Environmental risk assessment for carbon capture and storage 2011

Report – GEHO0411BTSN-E-E

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Environment Agency
Horizon House, Deanery Road,
Bristol BS1 5AH
Tel: 0117 9334 4000
Email: enquiries@environment-agency.gov.uk
www.environment-agency.gov.uk

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Foreword

The Climate Change Act 2008 created a legally binding target to reduce the UK's emissions of greenhouse gases to at least 80% below 1990 levels by 2050. Carbon dioxide from fossil fuel power stations accounts for about 30% of UK greenhouse gas emissions and carbon capture and storage (CCS) technology has the potential to reduce these emissions by around 90%.

The government has a number of activities underway to support the demonstration of CCS technology and facilitate its development in the UK. These include a programme to build four commercial scale demonstration plants at coal and gas fired power stations by 2020 and the wider deployment of CCS from 2020 onwards. For further details see the Department of Energy and Climate Change (DECC)) website.

In our corporate strategy, *Creating a better place 2010-15*, we have said that we will act to reduce climate change and its consequences. This will include using our regulatory work to support and develop the use of low carbon technologies such as CCS. This report on our environmental risk assessment (ERA) is part of our preparations to regulate CCS technology from now until 2020 and beyond. We have published it on our website to inform the public debate on CCS and demonstrate openness and transparency in our work as an environmental regulator

April 2011

Executive summary

Carbon capture and storage (CCS) is a method of reducing carbon dioxide emissions to the atmosphere from fossil fuel power stations and other large industrial sources. It involves capturing the carbon dioxide (either before or after burning), transporting it in pipelines or by ship and permanently storing it deep underground in suitable geological formations.

We regulate the operation of fossil fuel power stations in England and Wales and will issue permits for the operation of carbon capture equipment to ensure the protection of the environment. We will also be a statutory consultee on planning applications for new CCS infrastructure such as carbon dioxide pipelines and ship loading facilities. Our remit does not cover ship transport or offshore operations.

We have produced this qualitative environmental risk assessment (ERA) for CCS to provide a high level screening of the key regulatory issues that fall within our remit. It uses a classic source ➔ pathway ➔ receptor model, to screen and rank the risks then describes how the risks will be reduced to an acceptable level. In addition to this high level generic ERA, each operator wanting to install carbon capture equipment at a power station will have to carry out a detailed site-specific ERA as part of their application for an environmental permit.

The key findings of the ERA are:

Permitting CCS technologies. We expect to be able to issue environmental permits for all the proposed CCS technologies, because we believe that the environmental risks of CCS technologies can be controlled so that they are no higher than the risks posed by existing power stations and other industrial processes we already regulate.

Regulatory controls. We do not need additional environmental regulations to cover CCS activities because we expect to be able to control all the environmental risks using our existing regulatory powers.

CCS technologies. CCS involves using existing technology, so there is a significantly lower environmental risk compared to using a new technology. Capture, transport and storage are established industrial processes so the risks are well known and are already being managed successfully elsewhere.

CCS substances. CCS involves using existing substances, so there is a significantly lower environmental risk compared to processes deliberately producing or using new substances. The substances that will be used (and released into the environment) are already being used in established industrial processes so the risks are well known and are already being managed successfully elsewhere.

Staged implementation. We expect the magnitude of many environmental risks to reduce between now and 2020 as a result of information obtained from research activities and the operation of pilot plants and demonstration plants. Staged implementation has emerged as a key risk control measure

Risk management measures. The measures identified in the ERA provide a firm evidence base for our plans to regulate CCS technology up to 2020 and beyond.

Acknowledgements

We would like to thank the organisations that have contributed to the development of this environmental risk assessment for CCS, including; the Office for Carbon Capture and Storage at the Department of Energy and Climate Change, the Carbon Capture and Storage Association, the Institution of Chemical Engineers, National Grid, Health and Safety Executive, Scottish Environment Protection Agency and the Northern Ireland Environment Agency.

Particular thanks go to Professors Simon Pollard and John Oakey at Cranfield University who provided the academic peer review.

We published this report on the ERA on our website in April 2011 to coincide with the presentation of a paper at the Hazards XXII symposium organised by the Institution of Chemical Engineers in Liverpool, UK.

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1 An environmental risk assessment for carbon capture and storage

1.1 The UK CCS programme

There is a growing consensus that the UK can only achieve its climate change targets and achieve security of electricity supply by pursuing all four of the available climate change mitigation techniques (Royal Academy of Engineering, March 2010):

- improving energy efficiency such as home insulation and combined heat and power;
- increasing the use of renewable energy such as wind, wave, tidal and solar;
- building a new generation of nuclear power stations;
- installing CCS on fossil fuel power stations, steelworks and cement works.

The UK government believes that carbon capture and storage (CCS) has the potential to be an important technology in climate change mitigation. It therefore has a number of activities underway to support the demonstration of CCS technology and facilitate its development in the UK. This work is being led by the Office for Carbon Capture and Storage (OCCS) at the Department of Energy and Climate Change (DECC).

In May 2010, the coalition Government confirmed continuing support for a programme of four commercial scale CCS demonstration projects that will capture carbon dioxide from power stations and transport it to underground geological storage facilities located offshore. If the demonstrations are successful, the Government is expecting the wider deployment of CCS from 2020 onwards. The coalition programme also included a commitment to introducing an emissions performance standard (EPS) that will prevent coal-fired power stations being built unless they are equipped with sufficient CCS.

In November 2010 the Government opened up the CCS demonstration programme to also include gas-fired power stations. The October 2010 spending review confirmed funding of up to £1bn from general public spending for the first demonstration project. The March 2011 budget announced that all demonstration projects will be funded from general public spending rather than a CCS levy as had been proposed previously.

1.2 Our roles on CCS

We have a number of current roles related to CCS technology in England and Wales (SEPA have the equivalent role in Scotland):

- Under the Environmental Permitting Regulations (EPR), we will issue permits for the operation of carbon dioxide capture equipment at fossil fuel power stations.

- Under the EU Emissions Trading System (EUETS), we will issue permits to carbon dioxide capture and onshore transport activities whilst DECC will issue EUETS permits for offshore transport and storage activities. We maintain the register of all EUETS permits (issued by SEPA, DECC and ourselves) as well as the releases on behalf of the UK government.

- If carbon dioxide capture equipment uses large quantities of hazardous substances, the power station will come under the Control of Major Accident Hazards (COMAH) regulations and we will be joint regulators with the Health and Safety Executive (HSE).

- Since April 2009 all new power stations have to be designed and built to be carbon capture ready (CCR), so that CCS technology can be retro-fitted at a later date. The operator provides CCR information as part of their application for development consent submitted to the planning body under the Planning Act 2008. We advise the planning body on some aspects of carbon capture readiness - technical feasibility and available space. The planning body used to be DECC, is currently the Infrastructure Planning Commission and in the future it is proposed to be the Major Infrastructure Planning Unit in the Planning Inspectorate.

- We will be a statutory consultee on any planning applications for new carbon dioxide pipelines and facilities for the bulk storage and ship loading of carbon dioxide.

Further information on our current roles is given in the CCS fact sheet on our website.

The Government may decide to give us additional roles following the consultation on electricity market reform in Autumn 2010 and the white paper due to be published in April 2011.

1.3 Implementation of CCS technology in the UK

The Government, regulators, industry and universities have been working together for several years to implement CCS technology in the UK. Regulatory and financial frameworks are being established, operators are building pilot plants and bringing forward engineering proposals for demonstration plants and university research is filling the knowledge gaps. The European Commission (EC) is also supporting CCS technology, providing financial support to a number of CCS demonstration projects.

The major regulatory developments in the UK over the last few years include:

- In November 2007 DECC launched a competition to build the first 300MW CCS demonstration plant that will capture carbon dioxide from a power station and transport it to an underground geological storage facility located offshore under the North Sea. The competition was restricted to post combustion capture technology on coal-fired power stations.

- The Climate Change Act 2008 created a legally binding target for the UK to reduce its greenhouse gas emissions by 80% by 2050, compared to a baseline of 1990 emissions. The Energy Act 2008 created a legislative basis in the UK for permitting the offshore storage of carbon dioxide.

- In April 2009 a policy was introduced requiring any new combustion power station to be built 'carbon capture ready'. Amongst the requirements is that new stations must have enough space available on site to allow the retrofitting of capture equipment and they must identify a transport (pipeline) route to a suitable carbon dioxide storage site (DECC April 2009).

- In November 2009 *A framework for the development of clean coal* was published (DECC November 2009). The key elements were a programme of four commercial scale demonstration projects and any new coal-fired power stations would have to operate CCS on at least part of its capacity.

- In March 2010 *Clean coal: an industrial strategy for the development of carbon capture and storage across the UK* was published.

- In October 2010 the Government spending review confirmed funding of up to £1bn for the first demonstration project. RWE npower at Tilbury in Essex withdrew from the competition at the end of 2009 and E.ON at Kingsnorth in Kent withdrew in October 2010, leaving Scottish Power at Longannet in Fife as the only entrant in the competition.

- In October 2010 the Government spending review said that a decision on the funding for demonstration projects two, three and four would be made following a consultation on electricity market reform. They confirmed that the competition for projects two to four would be open to gas-fired as well as coal-fired power stations, in line with a recommendation made by the Committee on Climate Change.

- In December 2010 the Government issued a consultation on electricity market reform which contained proposals to encourage investment in low-carbon technologies including CCS. It also included proposals for a carbon dioxide emissions performance standard (EPR), which will require coal fired power stations to be built with CCS on a significant proportion of the output.

- The March 2011 budget announced that demonstration projects two, three and four would be funded from general public spending rather than a CCS levy as had been proposed previously.

The major engineering projects in the UK over the last few years include:

- In May 2009 Scottish Power started trials of a 1MW CCS pilot plant at its coal-fired Longannet power station in Fife. This is a 'capture and release' plant that uses amines to absorb carbon dioxide then desorbs the carbon dioxide and releases it back into the atmosphere. The objective was to test one of the options for the capture stage of CCS and not the transport or storage stages. (Scottish Power, 2009).

- In July 2009 Doosan Babcock opened a 40MW oxyfuel combustion pilot plant at its research facility in Renfrew. This separates air into nitrogen and oxygen then burns coal in the oxygen. The resulting flue gas comprises mostly water vapour and carbon dioxide which could be compressed and dried to produce carbon dioxide suitable for transport to a storage facility. (Doosan Babcock 2009).

- In December 2009 Powerfuel received a grant of £156m from the EC towards the cost of building an integrated gasification combined cycle (IGCC) coal fired power station at Hatfield, in Yorkshire (Powerfuel, 2009) and (European Energy Programme for Recovery, 2009). [Note: Powerfuel went into administration in November 2010 so there is some doubt about the future of this project.]

- In December 2009 RWE npower announced plans to build a 3MW CCS pilot plant at its coal-fired Aberthaw power station in South Wales, in addition to the existing CCS pilot plant it is operating at Didcot power station in Oxfordshire. Both will operate as 'capture and release' plants. (RWE npower, 2009).

- In March 2010 the Government awarded £6.3m of funding to Scottish and Southern Energy towards the construction of a 5MW CCS pilot plant on its coal-fired Ferrybridge power station. This will be a 'capture and release' plant due to start up in April 2011 (Scottish and Southern Energy, 2010) and (DECC, March 2010). In November 2010 the Environment Agency issued a variation to the power station permit, allowing the operation of the pilot plant.

- If all these proposals go ahead the UK will have five CCS pilot plants and four CCS demonstration plants. The data gathered from the demonstration plants will inform decisions on the wider deployment of CCS from 2020 onwards.

2 Producing and publishing an ERA

2.1 Reasons for producing the ERA

The conventional approach to regulating the environmental risks from power stations is for us to use the Environmental Permitting Regulations (EPR) to implement the requirements of the EC Integrated Pollution Prevention and Control (IPPC) directive. This requires the use of 'Best Available Techniques (BAT) to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole'. The EC BAT bureau in Seville co-ordinates the production of BAT reference documents (BREFs) which provide guidance on BAT for each industrial process such as specifying equipment, emission limits and operational techniques. New installations should be built to comply with the BAT standards and existing installations upgraded to the BAT standard if it is technically and economically feasible to do so. The IPPC directive will be superseded by the Industrial Emissions Directive within a few years, but this will not alter the BAT requirements.

Operators applying for an EPR permit must demonstrate that their proposed process represents BAT and must assess the environmental impacts of the releases. This is effectively a site-specific environmental risk assessment for operating that process in that location. We assess the information provided and decide whether to refuse the application or issue a permit containing conditions to ensure the protection of the environment, such as emission limits and monitoring requirements. We subsequently carry out inspections to ensure that the operator is complying with the permit conditions and will, if necessary, take enforcement action to ensure the protection of the environment.

This approach works well for an established industry but is not suitable for a major emerging technology such as CCS. Firstly, because there is no established definition of BAT for CCS; the EC and UK demonstration programmes can be considered to be an experiment to determine what is BAT. Secondly, because it may be several years before operators submit EPR applications and we need to start assessing the environmental impacts in advance so that we can develop assessment tools and provide pre-application guidance to potential operators.

With no agreed definition of BAT and no site specific EPR applications to work on, we decided to produce a qualitative environmental risk assessment (ERA) for CCS that provides a high level screening of the key regulatory issues that fall within our remit. It provides a systematic framework for listing the generic risks, evaluating their significance and determining the risk management measures needed to reduce the risks to an acceptable level. These measures will form the basis of our action plan for regulating onshore CCS technology up to 2020. In addition to this high level generic ERA, each operator will still have to submit EPR applications that include an assessment of the site-specific environmental impacts of the particular CCS technology they wish to use and we will determine the applications in the usual way. The work done on this generic ERA should enable the EPR applications to be determined more quickly and efficiently.

In our corporate strategy we have committed to using our regulatory work to support and develop the use of low-carbon technologies, including CCS. We must ensure that this support does not compromise any of our statutory duties to ensure the protection of the environment. The ERA demonstrates that we are aware of all our statutory duties and are acting to fulfil them.

2.2 Reasons for publishing the ERA

We could have produced the ERA as an internal document and used it to plan our own CCS work programme. However we decided to publish the ERA on our website for a number of reasons:

- It will be useful to the government and other CCS regulators because it clarifies our position and our interaction with them.
- It will be useful to CCS plant operators and equipment suppliers because they can see how we are addressing the risks associated with their technology. The industry has already had the opportunity to comment on the draft ERA which has generated a debate about the relative importance of various risk management measures.
- It demonstrates that we are operating in an open and transparent manner as we prepare to carry out our role as a regulator of CCS technology.
- The Government, regulators and industry all agree that effective public engagement is important for the successful implementation of CCS in the UK. We have substantial experience of dealing with public concerns about the environmental consequences of contentious industrial projects. A common complaint from the public and NGOs is a lack of objective information about the risks involved, so publishing the ERA will help to fill that information gap.
- Publication of information about the generic environmental risks will facilitate early public debate on CCS. The site specific details of each project will then be considered as part of the planning application or when we carry out a public consultation on the EPR application.
- It will also increase public confidence in the regulatory process if we publish risk information voluntarily, rather than it being obtained by pressure groups using Freedom of Information requests.

2.3 The scope of the ERA

The scope is restricted to our regulatory remit, so it covers environmental risks, onshore, in England and Wales.

The principal areas covered are:

- capture at fossil fuel power stations (over 50MW thermal input)
- transport by onshore pipeline
- temporary bulk storage for ship loading.

The ERA covers the whole life cycle of CCS technology; construction, routine operation, abnormal operation (for example, accidental releases) and decommissioning. It also includes some risks that occur elsewhere, such as the off-site disposal of wastes produced at the power station.

The ERA does not cover:

- the existing risks of fossil fuel power stations (such as SOx and NOx releases), because we assume these are adequately controlled by our existing regulatory procedures under EPR and COMAH, such as assessing applications, setting conditions in permits, inspections, operator monitoring and reporting. (However the ERA has identified that installing CCS technology may affect the existing risks, for example, by changing the dispersion characteristics of the flue gases);

- underground coal gasification; pre-combustion only considers the gasification of coal in process equipment located above ground;

- CCS at other installations, such as steelworks and cement works, because the Government programme only covers the installation of CCS at power stations;

- transport by offshore pipeline;

- permanent geological storage onshore, because the Government has no plans to include onshore storage as part of the CCS programme;

- permanent geological storage offshore.

Producing the ERA has highlighted the relationship between ourselves and the other CCS regulators:

- We have liaised with the Scottish Environment Protection Agency (SEPA) at each stage of producing the ERA. All of the risks that have been identified apply equally to Scotland and no additional risks have been identified that are unique to Scotland. SEPA have therefore endorsed the ERA and it can be considered to apply equally well to Scotland.

- Similarly we have liaised with the Northern Ireland Environment Agency (NIEA) who have endorsed the ERA and it can be considered to apply equally well to Northern Ireland. (Note: There are currently no plans to build any CCS facilities in Northern Ireland).

- We are joint regulators with the Health and Safety Executive (HSE) of any establishments subject to the Control of Major Accident Hazards (COMAH) Regulations. These regulations already apply to some fossil-fuel power stations and may apply to more stations when carbon capture equipment is installed.

- A number of the environmental risks identified in the ERA will also pose a health and safety risk that will be regulated by HSE under the Health and Safety at Work Act. For some activities, HSE has a regulatory duty to control the health and safety risks, but we are not required to issue a permit to control the environmental risks (for example, carbon dioxide pipelines). In most of these cases the ERA has identified that the risk management measures required by HSE will be sufficient to ensure that the residual risk to the environment will be acceptably low. Therefore there are no further environmental risk management measures required and we will leave HSE to regulate these risks. This will avoid duplication of effort by the regulators and possible confusion for operators. We have discussed these risks with HSE who have confirmed that this approach is valid.

- The environmental aspects of carbon dioxide transport and storage offshore will be regulated by the DECC Energy Development Unit, based in Aberdeen.

- The Government has no plans to include large scale underground carbon dioxide storage onshore in the UK as part of the demonstration programme, so it has been excluded from the scope of the ERA. If the Government decides to allow onshore underground storage in the future then it will be added to the ERA.

2.4 The data structure of the ERA

The data structure of the ERA is based on our existing template using an excel spreadsheet. It uses a classic source ➔ pathway ➔ receptor model. Judgement is used to assign the probability and consequence of the exposure as high/medium/low/very low. The overall magnitude of the risk is evaluated as high/medium/low/very low using the risk matrix shown in figure 1.1. This overall value is very much a worst case scenario, which assumes the absence or failure of technical and operational controls.

Figure 1 Risk matrix used to evaluate overall risk

Figure 1 Risk matrix used to evaluate overall magnitude of risk

	Probability very low	Probability low	Probability medium	Probability high
Consequence very low	Low	Low	Low	Low
Consequence low	Low	Low	Medium	Medium
Consequence medium	Low	Medium	Medium	High
Consequence high	Low	Medium	High	High

Overall magnitude of risk	Low	Medium	High

The spreadsheet then describes the risk management measures that need to be taken to reduce the risks and evaluates the residual risk as high/medium/low/very low. These risk management measures will form the basis of our action plan for regulating CCS technology up to 2020, which is likely to involve more detailed risk assessments of some issues. In addition to this high-level generic ERA, each operator wanting to install CCS technology at a power station will have to carry out a site-specific ERA as part of their application for an environmental permit.

The data for the ERA consists of six separate excel worksheets reproduced in this report. They cover:

- overall risks for the CCS system – capture, transport and storage;
- post-combustion capture of carbon dioxide;
- pre-combustion capture of carbon dioxide;
- oxy-fuel combustion and capture of carbon dioxide;
- carbon dioxide transport by pipeline onshore;
- bulk storage and ship loading of carbon dioxide.

Further information on these CCS technologies, can be found on the websites of the Department of energy and Climate change (DECC), the Carbon Capture and Storage Association (CCSA) and the Scottish Centre for Carbon Storage (SCCS).

3 Findings of the ERA

A selection of the findings of the ERA are listed below, with some additional description and comment:

- **Permitting CCS technologies.** We believe that the environmental risks of CCS technologies can be controlled so that they are no higher than the risks posed by existing power stations and other industrial processes we already regulate. Therefore we expect to be able to issue environmental permits for all the proposed CCS technologies.

- **Regulatory controls of CCS activities.** We expect to be able to control all of the risks that have been identified using our existing regulatory powers. So we do not need any additional environmental regulations to cover CCS activities.

- **CCS technologies.** If CCS involved the use of new technologies it would be difficult for us to assess the environmental risks and impacts. However each of the individual elements (capture, transport and storage) are established industrial processes so the risks are well known and are already being managed successfully elsewhere. The challenge of CCS implementation is to build each element on a large scale and put the elements together to create a fully operational CCS chain. This carries a significantly lower environmental risk than using a new technology.

- **CCS substances.** If CCS involved the deliberate production or use of new substances it would be difficult for us to assess the environmental risks and impacts. However all the substances are already being used in established industrial processes so the risks are well known and are already being managed successfully elsewhere. The scale of demonstration projects may mean that large quantities of amines (and the associated break-down products) will be released from some post combustion capture plants (see amine releases below) but these involve a significantly lower environmental risk than deliberately producing or using new substances.

- **Staged implementation.** This has emerged as a key risk control measure with the magnitude of many environmental risks expected to reduce between now and 2020. Staged implementation involves starting with university research, moving on to small pilot plants (typically less than 10MW) and then demonstration plants (typically 300MW), before making a decision on full scale implementation on UK power stations (typically with capacities from 700MW to 2000MW). The information gathered at each stage is used to improve the design of the next stage. This approach (with a scale-up at each stage), is the classic chemical engineering technique for reducing project risks when developing new products and technologies. We have every reason to believe that this tried and tested approach will work well in controlling the environmental risks associated with the development of CCS technology. The benefit of this approach emerges clearly in the ERA.

- **CCS system operation.** Capture, transport and storage are likely to involve three different operators located hundreds of kilometres apart. This raises questions about the overall control of the system, such as how and where carbon dioxide will be vented during emergency shutdowns. Operators will need to address the issue of whole-CCS system operation, to the satisfaction of the regulators, prior to the start-up of the demonstration plants.

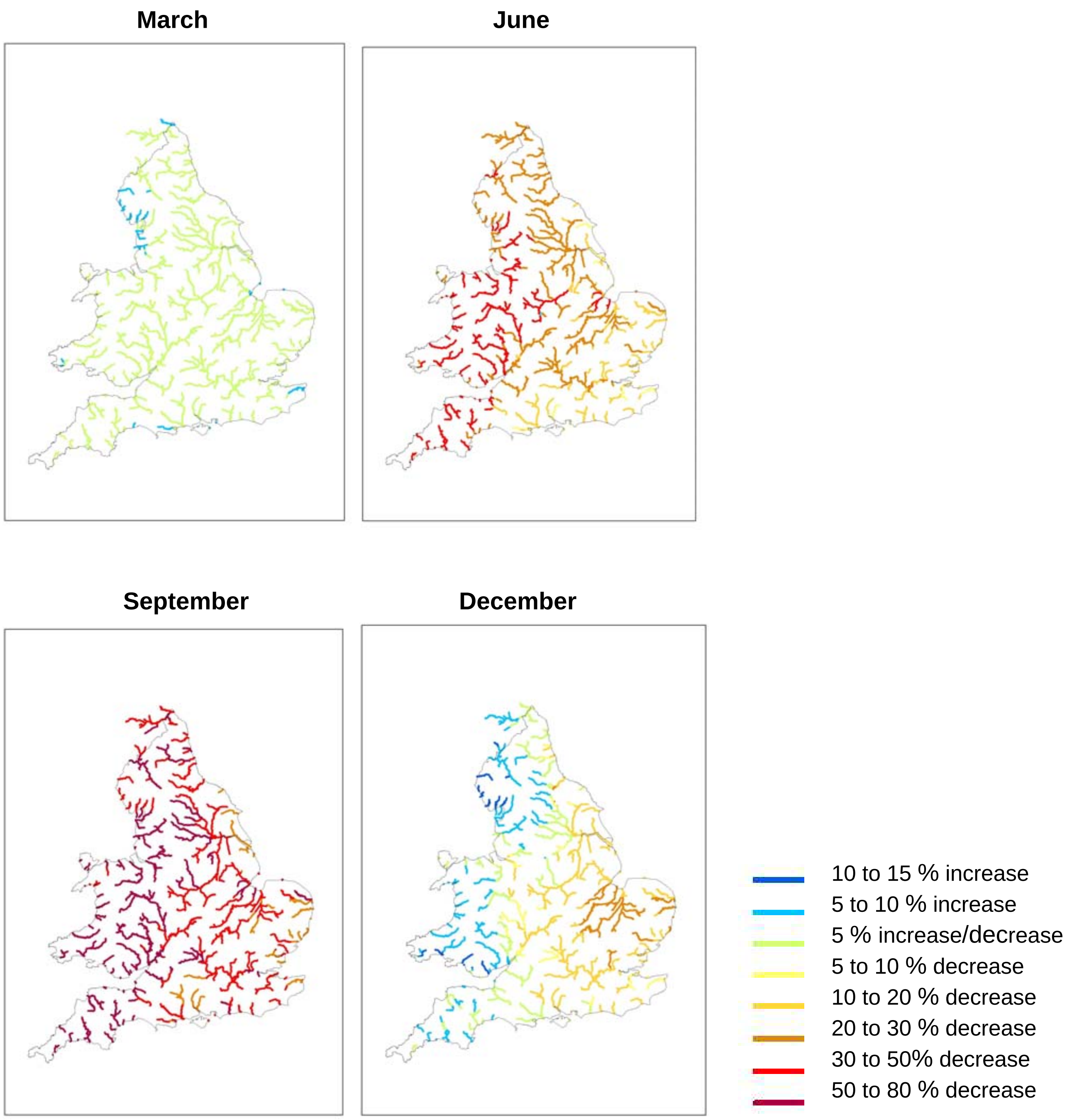
- **Amine releases into the air.** The potential releases of amines and amine degradation products into the air from post combustion capture plants could cause significant pollution without sufficient abatement. Whilst the concentration of these chemicals will be low, the volumes of flue gas being treated and released will be very large so the annual mass releases may be significant. Some capture technologies do not use amines and so will eliminate these releases altogether. If amines are used, the main risk management measure will be to utilise the operational experience and monitoring data obtained during the pilot and demonstration projects. This information will be used to improve the design of the full scale CCS plants. It might, for example, involve using abatement technology to reduce the total amine releases or using less volatile amines that will result in lower levels of emissions.

- **Waste amine disposal.** The quantity of waste amines produced by post combustion capture could become a problem if the UK did not have sufficient hazardous waste disposal capacity. The data obtained from operating the pilot plants will be used to estimate the quantities of waste likely to be produced by the demonstration plants. We will ensure that the power station operators address the waste disposal issue and that there is sufficient UK disposal capacity so that waste is not stockpiled. We have a particular interest in this issue because we regulate all hazardous waste treatment and disposal facilities.

- **Carbon dioxide pipelines.** Some of the environmental risks identified in the ERA will also pose a health and safety risk that will be regulated by HSE under the Health and Safety at Work Act. In most cases, the risk management measures required by HSE will be sufficient to ensure that residual risk to the environment will be acceptably low. Therefore there are no further environmental risk management measures required and we will leave HSE to regulate these risks. Our involvement will be limited to a few specific issues such as using our role as a statutory consultee on planning applications to check that pipeline construction does not compromise the integrity of any flood defence structures and that (as far as practicable), pipeline routes avoid sensitive and protected habitats.

- **Cooling water demand.** CCS equipment is likely to significantly increase the cooling requirements at power stations because of the additional low-grade heat produced by amine regeneration and carbon dioxide compression. If evaporative or once-through cooling is used, there may not be sufficient water available to meet the increased cooling demand. This problem may become worse in the future for power stations located on rivers, because climate change is predicted to reduce UK summer rainfall. We are responsible for water resources and we have developed computer models to forecast the effects of climate change on river water flows. The forecasts based on the UKCIP02 data show that rivers in Wales, northern and western England will have low flows in early and mid-summer because they are fed directly by rainfall, whereas rivers in southern and eastern England, will exhibit a time lag with low flows in late summer and autumn because they are fed by groundwater (Figure 2). We are currently revising these forecasts using UKCIP09 data and we expect to have results available later in 2011. We will include the cooling water demand of retro-fitting full CCS on existing power stations in future modelling work to see if there will be sufficient water available between now and the 2050s. We will also develop the computer model so it can be used to assess the impact of any proposed new power stations. This information will enable operators to optimise the location and cooling system design of new power stations.

Figure 2 Projected percentage change in mean monthly river flow between now and the 2050s using the medium-high UKCIP02 scenario



4 Conclusions

We have found producing an ERA to be a useful exercise, bringing together our knowledge and expertise in a systematic manner. The ERA has clarified our role in relation to the Government and other regulators, identified knowledge gaps and the measures that need to be taken to reduce the residual risks to an acceptable level. The risk management measures provide a firm evidence base for our action plan to regulate CCS technology up to 2020.

The key finding is, we believe, that the environmental risks of CCS technologies can be controlled so that they are no higher than the risks posed by existing power stations and industrial processes. We therefore expect to be able to issue environmental permits for all the CCS technologies currently proposed. Staged implementation has emerged as a key risk control measure with the magnitude of many risks expected to reduce over time as a result of information obtained from research and the operation of pilot and demonstration plants.

5 ERA data on individual risks

5.1 Overall risks for the CCS system – capture, transport and storage

Environmental Risk Assessment for Carbon Capture and Storage: Overall risks for the whole CCS system - capture, transport and storage

5.1 Overall risks for the CCS system - capture, transport and storage

Data and information				Judgement				Action	
Source (Hazard)	**Pathway**	**Receptor**	**Harm**	**Probability of exposure**	**Consequence**	**Magnitude of risk**	**Justification for magnitude**	**Risk management**	**Residual risk**
What is the agent or process with potential to cause harm?	**How might the receptor come into contact with the source?**	**What is at risk? What do I wish to protect?**	**What are the harmful consequences if things go wrong?**	**How likely is this contact?**	**How severe will the consequences be if this occurs?**	**What is the overall magnitude of the risk?**	**On what did I base my judgement?**	**How can I best manage the risk to reduce the magnitude?**	**What is the magnitude of the risk after management?**
Pollution caused by a substance released from a CCS process is significant enough to cause a breach of an existing environmental standard, even after the application of BAT, to prevent, minimise and render harmless the release of the substance (or the EA identifies that a breach is likely to occur).	Any	People and the environment located near the PS, pipeline or ship loading site.	Any type of harm to people and the environment. Harm to the credibility of CCS technology and all organisations involved in its development (Government, regulators and operators).	Low	High	**Medium**	Probability is low because no such problem has been identified yet. Consequence is high because there would be a potential conflict between protecting the local environment and meeting UK climate change mitigation targets to prevent global climate change.	Action: EA - Ensure that all CCS processes comply with existing environmental standards and regulatory requirements. If they do not comply then the EA would refuse to issue a permit or take enforcement action to ensure compliance and prevent breaches, as appropriate. (The reputation of the EA would be damaged if it allowed the process to continue to operate with an ongoing breach of an existing environmental standard, or if it believed that such a breach was likely to occur). Action: EA - Alert the UK Government to any breaches or likely breaches as soon as possible. Action: UK Govt - Evaluate options to resolve the breach and implement a solution e.g. revise the environmental standard if it is outdated or inappropriate (if this was an EC standard the issue would have to be raised with the EC), abandon the CCS process causing the breach, or direct the Agency to allow the process to operate despite the breach (if the climate change benefits outweigh the consequences of the breach).	Low. The staged implementation of CCS using pilot plants followed by demonstration plants should allow any potential breaches to be identified and prevented at an early stage. Hence there is only a low risk of a breach that would cause significant environmental damage actually happening.

Data and information				Judgement				Action	
Source (Hazard)	**Pathway**	**Receptor**	**Harm**	**Probability of exposure**	**Consequence**	**Magnitude of risk**	**Justification for magnitude**	**Risk management**	**Residual risk**
Loss of control at one point in the CCS chain (PS, pipeline, ship loading site or storage site) leading to accidental short-term releases of CO2, CCS chemicals, fuel or combustion products from any point on the CCS chain	Air transport of gases and particulates and deposition onto the land. Spillage of liquids into controlled waters or groundwater or onto land.	People and the environment located near the PS, pipeline or ship loading site	Exposure to CO2, CCS chemicals, fuel or combustion products, possibly at high concentrations. This will probably be a short term exposure while control is restored or equipment is shut-down.	Low	High	**Medium**	Risk is not low because operation of CCS chain is technically complex and is likely to involve several operators separated by long distances. Risk is not high because the UK already has experience of operating fossil fuel power stations with complex abatement systems (e.g. flue-gas de-sulphurisation), power stations linked to high pressure cross country pipeline systems linked to offshore production platforms (e.g. the natural gas transmission system) and bulk terminals for ship loading/unloading of liquids (e.g. liquified natural gas).	ACTION: EA/HSE - require operators to produce an operational safety case describing how the whole CCS chain will be controlled, before allowing operations to commence. 2011 is too early to expect the operators to have produced such a safety case. ACTION: Academia and industry to continue existing research into CO2 transport properties and the dynamics of operating transport systems. This will include networks e.g. several power stations sharing the same pipeline.	Low - provided that control systems are in place. The staged implementation of CCS using pilot plants followed by demonstration plants should allow any potential process instability problems to be identified and prevented at an early stage.
Any CCS process equipment contaminated with hazardous materials such that it cannot be easily decommissioned and disposed of at the end of its useful life.	Air transport of gases and particulates and deposition onto the land. Spillage of liquids into controlled waters or groundwater or onto land.	People and the environment located near the PS, pipeline or ship loading site or located near coastal facilities used for the interim storage/final disposal of ships/offshore structures or near any onshore facility used for final disposal of any equipment.	Exposure to hazardous materials. Harm to the credibility of CCS technology and all organisations involved in its development (Government, regulators and operators) if there are any significant final disposal issues.	Very low	High	**Low**	Probability is very low because there is no evidence that any of the CCS process options currently under consideration will contaminate process equipment and cause a significant problem for final disposal	ACTION: EA - ensure that none of the onshore CCS process options will result in contaminated equipment that presents final disposal problems. For capture equipment this will be carried out as part of the assessment of EPR applications submitted by the power station operators. ACTION: EA - Discuss with DECC Energy Development Unit to ensure that none of the offshore process options will result in contaminated equipment that presents final disposal problems. [Note: offshore CCS process equipment is outside the remit of the EA but it could become an EA problem if it is moved to coastal facilities for interim storage and/or final disposal.	Very low - provided that decommissioning and final disposal of equipment is considered as part of the CCS process development programme.

5.2 Post-combustion capture of carbon dioxide

Environmental Risk Assessment for Carbon Capture and Storage: Post-Combustion Capture of CO2

Data and information				Judgement				Action	
Source (Hazard)	**Pathway**	**Receptor**	**Harm**	**Probability of exposure**	**Consequence**	**Magnitude of risk**	**Justification for magnitude**	**Risk management**	**Residual risk**
What is the agent or process with potential to cause harm?	**How might the receptor come into contact with the source?**	**What is at risk? What do I wish to protect?**	**What are the harmful consequences if things go wrong?**	**How likely is this contact?**	**How severe will the consequences be if this occurs?**	**What is the overall magnitude of the risk?**	**On what did I base my judgement?**	**How can I best manage the risk to reduce the magnitude?**	**What is the magnitude of the risk after management?**
Chemicals used in proprietary CO2 absorbents. Current proposals for pilot and demonstration plants involve using mixtures of amines (usually ethanolamines) and surfactants. Amines are volatile and will be released continuously in the flue gas from the CO2 scrubber.	Directly by air transport then inhalation or skin contact. Indirectly by air transport, deposition on plants eaten by animals and people or deposition on soil and uptake by plants eaten by animals and people. Directly in water discharges contacting aquatic organisms. Indirectly by water discharges and uptake by plants and animals eaten by other animals and people. Indirect effects will only occur if chemicals are persistent and/or bio-accumulative.	Local human population, animals and plants	Any harm to the health of humans, animals and plants from emissions controlled under EPR (non-COMAH).	Medium	Medium	**Medium**	Risk is medium rather than high because ethanolamines and other amines have been used for many years on an industrial scale in CO2 absorbent systems e.g. in oil and gas refining. Risk would also be medium for alternative options that are established processes such as liquid ammonia, the Rectisol process (using methanol) or the Selexol process (using dimethyl ethers of polyethelene glycol). However we will apply the precautionary principle and increase the risk to high for any proposals involving processes and chemicals that have not previously been used on an industrial scale.	Action: EA - use EPR to ensure operators minimise releases and substitute less harmful chemicals, set emission limits and environmental monitoring requirements etc. ACTION: EA - issue variations to PS permits for the operation of CCS pilot plants, specifying monitoring and reporting of releases and requiring reports on the estimated emissions from full-scale CCS plant and their environmental effects. [Note: There may be commercial confidentiality issues for some of the substances]. ACTION: EA - review reports of the pilot plant releases, publish original reports or a summary report and produce a monitoring plan for CCS demonstration projects. ACTION: EA - Collect and assess evidence on reseach into novel CO2 processes at UK universities (and worldwide) and their development at laboratory scale e.g. using solid sorbents. ACTION: EA - Collect and assess evidence on amine releases from other CCS projects e.g. Norwegian Institute for Air Research and EC demonstration projects.	Very low for pilot plant trials - the releases will be small because the pilot plants are small. Low for demonstration plants provided that the operators can supply detailed information on releases (e.g obtained from pilot plants) and their environmental effects and the EA carries out detailed assessment of the releases before issuing the permit.

Data and information				Judgement				Action	
Source (Hazard)	**Pathway**	**Receptor**	**Harm**	**Probability of exposure**	**Consequence**	**Magnitude of risk**	**Justification for magnitude**	**Risk management**	**Residual risk**
Contaminants produced in the CO_2 absorbent system, including, corrosion products, breakdown products and new chemical species created in-situ e.g. nitrosamines. Also new chemical species created in the environment from substances after they have been emitted from the process.	as above	as above	as above	Medium	High	**High**	Risk is high because the CO_2 absorbants may produce different contaminants when scrubbing power station flue gases compared to previous industrial applications in the oil and gas industry.	as above	as above
Increased pollution caused by increased production and transport of organic chemicals used in proprietary CO_2 absorbents - principally ethanolamines and surfactants	Release of pollutants to air, water and land from production sites or from transport accidents	Human population, animals and plants near the chemical production sites and the transport routes. [Note: These may be outside the UK]	Any harm to the health of humans, animals and plants	Low	Low	**Low**	Risk is low because the chemicals used for CCS processes are already being produced in industrial quantities. Risk might be reduced to very low if the production sites are subject to effective environmental regulation. However we will apply the precautionary principle and increase the risk to medium if CCS processes use any chemicals that have not previously been produced in industrial quantities, if the production sites are not subject to effective environmental regulation, or if the percentage increase in production to satisfy CCS requirements is very high (e.g greater than 100% increase).	ACTION: EA - for chemicals produced in England and Wales the environmental consequences will be controlled under EPR (and similar controls will be exercised by SEPA in Scotland). ACTION: EA - ensure that the environmental consequences of producing and transporting CCS chemicals, inside and outside the UK, is considered when making decisions on widespread adoption of CCS technology. This will be based on information obtained from the pilot plants and demonstration plants and is not likely to happen before 2018. The credibility of CCS might be damaged if increased production of these chemicals causes significant pollution - either inside or outside the UK.	Low. Risk might be reduced following the assessment of the environmental consequences.

Data and information				Judgement				Action	
Source (Hazard)	**Pathway**	**Receptor**	**Harm**	**Probability of exposure**	**Consequence**	**Magnitude of risk**	**Justification for magnitude**	**Risk management**	**Residual risk**
Increased pollution caused by increased storage, transport and disposal of waste organic chemicals used in proprietary CO2 absorbents (principally ethanolamines and surfactants) and impurities, breakdown products and species created in-situ e.g. nitrosamines	Release of pollutants to air, water and land from transport accidents, storage at transfer stations and disposal sites.	Human population, animals and plants located near the transport routes, transfer stations and chemical disposal sites. [Note: These will probably be inside the UK, because the waste is unlikely to be exported]	Any harm to the health of humans, animals and plants	Low	Low	**Low**	Risk is low because the chemicals used for CCS processes are already being used in the UK in industrial quantities and there are established disposal routes regulated by the EA/SEPA, or if the waste is exported for recovery or disposal it will be subject to control through the TFS regulations. Risk could be reduced to very low if the percentage increase in this type of waste chemical arising from CCS operations is low (e.g less than a 100% increase). However we will apply the precautionary principle and increase the risk to medium if waste has to be stored for prolonged periods because of a lack of suitable disposal capacity, new disposal routes are required for waste chemicals	ACTION: EA - for waste chemicals produced in England and Wales the environmental consequences will be controlled under EPR (and similar controls will be exercised by SEPA in Scotland). ACTION: EA - ensure that the environmental consequences of producing and transporting waste CCS chemicals, inside and outside the UK, is considered when making decisions on widespread adoption of CCS technology. This will be based on information obtained from the pilot plants and demonstration plants and is not likely to happen before 2018. The credibility of CCS might be damaged if these wastes had to be stockpiled due to a lack of UK disposal capacity.	Low. Risk might be reduced to very low following the assessment of UK disposal capacity and the environmental consequences of disposal.

Data and information				Judgement				Action	
Source (Hazard)	**Pathway**	**Receptor**	**Harm**	**Probability of exposure**	**Consequence**	**Magnitude of risk**	**Justification for magnitude**	**Risk management**	**Residual risk**
Releases of low pressure carbon dioxide e.g. Rupture of pipework or fugitive releases from valves and pipework. CO2 would be present as gas phase and could be hot, at ambient temperature or cool but not cold.	Releases indoors could result in high CO2 concentrations accumulating throughout the building. Releases of cold gas outdoors could produce a gas cloud that could drift downwind and downhill and collect in any low points, particularly under calm weather conditions.	Local human population and animals	Any type of harm to the health of humans and animals from increased CO2 concentration. Human risks are asphyxiation at high concentrations and physiological effects at lower concentrations. Effects on humans are well understood and effects on animals are assumed to be equivalent. Plants will not be harmed.	Medium	Medium	**medium**	Medium probability is an average value - small scale fugitive releases from valves and pipe flanges will be more likely than large scale releases from rupture of vessels or pipework. Risk to humans will be medium x medium = medium if they are close to the hazard, working inside buildings or in other enclosed spaces. The risk to humans and animals will be very low x medium = low if they are in open spaces and not close to the hazard (more than a few tens of metres from the release point).	ACTION: Operators will ensure that all valves and pipework are within the site boundary so these releases will only occur in a secure site with no public access. Hence risk to workers will be medium and risk to members of the public and animals will be low (though some animals might be present within the site boundary). ACTION: HSE - regulate under HSAWA to ensure that the risk to site workers is minimised. Action: Operators - assess the releases from main chimney stack and any CO2 vents as part of their EPR application. (Note: CO2 releases from main stack will reduce by 90% when CCS is running but other flue gas parameters will also change which will affect dispersion). Action: EA - check the operators assessment before issuing any EPR permit.	Measures taken by HSE and operators to reduce the risk to site workers to "low" will reduce the residual risk to local residents and the environment to "very low". No additional environmental risk management measures are likely to be required (this will be confirmed by EA participation in the CO2RISKMAN project).
Organic chemicals in proprietary CO2 absorbents - principally ethanolamines and surfactants, including impurities, breakdown products and species created in-situ e.g. nitrosamines	Leaks and spillages into surface water drains or ETP. Permitted releases from the ETP	Surface waters (rivers or estuaries)	Oxygen depletion and/or toxicity causing death of aquatic organisms (mammals, birds, fish, invertebrates, plants). Closure of drinking water intakes. Contaminated fish/shellfish entering human food chain (will only happen if chemicals are persistent and/or bio-accumulative). Loss of recreational use.	Medium	Medium	**medium**	Risk is likely to be medium rather than high because most of these chemicals are already used on an industrial scale in CO2 absorbent systems e.g. in oil and gas refining. However we will apply the precautionary principle and increase the risk to high for any chemical that has not previously been used in large scale industrial applications.	Action: Operators - provide tank bunding, impermeable surfaces, sealed drainage systems and spillage containment. Action: EA - review pollution prevention measures during pre-application discussions, permit determination and commissioning. (Note: Any existing oil interceptors will be ineffective because CO2 absorbent chemicals are water soluble). Action: Operators - assess the releases from ETP as part of their EPR application. Action: EA - check the operators assessment before issuing any EPR permit.	Low. No new risk management measures are required.

Data and information				Judgement				Action	
Source (Hazard)	**Pathway**	**Receptor**	**Harm**	**Probability of exposure**	**Consequence**	**Magnitude of risk**	**Justification for magnitude**	**Risk management**	**Residual risk**
As above	Direct spillage onto the ground or leakage from damaged drainage systems	Groundwater	Pollution of groundwater restricting its use as a resource or requiring clean-up prior to use. Pollution of surface waters by groundwater (as above)	Medium	Medium	**Medium**	Risk is likely to be medium rather than high in most locations. However increase risk to high if PS is located above a drinking water aquifer.	Action: Operators - provide tank bunding, impermeable surfaces, sealed drainage systems and spillage containment. Action: EA - review polution prevention measures during pre-application discussions, permit determination and commissioning.	Low. No new risk management measures are required.
Construction activities producing mud/silt run-off or leaks from the existing site services (fractured oil pipes, effluent pipes etc)	Leaks and spillages into surface water drains or ETP. Direct spillage onto the ground or leakage from damaged drainage systems	Surface waters and groundwaters	As above for surface and groundwaters	Low	Low	**Low**	Risk is low because construction activities are easy to control on an established site. All coal-fired PSs have recent experience of carrying out major construction projects e.g. flue gas desulphurisation.	ACTION: Operators - Use their exissting procedures for managing contractors and on-site construction activities.	Very low. No new risk management measures are required.
Increased temperature of once through cooling water discharge or ETP discharge	Direct discharge into rivers/estuaries	Aquatic ecosystems	Direct contact due to inadequate mixing and high heat load (short term, high temperature change). Alteration to aquatic and benthic habitats (long term, small temperature change).	Medium	High	**High**	If PS uses river water for once through cooling risk will be high. If PS uses estuary water for once through cooling risk may be reduced to medium. If PS uses evaporative cooling the only source will be the ETP discharge so risk will be medium if located on a river or low if located on an estuary.	Action: Operators - assess the options for process cooling and the releases of heat into aquatic ecosystems as part of their EPR application for the demonstration plants. (Note: The chosen option for process cooling (once-through, evaporative or air cooling) will depend on local factors). Action: EA - check the operators assessment as part of a habitats assessment before issuing any EPR permit and set improvement conditions requiring reports on the process cooling options from full-scale CCS plant and their environmental effects. Note: The chosen option for process cooling may involve significant additional costs and reduced process effficiency to avoid causing harm to aquatic ecosystems, thus reducing the CO2 saved per unit of energy generated.	Low. The staged implementation of CCS using pilot plants followed by demonstration plants should allow any potential problems to be identified and prevented before building full scale CCS plants. Note: Climate change may cause significant reductions in river flow rates at certain times of year over next few decades.

Data and information				Judgement				Action	
Source (Hazard)	**Pathway**	**Receptor**	**Harm**	**Probability of exposure**	**Consequence**	**Magnitude of risk**	**Justification for magnitude**	**Risk management**	**Residual risk**
Increased fresh water demand for process use or evaporative cooling.	Abstraction from surface waters or groundwater	Water resources - surface water flows and groundwater levels. Aquatic ecosystems. Recreational use.	Less fresh water available for other users - people, industry, agriculture and wildlife	Medium	High	**High**	If PS uses evaporative cooling risk will be high unless there is surplus local water when it might reduce to medium. If once through cooling is used risk may be reduced to low.	Action: Operators - assess the option for process cooling and the demand for water resources as part of their EPR application for the demonstration plants. (Note: The chosen option for process cooling (once-through, evaporative or air cooling) will depend on local factors). Action: EA - check the operators assessment of demand for water resources before issuing any EPR permit and set improvement conditions requiring reports on the process cooling options from full-scale CCS plant and their environmental effects. Action: EA - The data from the operation of the demonstration plants will not be available until 2016-18. We will review the CCS demand for water resources and the consequences of increased water discharge temperatures by 2016-2018 to inform the government's decisions on full-scale implementation of CCS.	Low. The staged implementation of CCS using pilot plants followed by demonstration plants should allow any potential problems to be identified and prevented before building full scale CCS plants. Note: Climate change may cause significant reductions in river flow rates at certain times of year over next few decades. Note: Availability of cooling water may become a more significant factor in choosing the cooling system and location for new Power Stations e.g. choosing air cooling or coastal locations using sea water cooling.

Data and information				Judgement				Action	
Source (Hazard)	**Pathway**	**Receptor**	**Harm**	**Probability of exposure**	**Consequence**	**Magnitude of risk**	**Justification for magnitude**	**Risk management**	**Residual risk**
Adding CCS technology increases the harm caused by substances released from the existing combustion process.	The pathway may be altered by adding CCS technology e.g. the CCS plant may remove substances from the flue gases and transfer them into a liquid effluent stream or the CCS plant may affect the dispersion characteristics of the flue gases (volume, temperature, discharge velocity etc).	People and the environment located near the PS	Any harm to the health of humans, animals and plants	Low	Medium	**Medium**	Adding CCS technology will provide an opportunity to reduce some existing releases and their environmental consequences, whilst others may increase. No significant increase have been identified so far hence the overall risk is considered to be medium.	Action: Operators - assess the consequences of CCS on existing discharges as part of their EPR application for the demonstration plants. Action: EA - check the operators assessment before issuing any EPR permit and set improvement conditions requiring reports on the environmental consequences of full-scale CCS plant.	Very low.

5.3 Pre-combustion capture of carbon dioxide

Environmental Risk Assessment for Carbon Capture and Storage: Pre-Combustion Capture of CO2

Source (Hazard)	Pathway	Receptor	Harm	Probability of exposure	Consequence	Magnitude of risk	Justification for magnitude	Risk management	Residual risk
What is the agent or process with potential to cause harm?	**How might the receptor come into contact with the source?**	**What is at risk? What do I wish to protect?**	**What are the harmful consequences if things go wrong?**	**How likely is this contact?**	**How severe will the consequences be if this occurs?**	**What is the overall magnitude of the risk?**	**On what did I base my judgement?**	**How can I best manage the risk to reduce the magnitude?**	**What is the magnitude of the risk after management?**
Short term high concentration releases of syngas (principally a mixture of H2, CH4, CO and CO2) e.g. accidental failure of pipework or vessels. Gas may disperse or ignite causing fires/explosions. Note: It is assumed that any deliberate venting of pipework and vessels will be to a flarestack, ensuring safe and complete combustion e.g. prior to maintenance activities or during start-ups and shutdowns.	Directly by air transport of gas cloud.	Local human population, animals and plants	Harm to the health of humans and animals from inhaling the toxic gas cloud if it does not ignite (effects dominated by CO toxicity). If it does ignite, thermal radiation from fires, overpressure and shrapnel from explosions. Possible secondary release of chemicals from equipment damaged by fire and explosions.	Low	High	**medium**	The risk is not high because the UK has 50 years experience of operating similar processes on refineries and steelworks, with a good safety record. Much of that experience is directly applicable to operating a gasifier on a power station. Any major loss of containment will be detected quickly and the process will be shut down with the gases sent to the flarestack. Risk to site workers will be low x high = medium because they are close to the hazard. The off-site risks to humans will be: very low x high = low if the inventory of syn-gas is below the COMAH threshold and low x high = medium if the COMAH regulations apply.	Action: HSE - If the COMAH regulations do not apply regulate under HSAWA to reduce the on-site and off-site risks to people. Action: Operator - if the establishment is covered by the COMAH regs produce safety report or MAPP to address risks to workers, people off-site and the environment. Action: HSE & EA - assess safety report or MAPP and regulate site under COMAH.	Low. Measures taken by HSE and operators to reduce the on-site and off-site risk to people to "low" will reduce the residual risk to the environment to "very low".

Source (Hazard)	Pathway	Receptor	Harm	Probability of exposure	Consequence	Magnitude of risk	Justification for magnitude	Risk management	Residual risk
Long term low concentration releases of syn-gas (principally a mixture of H2, CH4, CO and CO2) and impurities (NH3, H2S, water, ash, PAHs, phenols, water etc) e.g. fugitive releases from valves and pipework, routine releases from vents.	Directly by air transport then inhalation or skin contact. Indirectly by air transport, deposition on plants eaten by animals and people or deposition on soil and uptake by plants eaten by animals and people. Indirect effects will only occur for those chemicals that are persistent and/or bio-accumulative e.g. PAHs.	Local human population, animals and plants	Any harm to the health of humans and animals from inhaling the gases (concentration assumed to be too low for the gases to ignite). Any harm to the health of plants from uptake of chemicals deposited on soils and any harm to humans and animals from eating contaminated plants.	Low	Medium	**medium**	Risk to site workers will be medium because they are close to the hazard. The off-site risks will be low because the concentration of syn-gas will be low. Risk is not high because syn-gas is already used on an industrial scale e.g. in steelworks and the toxicology of syn-gas components is well known .	Action: HSE - regulate under HSAWA to ensure that the risk to site workers is minimised. Measures taken to reduce the on-site risk to workers will also reduce the off-site risks Action: Operators - assess the releases from any syn-gas vents as part of their EPR application. Action: EA - check the operators assessment before issuing any EPR permit.	Low for on-site risks. Very low for off-site risks
Waste water from coal gasifier	Accidental release into site drainage system then into controlled waters. Accidental spillage onto ground. Permitted release of treated effluent into controlled waters.	Surface waters and groundwaters	Oxygen depletion and/or toxicity causing death of aquatic organisms (mammals, birds, fish, invertebrates, plants). Closure of drinking water intakes. Contaminated fish/shellfish entering human food chain (will only happen if chemicals are persistent and/or bio-accumulative). Loss of recreational use. Pollution of groundwater restricting its use as a resource or requiring clean-up prior to use.	Low	Medium	**Medium**	Risk is medium because the waste water will contain significant quantities of pollutants. Risk is not high because similar waste water is already produced on an industrial scale e.g. in steelworks and the toxicology of polluting components is well known	Action: Operators - provide tank bunding, impermeable surfaces, sealed drainage systems and spillage containment. Action: EA - review pollution prevention measures during pre-application discussions, permit determination and commissioning. Action: Operators - assess the releases from ETP as part of their EPR application. Action: EA - check the operators assessment before issuing any EPR permit.	Low. No new risk management measures are required.

Source (Hazard)	Pathway	Receptor	Harm	Probability of exposure	Consequence	Magnitude of risk	Justification for magnitude	Risk management	Residual risk
liquid and solid sulphur from sulphur recovery plant	Accidental spillage of liquid sulphur on site or off-site during transport. Solid sulphur sent off-site for waste disposal.	People, animals and plants located near the PS or transport routes, transfer stations and chemical disposal sites.	Any harm to the health of humans, animals and plants	Very low	Low	**Low**	Any spillage of molten sulphur will cool and solidify and then be mechanically removed. The risk from molten sulphur will be localised and short term. Risk is not medium or high because sulphur has been prodced on oil refineries and transported by tanker for many years.	Action EA: Assess the state of the market for sulphur in the UK. Will an increase in sulphur production be used as a product or will it become waste?	Very low
gasifier slag	leaching of pollutants from slag stored on-site, re-used in construction or disposed of in landfill. Dust blown off slag stored on-site, during transport, when re-used in construction or disposed of in landfill.	Surface waters and groundwaters. People, animals and plants located near the transport routes, transfer stations and slag processing or disposal sites.	Any harm to the health of humans, animals and plants	Very low	Low	**Low**	Any spillage slag will be mechanically removed. The risk from slag will be localised and short term. Risk is not low because similar slags have been produced on steelworks and transported by lorry for many years.	Action EA: Obtain data on slags from operators as part of their EPR application, or from vendors of coal gasifiers. Assess the state of market for slag in the UK. Will an increase in slag production be used as a product or will it become waste	very low

5.4 Oxy-fuel combustion and capture of carbon dioxide

Environmental Risk Assessment for Carbon Capture and Storage: Oxy-Fuel Combustion and capture of CO2

5.4 Oxy-Fuel Combustion and capture of CO2

Source	Pathway	Receptor	Harm	Probability of exposure	Consequence	Magnitude of risk	Justification for magnitude	Risk management	Residual risk
What is the agent or process with potential to cause harm?	**How might the receptor come into contact with the source?**	**What is at risk? What do I wish to protect?**	**What are the harmful consequences if things go wrong?**	**How likely is this contact?**	**How severe will the consequences be if this occurs?**	**What is the overall magnitude of the risk?**	**On what did I base my judgement?**	**How can I best manage the risk to reduce the magnitude?**	**What is the magnitude of the risk after management?**
Oxygen release from the air separation plant causing fires/explosions.	Directly by air transport of oxygen gas cloud.	Local human population, animals and plants	Thermal radiation from fires, overpressure and shrapnel from explosions. Secondary release of chemicals from equipment damaged by fire and expolsions	Low	High	**Medium**	Air separation is a common industrial process with a standard plant design. It is not a PPC Directive activity and does not require an EPR Permit, irrespective of its size. Risk will be low if the oxygen storage capacity is less than the COMAH lower tier threshold of 200te because there will be insufficient oxygen to have significant off-site effects. However if there is a large oxygen storage capacity the establishment will be controlled by the COMAH regulations. If the oxygen storage capacity is greater than the lower tier threshold of 200te and less than the top tier threshold of 2,000te then risk will be medium. If the oxygen storage capacity is higher than 2,000te then risk will be high.	Action: Operator - if the establishment is covered by the COMAH regs produce safety report or Major Acccident Prevention Policy (MAPP) to address risks to workers, people off-site and the environment. Action: HSE & EA - assess safety report or MAPP and regulate site under COMAH. Action: HSE - If the COMAH regulations do not apply, regulate under HSAWA to ensure that the risk to site workers is minimised. Operation of an air separation plant by the equipment supplier - who has the operational expertise (which is common practice). Locate the air separation plant away from the CCS plant and fuel/chemical storage.	Very low if oxygen storage capacity is below COMAH lower tier threshold. Low if the COMAH regulations apply. Measures taken by HSE and operators to reduce the on-site and off-site risk to people will reduce the residual risk to the environment to "very low".

Source	Pathway	Receptor	Harm	Probability of exposure	Consequence	Magnitude of risk	Justification for magnitude	Risk management	Residual risk
Nitrogen release from the air separation plant	Directly by air transport of nitrogen gas cloud	Local human population and animals. Plants will not be affected.	Nitrogen could cause asphixiation by displacing air.	Very low	High	**Low**	Air separation is a common industrial process with a standard plant design. It is not a PPC Directive activity and does not require an Environmental Permit, irrespective of its size. Risk to site workers will be high because they are close to the hazard (or even inside the hazardous area e.g. asphixiation risk during vessel entry). The off-site risks will be very low which is why the bulk storage of nitrogen is not covered by the COMAH regulations.	Low. Measures taken by HSE and operators to reduce the on-site risk to people to "low" will reduce the residual risk off-site people and the environment to "very low".	Low. Measures taken by HSE and operators to reduce the on-site risk to people to "low" will reduce the residual risk off-site people and the environment to "very low".

5.5 Carbon dioxide transport by pipeline onshore

Environmental risk assessment for Carbon Capture and Storage: CO_2 transport by pipeline onshore

Data and information				Judgement				Action	
Source (Hazard)	**Pathway**	**Receptor**	**Harm**	**Probability of exposure**	**Consequence**	**Magnitude of risk**	**Justification for magnitude**	**Risk management**	**Residual risk**
What is the agent or process with potential to cause harm?	**How might the receptor come into contact with the source?**	**What is at risk? What do I wish to protect?**	**What are the harmful consequences if things go wrong?**	**How likely is this contact?**	**How severe will the consequences be if this occurs?**	**What is the overall magnitude of the risk?**	**On what did I base my judgement?**	**How can I best manage the risk to reduce the magnitude?**	**What is the magnitude of the risk after management?**
Large scale, short term releases of carbon dioxide e.g. rupture of a cross-country underground pipeline or major loss of containment at a compressor, pumping station or manifold. Dense phase CO2 will partition into a gas cloud and solid "snow" which will then sublime to produce more gas	Direct contact with cold CO2 gas and "snow" close to the release point. As the CO2 is released it will be diluted by entraining large volumes of surrounding air followed by a more gradual dilution and dispersion. The gas cloud will be cold and denser than air so it could drift downwind and downhill and collect in any low points, particularly under calm weather conditions.	Local human population, animals and plants. Equipment and structures close to the release point may be damaged by extreme cold e.g. metal embrittlement leading to structural failure.	Any type of harm to the health of humans, animals and plants from cold gas or increased CO2 concentration. Human risk of asphyxiation at high concentrations and physiological effects at lower concentrations. Effects on humans are well understood and effects on animals are assumed to be equivalent. Plants would only be harmed if they were frozen by direct contact with cold CO2. Cold equipment or structures may fail causing direct physical harm, further releases of CO2 or a domino effect and the release of other substances.	Low	High	**medium**	The risk is not high because the UK has 50 years experience of operating a high pressure cross-country underground pipeline network carrying natural gas, with a good safety record. Much of that experience is directly applicable to operating a safe CO2 pipeline system. Any major loss of containment on a CO2 pipeline will be detected quickly and the pipeline will be shut down (typically within 5 to 15 minutes). The risk of harm will only exist until the pipeline has emptied and depressurised (typically 10 to 20 hours at a maximum). The risk of harm from the cooling effect of CO2 will only exist very close to the release point (typically tens of metres at a maximum). The risk of harm from elevated CO2 concentration will only exist close to, downwind and downhill of the release point (typically within a few hundred metres maximum).	ACTION: The Government, HSE and operators are currently funding research by HSL, academia and consultants to resolve the uncertainties of system parameters such as CO2 pipeline failure rates, release rates and dispersion rates. The research will lead to the development of pipeline design codes etc. which should enable CO2 pipeline systems to achieve a safety standard equivalent to that of the existing natural gas pipeline system. Action: HSE, EA and operators - during 2011 participate in the CO2RISKMAN project being organised by DNV consultants that will develop best practice guidance for management of CCS CO2 major accident safety and environmental risks. ACTION: Operators (and HSE and EA - as consultees on planning applications) ensure that selected pipeline routes minimise the potential exposure of people and sensitive habitats. Action: HSE regulate pipeline construction and operation etc under HASAWA.	Low at present , probably reducing to very low once design codes and safety distances have been established. Measures taken by HSE and operators to reduce the on-site and off-site risk to people will reduce the residual risk to the environment to "very low". No additional environmental risk management measures are likely to be required (this will be confirmed by EA participation in the CO2RISKMAN project).

Data and information				Judgement				Action	
Source (Hazard)	**Pathway**	**Receptor**	**Harm**	**Probability of exposure**	**Consequence**	**Magnitude of risk**	**Justification for magnitude**	**Risk management**	**Residual risk**
Small scale long term releases of carbon dioxide ocurring above ground e.g. fugitive releases from valves and pipework. CO2 would be present as gas phase and at ambient temperature or cool but not cold.	Releases inside poorly ventilated buildings could result in high CO2 concentrations accumulating throughout the building. Releases outdoors could only result in high CO2 concentrations close to the release point or accumulating in low points such as drainage pits and open trenches, especially under calm weather conditions.	Local human population and animals.	Any type of harm to the health of humans and animals from increased CO2 concentration. Human risks are asphyxiation at high concentrations and physiological effects at lower concentrations. Effects on humans are well understood and effects on animals are assumed to be equivalent. Plants will not be harmed.	Medium	Medium	**Medium**	Risk to humans will be medium x medium = medium if they are close to the hazard, working inside buildings or in other enclosed spaces. The risk to humans and animals will be very low x medium = low if they are in open spaces and not close to the hazard (more than a few tens of metres from the release point).	ACTION: Operators will ensure that all valves and pipework are within the site boundary so these releases will only occur in a secure site with no public access. Hence risk to workers will be medium and risk to members of the public and animals will be low (though some animals might be present within the site boundary). ACTION: HSE - regulate under HSAWA to ensure that the risk to site workers is minimised.	Measures taken by HSE and operators to reduce the risk to site workers to "low" will reduce the residual risk to local residents and the environment to "very low". No additional environmental risk management measures are likely to be required (this will be confirmed by EA participation in the CO2RISKMAN project).
Small scale, long term releases of carbon dioxide occurring below ground e.g. fugitive releases from pipework. CO2 would be present as gas phase and at ambient temperature or cool but not cold.	The CO2 concentration would build up in the soil, displacing oxygen, and this CO2 zone would grow outwards from the release point. CO2 could accumulate in low points such as drainage pits, open trenches and ditches, particularly during calm weather conditions. If the zone extended to nearby properties then CO2 could accumulate in cellars.	Local human population, animals and plants.	Any type of harm to the health of humans and animals from increased CO2 concentration. Human risks are asphyxiation at high concentrations and physiological effects at lower concentrations. Effects on humans are well understood and effects on animals are assumed to be equivalent. Animals living below ground and vegetation within the affected zone could be asphyxiated because the leaking CO2 will displace oxygen from the soil.	Very low	Medium	**Low**	These releases could occur in open countryside accessible to the public and where animals are permanently present. The risk to humans and animals living above ground will be very low x medium = low because harm will only occur if the CO2 accumulates in an underground enclosed space e.g. cellars of houses, excavation trenches, ditches etc. (Problems have ocurred in Italy with naturally ocurring CO2 releases in volcanic areas accumulating in cellars and in the UK with releases of landfill gas accumulating in cellars). The risk to animals living below ground and vegetation will be low x low = low because they may be affected before the leak is detected. Vegetation damage close to the pipeline will give an early indication of problems, especially during the summer months.	ACTION EA: Discuss with HSE and pipeline operators to establish if small scale underground leaks can occur, how soon they might be detected etc. This may result in the magnitiude of risk being reduced. ACTION: Operators (and HSE and EA - as consultees on planning applications) ensure that selected pipeline routes minimise the potential exposure of people and sensitive habitats (the CO2 zone in the soil will only occur close to the underground release point - typically a few tens of metres maximum). Action: HSE regulate pipeline construction and operation etc under HASAWA.	Low. Might be reduced to "very low" following discussions with HSE and pipeline operators.

Data and information				Judgement				Action	
Source (Hazard)	**Pathway**	**Receptor**	**Harm**	**Probability of exposure**	**Consequence**	**Magnitude of risk**	**Justification for magnitude**	**Risk management**	**Residual risk**
The selected pipeline route causes unavoidable damage to the environment during the construction of the pipeline	Direct physical damage to the protected habitat e.g trees felled	Any protected habitat (e.g Sites of Special Scientific Interest SSSIs). Any non-protected habitat.	Direct physical damage by vehicles, site clearance works and the digging of the pipeline trench	High	Medium	**High**	Risk is high because pipeline construction inevitably damages the soil and vegetation tens of metres either side of the pipeline.	ACTION: Operators (and HSE and EA - as consultees on planning applications) ensure that selected pipeline routes minimise the potential exposure of sensitive habitats and that damage is repaired e.g hedgerows are re-planted afterwards. Action: HSE regulate pipeline construction under HASAWA.	Low because protected habitats will be avoided and non-protected habitats will be re-instated. No new risk management measures are required.
Accidents during pipeline construction activities producing mud/silt run-off or leaks from the existing underground services (oil and gas pipelines, sewer pipes etc)	Direct spillage onto the ground polluting the soil and soaking into groundwater or run-off entering local watercourses	Animals and plants in the soil. Groundwater quality. Aquatic organisms (mammals, birds, fish, invertebrates, plants). Recreational users of surface waters.	Smothering or toxicity causing death of animals or plants in the soil. Oxygen depletion or toxicity causing death of aquatic organisms (mammals, birds, fish, invertebrates, plants). Loss of recreational use of watercourses. Closure of surface and ground water drinking intakes.	Medium	Low	**Medium**	Risk is medium because construction activities in open countryside are more difficult to control than on fixed sites such as power stations. Risk is not high because the effects of mud/silt run-off are likley to be localised.	ACTION: Operators (and their contractors) ensure that pipeline construction procedures reduce the pollution risks e.g. the workforce are aware of the location of existing pipelines. The EA has published pollution prevention guidance for construction activities. The operators have substantial recent experience of building cross-country natural gas pipelines which have similar risks e.g. in South Wales	Low. No new risk management measures are required.

5.6 Bulk storage and ship loading of carbon dioxide

Environmental Risk Assessment for Carbon Capture and Storage: CO_2 bulk storage and ship loading

Data and information				Judgement				Action	
Source (Hazard)	**Pathway**	**Receptor**	**Harm**	**Probability of exposure**	**Consequence**	**Magnitude of risk**	**Justification for magnitude**	**Risk management**	**Residual risk**
What is the agent or process with potential to cause harm?	**How might the receptor come into contact with the source?**	**What is at risk? What do I wish to protect?**	**What are the harmful consequences if things go wrong?**	**How likely is this contact?**	**How severe will the consequences be if this occurs?**	**What is the overall magnitude of the risk?**	**On what did I base my judgement?**	**How can I best manage the risk to reduce the magnitude?**	**What is the magnitude of the risk after management?**
Large scale, short term releases of carbon dioxide on or near the shore e.g. pipeline rupture or major loss of containment from storage tanks, pipework or ship (during loading). Dense phase CO_2 will partition into a gas cloud and "snow" which will then sublime to form more gas. Note: Release rate and quantities could be an order of magnitude higher for bulk storage compared to a pipeline.	Direct contact with cold CO_2 gas and "snow" close to release point. As the CO_2 is released it will be diluted by entraining large volumes of surrounding air followed by a more gradual dilution and dispersion. The gas cloud will be cold and denser than air so it could drift downwind and downhill and collect in any low points, particularly under calm weather conditions.	Local human population, animals and plants. Equipment and structures close to the release point may be damaged by extreme cold e.g. metal embrittlement leading to structural failure.	Any type of harm to the health of humans, animals and plants from cold gas or increased CO_2 concentration. Human toxicology is well understood and animal toxicology is assumed to be equivalent. Plants would only be harmed if they were frozen by direct contact with cold CO_2. Cold equipment or structures may fail causing direct physical harm, further releases of CO_2 or a domino effect and the release of other substances.	Low	High	**Medium**	The risk is not high because the UK has 50 years experience of operating bulk liquified gas storage facilities for liquified natural gas (LNG) and liquified petroleum gas (LPG), with a good safety record. Much of that experience is directly applicable to operating a safe CO_2 bulk storage system. The COMAH regulations may be amended to include CO_2 and it is assumed that a storage and ship loading facility would store more than the top tier quantity. Consequence is high because humans located off-site could be harmed which is why it would be COMAH top tier.	ACTION: Government, HSE and operators. There are currently no proposals to build bulk CO_2 storage facilities in the UK, but if proposals come forward the research currently being undertaken on pipelines would have to be extended to cover bulk CO_2 storage with the aim of achieving a safety standard equivalent to that of the existing LNG and LPG storage systems. Action: HSE, EA and operators - during 2011 participate in the CO2RISKMAN project being organised by DNV consultants that will develop best practice guidance for management of CCS CO_2 major accident safety and environmental risks. ACTION: Operators (and HSE and EA - as consultees on planning applications) ensure that the locations of bulk CO_2 storage facilities minimise the potential exposure of people and sensitive habitats. Action: HSE regulate bulk CO_2 storage construction and operation etc under HASAWA (or jointly with EA if COMAH applies).	Medium at present, probably reducing to low once design codes have been established and major accident hazards evaluated. Measures taken by HSE and operators to reduce the on-site and off-site risk to people "low" will reduce the residual risk to the environment to "very low". No additional environmental risk management measures are likely to be required (this will be confirmed by EA participation in the CO2RISKMAN project).

Data and information				Judgement				Action	
Source (Hazard)	Pathway	Receptor	Harm	Probability of exposure	Consequence	Magnitude of risk	Justification for magnitude	Risk management	Residual risk
Small scale long term releases of carbon dioxide ocurring above ground e.g. fugitive releases from valves and pipework. CO2 would be present as gas phase and at ambient temperature or cool but not cold.	Releases inside poorly ventilated buildings could result in high CO2 concentrations accumulating throughout the building. Releases outdoors could only result in high CO2 concentrations close to the release point or accumulating in low points such as drainage pits and open trenches, especially under calm weather conditions.	Local human population and animals	Any type of harm to the health of humans and animals from increased CO2 concentration. Human risks are asphyxiation at high concentrations and physiological effects at lower concentrations. Effects on humans are well understood and effects on animals are assumed to be equivalent. Plants will not be harmed.	Medium	Medium	**medium**	Risk to humans will be medium x medium = medium if they are close to the hazard, working inside buildings or in other enclosed spaces. The risk to humans and animals will be very low x medium = low if they are in open spaces and not close to the hazard (more than a few tens of metres from the release point).	ACTION: Operators will ensure that all valves and pipework are within the site boundary so these releases will only occur in a secure site with no public access. Hence risk to workers will be medium and risk to members of the public and animals will be low (though some animals might be present within the site boundary). ACTION: HSE - regulate under HSAWA to ensure that the risk to site workers is minimised.	Measures taken by HSE and operators to reduce the risk to site workers to "low" will reduce the residual risk to local residents and the environment to "very low". No additional environmental risk management measures are likely to be required (this will be confirmed by EA participation in the CO2RISKMAN project).

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List of abbreviations

CCS - Carbon capture and storage

CO2 - carbon dioxide

COMAH - Control of Major Accident Hazards regulations 1999

EA - Environment Agency

EAL - Environmental Action Level

EPR - Environmental Permitting Regulations

ERA - Environmental Risk Assessment

ETP - Effluent Treatment plant

HASAWA - Health and Safety at Work Act

HSE - Health and Safety Executive

HSL - Health and Safety Laboratory

LCA - life cycle assessment

NGO - Non-Governmental Organisation

OEL - Occupational Exposure Level

PS - Power station

PSR - Pipeline Safety Regulations

SEPA - Scottish Environment Protection Agency

UKCIP02 - United Kingdom Climate Impacts Programme 2002

UKCIP09 - United Kingdom Climate Impacts Programme 2009

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