Technology Collaboration Programme
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Evaluating technology options to mitigate greenhouse gas emissions

IEAGHG Technical Review
2019-TR01
September 2019

Guide to Front End Engineering Design Studies for Selected CO_2 Capture and Storage Projects

IEA GREENHOUSE GAS R&D PROGRAMME

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'IEAGHG, "Guide to Front End Engineering Design Studies for Selected CO_2 Capture and Storage Projects, 2019-TR01, September, 2019.'

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Executive Summary

This Technical Review is a guide for locating key references of selected Front End Engineering (FEED) design studies for CO_2 Capture and Storage (CCS) projects. Its primary aim is to provide a convenient source of key references for these FEED studies with a specific focus on technical and cost information that are in the public domain. The guide also includes a brief summary of cost information for four high profile demonstration sites that have either been planned, or in one case built and operated. They include: Peterhead – Goldeneye; Quest, White Rose and Mountaineer. A brief commentary on the basis for the cost ranges presented, and the percentage variation applied in each example, is also covered. The derivation of cost estimates shows that there are differences in approach and levels of accuracy. If this information is important a direct approach to the lead developer is recommended.

The level of detail and availability of FEED studies varies considerably. Some documents are publically accessible and can be downloaded from internet websites, whereas other material is held by lead developers who would need to be approached. Table 1 lists major CCS projects where FEED studies are known to exist and relevant contact details.

Section 1. Introduction

This Technical Review is a guide for locating selected Front End Engineering (FEED) design studies for CO_2 Capture and Storage (CCS) projects. Its primary aim is to provide a convenient source of key references for FEED studies with a specific focus on technical and cost information for selected examples where information is publically available. The guide includes a summary table that incorporates web-site links to either references that include FEED information or links to contacts associated with specific projects. Most major CCS demonstration projects which have either reached a more detailed planning stage, or have advanced to an operational stage, are listed. Some of these projects did not proceed beyond a detailed design stage, but they are included because FEED information was produced and may have some relevance to future projects or may even be resurrected. The selected examples are European or North American plus two examples from Asia. This guide includes an appendix of all active CCS projects where FEED studies are known to have been undertaken subdivided by geographic region. There is also a list of CCS projects either planned or under development in the Peoples' Republic of China to highlight the extent of technological advances in that country.

There is a broad spectrum of reference material. Some documents are not only publically available but also relatively detailed. Other documents contain only limited detail on technical and cost information; whilst some other material has not been published although specific documents are referred to. Contact details are provided to enable further enquiries to be made (see Section 2).

Some high profile projects have led to the release of information into the public domain which can provided an insight into the level of detailed information that can be extracted from FEEDs. This guide includes a brief commentary on this reference material particularly the basis for the cost range and percentage variation of each example. The selection of FEED examples highlights both the extent of detail applied in each study and subsequently published. The references used in this guide are all from public domain sources.

The guide includes a brief summary of cost information for each high profile project where this information is publically available. This information has been included in this guide to highlight the contrasts in estimated cost ranges which are discussed in Section 3. The following examples are covered in this guide

Peterhead – Goldeneye	Shell	(Appendix 1)
Quest	Shell	(Appendix 2)
White Rose	National Grid	(Appendix 3)
Mountaineer	American Electric Power	(Appendix 4)

Section 2. Key References

Table 1 provides details of major CCS demonstration projects which have recognised web-site references. The table also shows whether FEED documentation is publically available or whether investigators need to approach project developers directly for FEED information. Examples have been selected from Europe and North America, with two projects from Asia. The number and quantity of information from Europe and North America as compared with Asia is purely a reflection of what is currently available in the public domain. A generic reference has also been included which provides a quick-look reference for all CO_2 sequestration projects in a GIS format.

Some web-site references are comparatively easy to find, whereas others, notably some documentation issued by the UK Government, are less obvious. In the case of the UK, published information about projects that have not advanced beyond a detailed design stage is archived. The web addresses provided will direct investigators to the target references including archived material.

Table 1 Key References for CCS Projects where FEED studies have been conducted

Project	Leader	Location	FEED completed	FEED publically available	Internet References	Comments	Further Information
Europe							
Peterhead - Goldeneye	Shell	UK (Scotland) / N Sea	✓	✓	https://www.gov.uk/government/publications/carbon-capture-and-storage-knowledge-sharing-technical-subsurface-and-well-engineering	Carbon Capture and Storage Knowledge Sharing: Technical - Subsurface and Well Engineering – website with a series of technical reports on the Peterhead - Goldeneye	Detailed reports available see Appendix 1
					https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/531408/DECC_Deliverable_11_043_-Cost_Estimate_Report.pdf		Shell. (2015). Cost Estimate Report - Peterhead CCS Project (PCCS-00-MM-FA-3101-00001). London: DECC.
					http://webarchive.nationalarchives.gov.uk/20111205110805/https://www.decc.gov.uk/en/content/cms/emissions/ccs/demo_prog/feed/scottish_power/feed_cost/feed_cost.aspx	Available through UK Government national web-archives	Peterhead – Goldeneye FEED close out report and related documents

Project	Leader	Location	FEED completed	FEED publically available	Internet References	Comments	Further Information
White Rose	National Grid?	UK / N Sea	✓	✓	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/531922/K15_Full_chain_FEED_cost_breakdown.pdf	White Rose K.15 Full chain FEED cost breakdown Project Management: Full Chain	Reports available see Appendix 2
					https://www.gov.uk/government/collections/carbon-capture-and-storage-knowledge-sharing	Collection of Carbon Capture and Storage knowledge sharing Knowledge collected from UK CCS projects.	
					http://documents.ieaghg.org/index.php/s/WNfsbBQHmjgD6E8	IEAGHG Information Paper: 2015-IP17; First reports released from UK FEED on Peterhead and White Rose Projects.	Outline information on these FEED reports

Project	Leader	Location	FEED completed	FEED publically available	Internet References	Comments	Further Information
Kingsnorth	E.On	UK / N Sea	✓	✓	http://webarchive.nationalarchives.gov.uk/20130104023654/http://www.decc.gov.uk/assets/decc/11/ccs/chapter1-3/key-knowledge-reference-book.pdf	Key Knowledge Reference Book. February 2011_e.on	UK Carbon Capture and Storage Demonstration Competition SP-SP 6.0 - RT015 FEED Close Out Report CCS Project Costs
					http://webarchive.nationalarchives.gov.uk/20111205145054/https://www.decc.gov.uk/assets/decc/11/ccs/chapter10/10.14-post-feed-project-cost-estimates.pdf	Kingsnorth Carbon Capture & Storage Project available through UK Government national web-archives	Post-FEED Project Cost Estimates (spreadsheet summary) KCP-EUK-FIN-LIS-0002.
					http://documents.ieaghg.org/index.php/s/hkqV5Qpi07W5r6u. 'IEAGHG, "UK FEED Studies 2011 – A Summary", 2013/12, October 2013.'	Front end engineering design studies for demonstration scale CCS systems serving Longannet and Kingsnorth power stations in the UK	This report, available from the IEAGHG website, contains a high level FEED cost summary split between labour and non labour costs.

Project	Leader	Location	FEED completed	FEED publically available	Internet References	Comments	Further Information
ROAD		NL / N Sea	✓	✓	https://www.globalccsinstitute.com/publications/road-ccs-project-non-confidential-feed-study-report	ROAD CCS non-confidential FEED study report: special report for the Global Carbon Capture and Storage Institute. Contains only limited non confidential information.	
Compostilla OXYCFB300	ENDESA Generacion S.A.	Spain	✓	✓	http://hub.globalccsinstitute.com/sites/default/files/publications/137158/Compostilla-project-OXYCFB300-carbon-capture-storage-demonstration-project-knowledge-sharing-FEED-report.pdf	Detailed report available. Covers FEED Project Management, Design, CCS capture, transport & storage	OXYCFB300 Compostilla Carbon Capture and Storage Demonstration Project Knowledge Sharing FEED Report

Project	Leader	Location	FEED completed	FEED publically available	Internet References	Comments	Further Information
North America							
Boundary Dam	SaskPower	SK, Canada	✓	X	Detailed technical reports are not publically available	Detailed technical reports only available through SaskPower CCS Global Consortium	Detailed technical reports only available through SaskPower CCS Global Consortium see Index ref SaskPower CCS Global Consortium – Bringing Boundary Dam to the World. Contact Michael J Monea mmonea@saskpower.com Retrofit of CCS to rebuilt Unit 3 at Boundary Dam power station, captured CO_2 sold to Cenovus for use in EOR. FEED study by Fluor in 2009. Shell subsidiary Cansolv Technologies and partner SNC Lavalin contracted for capture system. Andy Sundararajan Manager, Business Development SNC-Lavalin Inc. 2275 Upper Middle Road East Oakville, ON, Canada L6H 0C3 Tel no.: (289) 291-4295 email: andy.sundararajan@snclavalin.com Flour FEED Capabilities https://www.fluor.com/services/engineering/front-end-engineering-design Mentions Quest but not Boundary Dam on company website

Project	Leader	Location	FEED completed	FEED publically available	Internet References	Comments	Further Information
Boundary Dam	SaskPower	SK, Canada			file://fscluster2/data/IEAGHG/Homes/James/Downloads/All%20Technical%20Reports%202005%20-%202019%20(3).pdf	This report summarises the experience and learnings of SaskPower in the development of this first-of-a-kind capture and storage project. This report does not contain a detailed breakdown of FEED costs.	'IEAGHG, "Integrated Carbon Capture and Storage Project at SaskPower's Boundary Dam Power Station", 2015/06 , August 2015'
Illinois Basin – Decatur Project (IBDP)	Archer Daniels Midland – Illinois State Geological Survey	IL, USA	✓	X	https://www.osti.gov/servlets/purl/1328392	Pipeline and Regional Carbon Capture Storage Project - Final Scientific and Technical Report, August 2015 Report gives outline description of costs – details referred in the text are in appendices that have not been published.	Appendix 1H. Appendix 2E – Pipeline FEED Report Appendix 3A – Storage Site Surface FEED Report Appendix 4G – Subsurface FEED Appendix 4G-1: Subsurface Storage and MVA – 90% Design Document Appendix 4G-2: Subsurface Storage and MVA – 90% Design Cost Estimate
					https://www.cslforum.org/cslf/Members/United-States		CCUS activities in USA Links via CSLF website
Petra Nova	NRG Energy	TX, USA	✓	✓	https://www.osti.gov/servlets/purl/1344080	NRG Energy, JX Nippon World's Largest Post-Combustion Carbon Capture Facility	W.A. Parish Post-Combustion CO_2 Capture and Sequestration Project – Topical Report Final Public Report
					https://www.businesswire.com/news/home/20170109006496/en/		

Project	Leader	Location	FEED completed	FEED publically available	Internet References	Comments	Further Information
Mountaineer	American Electric Power	WV, USA	✓	✓	https://www.globalccsinstitute.com/publications/aep-mountaineer-ii-project-front-end-engineering-and-design-feed-report	CCS Front End Engineering & Design Report American Electric Power Mountaineer CCS II Project Phase 1. Prepared for The Global CCS Institute Project # PRO 004 January 30, 2012	See extract in Appendix 4
					https://www.netl.doe.gov/File%20Library/Research/Coal/major%20demonstrations/ccpi/MTCCS-II-Final-Technical-Report-Rev1.pdf	Mountaineer Commercial Scale Carbon Capture and Storage (CCS) Project - Final Technical Report AEP_2011	

Project	Leader	Location	FEED completed	FEED publically available	Internet References	Comments	Further Information
Tenaska Trailblazer	Tenaska & Arch Coal, Inc	TX, USA	✓	✓	https://hub.globalccsinstitute.com/publications/final-front-end-engineering-design-feed-study-report	This report is a complete summary of the FEED study including project background information, the scope of facilities covered, the scope of the FEED study services, identification and treatment HSE and risk issues, cost analysis, scalability assessment, highlights and challenges, next steps, lessons learnt and other conclusions Report can be read online, but does not appear to download	Tenaska selected Fluor Econamine FG PlusSM technology and contracted with Fluor to complete a front end engineering and design (FEED) study for the carbon dioxide capture portion of the project.
Kemper	Southern Company Services, Inc.	MS, USA	✓	X	https://www.osti.gov/servlets/purl/1080351	Kemper County IGCCTM Project. Preliminary Public Design Report. Report refers to some aspects of FEED but does not include direct references.	.
					https://www.cslforum.org/cslf/Projects/Kemper		For contact with project, CSLF website which has links to :

Project	Leader	Location	FEED completed	FEED publically available	Internet References	Comments	Further Information
Plant Barry - Citronelle	Southern Company Services, Inc.	AL, USA	✓	X	https://www.globalccsinstitute.com/sites/www.globalccsinstitute.com/files/content/page/122975/files/Plant%20Barry.pdf	GCCI factsheet includes useful links about project & contacts	
					https://www.netl.doe.gov/File%20Library/Events/2015/co2captureproceedings/J-Thomas-Southern-Waste-Heat-Integration-with-Solvent.pdf	PPT mentions FEED	
					https://sequestration.mit.edu/tools/projects/plant_barry.html		
					https://www.cslforum.org/cslf/Projects/PlantBarry	No direct references to FEED studies for Capture, pipeline or storage FEED but contact details for lead Partner, Southern Company are included.	

Project	Leader	Location	FEED completed	FEED publically available	Internet References	Comments	Further Information
Plant Barry - Citronelle	Southern Company Services, Inc.	AL, USA	✓	X	https://www.mhi.com/news/story/1209141573.html	Capture from flue gas of a coal-fired plant by a CO_2 capture facility built at Southern Company's Plant Barry in Alabama. Storage in a saline formation at a depth of 3,000-3,400 meters in the Citronelle Dome geological structure, which is approximately 12 miles west from the plant. The storage aspect of the project is being conducted as Phase III of the RCSP program.	Links to other websites and Mitsubishi Heavy Industries related information.

Project	Leader	Location	FEED completed	FEED publically available	Internet References	Comments	Further Information
Port Arthur	Air Products	Port Aurthur, TX, USA	✓	X	http://documents.ieaghg.org/index.php/s/hkqV5Qpi07W5r6u The Carbon Capture Project at Air Products' Port Arthur Hydrogen Production Facility 2018/05, December 2018	This report covers the project undertaken by Air Products and Chemicals Inc. (Air Products), in partnership with Valero Energy and Denbury Onshore, LLC, as part of the US Department of Energy's Industrial Carbon Capture and Storage (ICCS) Programme.	The project captures CO_2 from Air Products' hydrogen plants located at the Valero Port Arthur Refinery and transport it via pipeline to the for use in CO_2-EOR in the West Hastings oil field for operation operated by Denbury.
					https://sequestration.mit.edu/tools/projects/port_arthur.html	Port Arthur Fact Sheet: Carbon Dioxide Capture and Storage Project. Includes headline costs for the project but not a detailed breakdown of the FEED costs	

Project	Leader	Location	FEED completed	FEED publically available	Internet References	Comments	Further Information
Quest	Shell Canada	Alberta, Canada	✓	✓	https://open.alberta.ca/dataset/quest-carbon-capture-and-storage-project-report-2014	Report gives detailed account of overall facility design, construction schedule, storage formation selection, capture and transport operations, storage operations including monitoring, regulatory approvals, public engagement, costs and revenues plus general project assessment.	Quest Carbon Capture and Storage Project - Annual Summary Report - Alberta Department of Energy: 2014, March 2015 Shell Canada Limited For further details on costs see Appendix 2 of the 2014 report
					IEAGHG, "The Shell Quest Carbon Capture and Storage Project", 2019 (in press). Final report will be uploaded onto the IEAGHG website when published.	Report gives an overview of the entire project from inception to completion. It describes the capture technology, pipeline route and storage formation features.	This report only gives an outline of the key costs in the project. It does have two complementary references: ***Shell, 2016a***. "Shell Annual Report 2016". http://reports.shell.com/annual-report/2016/strategic-report/summary-of-results.php. ***Shell, 2017m.*** T. Wiwchar. Shell Canada Energy Ltd. "Quest CCS. Future Pathways to More CCS/CCUS Deployment Based on the Success of Quest". COP 23 – IETA Business Hub Programme. Bonn, Germany. November 2017. https://www.ieta.org/resources/COP%2023/Side-Event-Presentations/COP%2023%20-%20Quest.pdf.

Project	Leader	Location	FEED completed	FEED publically available	Internet References	Comments	Further Information
Asia							
Al Reyadah CCUS Project	Emirates Steel & Abu Dhabi National Oil Company (ADNOC).	Abu Dhabi, UAE	✓	X	https://masdar.ae/assets/downloads/content/5102/al_reyadah_factsheet-final-jan_8,_2017.pdf	Contact details for the project not necessarily FEED documentation or references	
					https://www.cslforum.org/cslf/sites/default/files/documents/AbuDhabi2017/AbuDhabi17-TW-Sakaria-Session2.pdf	PPT mentions FEED completed April 2010	
Yanchang Integrated Carbon Capture and Storage Demonstration Project	Shaanxi Yanchang Petroleum (Group) Corp., Ltd	Shaanxi Province, China	✓	X	http://www.decarboni.se/insights/yanchang-co2-eor-unique-geology-unique-challenges	Mentions FEED completion Jan 2011 & September for two different capture plants	CCS: A China Perspective Yanchang Petroleum Report 1: Capturing CO_2 from Coal to Chemical Process - Shaanxi Yanchang Petroleum (Group) Co., Ltd. & GCCSI June 2015
Generic Info					https://ge.lokaler.de/	Provides thumb-nail descriptions of global projects involved in CO_2 capture or sequestration based on GSI format which shows global location.	Geographic reference map

The Global Carbon Capture and Storage Institute (GCCSI) has a publically available projects database of global large-scale CCS facilities, which offers a useful single point of reference for CCS projects. The definitions used here are taken directly from the GCCSI website.

Large-scale CCS facilities - definition

Large-scale integrated CCS facilities are defined as facilities involving the capture, transport, and storage of CO_2 at a scale of:

- at least 800,000 tonnes of CO_2 annually for a coal–based power plant, or
- at least 400,000 tonnes of CO_2 annually for other emissions–intensive industrial facilities (including natural gas–based power generation).

The thresholds listed above correspond to the minimum amounts of CO_2 typically emitted by commercial–scale power plants and other industrial facilities. Carbon capture and storage facilities at this scale must inject anthropogenic CO_2 into either dedicated geological storage sites and/or enhanced oil recovery (CO_2-EOR) operations, to be categorised by the GCCSI as large-scale CCS facilities.

Enhanced oil recovery may result in partial (incidental) or complete storage of injected CO_2 in oil reservoirs, subject to technical and economic factors. The GCCSI acknowledges that in some cases and jurisdictions, CO_2-EOR operators and/or regulatory authorities may not operate or permit CO_2-EOR sites for greenhouse gas mitigation purposes. Nevertheless, such EOR operations can demonstrate both the successful operation of full chain CCS facilities and the secure underground injection of CO_2 at industrial scale.

Early Development – proponents carry out studies and comparisons of alternative CCS facilities development concepts, including alternative CO_2 capture sources, technologies, storage locations, facility configurations, etc. For each alternative, costs, benefits, risks and opportunities are identified. During this stage, proponents must continue to consider, for each option, all relevant aspects of the development (i.e. stakeholder management, regulatory approvals, infrastructure, as well as the physical CCS facilities). At the end of this stage, the preferred development option is selected and becomes the subject of the Advanced Development stage. Usually, no more than one option is studied in Advanced Development.

Advanced Development - the selected development option is investigated in greater detail through feasibility and preliminary front-end engineering design (FEED). This may involve determining the specific technology to be used, design and overall project costs, required permits and approvals, and key risks to the development. Other key activities include conducting focused stakeholder engagement processes, seeking out finance or funding opportunities, and undertaking tender processes for engineering, procurement, and contracting suppliers. At the end of this stage, the development must be sufficiently defined for a final investment decision (FID) to be made.

In Construction - the detailed engineering design is finalised, construction and commissioning of the CCS facilities occurs, and the organisation to operate the facilities is established. Once this is completed, the development then moves into operations.

Operating - CCS facilities are operated within regulatory requirements, and maintained and modified, as needed, to improve performance.

Completion – CCS facilities are being/have been decommissioned and a post-injection monitoring program is implemented.

https://www.globalccsinstitute.com/projects/large-scale-ccs-projects-definitions

Large Scale Carbon Capture Projects Database

Data source copyrights: http://www.globalccsinstitute.com/copyright-statement

Globally, there are 15 large-scale CCS projects in operation, with a further seven under construction. The 22 projects in operation or under construction represents a doubling since the start of this decade. The total CO_2 capture capacity of these 22 projects is around 40 million tonnes per annum (Mtpa).

There are another 10 large-scale CCS projects at the most advanced stage of development planning, the Concept Definition (or Define) stage, with a total CO_2 capture capacity of around 14 Mtpa. A further 12 large-scale CCS projects are in earlier stages of development planning (the Evaluate and Identify stages) and have a total CO_2 capture capacity of around 25 Mtpa.

It is not certain how up-to-date this database is but it does list all known capture plants. Definitions are not all up-to-date, for example In Salah is classified as operational but injection ceased in June 2011.

Definitions from this website are also inferred from wording on the website and from the GCCSI website.

According to this web-site accessed on 5/10/18

Project Lifecycle Stage

- Identify 3
- Evaluate 9
- Define (advanced stage of development) 10*
- Execute (in construction) 7*
- Operate 15*

FEED either completed or in progress

https://data.opendatasoft.com/explore/dataset/large-scale-carbon-capture-projects-database%40kapsarc/table/?sort=time_period&disjunctive.project_name&disjunctive.project_lifecycle_stage&disjunctive.country&disjunctive.industry&disjunctive.primary_storage_type&disjunctive.capture_type

This is a free access web-site but requires registration. To gain access

https://data.opendatasoft.com/pages/home/

click “Search datasets”

input “carbon capture and storage”

enter

then click “Large Scale Carbon Capture Projects Database”

enter “table”

Section 3: Comparison of Cost Data

Some of the references on CCS project FEEDs have revealed varying degrees of technical and cost information. In the latter case it is worth noting that the approach to cost estimation does vary. This section explains these differences to highlight the level of caution that should be applied to FEED cost data. The examples highlighted in this review reveal that there are distinct differences in the approach to cost estimation, specifically the range of positive and negative uncertainty on capital expenditure (CAPEX) and operational expenditure (OPEX). It is standard practice to apply a statistical analysis to cost estimation (Confidence levels are expressed as P10, 10% probability that the project will come in or under budget) P50 (equal probability of meeting budget) and P90, (90% probability that the project will come in or under budget). However, there are differences in what these confidence levels represent in different projects. In the Peterhead - Goldeneye project the P90 value CAPEX estimate represents a 12% over-run and the P10 value represents a -11% (under spend), when compared to the most likely (P50) outturn value. The P90 value of the OPEX estimate represents a 24% over-run and the P10 value represents a -16% (under spend), when compared to the most likely (P50) outturn value. This level of statistical detail is not evident in public documentation from other projects. In cases where the spread of cost uncertainty is expressed the values tend to be quoted as percentage variations of the P50 value (see Table 2).

Table 2 Comparison of the range of costs estimates from four CCS projects

	Peterhead - Goldeneye	White Rose	Quest	Mountaineer
Capture plant Capex cost range	-10% / +15%[1]			
Storage cost range				
Opex plant cost range	-15% / +25%			
Total project cost range (if undifferentiated)		-21% / +35%[2]	+2.8%#[3]	+/- 25%[4]

expressed as a contingency for total project cost

The level of cost estimation refinement and the adopted standard is explained in some references. In the case of the Peterhead – Goldeneye project two different levels were applied to CAPEX (Type 3 +15% / -10%) and OPEX (Type 2 +25% / -15%). The Type 2 estimate is based on the known cost base in 2015 and is therefore presented in Real Terms for that year. There is no market escalation or inflation applied to the presented values. The Type 3 estimate is expressed in "Money of the Day" (MOD) terms which includes inflation and escalation to the most likely date of expenditure (i.e. the known cost in 2015 has been escalated and inflated, at 2% per annum). As the project progresses from concept to reality cost estimates should become more reliable and the levels of contingency should decline.

[1] Peterhead CCS Project, Doc Title: Cost Estimate Report, Doc No. PCCS-00-MM-FA-3101-00001

[2] White Rose K.01 Full Chain FEED Summary Report

[3] Quest Carbon Capture and Storage Project. Annual Summary Report - Alberta Department of Energy: 2014

[4] CCS Front End Engineering & Design Report, American Electric Power, Mountaineer CCS II Project, Phase 1

In the case of the White Rose project (Appendix 3) the vast majority of the costs (over 90%) were equivalent to an Association for the Advancement of Cost Engineering (AACE) cost estimate Level 2 for the majority of capital expenditure items. The typical accuracy for Level 2 is +12.5% to +35% and -7.5% to -21%. Costs based on a Notice To Proceed (NTP) date of April 2016 and on exchange rates of the day. Costs presented in the report have been adjusted to the assumed NTP date and exchange rates as at 30 November 2015. Uncertainty bands were generated through Monte Carlo analysis.

In the case of the Mountaineer project (Appendix 4) the FEED cost estimates were expressed in overnight project values (i.e. the yet-to-be escalated project cost to account for future year spending) and based on a 26 month construction schedule (five days per week - eight hours per day). The anticipated accuracy was +/- 25%.

In contrast to the projects that have yet to proceed the cost forecasts for Quest (Appendix 2) were refined as the project progressed to full-scale development. Development costs for the Project for the FEED stage (January 1, 2009 to December 31, 2011) are included in Appendix 2. In this case the CAPEX cost break down is subdivided into each key element (tie-in work, the capture facility, wells, and pipeline). CAPEX expenditure is also subdivided by fiscal year from January 1st 2011 until March 31st 2016. Total contingency, inflation and market escalation and lumped together, but only for the last two fiscal years 2014 and 2015.

Section 4. Summary

- There are a number of FEED studies for a range of CCS demonstration projects, some now in operation, but others have either not proceeded beyond a design stage or are awaiting a development decision.
- The level of detail and availability of FEED studies varies considerably. Some documents are publically accessible and can be downloaded from internet websites, whereas other material is held by lead developers who would need to be approached. Table 1 lists major CCS projects where FEED studies are known to exist and relevant contact details.
- The derivation of cost estimates shows that there are differences in approach and levels of accuracy. If this information is important a direct approach to the lead developer is recommended.

Appendix 1

Peterhead – Goldeneye CCS Project Cost Summary

The FEED study for the Peterhead – Goldeneye (Peterhead CCS Project abbreviated to PCCS) was one of a series of detailed reports prepared by Shell for the prospective CCS demonstration project. This was a detailed appraisal with an original budget of £43.82 M which actually cost £43.3 M by December 2015.

Uncertainty of CAPEX and OPEX Estimates

Shell uses proprietary simulation tools for cost risk analysis which apply an industry standard Monte Carlo simulation approach. This method generates a full range of possible outcomes and their associated probability of occurrence and is based on:

- Deterministic cost inputs and ranges;
- Probability distribution curves;
- Risks;
- Opportunities; and
- Levels of effort

Shell have tackled the issue of cost uncertainty and likely variability by using a standard cost and schedule risk analysis probabilistic method. As the project progresses from concept to reality the cost estimates should become more reliable and the levels of contingency should decline. Three levels of accuracy have been applied.

Type 1 +40% / -25%
Type 2 +25% / -15%
Type 3 +15% / -10%

The Type 2 updated OPEX estimate is based on the known cost base in 2015 and is therefore already presented Real Terms (RT) 2015. There is no market escalation or inflation applied to the presented values. The Type 3 CAPEX estimate is expressed in "Money of the Day" (MOD) terms which includes inflation and escalation to the most likely date of expenditure (i.e. the known cost in 2015 has been escalated and inflated, at 2% per annum, as required in order to line up with the probabilistic execution schedule).

Confidence levels are expressed as P10, (10% probability that the project will come in or under budget) P50 (equal probability of meeting budget) and P90 (90% probability that the project will come in or under budget). For the CAPEX estimate, the P90 value represents a 12% over-run and the P10 value represents a -11% (under spend), when compared to the most likely (P50) outturn value.

For the OPEX estimate, the P90 value represents a 24% over-run and the P10 value represents a -16% (under spend), when compared to the most likely (P50) outturn value.

CAPEX cost estimates for Peterhead – Goldeneye

The CAPEX estimate is £999.7 million MOD (Money of the Day which refers to an estimate which is inclusive of inflation and escalation to the date of expenditure). The CAPEX costs quoted in the report cover pre-operational development i.e. engineering, procurement, construction and commissioning costs.

The split in CAPEX costs between onshore (64%), offshore (22%) and other (14%) has been further subdivided. The power plant forms 26% and carbon capture, compression and condition plant represents 74% of the onshore CAPEX.

The CAPEX cost estimate covers the entire scope of the Execute phase of the PCCS Project and is reported according to the following elements:

- Venture implementation costs;
- Onshore, covering Peterhead Power Station modification scope of work - including the new steam generator and associated balance of plant; and the Carbon Capture, Compression and Conditioning plant scope of work;
- Landfall, pipelines and subsea scope of work;
- Modifications to the Goldeneye platform and associated logistics scope of work;
- Wells and subsurface scope of work;
- Owner's costs; and
- Commissioning.

Table A1.1 represents the P50 MOD case. The figures presented in this table include contingency provisions and anticipated foreign exchange (FOREX) related costs.

Table A1.1: Base Estimate CAPEX Breakdown

Cost Element	Base Estimate P50 MOD case (£ k)	%
Venture (SPV) Implementation	10,620	1.1
Owner's Costs	108,990	10.9
Onshore	639,460	64.0
Landfall, Pipeline, Subsea	72,580	7.3
Goldeneye Modifications	60,690	6.1
Wells & Subsurface	88,470	8.8
Commissioning (Full CCS Chain)	18,500	1.72
FOREX	440	0.04
TOTAL	**999,750**	**100**

OPEX cost estimates for Peterhead – Goldeneye

The OPEX estimate covers costs between 2016 and 2041. It includes some costs incurred before full-scale operation. OPEX costs for this project cover a 15-year injection period and post-injection monitoring. The OPEX estimate excludes future decommissioning or abandonment costs. The OPEX estimate is broken down into:

- Power Plant: 79%
- Capture, Transport, Storage, Metering Monitoring and Verification: 21%

Within the Power Plant OPEX estimate, the costs are split approximately according to:

- Fuel Gas: 64%
- Other: 36%

The FEED study includes a further more detailed breakdown. The onshore capture plant included:

- Study performed to review and assess the impact of amine degradation;
- Performance of absorber Schoepentoeter computational fluid dynamics modelling;
- Study performed near the end of FEED to de-risk uncertainties in the waste water treatment plant design.

The subsea work covered the following items:

- Pipe SIM modelling and subsea isolation valve bypass review;
- Pipeline flow assurance study;
- Nearshore pipeline stability study.

The OPEX model used to estimate the costs in the FEED study was based on the latest project schedule; bottom-up, activity-based modelling techniques; and data from a financial model such as: fuel gas consumption, CO_2 emissions, amine consumption; and Carbon capture conditioning and compression parasitic load)see Table A1.2). This model has provided an estimate for the period from 2016 through to 2041. It included: pre start-up costs for the Goldeneye facility; early Measurement Monitoring and Verification (MMV) activities from 2016 to 2019; the injection phase costs for the full chain from 2020 to 2035; and post injection phase costs, excluding decommissioning.

Table A1.2: Base Estimate OPEX Breakdown

Cost Element Sub Element	Cost (£ k)	%
Base Plant	366,800	10.0
Fuel Gas	2,336,800	63.7
Peterhead CCS Project Cost Estimate		
Carbon Cost	196,900	5.4
Sub total Power Plant OPEX	**2,900,500**	
Pre Start-Up Costs	16,700	0.5
CCCC Plant Power Import	235,100	6.4
CCCC Plant Operations	387,500	10.6
Transport	89,700	2.4
Storage	1,800	0.05
Monitoring (during and post operations) MMV	37,400	0.95
Subtotal Carbon Capture, Transport and Storage OPEX	**768,200**	
TOTAL	**3,668,700**	**100.0**

Project management covers commercial support, legal support, regulatory and communications. Commercial is split between on and offshore, capture plant at Peterhead, pipelines and subsea, wells and subsurface.

Appendix 2

Quest CCS Project Cost Summary

The objective of Quest is to capture CO_2 produced at the Scotford Upgrader used to improve the quality of oil from the Athabasca Oil Sands Project (AOSP). The captured CO_2 is then compressed and transported via a 65 km pipeline to an injection site near Thorhild, Alberta. The storage formation is referred to as the Basal Cambrian Sands (BCS) which has excellent porosity, permeability properties, is extensive and has excellent widespread regional seals.

In 2014, all 3 Wells were ready for Operation although permitting activities remained. The D51 and D65 amendment for the Wells 5-35 and 7-11 were submitted and are awaiting AER approval. Storage properties of the BCS complex have been validated through analysis of the data obtained from drilling five wells into the BCS formation (two appraisal and three injection wells). Risks of CO_2 containment loss are comprehensively detailed along with mitigation activities in the Measurement Monitoring and Verification (MMV) plan.

A detailed MMV plan has been developed and adapted. All pre-injection activities have not been initiated with the last activity being the Microseismic monitoring. In the future, the MMV Plan will be integrated with the GHG reporting system in place at the Scotford Upgrader.

The entire carbon capture, transport and storage operation at Quest was commissioned in August 2015. It has been operating successfully ever since. A definitive account of the project, from inception to operation up to December 2017, will be published in an independent report, commissioned by US DOE. The purpose of this report is to ensure that the experience gained at Quest can be shared in the public domain with anyone with an interest in CCS. The report's title is 'IEAGHG, "The Shell Quest Carbon Capture and Storage Project", 2019' (in press).

CAPEX

The CAPEX cost estimate in this report is based on February 2015 values and present in Canadian $. The $812 million total value quoted in this report is a Base Case that includes three injection wells and a reduced pipeline length. Actual spending and forecasting is on an incurred basis.

Development costs for the Project for the FEED stage (January 1, 2009 to December 31, 2011) are included in the Table A2.1 and reflect costs associated with front end engineering for the capture and pipeline units as well as sub-surface modelling and early drilling. The CAPEX cost break down for Quest subdivides each key element that is: tie-in work, the capture facility, wells, and pipeline. CAPEX expenditure is also subdivided by fiscal year from January 1st 2011 until March 31st 2016. Total contingency, inflation and market escalation and lumped together, but only for the last two fiscal years 2014 and 2015.

OPEX Costs

OPEX in based on an average year spend. All years are anticipated to be similar, based on the injection profile of up to 1.2 Mt/year of CO_2 injected. Estimates previously provided were from the original assessment (see Table A2.2). No design changes have been implemented, but the operating costs has been updated with 2015 premise pricing. The premise natural gas price is $3.54/GJ and $111.00/MWhr for electricity.

Table A2.1 Estimated Quest Project Capital Costs at February 2015 (Canadian $)

	FEED							
	2009 - 2011 Jan 1 , 2009 – Dec 31, 2011	FISCAL 2011 Jan 1 , 2012 - March 31, 2012	FISCAL 2012 April 1 , 2012 - March 31, 2013	FISCAL 2013 April 1 , 2013 - March 31, 2014	FISCAL 2014 April 1 , 2014 - March 31, 2015	FISCAL 2015 April 1 , 2015 - March 31, 2016	Total (excluding FEED)	% Total (excluding FFED)
Shell labour & commissioning	19,470	5,414	32,639	23,466	48,078	27,745	137,342	16.9
Tie-in work / brownfield work								
Tie-in Turnaround Work Capture			7,331	10,234	9,607	9,808	36,990	
Tie-in work Pipeline			196	518	287	0	1,002	
Sub Total			**7,527**	**10,753**	**9,894**	**9,808**	**37,982**	**4.7**
Capture Facility	52,671							
Engineering		6,662	40,889	32,799	5,426	0	85,775	
Construction Management			218	16,967	21,859	-	39,044	
Material		6,092	42,315	56,502	11,309	-	116,218	
Site Labour				9,456	36,816	-	46,271	
Subcontracts				1,390	7,431	-	8,811	
Module Yard Labour including Pipe fabrication			14,250	60,697	29,832	-	104,780	
Indirect / Freight			15	32,339	12,832	-	44,885	
FGR* Mods/HMU# Revamps			97,688	0	0	-	0	
Sub-total	**52,671**	**12,753**	**97,688**	**210,141**	**125,203**	**-**	**445,785**	**54.9**

	FEED							
	2009 - 2011 Jan 1 , 2009 – Dec 31, 2011	FISCAL 2011 Jan 1 , 2012 - March 31, 2012	FISCAL 2012 April 1 , 2012 - March 31, 2013	FISCAL 2013 April 1 , 2013 - March 31, 2014	FISCAL 2014 April 1 , 2014 - March 31, 2015	FISCAL 2015 April 1 , 2015 - March 31, 2016	Total (excluding FEED)	% Total (excluding FFED)
Subsurface Wells	63,175							
Injection wells		1,090	17,970	3,641	276	671	23,648	
Monitoring wells			1,311	54	-20	0	1,345	
Water wells			1,620	-53	1	0	1,568	
Other MMV			1,657	3,309	5,774	3,094	13,833	
Subtotal	**63,175**	**1,090**	**22,558**	**6,951**	**6,031**	**3,765**	**40,395**	**5.0**
Pipelines - TOE	4,035							
Engineering		576	4,272	2,782	1,172	0	8,902	
Materials		0	1,878	24,823	4,736	0	31,437	
Services		0	0	60,101	26,984	375	87,460	
Subtotal	**4,035**	**576**	**6,150**	**87,706**	**32,892**	**375**	**127,698**	**15.7**
Total contingency, inflation & market escalation					1,926	20,562	22,488	2.8
Grand Total	**139,351**	**19,832**	**166,563**	**339,016**	**224,024**	**62,255**	**811,690**	**100.0**

* = flue gas recycling

= Hydrogen manufacturing unit

Table A.2 Anticipated Project Operating Costs (2015 Estimate)

Item	**Average Costs per Year Canadian $ (,000)**	% Total
Steam and Electricity	25,801	58.8
Chemicals	275	0.6
Labour & Maintenance	5,945	13.5
Insurance	178	0.4
Property Tax	4,286	9.8
Directs vs. indirect costs	183	0.4
MMV Costs	3,776	8.6
Tariffs	0	0
Sustaining Capital	1,359	3.1
Turnarounds	2,099	4.8
Total	**43,901**	**100.0**

Appendix 3

White Rose Full Chain Cost Summary

The White Rose Carbon Capture and Storage (CCS) Project (White Rose) is an integrated full chain CCS project comprising a new coal-fired Oxy Power Plant (OPP) and a Transport and Storage (T&S) network that will transfer the carbon dioxide from the OPP by pipeline for permanent storage under the southern North Sea. The report includes a summary of the breakdown of FEED costs which totalled £46.98 M.

The full-chain FEED report gives a full account of the technical development of the project including a full-chain description and design basis, operational aspects, effluent and emissions summary, project cost estimate, implementation plan, project risks, key findings from CCS specific environmental, health and safety reviews and 10 leading lessons learnt from the FEED study. A summary of commercial arrangements, transport and storage are also covered.

The estimation of the Full Chain project costs has been undertaken by the Key Sub-Contractors: GE, BOC, Drax and NGC for their respective areas of responsibility. The Key Sub-Contractors have estimated the vast majority of the costs. This implies that a market enquiry has been undertaken for over 90% of the project costs equivalent to an Association for the Advancement of Cost Engineering (AACE) cost estimate Level 2 for the majority of capital expenditure items. Typical accuracy for Level 2 is +12.5% to +35% and -7.5% to -21%. Costs provided to the development company Capture Power Limited were based on a Notice To Proceed (NTP) date of April 2016 and on exchange rates of the day. Costs presented in the report have been adjusted to the assumed NTP date and exchange rates as at 30 November 2015.

Uncertainty bands have been generated through Monte Carlo analysis, whereby a large number of simulations for each cost element are undertaken giving an overall probability distribution. This analysis has produced a: P50 cost which is equivalent to the cost that is likely to be sufficient with 50% certainty; a P10 value which is the cost that will be sufficient with a 10% probability; and a P90 value which is the cost that will be sufficient with a 90% probability.

The cost presented in Table A3.1 has been built up from the results of the detailed Key Sub-Contractor Monte Carlo analyses through importing the cost distribution for twenty-eight line items and subsequently re-running for the six cost elements shown. The basis of FEED was to reduce risk and associated uncertainty which has had the effect of increasing the P50 estimate and narrowing the uncertainty band on certain of the chain elements.

Capex for FEED purposes has been estimated on a complete basis for the specific equipment configuration, participants and location. This included costs that would not necessarily be incurred or incurred to the same extent if a similar oxy-fired CCS project was to be implemented at a different site, in a different country or by a different type of client. The site identified in the UK required significant preparation, in particular for flood protection. These site preparation costs have been excluded.

Costs for testing and commissioning of the project, including labour, consumables and utilities have been excluded as these will depend on the local cost of labour, fuels and utilities; and the Owner's costs for developing the project including project management, administration, development, insurance and hedging have been excluded as these will depend on the nature of any existing client/developer organisation.

Commodity prices, labour prices, new technology risks and for storage Commodity prices, labour prices, offshore risk, storage risk will all influence uncertainty.

CAPEX Cost Estimate

Table A3.1 presents the expected implementation phase CAPEX for the project. This shows the expected value for each cost (P50) and the percentage decrease or increase in cost relative to P10 and P90 respectively.

Table A3.1: Expected Implementation Phase Capex (Nominal Costs, NTP September 2017) Cost Element

Cost Element	**P50 value (£m)**	**P10**	**P90**	**% P50**
1. Externally supplied utilities [1]	49	-3%	+3%	2.6
2. Oxyfuel boiler, Air Separation Unit (ASU) and Gas Processing Unit (GPU)	455	-2%	+3%	23.9
3. OPP Generation Equipment and Balance of Plant (BoP) [2]	471	-3%	+4%	24.8
4. Onshore CO_2 pipeline and associated costs [3]	358	-6%	+6%	18.8
5. Offshore pipeline and associated costs [4]	225	-11%	+11%	11.8
6. Storage facilities [5]	344	-17%	+21%	18.1
TOTAL	**1,902**	**-6%**	**+7%**	**100.0**

Notes

1. Externally supplied utilities includes interconnections for coal, limestone, water and power.
2. OPP Generation Equipment and Balance of Plant (BoP) excludes costs for site raising, laydown areas and commissioning/ testing. It includes turbine, generators, environmental control equipment, transformers, switchgear, water systems (including raw, treatment, heating, cooling and waste), coal, limestone and ash handling systems, auxiliary systems, erection costs, project management costs and plant civil costs.
3. Onshore CO_2 pipeline and associated costs includes multi- junction, CO_2 pumping station, the land, meters and monitors, and NGC business costs.
4. Offshore pipeline and associated costs includes pipeline, landfall metering and monitoring and, NGC business costs.
5. Storage facilities includes the platform, the wells and any monitoring/ metering and NGC business costs.

OPEX Cost Estimates

The annual cost of operation for the Full Chain is shown in nominal terms for the first full year of operation for the project in Table A3.2. Uncertainty bands have been provided for the OPEX costs based on the variability for both time and cost and the lower maturity of OPEX cost estimation compared to capex.

Table A3.2: Annual OPEX

Cost Element	Expected Cost (£m per annum)	Uncertainty Band	% of expected annual operating cost
1. Projected fuel costs [1]	60	+/-25%	32.4
2. Projected externally supplied utility costs [2]	11	+/-25%	5.9
3. Projected operation and maintenance costs for OPP = Oxy Power Plant [3]	67	+/-20%	36.3
4. Projected operation and maintenance costs for T&S [4]	47	+/-27%	25.4
TOTAL	185		100.0

Notes

1. Projected fuel costs include Coal cost (including transport).
2. Projected externally supplied utility costs includes: water, power import, costs for start-ups, chemical costs and landfill costs. Costs will be agreed under long term contracts that will reflect market forces at the time they are let.
3. Projected operation and maintenance costs for OPP including ASU (air separation unit), GPU (Gas Processing Unit) and BoP (Balance of Plant). Costs will be driven mainly by labour market and commodity prices.
4. Projected operation and maintenance costs for T&S (transport & storage) includes full costs of onshore and offshore transport and storage. Costs will be driven mainly by labour market, commodity prices and insurance requirements.

Appendix 4

Mountaineer Cost Summary

One of the main deliverables for the Phase I scope of work for the Mountaineer project developed by American Electric Power (AEP) was to develop a +/- 25% cost estimate for the entire project June 30, 2011. The estimate that was developed covered project costs for: Phase II Detailed Engineering/Design & Permitting, Phase III Construction & Start-up, and Phase IV Operations (i.e. all direct and indirect project costs (overheads, etc) associated with the engineering, procurement, construction and operations & maintenance of the project through the expected project life up to June 28, 2019).

The FEED was performed to support a bottom up approach for development of the cost estimate. The overall rigor in the estimate resulted in an observation that the anticipated +/- 25% accuracy was exceeded.

The overnight project cost (i.e. the yet-to-be escalated project cost to account for future year spending) was based on a 26 month construction schedule (five days per week - eight hours per day) and owner election to use a multi-prime construction contracting approach[1]. The scope of the cost estimate includes the engineering, procurement, construction, start-up and fine tuning of the carbon capture and storage system retrofit systems. The scope of the cost does not include costs for system operations in Phase IV.

Major quantities associated with the estimate are shown below in Table A4.1. The quantities were not subject to a detailed optimization review and should be regarded as conservative from an Owner's risk management perspective. A number of opportunities for quantity reductions were identified for further evaluation in Phase II. The largest risks to the project lie in uncertainty associated with development and installation of the CO_2 storage system, followed by escalation volatility, and potential increases in labour costs. Lines shown for support steel are reflective of opportunities.

Table A4.1 Major Material/Equipment Quantities in Capture & Storage Systems

Chilled Ammonia Process Equip., Tie-in Duct, Storage Tanks, Buildings and Compression Equip.			**Wells**	
2,160,000 ft^3	(61,160 m^3)	Concrete	2	Injection Wells
9,500 ton (US short)	(8,620 tonne)	Structural Steel	9	Deep Monitoring Wells
118,000 ft.	(36,000 m.)	Piping	4	Intermediate Monitoring Wells
127,000 ft.	(38,710 m.)	Conduit/Cable Tray	8	Groundwater Monitoring Wells
1.2-MM ft.	(365 km.)	Electrical Cable	**Pipeline**	
			10 mi. (16km)	CO_2 Transport Pipeline

The overall total project cost includes an estimated $66-million dollars associated with Phase IV operations of the capture and storage systems over a planned four year DOE project operating life, starting September 1, 2015 and ending June 28, 2019. The project cost estimate, summarised in Table A3.2 includes escalation, risk based contingency and Phase IV Operational costs. The $1.065-billion dollar figure represents an approximate 99.5% level of confidence that the project will under run that amount. Detailed cost estimate for each of the core elements itemised in Table A4.2 were not published in the Mountaineer FEED report.

Table A4.2 Cost breakdown for the Mountaineer Carbon Capture and Storage Project

System (Phases I, II & III)	Estimate ($ x million) USD	% total DOE Project Cost
Capture System	$665	62.4
Storage System	$160	15.0
Sub-Total (Overnight Cost)	**$825**	
Escalation	$71	6.7
Sub-Total (As Spent)	**$896**	
Risk Based Contingency	$103	9.7
Total Constructed Cost	**$999**	
Phase IV Operations	$66	6.2
Total DOE Project Cost	**$1,065**	**100.0**

The $825-million cost estimate (2011 $USD) covers the engineering, procurement, construction, start-up and fine tuning of the carbon capture and storage system retrofits. The $71-million of escalation is included to account for the time value of money as-spent over the project life. A risk based evaluation of the cost estimate added up to $103 million of contingency funding. No detail of this risk evaluation, or the derivation of costs, is included in the FEED report. The contingency funding accounts for the uncertainties associated with the permit applications and construction of the CO_2 storage system, volatility of projected escalation, and potential labour cost escalation during the construction and commissioning phases. The Phase IV operations, between September 2015 and June 2019 included an estimated $66-million for operations, maintenance and consumables. The total project upper cost limit estimate of $1.065 billion represents an approximate 99.5% level of confidence that the project will meet or under run that amount.

Based on the work completed in the FEED package, AEP and its extended project team also:

- Developed a +/- 25% cost estimate,
- Developed a detailed Phase II project schedule,
- Provided US DOE (US Department of Energy) with all the information it needed to complete the NEPA (National Environmental Policy Act) process,
- Developed a multi prime construction contracting strategy for Phase III,

- Issued preliminary Process Flow Diagramme and overall mass and energy balances, and
- Completed preliminary project design.

1 from Hunker website
https://www.hunker.com/12423120/construction-contracts-single-prime-vs-multiple

This definition for Multiple prime contracts has been taken from the US Hunker website. Multiple prime contracts are used for phased construction. These are contracts that are awarded sequentially for each portion of a construction project. For example, contracts for a building structure would be awarded after the foundation of a building has been finished. These contracts require more careful coordination and close monitoring because numerous contractors may be involved in the project, and no specific contractor is held responsible for the job as a whole.

Appendix 5

CCS under development in the Peoples' Republic of China from (Global CCS Institute CO_2RE Database)

Name	Location	Scale	Year	Capacity (tpa)	Industrial source	Storage
Yangchang Integrated CCS Demonstration (Under Construction)	Shaanxi Province	Large-scale Demonstration	2020 2012	410,000 50,000	Chemical production	EOR
Sinopec Qilu Petrochemical CCS (Under Construction)	Shandong Province	Large-scale	2019	400,000	Chemical production	EOR
Sinopec Shengli Power Plant CCS (Advanced Development)(	Shandong Province	Large-scale Demonstration facility	2020s 2010	1,000,000 40,000	Power Generation	EOR
Sinopec Eastern China CCS (Early Development)	Jiangsu Province	Large-scale Demonstration facility	2020 2015	500,000 50,000	Chemical Production	EOR
Huaneng GreenGen IGCC (Early Development)	Binhai New Area, Tianjin	Large-scale Demonstration facility	2020s 2016	2,000,000 100,000	Power Generation	EOR
China Resources Power (Haifeng) Integrated CCS Demonstration (Early Development)	Shanwei, Guagdong Province	Large-scale facility Capture Test Platform	2020s 2018	1,000,000 25,000	Power Generation	Dedicated offshore Geological Storage (DSF)
Shanxi International Energy Group CCUS (Early Development)	Shanxi Proince	Large-scale facility	2020s	2,000,000	Power Generation	Under Evaluation
Shenhua Ningxia CTL (Early Development)	Ningxia Province	Large-scale facility	2020s	2,000,000	Coal-to-liquids	Under Evaluation
Daqing Oil Field EOR Demonstration	Heilongjiang Province	Demonstration-scale facility	2003	2000,000	Natural gas processing, etc	EOR

Name	Location	Scale	Year	Capacity (tpa)	Industrial source	Storage
Jilin Oil Field EOR Demonstration	Jilin Province	Demonstration-scale facility	2006	350,000	Natural gas processing	EOR
Shenhua Group Ordos CCS Demonstration	Ordos, Inner Mongolia Province	Demonstration-scale facility	2011 - 2014	100,000	Coal-to-liquids	Dedicated geological storage
Karamay Dunhua Oil Technology CCUS EOR	Karamay, Xinjiang Province	Demonstration-scale facility	2015	100,000	Chemical production	EOR
Sinopec Zhongyuan	Henan Province	Demonstration-scale facility	2015	120,000	Petrochemical production	EOR
PetroChina Changqing	Shaanxi Province	Demonstration-scale facility	2017	50,000	Coal-to-liquids	EOR
Guohua Jinjie CCS Full Chain Demonstration	Shaanxi Province	Demonstration-scale facility	2019	150,000	Power generation	Dedicated geological storage
Huaneng Gaobeidian Power Plant Carbon Capture Pilot Project	Beijing	CO_2 Utilisation Plant	2008	3,000	Power generation	Beverage industry
Shanghai Shidongkou 2nd Power Plant Carbon Capture Demonstration	Shanghai	CO_2 Utilisation Plant	2009	120,000	Power generation	Beverage industry
Chongqing Hechuan Shuanghuai Power Plant CO_2 Capture Industrial	Chongqing, Sichuan Province	CO_2 Utilisation Plant	2010	10,000	Power generation	Industrial use

Evaluating technology options to mitigate greenhouse gas emissions

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