SIX DEGREES, OXFORD CONSULTANCY FOR SUSTAINABILITY

CARBON CAPTURE & STORAGE

CURRENT TECHNOLOGY AND MARKET

Carbon Engineering Direct Air Capture

Report brief

University of Oxford is assessing options to compensate for unavoidable emissions. The University's sustainability office has measured that Oxford emits 30,000 tonnes of carbon per year from aviation-related emissions by staff and academics. Previously, Six Degrees assessed various commercial nature-based offset opportunities available to compensate for these emissions. This report is a follow-up analysis assessing the technology associated with and the availability, price, and capacity of geological sequestration opportunities currently in the market.

This report has been produced by an interdisciplinary team of consultants currently enrolled at the University of Oxford throughout Six Degrees Oxford Consultancy for Sustainability.

Hilary 2020

TABLE OF CONTENTS

GEOLOGICAL CARBON CAPTURE AND STORAGE (CCS) OVERVIEW

Carbon captured through nature-based solution such as afforestation can be seen as problematic. They are reversable, land and water intensive, and have a limited capacity when scaled globally. To reduce atmospheric CO2 we must continue to work towards reforestation, but also seek the use of negative emissions technologies as they are not constrained in their capacity. In addition to reducing overall emissions to reach net zero, there are emissions that are difficult to decarbonize such as air travel. These emissions can be offset by either reducing emissions elsewhere or by capturing and storing the equivalent amount of carbon. Current negative emissions technologies can store CO2 geologically in a way that is difficult to reverse, unlike afforestation.

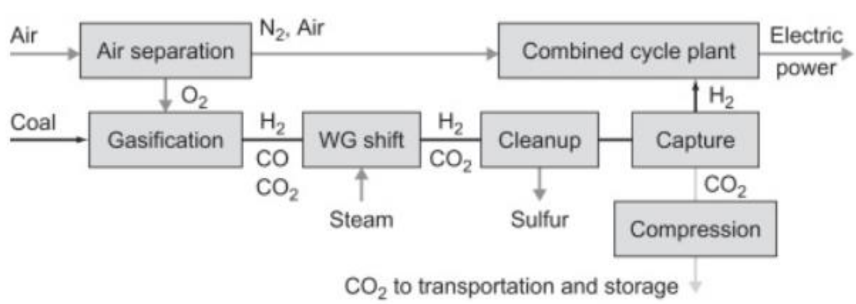
GEOLOGICAL CAPTURE, SEPARATION, TRANSPORTATION, AND STORAGE TECHNOLOGIES

FEATURED CAPTURE TECHNOLOGIES

1. Pre-combustion capture[1]
2. Post-combustion capture
3. Oxyfuel combustion
4. Direct Air Capture (DAC)
5. Bioenergy with CCS (BECCS)

PRE-COMBUSTION CAPTURE

Converting solid, liquid or gaseous fuel into a mixture of hydrogen and carbon dioxide using processes such as 'gasification' or 'reforming'. Chemically 'strips' off the carbon, leaving only hydrogen to burn. Occurs in coal gasification plants. Converts fuel into a mixture of hydrogen and CO2. CO2 is captured whilst H2 used as fuel.



ScienceDirect

[1] An overview of current status of carbon dioxide capture and storage technologies - Leung, Caramanna, Maroto-Valer 2014. https://www.sciencedirect.com/science/article/pii/S1364032114005450

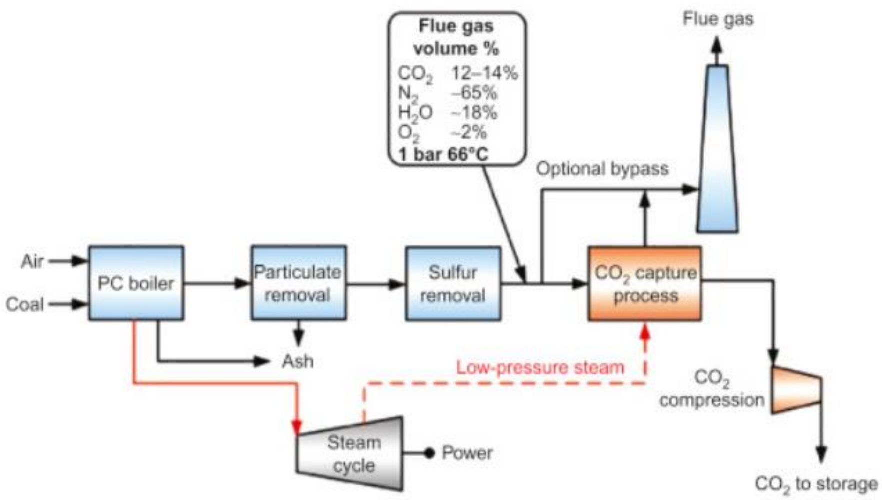
Geological Carbon Storage – Bickle 2009. https://www.nature.com/articles/ngeo687

CO2 Capture Technologies – 2011. https://unfccc.int/sites/default/files/overview_of_co2_capture_technologies.pdf

Pros	Cons
The hydrogen produced by these processes may be used, not only to fuel our electricity production, but also in the future to power our cars and heat our homes with near-zero emissions.	This technology has not yet been applied to a process as large as power generation.
High CO2 concentration enhances absorption efficiency	Needs to undergo a gasification process, which is expensive
This capture technology is well understood and is already used in industrial applications such as the production of carbon dioxide during production of hydrogen from splitting hydrocarbon in oil refineries.	Requires large modifications to existing plants

POST-COMBUSTION CAPTURE

CO2 captured from the exhaust of a combustion process by absorbing it in a suitable solvent/high pressure membrane filtration, adsorption/desorption processes/cryogenic separation, etc. There are also different strategies for post-combustion capture. Occurs in coal-fired and gas-fired plants. Removes CO2 from flue gases at power stations. Most mature technology.

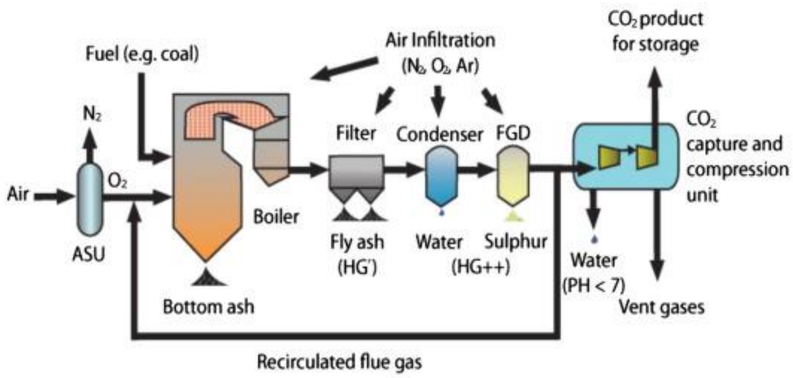


ScienceDirect

Pros	Cons
Could be retrofitted to existing power plants, such as those that burn coal (produces the most carbon dioxide per unit of electricity generated among the fossil fuels). Several sites around the UK are being considered for this.	Low CO2 concentration affects the capture efficiency
	Has not been proved on a large scale yet (power plants)
Solvent scrubbing, which is required in post combustion capture is a well-established technology.	Solvent losses and environmental pollution

OXYFUEL COMBUSTION

Oxygen is separated from air prior to combustion, then the fuel is combusted in oxygen diluted with recycled flue-gas rather than by air. Burns coal or gas in denitrified air to yield only CO2 and water. Occurs in coal-fired and gas-fired plants. Burns fossil fuel with pure oxygen. Results in almost pure CO2 which can be transported to sequestration site and stored.

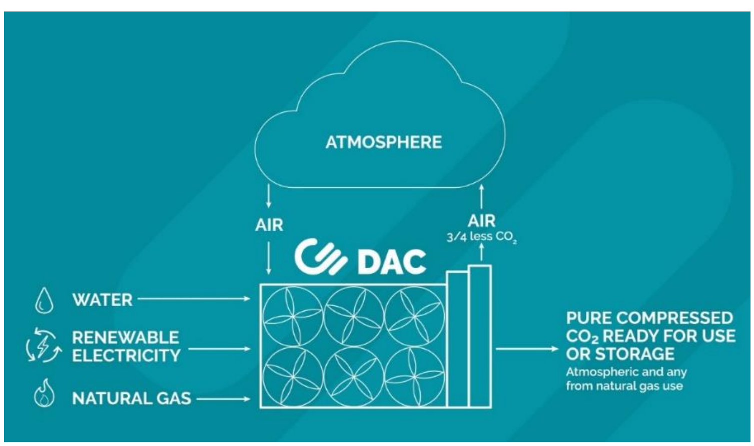


ScienceDirect

Pros	Cons
Results in final flue-gases that consist mainly of CO2 and H2O, so producing a more concentrated CO2 stream for easier purification	As of 2007, least developed of the three capture technologies
	Although air separation is a proven technology, it is also expensive
	Burning coal or gas in pure oxygen requires new technology
	Production of O2 is costly and may cause corrosion problems

DIRECT AIR CAPTURE

Filter and/or chemically concentrate CO2 out of air. The first cycle is the absorption of CO2 from the atmosphere in a device called an "air contactor" using an alkaline hydroxide solution. The second cycle regenerates the capture liquid used in the air contactor and delivers pure CO2 as an end product. The captured atmospheric CO2 can be stored underground, used for enhanced oil recovery.

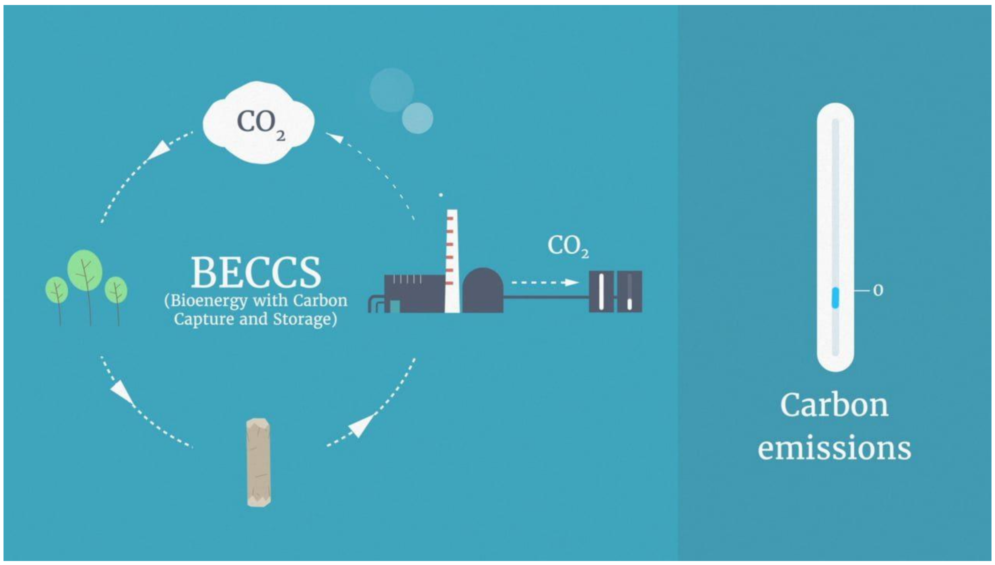


Carbon Engineering Direct Air Capture

Pros	Cons
Geographically agnostic	High energy use
	Expensive
	Not available at scale – current projects lacking investment

BECCS

BECCS is the process of growing crops to suck carbon out of the air and then burning them to generate electricity. During the burning process, the CO2 is captured during combustion.



Pros	Cons
Geographically agnostic	Expensive
Safe projects with legal monitoring to ensure liability	Not available at scale – current projects lacking investment

SEPARATION TECHNOLOGIES (SEPARATING CO2 FROM THE FLUE/FUEL GAS)

1. Separation with sorbents and solvents
2. Separation with membranes
3. Cryogenic distillation
4. Others include chemical looping combustion and Hydrate-based separation

SEPARATION WITH SORBENTS AND SOLVENTS

Passing the CO2-containing gas in intimate contact with a liquid absorbent or solid sorbent that is capable of capturing the CO2. Other emerging processes based on new liquid sorbents, or new solid regenerable sorbents are being developed with the aim of overcoming the limitations of the existing systems. This is a high cost method as the flow of sorbent between the vessels must be sufficiently large to match the huge flow of CO2 being processed in the power plant. This requires large equipment sizes and a large amount of energy for sorbent regeneration, which translates into efficiency penalty and added cost. Costs related to the purchase of the sorbent and the disposal of sorbent residues.

Pros	**Cons**
Using liquid solvent is the most mature method of separation and is also very efficient	There are potential environmental impacts related to sorbent degradation that have to be understood
Using solid sorbent is reversible, the adsorbent can be recycled and it is highly efficient	Significant amounts of heat for absorbent regeneration are required
	It is an energy-intensive process

SEPARATION WITH MEMBRANES

Membranes are specially manufactured materials that allow the selective permeation of gas. Flow of gas is usually driven by the pressure difference across the membrane. Therefore, high-pressure streams are usually preferred for membrane separation. Different types of membrane materials (polymeric, metallic, ceramic). Membranes can be used to allow only CO2 to pass through, while excluding other components of the flue gas. Past experiments have achieved a CO2 separation efficiency of 82-88%.

Pros	**Cons**
Currently used for commercial applications in industry (e.g. CO2 separation from natural gas)	Not yet been applied for the large scale and demanding conditions in terms of reliability and low-cost required for CO2 capture systems
	A large worldwide R&D effort is in progress aimed at the manufacture of more suitable membrane materials for CO2 capture in large-scale applications

CRYOGENIC DISTILLATION

Uses distillation at very low temperature and high pressure. Potential drawback: very energy intensive process. It is a mature technology.

CHEMICAL LOOPING COMBUSTION

Uses a metal oxide as an oxygen carrier. It avoids energy intensive air separation. There is no large scale operation experience.

HYDRATE-BASED SEPARATION

The exhaust gas containing CO2 is exposed to water under high pressure, forming hydrates as a result. The CO2 is then selectively engaged in the cages of hydrate and separated from other gases. This technology has a small energy penalty. However, more research is required.

TRANSPORTATION

After being captured and then compressed into a liquid state the CO2 is transported by pipeline, ship or road tanker. Currently there are special carbon dioxide pipelines e.g. USA's enhanced oil recovery (more efficient for distances up to 500 kilometres). Tanker ships are also used but in small amounts.

STORAGE

Geological storage of CO_2 has been a natural process in the Earth's upper crust for hundreds of millions of years, accumulating in the natural subsurface environment as carbonate minerals, in solution or in a gaseous or supercritical form, either as a gas mixture or as pure CO_2. To geologically store CO_2, it must first be compressed, usually to a dense fluid state known as 'supercritical'. Subsurface geological storage is possible both onshore and offshore, with offshore sites accessed through pipelines from the shore or from offshore platforms. Basins suitable for CO_2 storage have characteristics such as thick accumulations of sediments, permeable rock formations saturated with saline water (saline formations), extensive covers of low porosity rocks (acting as seals) and structural simplicity. The suitability of sedimentary basins for CO_2 storage depends in part on their location on the continental plate. The effectiveness of geological storage depends on a combination of physical and geochemical trapping mechanisms.

The most effective storage sites are those where **CO_2 is immobile** because it is:

- trapped permanently under a thick, low-permeability seal or
- is converted to solid minerals or
- is adsorbed on the surfaces of coal micropores or
- through a combination of physical and chemical trapping mechanisms.

In general, geological storage sites should have

1. adequate capacity and injectivity,
2. a satisfactory sealing caprock or confining unit and
3. a sufficiently stable geological environment to avoid compromising the integrity of the storage site.
4. monitoring systems that will last for decades

CO_2 can remain trapped underground by virtue of a number of mechanisms, such as:

- trapping below an impermeable, confining layer (caprock);
- retention as an immobile phase trapped in the pore spaces of the storage formation;
- dissolution in the in-situ formation fluids; and/or adsorption onto organic matter in coal and shale;
- trapping by reacting with the minerals in the storage formation and caprock to produce carbonate minerals.

CO_2 STORAGE METHODS

1. Depleted oil and gas reservoirs
2. Unmineable coal beds
3. Saline aquifer storage
4. Deep ocean storage
5. In-situ carbonation

DEPLETED OIL AND GAS RESERVOIRS

Economic incentive for using this method: by injecting CO_2 into depleted oil or gas reservoirs, residual oil and gas can be extracted. Currently utilized through enhanced oil recovery by many of the largest oil companies. e.g. Berlin Natural Gas Storage Project. As of 2007 estimates, oil and gas fields could hold about 30 years of emissions from UK power plants.

Pros	**Cons**
Considerable existing infrastructure, knowledge and technology	Programme of monitoring required after CO_2 injection
Existing knowledge and technology gained from Enhanced Oil Recovery: CO_2 injection has already been conducted on a range of sites, associated injection technology has been developed. E.g. Computer models have been developed in the oil and gas industry to predict the movement, displacement behaviour and trapping of hydrocarbons	Must ensure that pre-existing boreholes, which have punctured the natural cap rock seal, do not act as leakage pathways for CO_2
Some of the infrastructure and wells already in place may be used for handling CO_2 storage operations	Capacity of a reservoir is limited by the need to avoid exceeding pressures that damage the caprock
Proven integrity and safety	
The oil and gas that originally accumulated in traps (structural and stratigraphic) did not escape (in some cases for many millions of years)	

UNMINEABLE COAL BED STORAGE

Using this technology, CO_2 is injected into deep coal beds, and methane trapped in the porous structure of coal seams is recovered. Underground coal has a layer of natural gas (usually methane) chemically attached to it. Once CO_2 is injected, it will adsorb onto the coal in place of methane. The CO_2 is then stored in the void fraction made available by the removal of the trapped methane in the coal seams.

Pros	**Cons**
During carbon dioxide injection, the methane could be recovered and used to produce energy. This could be used to cover some of the cost of the CO_2 storage	Burning of the methane will produce more CO_2
	In order for the carbon dioxide to be permanently stored the coal can never be mined, even if mining the coal becomes economically worthwhile to mine it in the future
	There are no coals in the UK (as of 2007) where this technique has been applied

SALINE AQUIFER STORAGE

Saline aquifers, deep underground stores of saltwater, are found in widespread areas, and so have enormous potential. E.g. The Sleipner Project, operated by Statoil in the North Sea about 250 km off the coast of Norway, is the first commercial-scale project dedicated to geological CO_2 storage in a saline formation.

Pros	Cons
Large capacity for storage of carbon dioxide, current estimates indicate that several centuries' worth of total UK carbon dioxide emissions could be held in these aquifers	Relatively limited existing knowledge, compared to old oil and gas reservoirs. Further research needs to be completed to determine if the potential storage capacity is as large as preliminary research suggests
Currently of no real use to humans due to the undrinkable water	Unlike storage in oil fields or coal deposits, there are no useful byproducts from using saline aquifers
Saline brines are used locally by the chemical industry and formation waters of varying salinity are used in health spas and for producing low-enthalpy geothermal energy	Estimating the CO2 storage capacity of deep saline formations is presently a challenge. Can be determined only on a case-by-case basis
UK North Sea contains several large saline aquifers and their use would keep transport costs to a minimum	

DEEP OCEAN STORAGE

At depths of >11482ft (3500m), the pressure would allow the CO2 to compress to a sludge that would naturally sink and remain at the bottom of the ocean floor. This may have unintended consequences on the environment, as it can cause ocean acidification, reducing biodiversity and profoundly altering ecosystems

IN-SITU CARBONATION (PERIDOTITE CARBONATION)

Atmospheric CO2 converted to solid carbonate minerals via peridotite weathering. Low-cost, safe and permanent.

CCS TECHNOLOGY CONCLUSION

There is an imminent need to transition offsetting programs from softer methods of carbon storage such as afforestation to harder storage through negative emissions technologies. To stabilize global temperatures at 1.5 to 2 degrees Celsius, all carbon emitted must be captured and sequestered. Since afforestation and utilization cannot meet the demand of carbon emissions in IPCC scenarios, there must be investment in negative emissions technologies to stabilize the planet's temperature.

There are many developed technologies associated with CCS. However, there are two distinct methods of capturing CO2. The first is point source where power plants and large industrial sites including refineries, steel making, fertilizers, ethanol formation, and cement manufacturing are adapted to include emissions reductions technologies. This captures CO2 emissions directly from an emitting source where CO2 concentration levels are near pure. Most conventional CCS projects involve separating CO2 from an industrial site, but the carbon it sequesters had a fossil source. It creates a reduction in the amount of CO2 in the atmosphere but is not a negative emission. The second method is from negative emissions technologies like DAC and BECCS. Rather than capturing CO2 from a direct emissions source, it is pulled from the atmosphere for sequestration. These technologies are geographically agnostic as they can be implemented anywhere.

The main challenge with CCS pertains to the ability to transport and store CO2 once it is captured. There are various proven methods to storing CO2, but they usually rely on developed infrastructure to transport the CO2 to storage sites. The next section will outline the players within the CCS market and how they are addressing some of the challenges associated with the technologies.

CURRENT VIABLE OPTIONS

VENTURES

There are many ventures looking to capitalize on the demand for negative emissions credits. Along with these smaller ventures are joint projects sponsored by energy companies and governments to set up transportation and storage infrastructure for more large-scale carbon capture and storage. Below is a list of what we found on the market as well as quick briefs for the three main projects the University should be aware of. This list provides an overview of the various types of CCS technologies available, but it is not exhaustive. Further information on global CCS projects can be found through the Global CCS Institute.

Name	Location	Price/tonne	Capacity	Ready by	Technology used	Website
Carbon Engineering	Canada	$200-300 USD per tonne (appx. (£152-229)	1 million tonnes per year	2022	Direct air capture; the CO2 is then used to produce hydrocarbon fuels.	https://carbonengineering.com/
Climeworks	Switzerland	CHF600-990 (appx. £500-800)	Currently 900 tonnes per year	100,000 and 1 million tonnes a year by 2023 and 2025 respectively	Direct air capture. CO2 sold for utilization.	https://www.climeworks.com/
Northern Lights CCS project (Norway, Shell, Total, Equinor)	Norway	Unknown. Will be driven by demand.	5M tonnes per year	2023	European transport and storage network	https://northernlightsccs.com/en
HyNet project	UK	Unknown	130M tonnes of storage	2023+	Project scoping for storage opportunities	https://hynet.co.uk/phase-1/
Pale Blue Dot Energy (Acorn project)	UK	£30 plus sequestration costs	2-20M tonne capacity	2021. Ready for onboarding	Post-combustion of natural gas	https://pale-blu.com/
Summit Carbon Capture (Caledonia Clean Energy Project)	US	Not for sale. Service focus on clean power generation.	Unknown	2020s	Post-combustion capture, storage in saline aquifers	https://summitpower.com/projects/carbon-capture/

Origen Power	UK	Unknown	Unknown	Prototype plant, need to raise £1.2M	Limestone CO_2 capture. Selling Pure CO_2, Lime, CO_2 removal.	https://www.origenpower.com/
Newlight Technologies	US	Unknown	Unknown	Unknown	Carbon sequestration into plastics, which are used	https://www.newlight.com/
Blue Planet	US	Unknown	Unknown	Ready	Capture CO_2 and turn it into aggregates for building. Sold to construction companies.	http://www.blueplanet-ltd.com/

CarbonEngineering

At this point, Carbon Engineering's capacity is only 1 tonne/day with a pilot plant in Squamish, BC. However, they are just beginning the commercialization of the business and the first industrial plant will capture 1 M tonnes annually. The capacity today is low but will be increasing at a significant rate in the near future. Regarding price, California regulation allows Carbon Engineering to sell negative emissions credits for over $200/tonne and are negotiating with organizations in the price range of $200-$300/tonne depending on the term and volume.

Capacity for 1 M tonnes will begin in 2023 or 2024 with the opening of their commercial plant. However, Carbon Engineering is working on creating a product that would be used to promote the development of future plants, perhaps in this case in the UK, where the customer can purchase and would receive futures in negative emissions. These emission credits would be essentially the same as a more standard negative emission credit but with a forward leaning focus.

Climeworks

Currently targeting individuals with a "Carbon Dioxide Removal" service and CO_2 utilization companies with modular CO_2 capture plants. Climeworks is currently operating on a relatively small scale. For individuals they offer a subscription service that will capture and store carbon as a carbonate mineral at their Iceland plant.

Capacity projections:

- 2020 – 900 tonnes of CO_2
- 2021 – 3,000 tonnes of CO_2
- 2023 – 100,000 tonnes of CO_2 – climate relevant
- 2025 – 1 M tonnes of CO_2

Depending how much Carbon Dioxide University of Oxford wants to remove, costs are 500-813 GBP per tonne CO_2.

Pale Blue Dot (Acorn Project)

Acorn CCS is a low-cost, low-risk, carbon capture and storage project that provides CO2 mitigation infrastructure essential for meeting the Scottish and UK Government Net Zero targets. Led by Pale Blue Dot Energy, with funding and support from industry partners (Chrysaor, Shell and Total) the UK and Scottish Governments, and the European Union. The project offers permanent CO2 sequestration service to emitters from industrial regions around the North Sea Basin, who are able to transport CO2 by ship to Peterhead deep water port or by pipe directly to St Fergus in North East Scotland. The Acorn CCS project will take responsibility for the CO2 at the point of transfer, and subsequently transport it to and store it in well appraised subsurface storage sites located around 100 km offshore.

Whilst the project will be initiated with a local CO2 source from the St Fergus area, the project is specifically designed to be open access in nature and can grow to a throughput capacity of over 15M tonnes per year without the addition of new offshore pipelines.

Strategic decision to situate in the north east coast of Scotland to make best use of the UK's built and natural assets:

- Access to extremely valuable offshore gas pipelines that are suitable for reuse for CO2 transport and still have long operational life expectancy.
- Access to world class, well understood geology for CO2 storage – the high confidence around these CO2 stores is due to a wealth of data from the previously active oil and gas industry in this area, but also the publicly available results of two previous UK Government-supported FEED studies and an Energy Technology Institute's assessment of the suitability of the area for CO2
- The ability to initiate CO2 capture at the St Fergus gas terminal, an existing industrial site where around 35% of all the natural gas used in the UK currently comes onshore.

Currently progressing the detailed engineering for this first phase of the project in the hope of reaching a final investment decision in late 2021.

OIL COMPANIES

Making up the vast majority of current carbon capture and storage projects are oil companies. At this time oil companies are mainly using these technologies for enhanced oil recovery, however, there is an opportunity for these services to be commercialized as the amount of carbon stored in an abandoned oil reserve can outmatch the amount of CO2 emissions extracted from it. With experience in capital intensive projects, oil companies have the opportunity to develop another revenue stream with capacity to capture and store large amounts of CO2. We have outlined below the efforts of seven large oil players and their current CCS efforts.

Sinopec

There are currently two CCS projects ongoing, Shengli Power Plant and Qilu Petrochemical[2]. The Shengli Power Plant project is categorised by the Global CCS Institute as in an advanced development stage. A demonstration facility was created in 2010 with a capacity of around 110 tonnes of CO2 per day. The second phase scheduled to finish in 2020 increase post-combustion capture capacity to around 1 million tonnes per year. CO2 is captured using post combustion technology which was retrofitted into the plant. The captured CO2 is transported via pipeline to inject into an oil field for

---

[2] Shengali Oil Field. https://sequestration.mit.edu/tools/projects/shengli.html

enhanced oil recovery. The project provides Sinopec with considerable financial earnings as there is a commercial deal with the Shengli oilfield[3].

The Qilu plant began operating in 2019 with a capacity of 400,000 to 500,000 tonnes of CO_2 per year. The captured CO_2 is also transported via pipeline to inject into an oil field for enhanced oil recovery. The commercial deal with the Shengli oilfield also applies to this plant[4].

China National Petroleum Corp (CNPC)

CNPC also uses CCS for enhanced oil recovery in the Shengli oilfield. The plant has a capacity to sequester around 800,000 to 1,000,000 tonnes of CO_2 per year[5]. The project also uses post-combustion capture technology and CO_2 is transferred through pipelines.

Total

Total is “fully engaged” with the global challenge of reducing greenhouse gas emissions. 10% of Total’s R&D project will be allocated to carbon capture, utilization and storage. Total is working to promote the implementation of a carbon pricing mechanism, as a way to send an economic message and make CCS profitable; Total hopes this will create incentives to “move the energy mix in the right direction.”

Total Carbon Capture, Utilization and Storage Project: “Northern Lights.” The aim is to build a new industrial sector at start-up pace by launching initiatives like this. Their aim is to have 2.4 billion tonnes of CO_2 stored by 2040. The Northern Lights project will start by capturing the CO_2 emissions generated by two industrial facilities in Norway - a cement works and a cogeneration plant. The CO_2 will be shipped in liquid form to an onshore storage site, before being transported by subsea pipeline to its injection site, a deep saline aquifer on the Norwegian Continental shelf. Northern Lights is expected to be in operation from the end of 2023.

Other projects related to CCS include:

- Improvement avenue - optimizing the design of the ships used for CO_2 transportation
- Investigating the possibility of low-pressure CO_2 transportation, which could be much more cost-effective than the current high-pressure design

ExxonMobil

ExxonMobil, is the largest publicly traded international oil and gas company. Projects ExxonMobil have embarked on include:

- ExxonMobil and FuelCell Energy, Inc., have partnered since 2016 to develop CO_2 capture technologies using carbonate fuel cells. While CCS technology can be applied to coal-fired power generation, the cost to capture CO_2 is about twice that of natural gas power generation. Because coal-fired power generation creates about twice as much CO_2 per unit of electricity generated, the geological storage space required to store the CO_2 produced from coal-fired generation is double that required for gas-fired generation.

---

[3] Sinopec Shengli PCC. http://www.zeroco2.no/projects/sinopec-shengli-pcc
[4] The Global Status of CCS – 2018. https://adobeindd.com/view/publications/2dab1be7-edd0-447d-b020-06242ea2cf3b/z3m9/publication-web-resources/pdf/CCS_Global_Status_Report_2018_Interactive_update.pdf
[5] Industrial CCS-EOR in CNPC's Jilin Oileld. http://www.cnpc.com.cn/en/xhtml/pdf/2018CCSEORinJilin.pdf

- Developing sub-surface CO2 storage capability by using knowledge gathered from years of experience in the market.
- ExxonMobil and Mosaic Materials are exploring new carbon capture technology through a process that uses porous solids, known as metal-organic frameworks, to separate carbon dioxide from air or flue gas, using moderate temperature and pressure changes, substantially increasing energy efficiency and decreasing costs.
- Up to $100 million agreement to research and develop advanced lower-emissions technologies with the U.S. Department of Energy's National Renewable Energy Laboratory and National Energy Technology Laboratory.

BP

BP is currently working with OGCI Climate Investments to bolster the UK's first commercial full value chain CCS project called the The Clean Gas Project. Through this project CO2 will be captured from more efficient gas-fired power plants and transported via pipeline to be stored under the southern North Sea. Key to this project is building out the infrastructure that can also be used by other industries in Teesside to store CO2 they capture from their processes. The project is going through a feasibility student and should be operational by around 2025.

SHELL

Shell is working on three CCS projects around the world including Gorgon in Australia, Quest in Canada, and Shell Cansol in Canada. Shell has partnered with Gordon liquifield natural gas project that will be the largest CCS project when complete. 3 to 4 million tonnes of CO2 will be captured each year with an expectation that 100 million tonnes will be captured and stored over the duration of the project.

Quest is an integrated project that will capture, transport, and then store carbon deep underground. This project has already stored 4 million tonnes of CO2 less than four years after the project started. Shell operates the project whereas initial investment came from the governments of Alberta and Canada.

The Shell Cansolv CCS technology project was created to ensure the Boundary Dam power station in Saskatchewan, Canada would be able to capture around 1 million tonnes of CO2 per year. After installing this technology at the dam, Shell is using the CO2 for enhanced oil recovery and will permanently store the carbon underground.

CHEVRON

Chevron is also a partner on the Gorgon and Quest projects mentioned above. Unsurprisingly, each company is counting the results of the project as their own, which will lead to double counting issues in the future.

EQUINOR (FORMERLY STATOIL)

Equinor is currently developing infrastructure on the Norwegian Continental Shelf for transport and storage of CO2 from various onshore industries, together with Shell and Total. The project, called Northern Lights, involves transporting liquified CO2 by pipeline to permanent offshore subsea storage.

Other projects include the Sleipner West natural gas field, which has been operational since 1996. About 1 million tonnes of CO2 is captured each year from the natural gas on the field in the Norwegian sector of the North Sea, and the CO2 is then stored in a saline formation 1 km below the seabed. More recently, from 2004 in Algeria, Equinor has helped capture and store CO2 in the In Salah gas field. More than three million tonnes of CO2 were stored before being stopped in 2011 due to capacity limitations in the geological structure[6].

PEER ACTIONS

UNIVERSITY OF CAMBRIDGE

Cambridge is the first university globally to announce that it has adopted a 1.5 degrees Science Based Target for carbon reduction, committing itself to having no energy-related carbon emissions by 2048. The University has also expressed an aspiration to be ten years ahead of its Science Based Target decarbonisation pathway at all times and to reach zero carbon by 2038, with a steep 75% decrease on 2015 emissions by 2030.[7]

CAMBRIDGE ZERO[8]

University research is connecting research groups and institutes across Cambridge including Centre for Carbon Reduction in Chemical Technology, and Centre for Sustainable Development. Cambridge Cleantech unites the creators of new cleantech technologies with the financiers, partners and customers who can bring their products and services to fruition. However, Cambridge Zero has been branded a University "greenwashing tactic" by student activist group Zero Carbon. The accusations come after Zero Carbon released a report in October detailing the University's close links with the fossil fuel industry, parts of which the University then erased from their online websites. It also follows The Guardian's revelations this month showing the University this year accepted a £6 million donation from Shell.

UNIVERSITY RESEARCH

- Capture technology: Chemical looping of solid fuels to produce clean CO2 free of nitrogen
- Storage technology: Seismological observations and the sampling of active injection sites & geological analogues

POINTS OF COLLABORATION[9]

In 2017, along with collaborators from Stanford and Melbourne Universities, they have recently started a new CCS project with the support of BHP, one of the world's largest mining and materials companies. The three-year project will develop and improve methods for the long-term storage of CO2, and will test them at Otway in southern Australia, one of the largest CCS test sites in the world. Using a mix of theoretical modelling and small-, medium- and large-scale experiments, the

---

[6] Equinor Carbon Capture and Storage. https://www.equinor.com/en/what-we-do/carbon-capture-and-storage.html

[7] University of Cambridge, Environmental Sustainability Report 2018. https://www.environment.admin.cam.ac.uk/files/uoc_environment_and_sustainability_report_for_web.pdf

[8] Zero Cambridge. https://www.zero.cam.ac.uk/

[9] Carbon capture: universities and industry work together to tackle emissions – 2017. https://www.cam.ac.uk/research/features/carbon-capture-universities-and-industry-work-together-to-tackle-emissions

researchers hope to significantly increase the types of sites where CCS is possible, including in China and developing economies.

The new research, which will support future large-scale CO2 storage, will consider whether CO2 could be effectively trapped without the top seal of impermeable rock, meaning that CCS could be deployed in a wider range of environments. Their research findings will be made publicly available to accelerate the broader deployment of CCS.

OFFSETTING

An option being given serious consideration by the Environmental Sustainability Strategy Committee is carbon offsetting, which involves paying a tariff to support initiatives that reduce the University's overall carbon impact. A working group is looking at how an offsetting scheme might work, with a view to implementing a scheme in the academic year 2020/2021. Among the questions the working group will address are how to cost a tonne of carbon (estimates vary wildly, from a few pounds to hundreds of pounds), what activities might offsetting cover, and how to offset – for example, paying into external schemes, or using funds to support the planting of trees on University land or to retrofit existing buildings to make them more sustainable.

UNIVERSITY OF EDINBURGH

The University of Edinburgh has committed to become zero carbon by 2040. The University's Climate Strategy 2016 lays out a comprehensive whole institution approach to climate change mitigation and adaptation in order to achieve its ambitious targets[10]. As they move towards their goal to become net zero by 2040, they are aware that not all carbon emissions can be removed. For remaining emissions, the University has committed to undertaking direct carbon sequestration[11].

CARBON CAPTURE RESEARCH

The carbon capture group at the University of Edinburgh's School of Engineering is one of the largest carbon capture research groupings in the United Kingdom, looking at capture of carbon dioxide.

Founded in 2005, the Scottish Carbon Capture and Storage (SCCS), alongside partners Heriot-Watt University, University of Strathclyde, the University of Aberdeen and the British Geological Survey (BGS). SCCS is the largest CCS research group in the UK, providing a single point of coordination for CCS research, from capture engineering and geoscience to social perceptions and environmental impact through to law and petroleum economics.

[10] University of Edinburgh, Climate Strategy 2016- 2026. https://www.ed.ac.uk/files/atoms/files/web_view_-_climate_strategy_2016-2026_spreads.pdf

[11] University Position on Carbon Sequestration and Carbon Offsets. https://www.ed.ac.uk/files/atoms/files/carbon_sequestration_-_positioning_paper.pdf

CURRENT ISSUES

While it has argued that CCS is a viable option for removing CO2 out of the atmosphere permanently, the are several issues that affect the viability of using such products currently. A major issue with CCS is that the technology needed is either not yet completely developed or able to be scaled up[12]. Currently, there are existing technologies that can capture, transport and store CO2. However, only one or two techniques are able to be used in a large scale, industrial context [13]. Furthermore, critics argue that the economics of CCS are not viable at the current state of development and that costs of projects remain prohibitively high for the market to grow and for research and investment to occur. As a result, currently there are only start-ups providing purchasable credit for the removal of CO2 while larger industrial processes are dominated by companies in the oil and petroleum industry. These companies could be the first commercially viable way to purchase negative emissions credits at scale. This would fill the need of the University to compensate for unavoidable emissions but may result in backlash. Although oil companies are considered the main part of the problem, they have the technologies, resources, and infrastructure to be part of the solution.

The major safety concern about CCS is potential leaks, both gradual and rapid. Recent studies have cast doubt on whether existing technology is able to store and retain CO2 in geological formations on an industrial scale. A large, sudden leak would have significant negative impacts on the environment. At high concentrations, CO2 can cause asphyxiation by displacing oxygen. CO2 leakage could result in ground and water displacement and groundwater contamination. Furthermore, CO2 leaks near human settlements in the past have resulted in deaths. Therefore, CO2 storage projects need to demonstrate to regulators that any leakage is negligible, and that the risk is low. Furthermore, this requires monitoring and verification procedures which can add considerably to the cost of storage. Thus, there is a scientific challenge to ensure that CO2 can be safely stored in sites for thousands of years and recent studies have cast doubt on whether geological formations are available to safety retain CO2 on the scale required [14].

---

[12] The Case for Carbon Capture and Storage – 2005. https://issues.org/stephens/

[13] Ibid.

[14] Sequestering Carbon Dioxide in a Closed Underground Volume - Ehlig-Economides and Economides 2010, Shukla et al 2010.
https://www.researchgate.net/publication/254530148_Sequestering_Carbon_Dioxide_in_a_Closed_Underground_Volume

RECOMMENDATION

Currently there is not a direct-action recommendation for University of Oxford to compensate for their 30,000 tonnes of emissions due to academic and staff airfare. Six Degrees recommends a three-part approach (monitor, phased implementation, and development) in relation to carbon capture and sequestration objectives.

MONITOR

Although negative emissions credits are not available at scale for 30,000 tonnes, nor affordable given the high costs associated with DAC and the size of the sustainability budget at this time, building relationships with negative emissions providers would be helpful in the long term.

1. We recommend building a relationship with Carbon Engineering as they are the lowest price and highest capacity DAC venture. Carbon Engineering has spoken with a few Canadian universities and are accustomed to working with the custom needs that Universities request. At this time University of Oxford cannot buy negative emissions credits at scale from Carbon Engineering since the capacity is not there. However, Carbon Engineering is rolling out custom schemes for clients to purchase negative emissions credits in advance.
2. Monitor Climeworks as their capacity expands. The price point is significantly higher than Carbon Engineering and their services are currently targeting smaller, more retail clients. As capacity expands their price is set to reduce.

PHASED IMPLEMENTATION

The University can consider a phased approach towards buying negative emissions credits. This could result in developing a plan to purchase an increasing amount of negative emissions credits each year to slowly work up to the 30,000 tonne target. Commitments instituted into a sustainability policy would signal to the Russell group Oxford's commitment towards investing in these technologies. This would be the first step towards spurring a nascent market for negative emissions credits for carbon capture and hard storage offsets.

DEVELOPMENT

Since there are not players that can currently service Oxford's, or any other large player's, demand for negative emissions credits, Oxford can take a position to support CCS research. There are opportunities to for further research alongside Edinburgh's SCCS. Supporting the development of these technologies through investment in research could be an effective way to develop the market for negative emissions credits to be sold at scale in the future.