GLOBAL CCS INSTITUTE SUBMISSION TO:

THE EUROPEAN COMMISSION'S EVALUATION PROCESS OF THE DIRECTIVE ON THE GEOLOGICAL STORAGE OF CARBON DIOXIDE

DIRECTIVE 2009/31/EC

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EXECUTIVE SUMMARY

This submission by the Global Carbon Capture and Storage Institute (the Institute) is in response to the European Commission's (EC) request for stakeholders to participate in the review of the application of the EU Directive 2009/31/EC (CCS Directive) on the geological storage of CO_2 and to provide an assessment of the state of CCS deployment and enabling policy in Europe.

The main observations of the Institute are as follows:

Evaluation of Directive 2009/31/EC

- The Institute recognises the importance of the CCS Directive and affirms the importance of legal and regulatory frameworks for ensuring project deployment.
- The Institute believes that a detailed assessment of the CCS Directive, of the nature proposed under the Directive, is premature at this point in time. The Institute makes this statement on the basis that there has been insufficient experience of the full spectrum of the Directive's provisions by European projects to date.
- The Institute does, however, consider that early European CCS demonstration projects offer important project-level perspectives of national regulatory models and the overarching European regime that may be pertinent to the review. These are most evident in issues arising from post-closure stewardship (transfer of responsibilities, liabilities). Addressing these issues in a manner that accommodates the risk profiles of governments and first mover project developers is critical to ensure the progression of CCS in Europe.

The status of CCS deployment and enabling policies

- Achieving decarbonisation at least cost is a challenge to be met by a number of clean energy solutions, including the use of fossil fuels and biomass with CCS. Over the past year, a substantial (and growing) number of independent studies and reports by government and industry bodies has reinforced these points.
- There are now 22 large-scale CCS projects in operation or under construction, a more than 50 per cent increase since 2011. This is a practical sign of the growing confidence in the application of CCS technologies.
- There has been significant progress in the United States, Canada and, more recently, China. Importantly, three large-scale CCS projects in the power sector are now in construction in North America – one of them, the Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project in Canada, is very close to reaching operational status. A number of projects in China may be in a position to take a final investment decision in 2014 or soon thereafter.
- In contrast, Europe has lost its position as a leader in developing large-scale CCS projects that it aspired to several years ago. Despite earlier high expectations and considerable advances in many areas, no new large-scale CCS projects have entered the Execute (or construction) stage in Europe in well over a decade.
- The ROAD Project in the Netherlands is one of the world's most advanced CCS projects in the power sector and is ready to take a positive final investment decision if additional funding can be secured. As such, the ROAD Project is of vital importance to CCS progress in Europe. The Peterhead CCS Project and the White Rose CCS Project have both progressed into the Define stage over the past six to nine months as CCS efforts are being re-energised in the United Kingdom.

- Policy efforts to accelerate the momentum of CCS projects in Europe must address the following issues:
    - Strong, sustainable technology-neutral emissions reduction policies to support longer-term deployment – this is critical to reduce uncertainty and provide the longer-term predictability required by project developers.
    - Strengthened incentive mechanisms to support the immediate demonstration effort – in the short term, financial support measures are needed that enable robust projects to progress faster through the development pipeline and enter construction. First mover projects incur higher risks and upfront costs than later projects; appropriate recognition of this should be taken into consideration in the framing of financial and policy support.
    - It is important that the benefits and value of CCS are continually asserted and that CCS is not disadvantaged in relation to other low-carbon technologies in policy considerations and government support.

CCS technology progress

- Knowledge in relation to the technical feasibility and performance of CCS technologies has been enhanced in recent years thanks to various activities around the world. Most European countries have been developing significant knowledge by means of pilot test projects and R&D efforts.
- The (growing) confidence that the technical challenges of integrating CCS technologies at large-scale in power and industrial application will be overcome with time is evidenced by the three large-scale CCS projects in the power sector now in construction (with two near operation) with a number of other project developers close to making a final investment decision, subject to securing financial support.
- Prospects for future cost reductions are significant, underpinned in Europe (and globally) by the interplay of lessons learnt from the first mover projects, continued strong funding for CCS R&D and collaborative approaches to knowledge sharing.
- Europe can create a positive pathway for CCS demonstration by advancing plans for storage site selection and encouraging linked transportation and storage solutions that reduce project costs and timelines.

A successful demonstration program in Europe is vital to establish a positive perception of CCS as an environmentally friendly technology and reinforce the important role of CCS in reducing global CO_2 emissions. It will build confidence by showing the technology in action, and through practical learnings from projects in operation combined with advances in CCS technologies, bring down costs.

INTRODUCTION

The Institute considers CCS is an integral part of a low-carbon future and champions CCS as a vital, safe and clean technology. CCS is one of a suite of technologies required to reduce greenhouse gas emissions from power generation and industrial sources.

The mission of the Institute is to accelerate the development, demonstration and deployment of CCS globally through our knowledge sharing activities, fact-based influential advice and advocacy, and work to create favourable conditions to implement CCS.

An important aspect of the Institute's effort to enable regional and local expertise on CCS is the management of the European CCS Demonstration Project Network. The Network provides a platform for project developers to learn from each other and address issues in the development of demonstration projects. Given experience with the Network and the regional and global activities undertaken by the Institute across the full spectrum of CCS activities, the Institute is well positioned to offer informed views to this review.

The Institute has contributed to the first phase of the stakeholder consultation process for the review of the CCS Directive, providing feedback through the online questionnaire[1].

The purpose of this document is to complement the Institute's feedback provided through the online questionnaire. In doing so, this document is structured into sections which link closely to the main purposes of the review:

- observations on specific aspects on the application of the CCS Directive
- observations on the status of CCS deployment and enabling policies in Europe
- observations on progress on the technical performance and cost of CCS technologies since the implementation of the CCS Directive.

EVALUATION OF DIRECTIVE 2009/31/EC (CCS DIRECTIVE)

This section provides the Institute's review observations on the application of the CCS Directive.

The Institute acknowledges the review provision contained in Article 38 of the CCS Directive, which requires the EC to review the application of the CCS Directive. The EC has a deadline of 31 March 2015 to submit the next Implementation Report to the European Parliament (EP) and to the Council as a review report on the implementation of the CCS Directive.

The objectives of the review of the CCS Directive are to assess the effectiveness, efficiency, ease of application and legal practicality of several of the CCS Directive provisions, as well as to consider the legislation's interaction with the wider European enabling policy framework for the technology.

The EU Directive establishes one of the world's first examples of CCS-specific legislation and provides the foundation for the legal and regulatory approach to the technology in the EU and its Member States. As such, the Institute welcomes this timely opportunity to reflect upon the CCS Community's early experience of the European regulatory model, particularly in light of the Member States' implementation of the Directive and the permitting experience garnered by Europe's early demonstration projects.

[1] http://www.ccs-directive-evaluation.eu/online-questionnaire/

It is the opinion of the Institute, however, that a detailed assessment of the Directive is premature at this time. The Institute makes this statement because there has been insufficient experience of the full spectrum of the Directive's provisions by European projects to date. Notwithstanding this position, the Institute believes that early project-level perspectives of national regulatory models and the overarching European regime, do offer important lessons pertinent to this review.

The Institute's engagement with European projects to date, through its research and support activities[2], as well as via knowledge sharing and international collaboration platforms[3], has revealed several regulatory issues which continue to impact upon project deployment in the EU. The following items have been highlighted by European projects in recent fora and publications.

- **Permitting considerations**

European demonstration projects have stressed the importance of flexibility in the permitting requirements for a project. An adaptive approach to permitting will lower particular barriers to the technology's deployment, and avoid burdening projects with unnecessary requirements. A study commissioned by the Institute in 2013, which examined the permitting experiences of early CCS demonstration projects under the Directive, observed that in some instances:

"Projects may be caught in a vicious circle as financing decisions depend upon projects securing all permits, while obtaining the permits may require a great deal of detail for which developers should allocate significant resources without the certainty of securing those permits"[4]

A further example, offered by the ROAD project[5], is the interaction between an application for a storage permit and the taking of a final investment decision. The project believed that the requirements and sequencing for a storage permit application, in accordance with Dutch law and the Directive, conflicted with the process for taking the FID. However, the regulator adopted a flexible approach in this instance, working in collaboration with the project, to provide a solution which was acceptable to all parties, including the EC. Such a flexible approach to permitting, in accordance with the Directive, would ideally continue to operate under other national regulatory models.

- **Transfer of liability**

The post-closure transfer of liabilities is also highlighted by early projects as an issue which requires further attention and clarification in the Directive. Early demonstration projects have expressed concern that there is a lack of clarity surrounding the criteria, which will enable a transfer of liability from the project to the competent authority post-closure.

A further issue raised in relation to transfer is the 20 year 'minimum period' provision contained in Article 18 and corresponding national frameworks. Several projects have highlighted this timeframe as an issue of concern, with some expressing unease that the criteria for enabling a transfer may change in such an extended timeframe.

- **Financial security**

Concern has also been voiced by projects in relation to the financial security requirements set out in Article 19 of the Directive. Financial security is required under the Directive to ensure that all permit obligations, closure and post-closure requirements and commitments arising from a storage site's inclusion under the EU Emissions Trading Directive, may be met by an Operator.

[2] The Global Status of CCS: February 2014 report; The Global Status of CCS: 2013 report; The Experience of CCS Demonstration Projects in the European Union with the Transposition of the CCS Directive, Global CCS Institute, October 2013; Permitting Process: Special Report on Getting a CCS Project Permitted, Maasvlakte Project C.V., Global CCS Institute, January 2013.

[3] For example the International CCS Test Centre Network, the International Organization for Standardization (ISO) Technical Committee (ISO/TC265), the European CCS Demonstration Project Network.

[4] The Experience of CCS Demonstration Projects in the European Union with the Transposition of the CCS Directive, Global CCS Institute, October 2013, at page 7.

[5] Permitting Process: Special Report on Getting a CCS Project Permitted, Maasvlakte Project C.V., Global CCS Institute, January 2013.

The Institute's 2013 commissioned report[6] observed that for a number of CCS demonstration projects, there remained significant concern in relation to the method of calculating the necessary financial security required under the Directive. In particular, projects expressed concern as to the considerable uncertainties surrounding the price of EU emissions allowances (EUAs) over a project's lifecycle, and how this uncertainty is to be addressed in determining appropriate levels of financial security.

- **Financial mechanism**

A further issue, emphasised by early demonstration projects, concerns the financial mechanism provisions in Article 20 of the Directive. In this instance, projects have expressed concern that the Directive's provisions may have the effect of limiting the transfer of responsibilities from the Operator to the competent authority.

THE STATUS OF CCS AND ENABLING POLICIES

This section provides some high level observations on the status of CCS and notes a renewed emphasis on policy and regulatory challenges can act as a stimulus to momentum in the development/deployment of CCS in Europe.

Growing confidence in application of CCS technologies at large scale

In recent publications and presentations the Institute has emphasised that the urgency for action to reduce CO_2 emissions continues to grow as each year passes. Achieving decarbonisation at least cost is a challenge to be met by a number of clean energy solutions, including the use of fossil fuels and biomass with CCS. Over the past year, a substantial (and growing) number of independent studies and reports by government and industry bodies has reinforced these points[7].

CCS is often mis-perceived as an unproven or experimental technology. In reality, the technology is generally well understood and has been used for decades at a large scale in certain applications. For example:

- large-scale separation of CO_2 is undertaken as a matter of routine in gas processing and industrial processes that produce high-purity CO_2
- CO_2 pipelines are an established technology, and
- large-scale injection and geological storage of CO_2 has been securely performed in saline reservoirs for more than 15 years and in oil and gas reservoirs for decades.

The key technical challenge for widespread CCS deployment is the integration of component technologies into large-scale projects in applications such as power generation and additional industrial processes. As this decade has progressed and the lessons from accumulated laboratory and project studies and experiences have become assimilated, there is growing confidence that the technical challenges of integrating CCS at large scale in these new applications will be overcome with time. Indeed, as noted below, the application of CCS to the power sector and additional industrial processes has started to happen and this momentum needs to be both nurtured and enhanced.

The global status of large-scale CCS projects

There are now 12 large-scale CCS projects in operation globally with ten under construction. Three of the ten are CCS projects in the power sector. There are also about six projects at an advanced stage of

[6] The Experience of CCS Demonstration Projects in the European Union with the Transposition of the CCS Directive, Global CCS Institute, October 2013

[7] See for example, Global CCS Institute, The Global Status of CCS: February 2014

development planning that may make a final investment decision over the course of 2014, though only one is in Europe (the ROAD Project in the Netherlands). The 22 projects in operation or under construction represents a more than 50 per cent increase since 2011, a practical sign of the growing confidence in the application of CCS technology at large-scale. The total CO_2 capture capacity of these 22 projects is around 40 million tonnes per annum.

Notwithstanding the significant progress in large-scale CCS projects in recent years, the momentum for further development and widespread deployment must be increased if CCS is to effectively contribute to climate change mitigation (as part of a broad portfolio of measures) and provide energy security. Successful demonstration of large-scale projects will build confidence by showing the technology in action, and through innovation combined with advances in capture technology, bring down costs.

Number of large-scale integrated projects by lifecycle stage

	Operate		Execute		Define	
	2014	**2011**	**2014**	**2011**	**2014**	**2011**
Europe	2	2	0	0	4	9
North America	8	5	7	5	7	13
Rest of world	2	1	3	1	4	2

CCS in North America

North America is leading in the implementation of large-scale CCS projects and China is quickly increasing in importance. The first large-scale CCS projects in the power sector – the Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project in Canada and the Kemper County Energy Facility Project in the United States – are nearing operational status. Boundary Dam's operational status is imminent while Kemper will start capturing CO_2 in 2015. Another, the Petra Nova Carbon Capture Project in Texas, has just entered construction and is anticipated to be operational by the end of 2016. These projects are of global importance in the development of CCS.

CCS in China

In China, there are two projects – the Yanchang Integrated Carbon Capture and Storage Demonstration Project and the Sinopec Qilu Petrochemical CCS Project – that may be in a position to make a final investment decision in 2014. In the Middle East, the world's first large-scale CCS project in the iron and steel sector (the Abu Dhabi CCS Project) has progressed into the construction phase.

CCS in Europe

Europe has lost its position as a leader in developing large-scale CCS projects that it aspired to several years ago, though the importance of CCS technologies at large scale and continued robust R&D efforts have been recognised a by a number of European bodies in recent months[8]. Despite earlier high expectations and considerable advances in many areas, no new large-scale CCS projects have entered the Execute (or construction) stage in Europe in well over a decade. Efforts are being re-energised in the United Kingdom (with both the Peterhead CCS Project and the White Rose CCS Project having progressed into the Define stage – the latter having received in July 2014 a funding award decision of up to Euro 300 million under the European NER300 programme) though prospective start dates are now around 2020. The ROAD project in the Netherlands is the most advanced project in Europe in development planning and is ready to take a positive final investment decision if additional funding can be secured. Therefore, the ROAD project is of vital importance to CCS progress in Europe.

[8] See Annex 1 for listing of large-scale integrated projects in Europe as of end July 2014

Renewed focus upon policy and regulatory challenges is critical

Policy and regulatory efforts to accelerate the momentum of CCS projects (globally and in Europe) must address the following issues:

Strong, sustainable emissions reduction policies to support longer-term deployment

Surveys of project proponents strongly highlight that there is too much policy uncertainty to support a business case for large-scale CCS projects. CCS projects have large capital costs and long development times. Investors require long-term predictability if they are to invest in CCS.

Strong and clear emission reduction policies that are technology neutral and encourage CCS and other low-carbon technologies are urgently needed and necessary for longer-term deployment. Continued uncertainty about the timing, manner, extent and durability of such policies is stalling development of CCS.

Strengthened incentive mechanisms to support the immediate demonstration effort

The Institute has previously highlighted that since 2009 funding support for CCS globally has fallen by more than US$7 billion from earlier commitments.[9] This reflected either changing government priorities or, as in the case of the EU Emissions Trading Scheme (ETS), a strong reliance on carbon price support that has subsequently collapsed. In the short term, therefore, financial support measures are needed that enable 'robust' projects to progress faster through the development pipeline and enter construction.

An extensive analysis of possible mechanisms to support long-term predictability and short-term funding commitments is provided in the Institute's submission to the European Commission's Consultative Communication on the Future of Carbon Capture and Storage in Europe[10]. This submission included recommendations to (a) identify a suite of CCS projects and quantum of funding necessary to support such program (above and beyond the support presently provided by the EU ETS), and (b) improve the design and operation of the EU ETS by drawing upon past experiences and lessons learnt from other market-based emission reduction schemes.

A broad, successful demonstration program in Europe is especially vital to establish a positive perception of CCS as an environmentally friendly technology and cement the important role of CCS in reducing global CO_2 emissions. First mover projects incur higher risks and upfront costs than later projects; appropriate recognition of this should be taken into consideration in the framing of financial and policy support for 'first movers'.

It is important that the benefits and value of CCS are continually asserted and that CCS is not disadvantaged in relation to other low-carbon technologies in policy considerations and government support.

Regulatory uncertainties still to be addressed

The European Union is among a core group of jurisdictions – Australia, Canada, and the United States – which may be defined as 'early movers' that have progressed the development and implementation of law and regulation for CCS. While these jurisdictions continue to remain at the forefront of legal and regulatory developments, many must address issues, discussed earlier, arising from post-closure stewardship (transfer of responsibilities, liabilities) in a way that accommodates the risk profiles of

[9] The Global CCS Institute, the Global Status of CCS 2013: Summary Report, October 2013.

[10] The Global CCS Institute Submission to The European Commission's Consultative Communication on the Future of Carbon Capture and Storage in Europe, July 2013.

governments and first mover project developers. Activities to remove these issues are necessary to ensure the progression of CCS in Europe.

CCS TECHNOLOGY PROGRESS

This section provides an analysis on the technical and cost aspects of the individual CCS elements from both a global and European context.

Capture

Capture performance

Knowledge in relation to CO_2 capture technical feasibility and performance has been enhanced in recent years thanks to various activities around the world. Most European countries have been developing significant knowledge of capture technologies and related issues by means of pilot projects and R&D. Large-scale implementation of CCS is today technically possible with minor risk: conventional capture technologies (i.e. MEA post-combustion, oxyfuel, syngas separation) are commercially available and the risk of scaling-up can be managed and mitigated within a reasonable limit.

The confidence in technical feasibility is especially demonstrated through three large-scale CCS projects being in the Execute phase in the power sector (all in North America) with a number of other power or industrial projects being in a position to make a final investment decision during 2014 or soon thereafter.

While the implementation and validation of CO_2 capture technologies at large scale continues in other regions of the world, this is not the case in Europe, where no large-scale CCS demonstration projects have progressed into construction since the Snøhvit CO_2 Injection Project in the early 2000s.

In Europe, the ROAD Project, for example, has worked with the Institute to produce a series of reports showing that amine post-combustion maturity is ready for large-scale implementation in the power sector. These reports included:

- ROAD CCS non-confidential FEED study report: special report for the Global Carbon Capture and Storage Institute – November 2011
- Mitigating project risks: special report to the Global Carbon Capture and Storage Institute – December 2011
- Integration of capture plant and power plant, Rotterdam Opslag en Afvang Demonstratieproject: special report for the Global Carbon Capture and Storage Institute – December 2013
- Flow assurance & control philosophy: Rotterdam Opslag en Afvang Demonstratieproject. Special report for the Global Carbon Capture and Storage Institute – July 2013.

Compared to the power sector, progress in industrial CCS is slower and there are currently few demonstration projects at significant scale. The Institute has worked with the IEAGHG and the European Cement Association to evaluate the technical feasibility of CO_2 capture in the cement industry and pilot tests are currently ongoing at the Norcem cement plant in Brevik, (Norway) for various technologies. The European Steel Association (Eurofer) has produced a steel roadmap for a low-carbon Europe 2050[11] but no pilot or demonstration projects exist at the moment. For oil refineries, a number of tests have been done at the Technology Centre Mongstad (TCM) in Norway using Catalytic Cracker flue gas.

[11] Europe Steel Association, A Steel Roadmap for a Low Carbon Europe 2050, 2013

Capture costs

Knowledge of CCS capture costs has increased in recent years. The FEED study of the ROAD Project in the Netherlands for instance has shed light on the CAPEX and OPEX requirements for a post-combustion carbon capture plant[12]. Other large-scale projects in Europe that have not progressed into construction or are currently undertaking advanced engineering studies have generated (or will soon generate) similar cost estimations, with different levels of accuracy. Also, more generic work on CCS costs has produced useful knowledge, like the work of the IEAGHG [13] and the UK Cost Reduction Task Force[14]. Such studies have involved several industrial partners to define standard methods and define costs based on vendor's experience. However, the slow progress of large-scale projects under construction, especially in Europe, has resulted in a lack of real project cost information. With more projects in execution the knowledge on real costs would be significantly improved and it would be much easier to assess the potential for future cost reduction (as has been the recent experience with the Boundary Dam Project in Canada).

There is significant potential for cost reduction for CO_2 capture. Reduction of capture costs (and demonstration of the technical maturity of the technology) can be achieved by supporting the deployment of a wider 'portfolio' of projects across different sectors, locations and capture technologies. The pipeline of advanced / first-mover CCS projects is strongest outside Europe at present, as discussed in the previous section on the status of CCS. On present planning, a number of CCS projects in the power sector in Europe could be operational around 2020; the only CCS power project capable of an earlier operations date in Europe is the ROAD project.

Learnings from individual large-scale projects can bring significant cost reductions. For instance, SaskPower has indicated that should Boundary Dam be replicated, the CAPEX cost could be 30 per cent less[15]. With support for a 'portfolio' of projects, the current commercially available technologies (1st generation) would be demonstrated at commercial scales before 2030. These capture technologies may include, but are not limited to, post-combustion capture (MEA, DEA, MDEA), oxyfuel capture (ASU and cryogenic) and IGCC pre-combustion capture (physical solvents and chemical solvents).

Development of new technologies is also key to increase performance and to reduce costs. New materials (solvents, membranes, and adsorbents), optimised heat integration, new hybrid processes, and new equipment could all contribute to the cost reductions for capture processes of the future.

Transportation

Established technology

The technology for CO_2 pipelines is well established. Transport of CO_2 and other gases by pipeline, barge and truck is already a reality, occurring daily in many parts of the world. Carbon dioxide transportation infrastructure continues to be commissioned and built, particularly in North America. There is also experience, albeit limited, with transport of CO_2 using offshore pipelines in the Snøhvit project in Norway. The technical requirements and conditions for CO_2 transport by ship has improved recently and CO_2 pipelines and ships pose no higher risk than is already managed for transporting natural gas and oil.

In Europe, particularly in countries around the North Sea, the focus has recently changed from realising multiple sources of CO_2 collected and transported by a shared infrastructure system to getting individual

[12] ROAD CCS non-confidential FEED study report: special report for the Global Carbon Capture and Storage Institute
[13] IEAGHG, 2014. CO2 capture at coal based power and hydrogen plants, Report 2014/3, May 2014. UK
[14] UK Department of Energy & Climate Change. CCS Cost Reduction Task Force final report. May 2013.
[15] SaskPower, Sharing the Learning II, 2013,
http://www.saskpowerccs.com/symposium/presentations/5%20%20%20Mike%20Monea%20-%20Outro%20-%20May%20%2013%20v5%20-%20F%20I%20N%20A%20L%20%20.pdf

projects over the line. Therefore, success of projects such as the ROAD Project and advanced projects in the United Kingdom to reach the Execute stage, is key to rolling out initial investments in CO_2 infrastructure, reforging the vision of CO_2 networks and hubs.

Long-term requirements

According to a study commissioned by the Institute in 2013[16], for CCS to contribute to meeting the IEA 2DS, the estimated length of CO_2 transportation infrastructure to be built in the coming 30-40 years is 100 times larger than currently exists. The main challenge is to develop long-term strategies for CO_2 source clusters and pipeline network that optimise source to sink transport. The costs of CO_2 transportation differ from project to project due to factors such as expected volumes of CO_2 and the corresponding pipe diameters, cost of labour, and economic life of the infrastructure. One way to reduce this cost is to realise economies of scale by sharing of CO_2 transportation and storage infrastructure systems among several operators of separate CO_2-generating plants.

The premise that shared transport and storage infrastructure could lead to significant cost savings has been confirmed by a study, guided by a group of major emitters in the Netherlands and Belgium with advanced plans for CCS. The aim of the study[17], led by the Rotterdam Climate Initiative, was to develop a financial model to assess the economics of alternative CO_2 transport and storage options in the North Sea, based on common user infrastructure. It found that shared infrastructure development and use was much more beneficial than multiple 'point-to-point' solutions and that tariffs for CO_2 transport and storage for emitters in Rotterdam and Antwerp ranged from €5.6 to €20.2 per tonne of CO_2.

Storage

Storage performance

Research into geological storage of CO_2 has been ongoing for at least 25 years. Whilst laboratory and pilot-scale field studies continue to enhance understanding of fundamental processes and improve the capability of predictive modelling, more large-scale operational CCS projects would be beneficial to demonstrate that storage can be effectively implemented across a range of storage scenarios and geological settings, and provide real world data for calibration of modelling and monitoring technologies.

The existing Norwegian storage projects at Sleipner and Snøhvit have continued to provide learnings; however, the slow progress of new operational storage projects within Europe over the last five years has restricted improvements in understanding of technical feasibility and performance.

In contrast to Europe, several significant demonstration projects have commenced operations in North America in the past five years across a range of storage scenarios and geological settings, adding to the knowledge and experience from existing large scale CO_2 injection associated with enhanced oil recovery projects such as Weyburn-Midale in Canada, or Rangeley in the United States. In particular, the US Department of Energy's Regional Carbon Sequestration Program[18] has now a portfolio of injection projects which are providing the evidence base for continued refinement of best practice manuals covering much of the technical activity associated with storage operations. Similarly, the Weyburn and Midale oilfields have now permanently stored just under 30 Mt of anthropogenic CO_2, enabling the associated research project to publish a best practice manual and a wealth of technical papers[19].

[16] http://www.globalccsinstitute.com/publications/capacity-charging-mechanism-shared-co2-transportation-and-storage-infrastructure
[17] http://www.globalccsinstitute.com/node/102826
[18] http://energy.gov/fe/science-innovation/carbon-capture-and-storage-research/regional-partnerships
[19] http://www.sciencedirect.com/science/journal/17505836/16/supp/S1

Storage outlook

Looking forward, there are presently ten large-scale CCS projects in the Execute phase, with the Quest Project in Canada, the Gorgon Carbon Dioxide Injection Project in Australia and the Illinois Industrial Carbon Capture and Storage Project in the United States pursuing onshore deep saline storage. These projects will be operational in the 2015-16 period.

The most advanced large-scale CCS project in Europe at present, outside the existing Norwegian projects, is the ROAD Project in the Netherlands (depleted gas reservoir storage) which can take a final investment decision if financing can be secured. The anticipated operational date is around 2017. A number of UK CCS projects in the power sector that are exploring storage in depleted gas fields or deep saline aquifers have an operational date of around 2020. Based on the assumption that Europe will host a number of large-scale demonstration projects over the next decade, knowledge of storage performance in a European context should be greatly enhanced by 2030. Whilst theoretical, laboratory and pilot-scale field projects have provided significant scientific and technical learnings, large-scale projects are required to demonstrate that sufficient numbers of storage sites will be available across a variety of geological settings that can provide sufficient capacity, injectivity and containment for widespread commercial deployment.

Further data from a greater variety of real life large-scale storage scenarios in Europe is vital to prove the effectiveness of commercialised, widely deployed CCS and in establishing CCS as an important part of a lowest-cost CO_2 emissions reduction portfolio.

Storage costs

Storage costs are generally regarded as significantly lower than capture costs for most CCS scenarios, for example between 15 per cent and 30 per cent of total CCS project costs[20], subject to a variety of project-specific factors including capture technology and fuel type, transport distance and storage scenario.

Within Europe, some progress has been made on the assessment of storage costs, through generic studies and activities such as the review of full chain CCS costs jointly undertaken by the Zero Emissions Platform (ZEP)[21] and the IEAGHG in 2011, the CCS cost workshops organised by the IEA, and through specific CCS projects at planning stages.

The ZEP/IEAGHG project included a detailed assessment of likely costs for the most common European storage scenarios (deep saline aquifers and depleted oil and gas fields either onshore or offshore, but not including enhanced oil recovery). Some key conclusions were drawn by the study, which identified likely cost ranges in Euros/tonnes of CO_2 stored for different storage scenarios and site-specific factors which would be the main controlling factors on costs. For example, storage in offshore deep saline aquifers – the scenario with the greatest potential capacity in Europe – could range between €6-€20/tonne. The majority of technologies involved in assessing, operating and monitoring storage projects are based on existing technologies as utilised for example by the oil industry; therefore, uncertainty relating to storage costs tends to be more an issue of regulatory uncertainty.

Outside Europe, further assessment of storage costs has been obtained through a combination of generic studies and operational demonstration projects of varying sizes – new projects emerging during the last five years being mostly located in North America. The economics of storage associated with enhanced oil recovery are also not easy to ascertain because CO_2 purchase agreements are usually confidential.

[20] http://www.zeroemissionsplatform.org/library/publication/165-zep-cost-report-summary.html
[21] www.zeroemissionsplatform.org/library/publication/168-zep-cost-report-storage.html

On the assumption that Europe will host a number of large-scale CCS projects over the next decade, learnings from these projects should assist in reducing storage costs as knowledge/expertise is gained and regulators and other stakeholders share increasing confidence in the technology. Many factors affecting project storage costs will be site-specific though and storage costs may be dominated by well drilling, installation and operation, which might not necessarily be reduced with increased numbers of projects.

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Annex I

Large-scale CCS projects in Europe, end July 2014

Name	Country	Project Lifecycle Stage	Capture type	Transport type	Storage type	Industry
C.GEN North Killingholme Power Project	United Kingdom	Evaluate	Pre-combustion capture (gasification)	Pipeline (onshore to offshore)	Under evaluation	Power generation
Captain Clean Energy Project	United Kingdom	Evaluate	Pre-combustion capture (gasification)	Pipeline (onshore to offshore)	Dedicated Geological Storage – offshore deep saline formations	Power generation
Don Valley Power Project	United Kingdom	Define	Pre-combustion capture (gasification)	Pipeline (onshore to offshore)	Dedicated Geological Storage – offshore deep saline formations	Power generation
Peterhead CCS Project	United Kingdom	Define	Post-combustion capture	Pipeline (online to offshore)	Dedicated Geological Storage – offshore depleted gas reservoir	Power generation
ROAD	The Netherlands	Define	Post-combustion capture	Pipeline (onshore to offshore)	Dedicated Geological Storage – offshore depleted gas reservoir	Power generation
Sleipner CO_2 Injection	Norway	Operate	Pre-combustion capture (natural gas separation)	No transport required (direct injection)	Dedicated Geological Storage – offshore deep saline formations	Natural gas processing
Snøhvit CO_2 Injection	Norway	Operate	Pre-combustion capture (natural gas separation)	Pipeline (onshore to offshore)	Dedicated Geological Storage – offshore deep saline formations	Natural gas processing
White Rose CCS Project	United Kingdom	Define	Oxyfuel combustion capture	Pipeline (onshore to offshore)	Dedicated Geological Storage – offshore deep saline formations	Power generation