INFORMATION SHEETS FOR CCS

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This report was originally intended to be 14 standalone information sheets on the many aspects of carbon dioxide capture and storage (CCS). The information sheets have been combined in one document to produce this report but it is recommended that the standalone original sheets are used primarily. These are available to download as separate files on the IEAGHG website (www.ieaghg.org).

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Terms and Concepts

This Information Sheet describes the main technical terms and processes that are used in discussing Carbon Dioxide Capture and Storage (CCS). It is not a complete explanation of every component, but covers most of those that are needed to give you a good introduction to the processes involved in CCS.

Carbon

Carbon is one of the basic building blocks of life on Earth; humans and other animals are all carbon based, and as an example, humans are about 18% (or just under one fifth) carbon.

Because of its role in creating and forming life, carbon is continually on the move, being absorbed and released by living things during life, growth, and finally death. This movement of carbon into different places and things is referred to as the Carbon Cycle, and describes how the carbon can move from one location to another; from a living animal or plant, through decomposition into gas form into the atmosphere, before being reabsorbed by plants breathing, or by the sea or other water bodies.

Carbon Dioxide - CO_2

This is what CCS is all about: carbon dioxide. CO_2 is a gas made up of carbon and oxygen. It is a large component of what humans and other animals breathe out, and what plants breathe in. In return, plants breathe out oxygen, and humans and animals breathe this in, completing part of a cycle.

CO_2 is also released by burning fossil fuels (see below) in generating electricity, and this is the main focus of CCS; capturing this and preventing it from being released into the atmosphere.

The Greenhouse Effect

Closely linked with both global warming and climate change, the greenhouse effect is what causes these to occur.

The 'greenhouse effect' is so called because the effect is exactly like being in a greenhouse where the glass prevents heat escaping back out, whereas in the atmosphere it is gases such as CO_2. There are a few other gases that have the same effect, but the impact of CO_2 is greater, and more directly linked to human activity. These gases are collectively known as greenhouse gases because of the role they play in this process.

The greenhouse effect is important; without it, life on this planet would not have been possible, but the impact humans are having on the amount of CO_2 in the atmosphere is increasing this effect beyond the Earths' capability to correct it. Since the industrial revolution in the 1800's, the amount of CO_2 in the atmosphere has increased greatly, as a direct result of burning fossil fuels like coal, oil and gas. We need to reduce the amount of CO_2 released by the burning of these fossil fuels, but of course we cannot instantly reduce the amount of electricity used by humans, so we need to find a way to remove the CO_2 from the exhaust gases from power stations; hence the need for CCS.

Carbon Dioxide Capture and Storage (CCS)

CCS is the name given to the process where CO_2 is captured from power stations or other sources, transported via pipelines or ships and injected into storage formations deep underground preventing the greenhouse gases from reaching the atmosphere and contributing to the greenhouse effect.

Fossil Fuels

Coal, oil and gas are fossil fuels. These fuels were created when organisms died on the Earth's surface and were subsequently buried by geological processes over millions of years. Different fossil fuels are created depending on which living things have been buried and the processes they are exposed to over a very long period of time. All of these carbon-rich materials can be burned as a fuel to produce energy. Currently, over 80% of the world's energy comes from burning fossil fuels.

Coal

Coal was formed by the burial of ancient forests under water (swamps and lakes). Over millions of years, the plant material was gradually compressed and heated in an environment where it was unable to decay. Coal is the world's second largest source of energy, providing 30% of the total supply. Due to the scale of its use and the large amount of carbon it contains, burning coal is the largest source of CO_2 emissions to the atmosphere from human activity, at 40% of the total.

Oil

Oil was formed from large quantities of tiny sea based organisms (such as algae) that have been buried under layers of other rocks over hundreds of millions of years, and subjected to high heat and pressure deep underground.

Around 4 billion tonnes of oil is produced and used each year, making it the third largest source of human CO_2 emissions, at 18% of the total.

Gas

Usually referred to as natural gas to distinguish it from other types of gas, natural gas is, like oil, made from the remains of ancient living organisms that have been buried deep in underground rocks. Although it occurs on its own in reservoirs, gas is also often found in the same reservoirs as oil. Natural gas makes a major contribution to human CO_2 emissions at around 10% of the total.

Rocks and Geological Terms

Rocks can broadly be classed into three types depending on how they were made. Igneous rocks are formed from cooling molten rock (from volcanoes etc.), sedimentary rocks are formed from the accumulation of lots of individual rock grains and other materials (such as sand) and metamorphic rocks are formed from the transformation of igneous or sedimentary rocks by extreme pressures and temperatures to form new rock. Sedimentary rocks are where fossil fuels are found, and where CO_2 storage can take place.

Sedimentary Rock

One of the more common sedimentary rocks is sandstone, made from ancient beaches or deserts that have been buried and compressed. Because of its structure, sedimentary rock is not always solid. Depending on the size and shape of the individual grains, and how well they are stuck together, tiny spaces (known as pores) can be found in between the grains. These pores are not empty – they contain other substances including air, water, natural gas, oil and CO_2.

Reservoir Rock

Sedimentary rocks in which oil or gas are found are often called reservoir rocks. These tend to have a high 'porosity' (meaning lots of the rock volume is made up of pores), and this means that when a well is drilled into the rock, the oil or gas can move through the rock and be extracted. Reservoir rocks are excellent candidates for storing CO_2 as lots of CO_2 can be relatively easily injected into them.

Cap Rock

If oil or gas can move through the rock, what stops the oil or gas moving through the rock to the surface? In most cases, reservoir rocks are overlain by layers of other rocks (usually also sedimentary). Often these rocks have a lower porosity so that substances can't move through them very easily, if at all. These rocks can 'seal' a reservoir by preventing the escape of the oil, gas, water or CO_2 in the reservoir rock and are called cap rocks.

Deep Saline Aquifer (Deep Saline Formation)

Another type of reservoir rock where CO_2 can be stored is a deep saline aquifer. A deep saline aquifer is a reservoir rock where the pore spaces in the rock are filled with salty water called brine, which is of no use for drinking or any other purpose.

If a deep saline aquifer has a suitable cap rock above it, CO_2 can potentially be injected into it for storage purposes. CO_2 is currently being injected for storage at a commercial scale (i.e. millions of tonnes per year) into deep saline aquifers in Norway and other locations around the world.

Depleted Oil and Gas Fields

Old oil and gas reservoirs, where as much of the oil or gas as is possible has been produced, are good options for storage. Because these reservoirs have contained oil and gas in the past, we know a lot about them, and we can also be reassured that the cap rock has sealed the reservoir without it leaking for millions of years.

Enhanced Oil Recovery

CO_2 can also be injected into oil reservoirs where production has slowed; this can make the costs of producing the remaining oil much cheaper, and is used widely around the world. This process is commonly referred to as CO_2 Enhanced Oil Recovery, or CO_2-EOR.

CO_2-EOR works by injecting CO_2 so that it effectively pushes or flushes the remaining oil towards the production wells, making it easier and cheaper to extract.

CO_2-EOR, as well as allowing more oil to be produced, has taught us a huge amount about how to inject CO_2 and how it behaves in deep underground rocks.

Summary

This sheet is not intended to cover all the terms that will be used in relation to CCS, but it should cover most of those needed to form an understanding of the process, the elements and technical ideas involved, and how each stage works.

CCS is a process consisting of several stages and each stage has its own technical terms, but here we aim to provide an introduction to the main terms.

Setting the Scene: Climate Change

What is Meant by 'Climate Change'?

As we all know, weather can change every day, when we talk about the 'climate' and specifically 'climate change' we are talking about long term averages and patterns, usually of at least three decades, if not more. Climate change refers to long-term changes in these averages, and includes factors such as rainfall and temperature. Climate change can lead to an increase in the severity and frequency of extreme weather events, such as the floods of 2007 which affected many areas of the UK.

While there are some natural forces that affect the climate, the levels of greenhouse gases in the atmosphere have a direct impact, and humans are largely responsible for recent increases in greenhouse gas concentrations, since the industrial revolution and the burning of fossil fuels for the generation of electricity.

We Live in a Greenhouse

The 'greenhouse effect' is so called because the effect is exactly like being in a greenhouse; in a greenhouse it is the glass that prevents heat escaping back out, whereas in the atmosphere it is gases such as Carbon Dioxide (CO_2). There are a few other gases that have the same effect, but the impact of CO_2 is greater, and more directly linked to human activity. These gases are collectively known as greenhouse gases because of the role they play in this process.

The Impact of Humans

There is a lot of debate as to whether climate change is a direct impact of human activities, but the Intergovernmental Panel on Climate Change (IPCC) recently concluded that the rises in global average temperature was 'very likely' a result of man-made greenhouse gas emissions. In this instance, 'very likely' means a greater than 90% chance.

Global temperature increases correspond very closely to the industrialisation of our civilisation, and as a result of this industrialisation, we have burnt ever-greater quantities of oil, gas, and coal, and cleared large areas of forest for agriculture and other development. All of these activities release CO_2 and other greenhouse gases into the atmosphere.

What is Carbon Dioxide?

Carbon dioxide (CO_2) is the most important of greenhouse gases. Made up of one carbon and two oxygen atoms, which are two of the most commonly occurring elements on the planet, it is the most influential greenhouse gas. It is also the one that man has contributed most in terms of increasing emissions due to the burning of fossil fuels to create electricity. CO_2 occurs naturally in freshwater and seawater, in some rock formations and in the soil. CO_2 is not toxic, explosive or flammable.

The Carbon Cycle

Taking a step back, the element of carbon, one of the components of CO_2 is naturally present in the Earths' atmosphere, water, soils, rocks, plants and animals. All of the carbon present in the Earth today has been here since the birth of the solar system, and it moves in a cycle, from one physical place and form to another. The amount of carbon in the cycle does not change it is simply exchanged between one store and another – land, sea and air. The human activity of burning fossil fuels changes the balance of this system, meaning more carbon is present in the atmosphere than the land or sea phases, and this in turn contributes to the greenhouse effect.

The Challenge Ahead

There are several options for changing the effect we are having on the climate; we can change our fuel generation practices for renewable or low-carbon options, we can increase fuel efficiency, so we use less to generate the same power, and we can prevent CO_2 from being released to the atmosphere by deploying CO_2 capture and storage (CCS).

Over the longer term, low carbon technologies and energy efficiency improvements provide the biggest and best chance for change. However if we do nothing while we wait for these technologies to be developed to the stage of readiness, so that they can replace fossil fuels in the energy generation mix, we will have passed the point of no return, and climate change will be insurmountable and the way in which we live will be changed forever.

We need to develop and deploy CCS technologies in the short to medium term in order to reduce the amount of carbon that we emit. The technology of CCS means that we can continue utilising fossil fuels while alternative fuel technology is developed, without releasing the CO_2 into the atmosphere.

The impact of insurmountable climate change would include social, economic and environmental effects, and could include impacts such as: spread of diseases, displaced communities, food shortages, extreme weather events, water shortages, drought and much more.

Summary

There are many options for reducing greenhouse gas emissions and all will be needed in order to prevent insurmountable climate change. The use of CCS does not mean that other options will be neglected or not researched and developed, all the options will be needed and CCS has the potential to make a big impact, relatively early. That is why more action is needed to deploy CCS projects around the world; it can make a difference quickly while other technologies are developed and brought to maturity.

A Brief History of CCS and Current Status

This information sheet aims to provide a brief history of the development of CO_2 capture and storage (CCS), and describes the different types of project. The important thing to take from this information sheet, is that although CCS is technically a relatively new technology, what CCS does is use existing, well proven technologies in new and innovative ways; the various parts of the process have been used extensively in other processes for decades in industry.

The Beginning...

The basic idea of CCS – capturing CO_2 and preventing it from being released into the atmosphere was first suggested in 1977; using existing technology in new ways.

CO_2 capture technology has been used since the 1920s for separating CO_2 sometimes found in natural gas reservoirs from the saleable methane gas.

In the early 1970s, some CO_2 captured in this way from the a gas processing facility in Texas (USA), was piped to a nearby oil field and injected to boost oil recovery. This process, known as Enhanced Oil Recovery (EOR) has proven very successful and millions of tonnes of CO_2 – both from natural accumulations of CO_2 in underground rocks and captured from industrial facilities – are now piped to and injected into oil fields in the USA and elsewhere every year.

Different options – different projects

Gas Processing

Gas processing facilities, which extract natural gas from underground fields, often have to clean the CO_2 from the natural gas in order to be able to sell it. These facilities therefore have to capture the CO_2 before they have a useable commodity.

Power Plants

Power plants that burn fossil fuels don't have to capture the CO_2 in order to produce electricity and the capture process will actually cost slightly more overall. So capturing CO_2 from power plants is purely done for emissions reduction reasons.

EOR

EOR projects have a use for the CO_2 captured in the earlier processes; this gives the CO_2 a value in monetary terms. The CO_2 is often extracted from the oil field along with the oil, but as it was expensive to purchase, this will be separated and can be used again to produce yet more oil. Eventually, when all the oil has been produced, the CO_2 can be left (stored) in the depleted oil field – permanently preventing that CO_2 from being released into the atmosphere and contributing to the greenhouse effect and global warming.

Where is CCS in its development?

With so much going on, and at a fast pace, it is very difficult to get a clear picture of how many projects are ongoing around the world. As of the end of 2012, there were 5 large scale CCS projects in operation around the world, with 3 operational full chain (with capture and storage) pilot projects also ongoing. However there are 23 large-scale projects being developed that have secured funding and if these continue to progress to large-scale operational projects, the future development could rapidly increase in pace.

The Global CCS Institute has a good handle on developments and their website www.globalccsinstitute.com/projects/browse gives a current picture for those interested.

Summary

It is clear that for CCS to make the maximum contribution to emissions reductions, the pace of development and deployment needs to increase substantially to get projects up and running in time to meet global targets. CCS has the potential to make a big difference to greenhouse gas emissions, but action is needed swiftly to allow the impact to take effect before temperatures rise, and the cost of battling climate change goes up.

Matching Sources to Stores

The aim of this information sheet is to look at one of the constraints on CO_2 capture and storage (CCS). In theory it sounds simple; capture CO_2 from power plants, store it in underground storage formations. But what if there aren't any nearby? Is there enough storage in the world? This sheet will answer these points.

What if There Are No Storage Options Nearby?

If there are no suitable storage formations nearby, then the captured CO_2 can be transported (albeit at a cost) and has been extensively for other purposes. Information Sheet 6 deals with transport in more detail, but for now we will simply state that captured CO_2 can be transported to suitable storage sites.

Is There Enough Storage?

In simple terms; yes. There is a lot of uncertainty of the actual amount of storage available, as many reservoirs and formations have not been thoroughly characterised and explored, but best estimations suggest they would operate satisfactorily. There are wildly varying estimates, from extremely conservative to extremely optimistic, but as more exploration continues, the range is reducing, and even at the lower end of the potential storage available it is sufficient to store emissions for long enough to enable other clean energy technology to develop to a stage where fossil fuels would not need to be relied upon. Many areas of intensive activity would be suited to networks where numerous capture facilities link up and the combined CO_2 is then stored as a single operation.

Some studies have shown that just one storage option, storage in saline formations, has great potential; in the USA, this option alone could store the equivalent of 100 years of CO_2 emissions at current levels. Oil and gas field storage would add yet more to this. Some regions in the world would struggle; others would have a surplus of storage potential, so the issue of transport is a key one, and one that will be dealt with in more detail in the Information Sheet on Transportation of CO_2.

Matching CO_2 Sources and Storage

So we know that there is enough storage around the world, but how does that match up to the locations where the emissions are produced?

Broadly speaking, all regions of the world have potential for storage. Estimates range from the USA having 77% of its subsurface showing a good chance of storage potential, through Europe with 57% and India with 43% so some regions will have more options available than others, and some regions may struggle to store their emissions for longer periods of time. Again, this is closely linked with transport – the cost of transport obviously goes up with the increased distance, and also regulations will come into play as there are strict rules governing the transport of CO_2, especially over national borders. This is addressed more in Information Sheet 12.

Summary

All regions have the potential to conduct large scale CCS, although some countries may struggle to find sufficient storage sooner than others. These are the situations where trans-boundary transport of CO_2 will be vital, and this is something that will need to be clarified by legislation sooner rather than later. Climate change is a global problem, and countries will need to cooperate over storage resources to overcome the problem.

Capturing Carbon Dioxide (CO_2)

In order to store CO_2, first we need to capture it. There is a lot of research being undertaken both into improving existing processes, and developing new methods of capture, but currently there are three main methods of CO_2 capture which capture the CO_2 either before combustion (burning) of the fuel, after it, or by combusting the fuel in a different environment, and these are described below.

Post-Combustion CO_2 Capture

Post combustion capture, as the name suggests, takes place after the normal combustion process has taken place, i.e. after the fuel has been burnt to produce electricity. Post combustion capture takes place in the chimney of a power station, also known as the 'flue'.

A chemical (or solvent) is washed through the exhaust gases, and this chemical effectively removes the CO_2 from the exhaust gases. This chemical, now containing the captured CO_2, is collected at the bottom of the flue and the CO_2 can be removed for transport and storage, while the chemical can be re-used.

First examples of this exhaust gas cleaning have been used since the 1930's, and because the capture takes place after combustion and after the electricity has been produced, no changes need to be made to the power station other than adding the capture system to the end of the process. This makes post combustion capture particularly suited to power stations that are not due to be replaced, and are still operating as relatively new power stations.

Pre-Combustion Capture

Again, the name of the process suggests where the capture takes place; pre-combustion capture takes place by removing the CO_2 from the raw fuel.

The fuel is subjected to a chemical reaction which converts the fuel into a gas mixture made up of hydrogen, carbon monoxide, and oxygen. A second stage reaction converts this into hydrogen and CO_2. The CO_2 is removed, and the hydrogen is combusted with air to produce electricity. The only waste product to come out of this process is water.

This is a very clean process, and also eliminates many other emissions. It is a more expensive option, and as the combustion process is significantly altered, it is less applicable to existing power stations, and is much better suited to new-build stations.

Oxyfuel Combustion

The third option is different in that instead of burning fossil fuels in air, which conventional power stations do, the fuels are burnt in oxygen. This means that the waste products are CO_2 and water which are easily separated.

Again, this process is more suited to new power stations, but can be fitted with minor changes to existing power stations. The main costs associated with this option are based around the supply of oxygen – this is done by removing the other components of air in a special process before the combustion process, and this is relatively expensive.

Summary

While all three options are viable, the choice remains dependant on the location, the need to fit the process to an existing power station or build a new one, and the availability of equipment and chemicals needed for each different process. All three are being tested, developed and demonstrated, and all have a part to play in emissions reductions.

Costs of CCS

It is understood and accepted that CO_2 capture and storage (CCS) is one of many options to mitigate the effects of climate change, however it is one of a few that have the potential to offer deep cuts in emissions. There remain some questions and uncertainties over the costs involved, and this information sheet aims to address these costs, and put them into context.

Why is CCS Expensive?

All new technologies, or new applications of existing technologies are expensive at first, and then reduce over time. Think of buying a mobile phone: when mobile phones were first available, the handsets were extremely expensive, but over time, as the technology becomes more established and widespread, newer handsets are developed at a cheaper cost. CCS can be seen to operate in a similar manner. First demonstrations will cost more, but once established, the ongoing costs will not be as high.

For the first developments the costs will be recognisably higher, but over time, as the technology is modified, improved and generally streamlined, these costs will reduce. The initial costs will more than likely be swallowed either by the energy company, or covered by government grants or subsidies. It should also be noted that some sources suggest the costs of not deploying CCS could be up to 9 times higher through increased insurance costs due to more severe weather events, increased costs of food production and other impacts of unmitigated climate change.

What Are the Costs?

Quite simply, the costs involved in CCS either apply to capture, transport or storage. Capture costs are incurred by the physical machinery and equipment needed to capture the CO_2. A one off cost at the start of a development and the ongoing costs for the actual capture; i.e. the chemicals or additional elements used in the capture process (solvents in post-combustion capture, oxygen in oxyfuel combustion and steam in pre-combustion capture).

These costs vary; the oxygen is produced using some specialist equipment, so this is primarily an up front cost, the solvents in post-combustion capture can be re-used to a certain degree, and the steam production for pre-combustion capture is the primary ongoing cost for this method.

Transport costs are simple to predict as gas transport by pipeline, truck or ship is already carried out all around the world, and the costs of transporting gases over distance are known. There is a possibility of a cost reduction in this part of the chain as pipeline infrastructure reuse is a possibility; using gas pipelines that transported natural gas from a gas field to a processing facility to transport the captured CO_2 to a storage formation.

Storage costs are less simple to predict; drilling of new injection wells is a costly process, possibly minimised by converting existing production wells (in the case of oil and gas field storage) into injection wells. Although a great deal is known about the drilling of wells, observation, monitoring and exploration of potential storage sites can add substantially to the cost of a project. As time goes on and more is known about large-scale storage, these costs will be expected to reduce.

What Do We Know About Costs?

To a certain degree, we don't know a great deal about firm costs, this is because there isn't a large-scale capture and storage project in operation. Many projects are underway at smaller scales, and this is an area that is under constant development.

Some Europe-wide initiatives are in place to share data and information as it becomes available, and as an example, the UK government carried out extensive initial work in determining the feasibility of a proposed project in Scotland. The project was cancelled, but the information has been made publicly available to any parties looking at similar projects.

Summary

While firm data is currently unavailable, or unreliable for costs, it is clear that there is a great deal of knowledge and experience that can be applied to CCS. It is hoped that as more information becomes available, the variations in cost estimates will reduce, and a clearer picture will be developed.

What is clear is that CCS will cost money, however this will likely not impact greatly on consumers and the costs of not deploying CCS would likely be much higher.

Transporting Carbon Dioxide

Transport is a necessary stage in the Carbon Dioxide (CO_2) capture and storage (CCS) chain as it is not common for power stations to be built in close proximity to potential storage formations, especially as many storage options are off-shore. Pipelines and ships are therefore needed to transport the CO_2 from the source to the storage area.

Existing Pipelines

CO_2 has been transported via pipelines since the 1970's, predominantly in relation to Enhanced Oil Recovery (EOR). As described in another Information Sheet, EOR is an expanding industrial activity, where CO_2 is used to produce more oil than conventional methods would otherwise manage. As EOR is conducted more extensively, pipeline networks are being built to facilitate this, and in 2013 there are almost 6000km of CO_2 carrying pipelines in the world, mainly in the USA.

Another potential benefit is that the existing pipelines that are currently used to transport oil and gas from where they are produced could be re-used to transport the captured CO_2 to storage formations.

Transport via Pipelines and Ships

In many ways, the transport element of CCS can be viewed as the simplest – there is a vast amount of experience in terms of transporting gas via pipelines and ships, and the technical side of this part is quite straightforward. Costs vary depending on location, terrain and method of transport. Depending on the length of transport needed and the likely length of time that the CO_2 will be transported to a specific location will affect which is the more economical option: pipes or ships.

Pipeline Networks

Although predominantly associated with power stations, CCS can also be applied to some industrial processes, and it is often the case that industrial sites that have high potential for CO_2 capture are found in the same region. This provides an opportunity to simplify the pipeline or transport aspect, as the captured CO_2 can be merged and transported as one, rather than each capture plant having its own dedicated pipeline. This can help to reduce the costs of transport infrastructure, and the costs of transport itself.

It is anticipated that where several storage formations are found in close proximity that there could be similar networks at the other end of the pipeline, where CO_2 can be diverted to one storage formation or another, after sharing the pipeline that transported the CO_2 from the capture facility.

Summary

Transport is likely to be the simplest element in technical terms of CCS, however concerns exist over routes and the appearance of pipelines. It is anticipated that pipeline routes will likely follow existing 'corridors', alongside existing pipelines to minimise impacts, however this may not always be possible, and each case would need assessing on its own merits.

Naturally Occurring Carbon Dioxide

Natural Carbon Dioxide (CO_2) reservoirs exist underground in normal circumstances, and these naturally occurring stores of CO_2 have securely held the CO_2 in place for thousands, or even millions of years. These natural CO_2 stores have been extensively studied, and the knowledge gained has been incredibly useful in estimating the storage potential and learning about trapping mechanisms for CO_2 capture and storage (CCS). The knowledge gained from this allows scientists to predict the behaviour of stored CO_2, and gives the ability to perfect monitoring technologies that can then be applied to CCS.

Natural sources

CO_2 is found in two main types of location; sedimentary basins where water containing CO_2 becomes trapped, and in volcanic areas, where CO_2 is released from the magma (molten rock) as the pressure underground changes.

Where naturally occurring CO_2 is found in sedimentary rocks, like those that hold oil and natural gas, these stores are secure, with no pathways or routes for the CO_2 to escape. Such stores have existed, securely holding natural CO_2 for millions of years. One particular example is a geological structure deep underground in Mississippi, USA, which holds an extremely large quantity of CO_2, significantly larger than would ever be considered for a CCS project. This CO_2 entered the geological storage formation 65 million years ago (around the time that dinosaurs roamed the Earth), and has remained there ever since.

Examples such as this are not uncommon, and give clear evidence that appropriate geological structures can contain injected CO_2 for the periods of time required for CCS to effectively mitigate climate change.

Although extremely rare, sometimes naturally occurring CO_2 can leak upwards through the subsurface and release to the atmosphere, usually at a slow rate, with no adverse effects to plants or animals in the area. This is part of the natural CO_2 cycle between land, atmosphere and water. These leaks can teach scientists how CO_2 acts in the subsurface, and allows subsurface monitoring and detection tools to be perfected. It is very important to note that CCS sites would be carefully selected to avoid geology that would be susceptible to leaks and that these natural leaks are used as a positive learning experience.

In low concentrations (typically below 3%) CO_2 is harmless, causing tiredness and an increase in breathing rate, but with no lasting consequences. Above this level however, prolonged CO_2 exposure can lead to unconsciousness and possibly death if the affected person is not moved to a location with clearer air. While this is worrying when taken as a single fact, it should be noted that such high concentrations of CO_2 are rare, and would not remain in open areas as the CO_2 would mix with the surrounding air and disperse.

Natural disasters

There have been isolated instances in the past when a large release of naturally occurring CO_2 has lead to loss of life in natural disasters. While this is extremely rare, and in the following example a specific set of circumstances combined to facilitate the disaster, it is important to highlight the event, recognise the circumstances that occurred which lead to it, and recognise that the situation would not arise in the same manner in a CCS project. CCS sites would be selected in stable areas and safeguards would be in place to alert of any dangers in the unlikely event that something should go wrong.

In 1986, in a place called Lake Nyos in Cameroon, a natural disaster claimed the lives of 1700 people and 3500 animals. Lake Nyos is situated in a volcanic crater, where due to tropical conditions, and stable temperatures, the CO_2 that accumulates in the bottom layers of the lake do not mix and slowly release to the atmosphere. A geological event, possibly a landslide, disturbed the layers of water, releasing the CO_2, which (being heavier than air) flowed down the valleys and into several villages, asphyxiating the locals. Since then, pipelines have been installed to link the lower levels of CO_2 saturated water with the lake surface to prevent reoccurrence.

It is important to note that the incident at Lake Nyos and other similar disasters cannot be used as examples of what could happen with CCS sites; CCS would only be carried out at sites not subject to the kind of geological events that could cause leaks, and monitoring tools would minimise risks of undetected leaks.

Using Natural Sources to Learn

Being able to study and monitor natural sources of CO_2 in the subsurface enables scientists to learn how CO_2 behaves in underground storage formations at depth and pressures similar to those that will be used for CCS.

Studying natural leaks also enables scientists to fine tune monitoring technologies and develop early detection systems that can then be deployed near storage sites.

Summary

A great deal can be learned from natural underground stores of CO_2 and the very fact that these naturally occurring reservoirs have securely held CO_2 for thousands or even millions of years demonstrates the feasibility of CCS.

The situations that led to the few isolated natural disasters would not occur in carefully selected storage formations for CCS. For CCS, sites would be carefully selected in geologically secure areas, with little or no volcanic or tectonic (earthquake) activity, and with thorough and rigorous detection and monitoring systems in place with plans for the remediation of any leaks or releases.

Storing Carbon Dioxide (CO_2) Underground

Once the CO_2 has been captured and transported to a suitable storage site, we need to ensure that it will stay underground. There are several mechanisms that ensure the storage is permanent, and this information sheet aims to describe these in broad terms.

Site Selection

The first thing to determine is where to store the CO_2. There are several physical things necessary for this, and the site selection process will ensure that only the best, safest and most secure sites are selected. These sites will have a suitably sized storage formation in which the CO_2 can be injected, with a suitably impermeable cap rock above it to prevent the CO_2 from escaping upwards through the ground. Other factors will be considered during site selection, such as accessibility, proximity to capture plant and ease of transport, but also other factors such as geological stability (not in an area prone to earthquakes), and other technical requirements.

Rock Types

The storage formation, or 'reservoir rock' itself will be permeable so the CO_2 can be injected into it, porous, so there is enough space to store the CO_2, and deep enough that the CO_2 has no opportunity to escape to higher levels, and ultimately the atmosphere.

The cap rock will lie directly on top of the storage formation, and will act as a barrier so that the CO_2 cannot pass out of the storage formation. A good analogy for these two rocks is that the storage formation acts as a sponge, and the CO_2 can be held within it, and the cap rock is like a rubber sheet, not allowing any liquids or gas to pass through it.

Storage Formation Options

Storage formations come in two types – depleted hydrocarbon reservoirs (oil and gas fields) or deep saline formations. The deep saline formations simply hold very salty (brine) water that has no value for anything, whereas the depleted hydrocarbon reservoirs would originally have held oil or gas. Other than that, the basic geology is the same – both will be rocks similar to sandstone, and have lots of little spaces between the grains which the CO_2 will be stored in. The main differences between the two options will be in terms of location, capacity, and how easily the CO_2 can be injected.

Current Projects

Although this will be subject to change, in 2013, there are a number of projects in operation around the world, and in Norway there are two projects operating at a commercial scale, injecting and storing millions of tonnes of CO_2 every year. One of these, the Sleipner Project has been operating since the 1990's separating CO_2 from natural gas extracted from beneath the sea floor, and the separated CO_2 is then re-injected into an overlying formation. The natural gas is then piped to shore for further processing. There is an extensive monitoring project in operation around the injection programme, and much has been learnt about CO_2 and its behaviour when underground.

CO_2 Underground

While the cap rock initially prevents the CO_2 from escaping, over time, other mechanisms come into play.

Residual Trapping

As the CO_2 moves through the formation (because more is injected), some becomes trapped as small bubbles between the rock grains, and is unable to move any further.

Dissolution Trapping

Some CO_2 will be dissolved into the salty water that is in the storage formation. This CO_2 and water mix is then heavier than the normal water, and sinks to the bottom of the formation.

Mineral Trapping

Lastly, the CO_2 can react with the rock grains themselves, forming minerals within the rock. These minerals take a long time to form, but once formed, they effectively lock the CO_2 in place for millions of years.

With these mechanisms in place, and once the capacity of the formation has been reached, the wells are blocked off and sealed, and the CO_2 is effectively contained without any chance of escape.

Summary

The physical process of storage is relatively straightforward, and with the different storage mechanisms that take effect over time, the longer the CO_2 remains in the reservoir, the more confidence there is that it will never escape. Monitoring will still take place to detect leaks and enable operators to fix them, but as time goes by, storage can be relied upon more and more as permanent.

Effects of Carbon Dioxide (CO_2) Leaks Onshore

Whilst everything will be done to ensure leakage does not happen at any stage – capture, transport or storage, it is important to recognise that sometimes accidents can happen. Operators will be required to demonstrate that they are aware of the risks, and have a deep understanding of what the potential risks are, and how to deal with them to minimise and remediate any potential hazards.

Leak Sources

It is conceivable for CO_2 to leak from any stage of the process, capture, transport or storage, but all the risks can be managed to minimise and ensure swift detection and remedial action to remedy the problem.

Dangers and Environmental Impacts

CO_2 only presents a danger to humans when concentrations rise to over 3%. At this point it can lead to unconsciousness, and death if the casualty is not removed from the source of CO_2. However, the probability of exposure at high enough levels for long enough periods of time is unlikely as wind and air movements would dissipate any CO_2 very rapidly, and the length of exposure would likely be very short, with no lasting effects.

CO_2 is not to be confused with carbon monoxide (CO) as CO is very dangerous – many people will have CO detectors in their homes to detect leaks from their gas boiler. CO_2 is not in the same league, we breathe small amounts of CO_2 every day, in every breath, and it is the main constituent of what we breathe out.

Plants react in a similar manner, with one particular difference of note, and that is that at low concentrations, CO_2 can actively encourage growth and development in plants. Large numbers of commercial greenhouses (particularly in The Netherlands) use CO_2 captured from industrial processes to enhance the growth rate of their flowers which are then sold all over Europe. CO_2 does still pose a danger to plants, and at concentrations over 20%, plant death will occur.

Leakage Risks and Prevention Measures

Leakage from the capture or transport processes would occur on or near the surface, so any such leak would have an immediate and apparent effect, however the leak would also be easily detectable and manageable. Any changes in pressure within a pipeline system would instigate an immediate shut down and rapid repair. Any leaks at the capture process would be taking place in an industrial setting, with rigorous procedures in place for health and safety, and any leak here would also be shut down very quickly.

The larger risk would be leakage from the storage site. Any storage site will be around 1000m below the surface, or more, and therefore detection proves to be a more complex process. However, due to extensive site characterisation and monitoring before and during injection, any changes would be picked up quickly, and should a leak occur, injection would cease while the problem was dealt with. Over decades of oil and gas exploration and production, a vast suite of monitoring technologies has been developed, and site operators would have a large number of monitoring tools at their disposal. Seismic surveying works by sending sound waves into the earth, and monitoring the reflected signal – kind of like an echo. By interpreting the signal that returns, and measuring the time delay and other factors, operators can tell precisely where the CO_2 that has been injected is, and where it is moving. Any leaks from the storage reservoir would be detected by similar monitoring techniques and wells that were causing a leakage 'pathway' can be isolated, blocked and sealed to prevent such leaks reaching the surface.

Summary

While leakage is possible from the different elements of the whole process, operators would be required to minimise risks, operate within safe limits, and maintaining an extensive monitoring programme, with remediation plans in place should something go wrong. Leaks can be detected, isolated and repaired, whilst careful site and route selection will minimise or remove any potential risks to humans, animals or environmentally sensitive or protected plant species.

It is important not to ignore the risks associated with leaks, but it is also important to recognise that the risks are extremely small, and it is a simple matter to remediate them. The chances of extreme or dangerous accidents are low. Although some gases are flammable, CO_2 is not, so there is not a fire risk from any leakage – CO_2 is actually used in fire extinguishers.

Effects of A_p`ml Bgmvgbc &CO_2' Leaks Offshore

With most capture facilities being onshore, with the exception being gas processing facilities at sea, the principle offshore leakage potential routes are from subsea pipelines or storage formation leaks.

Leak Sources

Offshore transport of CO_2 would either be by pipeline or ships, with the CO_2 transported as a dense gas or liquid. Any leak would involve the pipe or ship storage tank rupturing, and would need repair to prevent the leak. Pipelines again could be shut down remotely, as with onshore pipelines, but the ship-based leak would be a more lengthy process, however it would also be much less likely to occur. Leaks from sub-seafloor storage reservoir would occur in the same way as onshore storage formations, but the detection and remediation actions would differ.

Offshore Transport

Operators of oil and gas production facilities have relevant experience of transporting high-pressure fluids and gases through seafloor pipelines. The extent of the experience in the offshore environment is less than the onshore equivalent, but the best source of experience and knowledge comes from the Snøhvit gas processing and CO_2 capture and storage (CCS) facility in the Barents Sea (Norway). Here the site operators have been processing natural gas produced from below the sea floor and storing the CO_2 since 2008 without incident, and the operators have contributed a great deal to the knowledge base used in the CCS industry as a whole.

Specific issues faced by offshore transport that do not apply to onshore situations are primarily around material selection and resistance to corrosion. Submersing metal pipelines in salt water adds a complexity and expense to these pipelines not present in onshore transport situations. Ships used for transport of liquids and dense gases are designed for purpose, and use double hulls to prevent leaks even in the event of an accident or running aground.

Leakage Risks and Prevention Measures

CO_2 leakage into seawater could cause the CO_2 to dissolve into the seawater, making it become more acidic which could have a detrimental affects on some sea life. The exact impact would be determined by the immediate environment; the existing chemical makeup of the seawater, the temperature, depth, pressure and the currents in a specific location. Mixing of the affected water and non-affected water by currents would lessen any effects.

The risks associated with leakage from the storage site would be similar to those described above, as the impacts would come into force once the CO_2 reached the seabed and was dissolved into the sea water. Remediation of any leaks from the storage reservoir would be similar to that in onshore reservoirs, although the costs of operating offshore and below the sea would be higher.

Once again, it needs to be highlighted that the probability of leakage from a carefully selected storage formation, deep under the seabed is extremely unlikely. Taking the Sleipner project example in the North Sea, monitoring has shown the CO_2 to have remained safely within the storage formation for many years, acting as predicted by scientific models. The chances of leaks are extremely small but even if a leak did occur, monitoring and remediation options are more than capable of stopping leaks and preventing damage to the environment.

Summary

Again, leakage is possible in offshore storage operations, but every measure would be taken to minimise or remove the opportunities for incidents. The risks remain fairly similar to those of onshore situations, and the monitoring, detection and remediation of any leaks would be similar, but with the added complexity of operating under the sea.

Although the risks are still present in offshore CCS, and although they are more expensive to remediate, the fact remains that the risks are extremely small, and the technologies and abilities to remediate leaks are in place and ready.

Monitoring A_p`mI Bgmvgbc+ CO_2

At the heart of any permission, license or other regulatory allowance to carry out a CO_2 capture and storage (CCS) project, is the ability to monitor the CO_2 that is injected and verify that it is where it is intended to be. Monitoring and verification continues past the injection stage and will carry on for years after a project has stopped injecting in order to demonstrate storage is permanent.

Why monitor?

For CCS to be categorised as a climate change mitigation option, it has to permanently prevent the emissions of CO_2 to the atmosphere. If CO_2 is injected into a storage formation, then for the operator to be able to class this as stored CO_2, they have to be able to demonstrate or prove that the CO_2 has remained stored securely.

Monitoring techniques have been developed to be able to show where the CO_2 that has been injected has gone, how far it has travelled, and how much is there.

How does monitoring work?

Subsurface monitoring uses pressure sensors, to monitor the pressures within the storage formation. By monitoring the pressure as it increases during injection, if a leak should occur the pressure would drop and indicate leakage. Other monitoring tools will then determine the location and rate of the leak and allow operators to fix it, preventing environmental impacts.

Seismic monitoring is used to create a picture, showing where the injected CO_2 is, both in terms of depth and how far it has spread out within the storage formation. The Sleipner project operating offshore of Norway has used seismic monitoring very effectively. The project has been operating for a number of years and the differences between the repeat surveys show the development of the CO_2 area in the subsurface. This allows operators to verify how much has been injected, where it has travelled, and where it is now. The images from seismic surveys look confusing to an untrained eye, but with the correct understanding, they can provide a wealth of information for the site operators.

Other monitoring techniques are available and are used to verify the same facts about the injected CO_2. Monitoring can also assess the condition of wells drilled into the storage formation, both old and new, and determine which need remediation or plugging / sealing before an injection project starts.

Surface and near surface monitoring focuses on water systems, air quality and ecosystems in the vicinity of a project. By monitoring the groundwater in an area, the operators can determine if any CO_2 has leaked to the groundwater. Surveys before injection starts are important here as groundwater can contain different levels of CO_2 depending on many external factors, so it is important to know what the original groundwater was before testing to see if any CO_2 has leaked into it.

Atmospheric monitoring tests the composition of the air to determine if the CO_2 levels are rising due to leaks. These tests can be very location specific, so if there is a leak, not only can these methods detect it, but they can also pinpoint it to allow site operators to determine where it is coming from and fix it.

By monitoring changes within ecosystems, both plant and animal, operators can detect if any small leaks are causing changes to the animals and vegetation in the area. Some species can act as early indicators, and can be used to identify any small changes over time.

Summary

With even the most rigorous site selection, and careful injection programme, there will be those who are cautious over the safety of CCS. By utilising and deploying monitoring technologies site operators can offer an extra reassurance that the site is operating properly, safely, and within pre-ordained restrictions laid down by regulators.

By demonstrating that the injected CO_2 is accountable, it is acting as expected, and is where it is expected to be, reassurance can be offered to interested parties and safety can be assured and demonstrated.

Legal and Regulatory Concerns

CO_2 capture and storage (CCS) projects will need to be subject to regulation and laws, and although there are some regional regulations that govern and allow pilot and demonstration projects, widespread and all encompassing regulations have so far been missing. There are numerous legal issues that will need to be addressed in order to draft full legislation that will regulate the CCS industry, specifically the storage side.

Is CO_2 a Waste or a Commodity?

This question has been answered and it is now known that CO_2 is to be classed as a commodity. There was a genuine worry that should it have been classed as a waste, there would have been issues relating to transport – wastes cannot be transported across international borders, so if CO_2 was classed as a waste, then some regions with less storage potential would have faced difficulties in mitigating their CO_2 emissions.

Permanence of Storage and Site Ownership

In order to be allocated credits under emissions trading programmes, the CO_2 must be permanently stored otherwise there would be no inherent desire of the operators to act to the best of their ability. In order to maximise operating efficiency, credits should only be allocated for confirmed permanent storage. However, the issue then lies in defining permanence. How long does the CO_2 need to stay there to be classed as permanent?

The aim of CCS is to store the CO_2 for thousands of years, but operators will need paying immediately, the issue of repayment in the event of leaks leads to a question of time limits… when does responsibility pass from the operator to another entity and which entity? Operators will not want to run sites where they are liable for many years after they stop injecting – at some point, the responsibility and ownership of the site will need to pass to a local or national authority, and this is debated around the world as to when this happens.

Ownership of Rocks

Another question comes up with the ownership of the pore space within the rocks. Landowners may want compensation, or other monetary exchange if CCS is taking place where the injected CO_2 will be under their land. In the USA, landowners generally own the geological formation under their land whereas in other regions of the world it is owned by other bodies depending on the presence of minerals and other factors. This will need addressing before CCS can take place.

As an example, some regions of the world have modified their laws so that the pore space within a rock formation is owned by the government while the rock and minerals remain the property of the landowner. This allows CCS to take place, but it remains to be seen how this will take effect in practice.

Sub Seafloor Storage

This is a more complicated area; the seafloor up to 12 miles from shore is subjected to the same laws as that country, however in northern Europe there are regulations in place that prohibit the disposal of wastes in or under the sea. This circles back to the question of whether CO_2 is a waste or a commodity.

Regional Laws

Some areas in the world have developed and implemented laws that will allow CCS to take place on an operational basis, providing that strict criteria have been met and safety measures are in place. These laws make some headway against the issues outlined above, but this is an ever-changing and developing area, so trying to define the conclusions in an Information Sheet such as this is not possible.

Summary

Regulations, legislation and laws will be required to successful deploy and operate CCS projects. Many regions are working on this, and some have put these into practice, but there is still some way to go before established legislation permits wide-scale deployment of CCS such as will be necessary to mitigate climate change.

Public Perceptions of CCS

With more and more CO_2 capture and storage (CCS) projects reaching the mainstream media and being reported in the news, public perception is an important aspect of a project. With access to information becoming ever simpler via the internet, it is very important for project operators to be open and honest, but above all proactive in their communications to the public.

Who are the public?

In this instance, the public can be considered anyone who is interested in the project for a variety of reasons. They may be scientifically trained and well aware of the processes involved, or they could be relatively uninformed, but equally interested with or without scientific background and training. This is why public perception is so vital – getting the right information to the people who want it and engaging with local populations from the earliest possible stage.

What do the public want to know?

Why, what, who, where, how; five simple questions that define what needs to be communicated from the operators to the public.

Why – they need to understand the basics and background of climate change, and what unabated climate change will mean.

What – they need an introduction to CCS – how it works, and what is involved.

Who – they need to understand who the companies are, why they are involved, and what their experience and expertise is; essentially why they are suitable operators for the project.

Where – they need to know where the project will operate, to understand if it will impact on their local environment and economy.

How – they will want to know the project details in terms of the specific elements involved, and what the risks, impacts and benefits to them will be from the project.

This demonstrates why it is important to treat public engagement as a new task for every project, because every local population will have specific concerns and worries which need to be addressed on a case-by-case basis.

Misconceptions

There will always be some misconceptions about CCS and CO_2 that will need to be addressed. Many people who haven't had a background in science may mistake CO_2 (carbon dioxide) for CO (carbon monoxide) – CO_2 is relatively safe, and is used in carbonated drinks, the food industry, and in fire extinguishers, CO is very dangerous, can kill and is why we have CO detectors in our homes to ensure that our household boilers aren't leaking. If CO_2 is mistaken for CO, then the resultant objections to a project may prove completely unfounded, but very hard to overcome.

Trust

Following on from effective communications and addressing of misconceptions, trust is an integral part of gaining public engagement and acceptance for a project. If the site operators are seen to be engaging with the local population, hearing their concerns and providing solutions and information, they are much more likely to gain trust and a project is therefore more likely to succeed. If operators are uncommunicative and do not engage the local populace, then the project will be looked at with more caution and concern, and will have a harder time gaining acceptance.

Benefits

It is worth considering that CCS projects will likely bring economic benefits to an area, creating jobs, both directly and indirectly, boosting the services trades in the area, and possibly bringing more people to an area, boosting house building, sales, rentals and associated businesses. CCS can be a change for good in a community, and this is often overlooked in public engagement practices.

Summary

Engagement with local communities should be actively pursued from an early stage, involving people at every stage of a project, and highlighting the potential benefits to all involved, both directly and indirectly. If public engagement is carried out openly and innovatively, then the chance of project success is much higher. Engage early, engage openly, and engage innovatively.