxide price in most compliance markets is currently lower than the overall cost of carbon capture and storage, governments need to step in to incentivize investment.

One way to do this is with a Contract for Difference (CfD). The emitter is paid the difference between an agreed strike price and the prevailing market price for carbon dioxide in the trading scheme.

Tax credits
Some governments offer performance-based tax credits designed to incentivize carbon capture and storage or utilization.

An example of this is the 45Q Carbon Capture Tax Credit in the US. Qualifying emitters such as power and industrial facilities can generate a federal tax liability offset per captured tonne of carbon dioxide stored securely or used in a way that prevents it from ever being released into the atmosphere. This offset can be used directly by the emitter or traded with other organizations in any US state.

Voluntary carbon markets
In the absence of a compliance market, emitters can potentially sell carbon credits in the voluntary carbon markets based on certified emissions avoided or reduced through their involvement in a CCUS hub.

Voluntary carbon markets are expanding rapidly, stimulated by growing corporate net zero commitments. The methodologies for CCUS, however, are still evolving. Initiatives such as CCS+ and ACCU are exploring transparent ways to create carbon credits and make use of Article 6 of the Paris Agreement that will regulate voluntary international trading of carbon credits. Until regulations are tightened, voluntary markets could play an important supporting role in funding CCUS.

Carbon dioxide as a commodity
Carbon dioxide is used in a number of agricultural, food production and industrial processes where it has a market value. It can be locked permanently into some products, for example in the production of certain types of cement and building aggregates or plastics. It can also be used in the production of zero carbon synthetic fuels. The utilization market is currently marginal but is expected to grow rapidly.

Low carbon products
Emitters may be able to attract a premium for lower carbon products enabled by CCUS. Some of these are regulated markets. For example, the USA Low Carbon Fuel Standard regulations introduced by California and now under development in 13 other states attracts a significant premium for fuels which meet lower carbon intensity standards. Canada has a similar system in place.

Low carbon procurement is also starting to create a potential revenue stream for CCUS-enabled industrial products. Consumer goods industries such as the automotive sector are looking at procuring low carbon industrial inputs such as steel to meet demand for greener products. Cities and regional governments are looking at low carbon procurement for commodities such as steel and cement, for use in infrastructure projects.

THE BUSINESS MODEL FOR TRANSPORT AND STORAGE OPERATORS

The business model for transport and storage (T&S) operators is relatively simple – they are paid a fee to transport and store the carbon dioxide emissions captured by their industrial customers. The tariff is structured to cover the operator's investment and operating costs and provide a return on capital employed.

The fee structure will cover the following elements:

- Connection – which relates to the costs incurred by the T&S operator in connecting the emitter to the transportation infrastructure.
- Capacity – which relates to the right the emitter has to flow carbon dioxide onto the transport and storage system.
- Commodity – which relates to the actual volume of carbon dioxide transported and stored on behalf of the emitter by the T&S operator.

Since carbon prices are low and demand for low carbon products is nascent, the current business model for carbon transport and storage is likely to require government support. There are three broad types of business model, reflecting different market conditions and levels of government involvement.

Contractor to the state: This model is suitable when market and policy incentives are weak.

Investments and operating costs are predominantly financed (or guaranteed) by the government, which contracts planning, development and operations to state owned or private entities. The contractor holds some 'skin in the game'.

Phase 1 of Longship/Northern Lights is an example of the contractor to the state model. The Norwegian government is funding 80% of the investment costs and up to 95% of the operational costs for the initial transport and storage infrastructure. The Northern Lights JV is responsible for developing the market further.

Enabled market: This is a hybrid model comprised of state intervention in some parts of the market and managed competition in other parts. A regulated entity - the 'Market Maker' - is responsible for developing the transport and storage infrastructure and is required to take all the carbon dioxide captured by the emitters. The Market Maker can be a private company although it will be strictly regulated.

Porthos/Rotterdam is another enabled market approach, with some capital funding from the EU and fees to emitters structured in a way that covers costs.

The **regulated asset base** approach being developed by the UK government for carbon transport and storage infrastructure, including that for Net Zero Teesside, is an example of the enabled market model. Here, an operator receives a licence from the government regulator, which grants it the right to charge a regulated price, or fee, to users in exchange for delivering and operating the transport and storage network. The charge is set by the regulator who considers allowable expenses, over a set period of time, to ensure costs are necessary and reasonable.

Liberalized market: This model is suitable where market and policy incentives are strong and private companies develop and manage pipelines and storage sites without specific state direction. Individual participants are free to decide how their business will be structured – whether to pre-invest in over-sized transport and storage capacity, and how to allocate risk and return.

This is how CCUS infrastructure is currently being developed in the US, for example in the Louisiana hub, where the initial storage sites are likely to be onshore and lower cost. Transport and storage infrastructure development in the US may follow the oil and gas industry where hubs emerge on the back of infrastructure developed by the private sector for CCUS point-to-point projects.

For more information on T&S business models see these resources from the UK BEIS on CCUS business models, or this report from ZEP on business models for commercial carbon transportation and storage.

HOW DO YOU MAKE A CCUS HUB BANKABLE?

There is growing demand from investors for opportunities to invest in zero and low carbon infrastructure projects, driven by stakeholder pressures and ESG criteria. Macquarie Group, the world's largest infrastructure asset manager, is investing in the Acorn CCUS hub project in Scotland. Private equity firms, such as Starwood Energy Ventures, are developing investment vehicles in the US (alongside OGCI Climate Investments) tied to 45Q-related federal tax credits.

To make CCUS hub projects bankable, two broad groups of investment risks need to be addressed in detail among the hub partners and government:

Project risks around technology, construction, price and operations, which are common to any infrastructure investment. For hubs, the specific risks are around volume, leakage and multi-stakeholder project development. These will be mitigated over time through learning by doing: as more CCUS hubs are built, technologies and supply chains mature and prices are driven down through competition; and hub developers and T&S operators gain more project experience.

Hard-to-reduce risks include revenue risk, relating to an insufficiently high carbon price, cross-chain risks arising from the interdependency of the CCUS value chain, and long-term storage liability risk. These require government support to manage at present. Regulators also need to factor in subsurface risks that impact capital, operational and performance risks.

For more information on unlocking private finance for CCUS investments see this report by the GCCSI. The Clean Energy Ministerial (CEM), working with public and private finance organisations, has developed a number of financing principles for CCUS. These provide a useful generic framework for stimulating the CCUS industry.

RISKS IN THE CCUS HUB VALUE CHAIN AND HOW THEY CAN BE MITIGATED

Project risks:

Volume risk
A key risk for CCUS hub projects is that the promised carbon dioxide does not arrive. This has two elements:

- *'Daily' volume risk* – the risk that volumes delivered by the emitter to the T&S operator are lower than expected.
- *During-life volume risk* – for example, the risk that at a certain point in time the emitter decides to reduce its production capacity and therefore, its associated emissions.

Possible contractual solutions to volume risk include:

- *A send-or-pay contract* – this de-risks the T&S operator by guaranteeing their revenues, but pushes the risk towards the emitter. It is possible to address this through banking or make-up rights, as feature in natural gas contracts.
- *A pay-as-you-go contract* – this is favourable for the emitter, but risks lower than expected volumes for the T&S operator who will address this risk by charging higher tariffs. One solution is to stipulate a minimum volume to keep the scheme operational.

Leakage risk
Leakage of carbon dioxide is a small risk during operations, taking place along the injection well bore or during maintenance, for example. That could result in carbon price exposure, depending on the regulatory regime.

The contract should address who bears the liability: the emitter or the T&S operator, or is it shared? This is more complex if it is across state or international boundaries.

Impurities risk
This relates to the consequence of impurities in the capture stream, like mercury, which can cause the pipelines to erode. The contract should addres the T&S developer, because they should have anticipated this, or the customer – or shared.

Project development risk
This relates to the timing risk on Final Investment Decision (FID) since multiple parties need to take their FIDs at the same time for the CCUS hub development to proceed.

On the T&S operator side, the risk can be managed by having a portfolio of emitter companies.

For emitters, this risk is more challenging as they are generally working with only one T&S company. Possible solutions include creating a contractual structure where the T&S company guarantees to take the carbon dioxide, or taking a direct ownership share in the T&S company.

Hard-to-reduce risks:

Insufficient value on carbon dioxide
A robust policy mechanism that places a sufficient value on carbon dioxide is needed to support investments in capture facilities that can then pass on a share of the benefit to transport and storage providers. This may take the form of a carbon tax, tax credit, emissions trading scheme, CCS obligation, emissions performance standard, or government procurement standards.

In markets where carbon prices exist, these prices may not be sufficiently high enough to incentivize investment in CCS projects and governments may need to introduce additional levels of support, through instruments such as a Contract for Difference.

Interdependency of the CCUS value chain
CCUS projects require the coordination of multiple investment decisions in different parts of the CCUS value chain, each with long lead times. This creates risks associated with relative timing and capacity management.

This interdependency continues during the operational phase where failure of one element of the CCUS value chain may affect the costs and revenues of other participants and prevent the value chain from performing as a whole.

Government ownership of the transport and storage infrastructure, or capital support can help mitigate the timing risk. As more emitters connect to the network the interdependency risk will be reduced. Government may then choose to sell the infrastructure to the private sector for a profit.

Hubs are also cooperating with each other to provide storage back-up if needed, for example in the North Sea region.

Long term storage liability
Legal and regulatory frameworks may place limits on private investors' exposure to any long-term storage liabilities. This can be managed by transferring these liabilities to the state after a specified period post-closure, subject to transparent monitoring and acceptable performance of the storage facility. Jurisdictions may specify a minimum number of years during which operators will have to continue post-closure monitoring of a site.

Another way long-term storage liability can be managed is through a risk capping mechanism. This would allow the private sector operator to take responsibility for risks incurred below a cap, whilst the government would take responsibility for all additional risks above that cap. The value of the cap could be a function of the balance of public and private equity in the storage operation, with higher private equity translating to a higher cap.

4. GETTING STARTED

4.1 POLITICAL DECISION-MAKERS

As net zero targets become mainstream, government officials at national, regional and local levels need solutions for decarbonizing existing heavy industry, as well as infrastructure for new clean industries to thrive. CCUS hubs can play an important role help industrial regions to keep existing jobs and attract new ones, accelerate the adoption of low carbon hydrogen across many sectors and create the infrastructure for carbon removal technologies. With momentum picking up in countries around the North Sea, in North America and Asia, what was once seen as an expensive, unproven technology is becoming a cost-effective decarbonization option for industries that have few alternatives currently available to them.

WHAT DO YOU NEED TO KNOW ABOUT CCUS HUBS BEFORE YOU START?

All the technologies required in the CCUS hub value chain are proven. Developing the market and the business models are the main challenges in these early hub developments.

For now, government support is required to tackle four main challenges:

- Incentivize emitters to invest in capturing their carbon dioxide emissions so they can maintain competitiveness until the carbon value is high enough to create a level playing field.
- Incentivize potential carbon transport and storage operators to invest in infrastructure – providing a business case despite the lack of a sufficiently high and stable carbon price.
- Address challenges throughout the CCUS value chain like performance risk and counterparty risk.
- Establish the permission space for a CCUS hub.

In the absence of sufficiently high carbon prices or mandates, governments are using a range of tools in different combinations to support CCUS hubs. These include feasibility study grants, capital grants, tax incentives, contracts for difference, regulated assets base, low carbon standards and public procurement requirements.

READ MORE

- Why should governments support CCUS hubs?
- Why do CCUS hubs need government support?
- What kind of policy enablers can support CCUS hubs?
- What are the policy support models used in early hubs?

WHAT ARE THE POLICY LESSONS LEARNED SO FAR?

Understand and align objectives

- Be clear why are you doing the project
- Make sure that the goals of government, emitters and hub developers are all moving in the same direction
- Establish priority objectives and build your policy framework around them
- Establish clear no-goes or boundaries; be flexible on things that are less important

Define roles

- Be clear on the different roles in the project – for example, the state as enabler sharing costs and risks, letting companies do what they are good at, such as selecting technologies

Build trust

- Create a forum to bring together government, emitters and storage service providers
- Co-develop national CCUS strategies
- Build confidence with a step-by-step process, showing good faith in feasibility studies, negotiations and other project stages, and articulating progress made

Design incentives

- Don't force industry to get on board, encourage them with incentives
- Understand companies' business models in order to incentivize them effectively
- Develop commercial models with industry up front so that the major risks are allocated before negotiations start
- Make sure incentives enable a long-term business rather than being purely subsidy dependent
- Get the incentives right, then let industry make their own decisions – they are making huge investments and things can change, so they need flexibility
- Look forward – ensure that policies incentivize scaling
- Align incentives with industrial strategy

Take care of regulations

- Work to harmonise international regulations (such as the London Protocol on transporting carbon dioxide), so they are appropriate for CCUS
- Be aware of changing protocols, standards and emerging regulations
- Broaden regulations on transport and storage to deal with the multiple emitters and carbon dioxide streams involved in hubs – existing regulations were developed for point-to-point CCUS
- Develop regulations to deal with cross-border transport of carbon dioxide, including carbon accounting systems – for example, how to account for emissions captured in one country but stored in another

Public and political support

- The right narratives are critical for gaining political and broad societal support. Emphasise that CCUS hubs are addressing climate change in a constructive way. They are needed to deal with heavy industry, not a fig leaf for polluting forms of energy
- Don't present CCUS as an alternative to other approaches – all tools are needed and some work better in specific contexts
- Consistent political support is vital, spanning a sequence of governments
- Prove the value of CCUS hubs. For example, NZT Power employed independent consultants to analyse the value of the project to the country's electrical power system

Keep communicating

- Maintain good communication between government and industry, explaining the different processes involved in business and the state. Forums such as the CCUS Advisory Group in the UK can help play this role
- Give decision makers the relevant information – not too much information
- As policy direction is often evolving in parallel with hub projects, industry needs to be consulted on policy development
- To help state and industry understand each other, it can be useful to have an agency in the middle, such as Gassnova in Norway, or a specialist CCS agency, such as the CCSA in the UK

READ MORE

- Designing effective policies for CCUS hubs
- Developing effective regulations for CCUS hubs

WHAT QUESTIONS SHOULD POLICYMAKERS ASK THEMSELVES WHEN DEVELOPING POLICIES AND REGULATIONS FOR CCUS HUBS?

Objectives

- What are our objectives? For example:
- reduce national emissions, to meet or beat NDCs
- preserve industrial activity and jobs
- stimulate a domestic CCUS industry, including equipment manufacturers and service companies
- catalyse global CCUS investment at scale
- How do our CCUS-specific objectives align with our climate targets and industrial strategy?
- What policies can reflect our objectives?
- Who can we learn from: other jurisdictions, other CCUS projects, other industries?

Working together

- What are the objectives of other project stakeholders: industry, local and national government, politicians, local communities, trade unions and NGOs?
- What are industry's risks, and why do they want to get involved in CCUS?
- How can we build and retain trust between state and industry during the process of setting up a hub?
- How do we make hubs sustainable so that the transport & storage service provider can expand as demand grows?
- What are the formal project development processes used in industry, and how can they work alongside the different processes of the state?
- How do we allocate risk and reward when expectations regarding return on investment vary?
- How do we understand the risk profile of different emitters?
- Which issues need compromises?
- How do we retain political and public support?

Policy design

- What market failures do we need to address?
- What are the key risks that government has to take on?
- How can we incentivize cost reductions?
- How can we incentivize scaling, for example incentivise sharing of project lessons?
- Where we are providing subsidies, what return can we allow commercial participants and how do we match it to risk and requirements for additional investment?
- Are commercial models clear for both the emitter and transport and storage side?
- How long should support last? What are the conditions to scale down and stop funding?
- What types of support are needed at different stages, such as concept definition, FEED, execution, operation?
- How do we create a robust policy mechanism, insulated from changes in government?
- Are we looking to work with other countries/ states, and what are the policy implications?
- Have we addressed global industrial competitiveness, for example through carbon border mechanisms?

Legal framework and regulations

- Do we have an appropriate legal and regulatory framework for CCS?
- Can CCUS be regulated under or adapted from current regulations for oil and gas?
- What is the reporting landscape for a CCUS project? What permits do they need and from whom?
- How do our CCS policies and regulations work together?
- Which other government departments should we be working with?
- Are there any international or regional legal obligations we need to consider, for example the 1996 London Protocol on export of carbon dioxide?

4.2 INDUSTRIAL EMITTERS

Hard-to-abate industrial companies in sectors like cement, steel, chemicals, fertilizers and waste-to-energy are increasingly looking at CCUS as part of their pathway to net zero. Finding the right business model to finance carbon capture is still tough, but that is changing in some countries as carbon prices rise, new low carbon product standards are introduced, and innovation funding is directed to companies in hard-to-abate sectors to speed up decarbonization. The emergence of CCUS hubs is making it easier to embrace CCUS, without having to take responsibility for building pipelines and drilling storage wells – and without long-term liability for the stored carbon dioxide.

WHAT ARE THE PROS AND CONS OF A CCUS HUB FOR AN EMITTER?

A CCUS hub takes carbon dioxide from several emitting sources, such as heavy industries and power, and then transports and stores it using common infrastructure. For emitters, the hub offering opens up CCUS as a decarbonization option without them having to take responsibility for building pipelines, drilling storage wells and monitoring carbon dioxide storage.

The downside is that developing a CCUS hub is complex. The value chain typically consists of a hub developer, that initiates and manages the value chain; multiple emitters who guarantee to capture and supply carbon dioxide; and a single transportation and storage company (that could serve several hubs).

Many industrial emitters with different industrial processes and specific regulatory constraints need to be pulled together in a big infrastructure project. So, it is important to communicate clearly to the hub developer and/or transport and storage operator what it will take to optimize your production operations – while capturing carbon dioxide.

Multiple parties need to take their Final Investment Decision at the same time for the CCUS hub development to proceed, representing a major project development risk. Possible solutions to the timing risk faced by emitters include creating a contractual structure where the transport and storage operator guarantees to take carbon dioxide or taking a direct ownership share in the T&S company.

READ MORE
› Why do a CCUS hub?

HOW DOES CARBON CAPTURE AND STORAGE WORK?

In the exhaust from industrial processes and fossil fuel powerplants, carbon dioxide is mixed in with nitrogen, oxygen and other gases. So CCUS first separates out the carbon dioxide. The main method currently used to do this is amine scrubbing. Flue gas is piped into the bottom of a vertical reactor vessel, where it rises up through a mist of a carbon dioxide absorbing liquid (usually an amine solution). The scrubbed gas is released at the top, with typically 90% or more of its carbon dioxide removed. The amine then goes to another vessel where high-temperature steam takes out the carbon dioxide. Finally, the near-pure carbon dioxide is compressed ready for transport.

In this early phase, emitters may need to test this technology on their processes. This will depend on the maturity of the capture technology and the industrial applications it has already been applied to. Testing would require additional expenditure by the emitter in the feasibility (pre-FEED) phase.

Before committing to expensive FEED studies, the emitter needs to get a clear understanding from the transport and storage operator that the proposed reservoir has sufficient permanent storage capacity and that the injection wells will work.

READ MORE
› Understanding CCUS

IS CARBON CAPTURE A COMMERCIALLY VIABLE WAY TO DECARBONIZE?

The exact cost of carbon capture depends to a great extent on the mixture of gases captured. If there is a high proportion of carbon dioxide, at high pressure and on a large scale, it is relatively easy to capture, making costs lower than for dilute or low-pressure exhaust gases.

Compression costs will vary depending on the capture and associated industrial process but can be high to meet pressure specifications. For industries making fertilizers or ethanol, capture cost is well below $50 per tonne; for steel it can be around $100 per tonne, rising up to around $250 per tonne for aluminium. Local storage and loading costs may be relevant if transportation of carbon dioxide to the permanent storage site is done by truck, ship or rail.

Emitters need certainty on the specifications around purity and pressure of carbon dioxide to be delivered to the transport and storage operator. The tighter the specifications, the higher the costs for the emitter. Impurities such as water, nitrogen, sulphur oxide, nitrogen oxide, carbon monoxide, hydrocarbons and mercury can have major implications, for example corrosion, for carbon dioxide transportation and storage infrastructure, and on how the carbon dioxide behaves once it is injected into the target reservoir deep underground.

Depending on their location, emitters may be able to secure income from multiple revenue streams, including compliance (carbon) markets such as the EU ETS, tax credits, voluntary carbon markets, carbon dioxide as a commodity and low carbon product markets.

Government support to emitters typically takes the form of capital grants and operational cost funding, through a contract for difference on a carbon price, as in the UK and Netherlands, or a storage tax credit combined with a low carbon fuel standard, as in the US.

Emitters are likely to recover their capex on investments in carbon capture over a longer period of time than is normal for other investments. Returns will effectively be regulated as opposed to market driven.

READ MORE
› The business model for emitters

WHAT SORT OF RISKS DO EMITTERS FACE?

A key part of the commercial negotiations between the emitter and transport and storage operator focuses on the allocation of risks. Emitters face project risks around technology, construction, price and operations, which are common to any infrastructure investment. For hubs, the specific project risks are around volume, leakage and multi-stakeholder project development.

Emitters' hard-to-reduce risks include revenue risk, relating to an insufficiently high carbon price, cross-chain risks arising from the interdependency of the CCUS value chain, and long-term storage liability risk.

READ MORE

› Risks in the CCUS hub value chain and how they can be mitigated

WHAT ARE THE QUESTIONS EMITTERS SHOULD ASK THEMSELVES?

- ☐ What forms of government support are in place for emitters to capture carbon dioxide?
- ☐ Will the proposed incentives provide appropriate support for our industry?
- ☐ Are the necessary regulations in place for my capture project?
- ☐ What revenue streams are available to our project?
- ☐ What are my likely returns on investment?
- ☐ How certain are we that carbon dioxide storage is sufficient and ready to be used?
- ☐ Will we need to test the capture technology on our processes?
- ☐ What are the carbon dioxide specifications required by the transport and storage operator?
- ☐ What are the compression costs?
- ☐ Are there any local storage and loading costs?
- ☐ How are we dealing with project and operational risks?

› Read more about how industrial emitters are using CCUS hubs as part of their decarbonization pathways – Fortum, Holcim, BASF

4.3 TRANSPORT AND STORAGE OPERATORS

The essence of a CCUS hub is collective transport and storage infrastructure, supporting a range of different emitters and possibly even several hubs. Transport and storage operators are responsible for transporting the captured carbon dioxide by pipeline, ship or other means to the storage site, where they inject it into the subsurface geology. They assume most of the liability for the captured carbon dioxide once it is handed over, and they are responsible for permanent storage and monitoring at least until the well is safely closed.

To date, transport and storage operators have tended to be large companies or joint ventures, with infrastructure and sub-surface knowledge, as well as experience in running major projects. They are often also involved in hub development, playing the role of integrator as well as operator. Where CCUS-relevant infrastructure (such as carbon dioxide pipelines in the US) are more mature, transport and storage operators will more frequently be brought in as service providers by emitters or other companies wanting to set up a hub. And as the CCUS ecosystem evolves, companies focusing only on transport or only on storage are starting to emerge.

Q: WHAT IS THE BUSINESS MODEL FOR TRANSPORT AND STORAGE OPERATORS?

The business model for transport and storage operators is relatively simple – they are paid a fee to transport and store the carbon dioxide emissions captured by their industrial customers. The tariff is structured to cover the operator's investment and operating costs and provide a return on capital employed.

Since carbon prices are low and demand for low carbon products is nascent, the current business model for carbon transport and storage is likely to involve government support and regulation, depending on market conditions.

Where transport and storage operations have the form of a natural monopoly – multiple emitters using a single piece of infrastructure – returns are likely to be regulated and comparable to those achieved by utilities and large-scale infrastructure companies.

As competition in transportation and storage services emerges, the need for regulation may decrease.

READ MORE

- Understanding the business model for transport and storage operators
- What are the policy support models used in early hubs?

WHAT SPECIFIC RISKS DO TRANSPORT AND STORAGE OPERATORS FACE?

Storage liabilities are a key risk for transport and storage operators. Government CCUS regulation should be clear on carbon dioxide storage liability: who is responsible at each stage of injection, monitoring and long-term stewardship; and how risk is shared and eventually transferred to government.

The transport and storage operator will need to spend money upfront to quantify the storage capacity and de-risk it for potential customers. For example, geological de-risking may require shooting seismic and drilling wells. Upfront investment in de-risking storage will make it much easier to scale CCUS hubs, but few policymakers have focused on this to date.

The operator will also need to identify the specifications around purity and pressure of the carbon dioxide to be delivered to the transport and storage operator. Looser specifications makes post-capture compression and purification cheaper for emitters, but impurities in the CO_2 – such as water, nitrogen, SOx, NOx, carbon monoxide, hydrocarbons and mercury – can have major implications, for example corrosion, for carbon dioxide transportation and storage infrastructure.

READ MORE

- Risks in the CCUS hub value chain and how they can be mitigated

WHAT REGULATIONS ARE NEEDED FOR CO_2 TRANSPORT AND STORAGE?

CCUS hubs require regulations relating to permitting, standards for construction and operation of transport and storage infrastructure and storage facilities, storage liabilities, monitoring, reporting and verification (MRV) protocols and rules for third party access.

Governments typically have the tools and experience to incentivize and regulate the carbon dioxide transportation business, but they can struggle with understanding geology and the associated storage risks.

READ MORE

- Developing effective regulations for CCUS hubs

4.4 POTENTIAL HUB DEVELOPERS

A CCUS hub requires a hub developer who initiates and drives stakeholder engagement, especially on the local level, and manages the value chain. Hub developers are often oil and gas or infrastructure companies looking to offer carbon transport and storage services. But they can also be state-owned entities aiming to develop strategic infrastructure to support industry and jobs in a region, or indeed an emitter or group of emitters looking for a cost-effective solution to decarbonization.

WHAT DO YOU NEED TO KNOW ABOUT HUBS BEFORE YOU START?

A CCUS hub is a highly complex collaboration.
All the technologies required in the CCUS hub value chain are proven. Developing the market and business models are the main challenges in these early hub developments. There are also uncertainties to be addressed in relation to government support mechanisms, regulations, geological storage verification and risk, commercial agreements and getting broader societal buy-in.

Navigating these requires a convergence of interests, as well as shared knowledge and a shared narrative from companies with subsurface and CCUS experience, national and local politicians and community groups, and multiple emitters. When this ecosystem is in place, it creates the conditions and momentum to build a business model around concrete hub opportunities.

Creating that ecosystem is a massive alignment and co-ordination challenge – among hub partners to coordinate different interests and investment processes; with government over support mechanisms and risk allocation; and more broadly in relation to the value the project delivers both at a local level and as a credible part of a country's overall energy transition.

Government support is essential
It is needed to tackle four main challenges:

- Incentivize emitters to invest in capturing their carbon dioxide emissions so they can maintain competitiveness until the carbon value is high enough to create a level playing field.
- Incentivize potential carbon transport and storage operators to invest in infrastructure – providing a business case despite the lack of a sufficiently high and stable carbon price.
- Address challenges throughout the CCUS value chain like performance risk and counterparty risk.
- Establish the permission space for a CCUS hub.

CCUS hubs require local backing
National-level support is critical to getting hubs off the ground, but it is not sufficient. CCUS hubs enable regional industrial decarbonization and a transition of existing industrial hubs to low carbon ones. Strong local on-the-ground support – from mayors, local authorities, local businesses, industrial associations, labour unions and community organizations – is needed to navigate the complexity involved in achieving that transformation process. It is not enough to agree on a single national approach to hub development.

READ MORE
› What are the advantages and disadvantages of a CCUS hub over a single project?

HOW DO YOU IDENTIFY A POTENTIAL HUB?

› The CCUS Hub Search

The identification of potential CCUS hub opportunities starts with two basic questions:

- where are the big industrial emission clusters?
- where are the potential geological storage sites?

High-level geospatial screening will suggest many possible hub locations. These then need to be analyzed along a number of dimensions to determine project viability:

- **Existing infrastructure and CCUS activity:** Are there any existing CCUS projects in the potential host country including demonstrations and pilots? Is there an existing CCUS and/ or oil and gas industry and associated supply chains? Is there an existing oil and gas pipeline infrastructure which links the industrial cluster to potential storage sites with existing oil and gas production infrastructure. What is the capacity of this infrastructure, and could it be retro-fitted for carbon dioxide (CO_2) transportation and storage? What are the estimated costs associated with carbon capture, transportation and storage?
- **Climate and CCUS targets, policies and regulations:** Does the government have clear and effective climate targets, for example, NDC commitments, and associated CCUS targets? What is the status of policy support for CCUS hubs? Is there any form of carbon pricing such as an emissions trading scheme or carbon tax? Are there any CCUS mandates? Are regulations for CCUS projects in place?

LEARN MORE

› The GCCSI's Global Policy Indicator (CCS-PI) is a useful resource which tracks the status of government CCUS policies.

HOW DO YOU GET SUPPORT FROM STAKEHOLDERS?

Multiple stakeholders are involved in and affected by CCUS hub projects. In addition to hub partners, these include national and regional governments, local authorities, industry regulators, trade unions, industry associations, local communities and NGOs. Establishing the permission space for CCUS in general and for the specific hub project is vital. How can this be done?

Stakeholder engagement should start with a listening process – aiming to understand the needs and goals of different stakeholders, their questions about CCUS and specific concerns about the hub project. This can be done through a combination of structured one-on-one interviews with key stakeholders, public meetings and even workshops to explore how to align their needs with the overall hub project. Early and frequent communication with stakeholder groups as the project progresses is essential.

At a broader societal level, the focus of the engagement is likely to be on the role of CCUS hubs in meeting climate targets and decarbonizing heavy industry. At a local level, topics such as the safeguarding of existing jobs and creation of new opportunities enabled by the hub project will be key.

The Climate Accord Process in the Netherlands provides a good example of engagement leading to broader acceptance of CCUS as a necessary climate technology in a country where scepticism was particularly high.

The government held a joint fact-finding process on the potential role of CCUS in the Dutch energy transition, led by independent, academic facilitators and involving NGOs, industry and industry associations. Eight roundtables were convened, structured around a list of questions. All stakeholders were invited to provide answers to these questions which gave the basis for a common view. While some NGOs pulled out of the process, there was alignment around the conclusion that CCUS would be necessary to get quick reductions in industrial emissions without stopping the economy.

This provided an important source of legitimacy for both CCUS and the Porthos project and gave the government confidence to let emitters compete for SDE++ CCUS funding, alongside other decarbonization projects, based on the cost of emissions reductions. Of the €5bn total pool of SDE++ funding up to €2.1bn (depending on the EU ETS price) went to emitters involved in Porthos, based on their low relative cost.

WHAT FOUNDATIONS DO YOU NEED WHEN LAUNCHING A HUB PROJECT?

Focus on getting collaboration with partners right: hubs bring together different industries which may, or may not, have pre-existing commercial relationships and different stakeholder groups all of which can have distinct and different goals and objectives. One lesson that emerges from the most advanced CCUS hubs is not to skimp on building solid collaboration at the beginning of the project. Ensuring that partners are aligned takes time but is critical.

How to get collaboration right

- **Establish strong foundations.** Start by agreeing why you are undertaking the project and why you need each other. Spend the necessary time to understand each other's business, key drivers, risks and company cultures.
- **Develop deep alignment.** Create a simple shared narrative built around a common vision across the whole value chain, and write it down to keep on track later. At this early stage of hub development, the focus should be on the why, rather than the what or how.
- **Build confidence and trust.** Build trust by sharing power and creating cross-partner teams to work together on progressing different elements of the hub development project. Create confidence and deepen trust by demonstrating and celebrating tangible progress at each stage in the hub development process.

Other lessons emphasised by hub developers include:

- **Get the right people on board.** Involve the right people and start the project with positive attitudes and mindsets. Invest in personal relationships.
- **Be agile.** Expect that the rules of the game will change in relation to government support, financing and customer needs. Think win-win and use agile working methods.
- **Understand your customers.** Hub projects involve multiple emitters operating different industrial processes each subject to different regulations and different internal processes. These are the customers for the hub and it is vital to understand their specific needs. They are typically low-margin businesses, and they are focused on optimizing their production operations – not on the amount of waste product, ie carbon dioxide, they produce. They will know very little about CCUS, their risks and how they can manage them. Even in the early stages, it's important to go beyond just one or two emitter customers – designing for what success would look like.
- **Do not play hide and seek.** Once you have built trust, show your weaknesses and organize for them. Hub partners should start by focusing on the risk areas and identifying positions to each other before embarking on technical detail otherwise big issues might be discovered at the last minute.
- **Learn how to work with government.** At this early stage of CCUS hub development, policy definition and hub developments are often proceeding in parallel. Resist the temptation to ramp the project up quickly if policy is not mature.

How to work with government – tips from the advanced hub developers:

- **Build confidence and trust.** Take a step-by-step approach when working with government. Build confidence and trust by demonstrating tangible progress at each stage. Take photographs so politicians have something to show.
- **Keep communicating.** During this early phase of hub development, there is so much uncertainty – policy development requires trust and continual dialogue between hub developers, transportation and storage developers, emitters, policy makers and politicians. Understand the political process.
- **Help governments understand the risks.** It is vital for the hub partners to provide input into the risks that government is taking. Governments typically have the tools and experience to incentivize and regulate the carbon dioxide transportation business but they can struggle with understanding geology and the associated storage risks.
- **Understand government processes and timelines.** Government timelines for deciding policy support are driven by political processes, whereas CCUS hub development timelines are driven by industrial project maturity processes. These two timelines do not always coincide and sometimes hub partners need to make commercial decisions before detailed technical work (FEED) is completed. Continued dialogue between government and hub partners is necessary.