AN ENVIRONMENTAL RISK ASSESSMENT FOR CARBON CAPTURE AND STORAGE†

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The UK government believes that carbon capture and storage (CCS) has the potential to be an important technology in climate change mitigation. The Department of Energy and Climate Change (DECC) is supporting a programme of four commercial scale demonstration plants 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 Environment Agency (EA) regulates the operation of fossil fuel power stations in England and Wales under the Environmental Permitting Regulations. It will issue permits for the operation of CCS equipment at power stations to ensure the protection of the environment and gather data on the performance of CCS technology.

The Environment Agency has produced a qualitative environmental risk assessment (ERA) for CCS that provides a high level screening of the key regulatory issues that fall within its remit. It uses a classic source → pathway → receptor model, screens and ranks the risks as high/medium/low/very low and describes how the risks will be reduced to an acceptable level. These risk management measures will form the basis of the EA's action plan for regulating CCS technology up to 2020. 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 detailed site-specific ERA as part of their application for an environmental permit.

The EA has published the ERA on its website to inform the public debate on CCS and demonstrate openness and transparency in its work as an environmental regulator.

KEYWORDS: carbon capture and storage, CCS, environmental risk assessment, ERA

IMPLEMENTATION OF CCS TECHNOLOGY IN THE UK

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

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

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. It also created a legislative basis in the UK for permitting the offshore storage of carbon dioxide.
- In April 2009 the Government introduced a policy requiring any new fossil fuel power station to be built "carbon capture ready". They 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 the Government published "A framework for the development of clean coal" (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 October 2010 the Government spending review confirmed funding of up to £1bn for the first demonstration project. RWE npower at Tilbury in Essex had withdrawn 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 2-4 will be made following a consultation on electricity market reform. They confirmed that the competition for projects 2-4 will 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 contains proposals to encourage investment in low-carbon technologies including CCS.

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 being 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) & (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 whether to go ahead with full scale implementation of CCS on UK fossil-fuel power stations from 2020 onwards.

A key feature of the Government's CCS programme is the staged implementation, starting with university research, moving on to pilot plants and then demonstration plants, before making a decision on full scale implementation, the information gathered at each stage being used to improve the design of the next stage. This staged approach with a scale-up at each stage is the classic chemical engineering technique for reducing project risks when developing new products and technologies. There is every reason to believe that this tried and tested approach will work well in the development of CCS technology. Staged implementation also provides a mechanism for controlling the environmental risks associated with CCS and the benefit of this approach emerges clearly in the ERA.

THE SCOPE OF THE ERA

The scope is restricted to the regulatory remit of the Environment Agency, so it covers environmental risks, onshore, in England and Wales. This includes environmental risks that occur outside power stations because they fall within the EA's wider responsibilities. For example the construction and operation of cross-country carbon dioxide pipelines and bulk storage/ship loading facilities. Defining the scope has highlighted the interactions between the EA and the other CCS regulators:

- The EA has 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 the EA has 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.)
- The EA and the Health and Safety Executive (HSE) are joint regulators 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 the EA is not required to issue a permit to control the environmental risks e.g. carbon dioxide pipelines. In 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. Hence there are no further environmental risk management measures required and the EA will leave HSE to regulate these risks. This will avoid duplication of effort by the regulators and possible confusion for operators. The EA has discussed these risks with HSE who have confirmed that this approach is valid.
- The environmental aspects of carbon dioxide transport and storage offshore will 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.

REASONS FOR PRODUCING THE ERA

The conventional approach to regulating the environmental risks from power stations is for the EA to use the Environmental Permitting Regulations (EPR) to implement the requirements of the EC Integrated Pollution Prevention and Control (IPPC) directive:

- The IPPC directive 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, specifying equipment, emission limits and operational techniques etc. 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.
- 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. The EA assesses the information provided and decides whether to refuse the application or issue a permit including conditions to ensure the protection of the environment, such as emission limits and monitoring requirements etc. The EA subsequently carries 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 conventional 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 the EA needs to start assessing the environmental impacts in advance so that it 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, the EA decided to produce its own generic ERA for CCS. This 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 the EA's action plan for regulating onshore CCS technology up to 2020. Operators 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 the EA will determine the applications in the usual way. The work done on the generic ERA should enable the EPR applications to be determined more quickly and efficiently.

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

REASONS FOR PUBLISHING THE ERA

The EA could have produced the ERA as an internal document and used it to plan its own CCS work programme. However it believes there are a number of advantages to publishing the ERA on its website:

- It will be useful to the government and other CCS regulators because it clarifies the position of, and their interaction with, the EA.
- It will be useful to CCS plant operators and equipment suppliers because they can see how the risks associated with their technology are being addressed by the EA. 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 the EA is operating in an open and transparent manner as it prepares to carry out its 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. The EA has a great deal of experience dealing with the 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 the EA carries out a public consultation on the EPR application.
- It will also increase public confidence in the regulatory process if risk information is published voluntarily by the regulator, rather than having to be obtained by pressure groups using Freedom of Information requests.

THE STRUCTURE OF THE ERA

The structure of the ERA is based on an existing EA template using an excel spreadsheet (see Figure 1). It uses a classic source → pathway → receptor model and evaluates the risks as high/medium/low/very low. It 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 the EA's 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 ERA consists of six separate excel worksheets covering:

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

FINDINGS OF THE ERA

The complete ERA can be viewed on the Environment Agency website at www.environment-agency.gov.uk/carboncapture. A selection of the findings are listed below, with some additional description and comment:

- **Regulatory controls of CCS activities.** All of the risks that have been identified can be controlled using the EA's existing regulatory powers. Hence there is no need for additional environmental regulations to cover CCS activities.
- **CCS technologies.** If CCS involved the use of new technologies it would be difficult 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 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. There are concerns about the large quantities of amines that might 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.
- **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. The ERA identifies that the operators 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 may be large enough to cause significant pollution. These concerns have been raised in reports published by several different bodies including the Norwegian Institute for Air Research (NILU, 2010). The concentration of amines released will be low, but the volumes of flue gas being treated and released will be very large so the annual mass releases may be significant. Amine releases could be eliminated by using amine-free capture technologies such as pre-combustion or oxy-fuel combustion. If amines are used, the main risk management measure will be to utilise the staged implementation of CCS to reduce the releases. The amine releases from the pilot plants will be monitored and the data used to improve the design of the demonstration plants. Similarly the amine releases from the demonstration plants will be monitored and the data used to improve the design of the full scale CCS plants. This might involve using abatement technology to reduce the total amine releases or using different types of amines that are less volatile and less harmful.
- **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. The EA will ensure that the power station operators address the waste disposal issue and ensure that there is sufficient UK disposal capacity so that waste is not stockpiled. The EA has a particular interest in this issue because it regulates all hazardous waste disposal facilities.
- **Cooling water demand.** CCS equipment is likely to significantly increase the cooling requirements at

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 CO_2 absorbents – principally volatile amines released continuously from the CO_2 scrubber	Directly by air transport then inhalation or skin contact. Indirectly by air transport and deposition on plants eaten by animals and people	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 amines have been used for many years on an industrial scale in CO_2 absorbent systems e.g. in oil and gas refining.	Action: EA – use EPR to ensure operators minimise releases, substitute less harmful chemicals, set emission limits and environmental monitoring requirements etc.	Low for pilot plant trials – the releases will be small because the plants are small. Low for demonstration plants provided the operators use the information obtained from pilot plants.
Increased pollution caused by disposal of waste proprietary CO_2 absorbents – principally amines	Release of pollutants to air, water and land from transport accidents, storage at transfer stations and disposal sites.	People, animals and plants near transport routes, storage & disposal sites.	Any harm to the health of humans, animals and plants	Medium	Medium	Medium	Risk is medium rather than high because the chemicals are already used in the UK in industrial quantities with established disposal routes regulated by the EA	ACTION: EA – use EPR to obtain data on waste types and quantities. Review existing UK disposal techniques and capacity for these wastes and publish results.	Low provided that UK disposal capacity is sufficient to avoid stockpiling of such wastes.
Increased fresh water demand for evaporative cooling.	Abstraction from surface waters or groundwater	Water resources – surface water flows and groundwater levels. Aquatic ecosystems	Less fresh water available for other users – people, industry, agriculture and wildlife	High	High	High	Risk will be high unless there is surplus local water both now and in the future (accounting for climate change effects on river flows, agricultural demand etc).	Action: Operators – assess water demands of process cooling options in EPR applications. Action: EA use computer models to predict future water resources	Low for demonstration plants. Medium for full scale CCS and new power stations – which may have to use air cooling or select coastal locations and sea water cooling.

Figure 1. Example sheet from the Environmental Risk Assessment – post combustion capture of carbon dioxide using amines

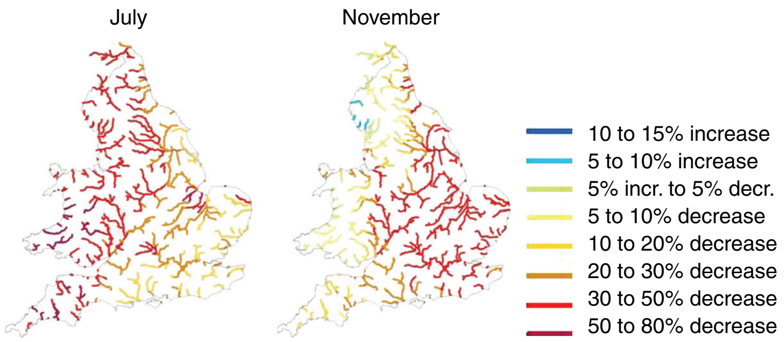

Figure 2. Percentage change in mean monthly river flows between now and 2050s using the medium-high UKCIP02 scenario. From Environment Agency science summary SC0700779/SS1

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. The EA is responsible for water resources and has developed computer models to forecast the effects of climate change on river water flows. These show that rivers in Wales, northern and western England will have low flows in 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). The EA 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. The computer model will also be developed so it can be used to assess the impact of any proposed new power stations.

- **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. Hence there are no further environmental risk management measures required and the EA will leave HSE to regulate these risks. EA involvement will be limited to a few specific issues, e.g. using its role as a statutory consultee on planning applications to check that as far as practicable, pipeline routes avoid sensitive and protected habitats.

PUBLICATION AND FUTURE DEVELOPMENT OF THE ERA

The Environment Agency published the ERA on its website at www.environment-agency.gov.uk in April 2011 to coincide with the presentation of this paper at the Hazards XXII symposium organised by the Institution of Chemical Engineers in Liverpool, UK. The EA believes that publication of the ERA will help to inform public debate on the risks associated with the development of CCS technology and will also demonstrate that it is performing its role in protecting the environment.

Comments on the ERA are welcomed and a dedicated email address has been set up to receive comments at carboncapture@environment-agency.gov.uk.

The EA expects to update the ERA to describe progress on implementing the risk management measures. If any significant new risks emerge in the next few years they will be added to future versions of the ERA.

CONCLUSIONS

The Environment Agency has found producing an ERA to be a useful exercise, bringing together its own knowledge and expertise in a systematic manner. The ERA has clarified the role of the EA vis-à-vis 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 the EA's action plan to regulate CCS technology from 2010 to 2020.

The EA believes 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. The EA therefore expects to be able to issue environmental permits for all the proposed CCS technologies. 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 the operation of pilot plants and demonstration plants.

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