Acorn

D20 Final Report

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February 2019

www.actacorn.eu

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The ACT Acorn consortium is led by Pale Blue Dot Energy and includes Bellona Foundation, Heriot-Watt University, Radboud University, Scottish Carbon Capture & Storage (SCCS), University of Aberdeen, University of Edinburgh and University of Liverpool.

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1.0 Foreword: Chris Stark, CEO, Committee on Climate Change

"The materials presented through this ACT Acorn programme are very topical to our work in the Committee on Climate Change. We are currently building an assessment of pathways to affirm the UK's obligations under the Paris Agreement.

As we consider deep emissions reduction, and even 'net zero', every scenario includes CCS. The success of projects like this is critical, therefore, to what must come next.

Accelerating deployment is key. In the UK, we have reached the moment when plans must become real projects. In doing so, projects will have the support of my Committee, but more importantly, they will enjoy the full backing of science and economics as we reach a crunch moment for global action on the climate.

The ACT Acorn research is further evidence that it is possible for the UK to begin deployment of CCS.

Let's get going."

At the Committee on Climate Change (CCC) we have long supported carbon capture and storage (CCS). It is an essential component of any serious steps towards decarbonisation and we have been clear in our advice to the UK Government that that they should not plan for 2050 emissions reduction without it. Put simply, it is too expensive to decarbonise every sector of the economy without CCS and the future of some sectors relies upon it. (Committee on Climate Change, 2018).

We like CCS because it gives us options. CCS is not like other decarbonisation technologies, it is strategic infrastructure that opens up a suite of options to decarbonise the whole economy in a cost-effective way. Geological storage of CO_2 will also help the UK, Europe and ultimately the World to decarbonise rapidly, as efforts to limit global temperature rise require.

There are a few very simple reasons for pursuing CCS that are worth articulating:

- CCS is a good partner for 'hard to decarbonise' sectors like heavy industry and chemicals where CO_2 production is often intrinsic to the process.
- CCS can be coupled with hydrogen production to create a very low carbon fuel, which we know is critically important to addressing challenges like decarbonising the heat and transport sectors.
- CCS can be married with biomass to form an essential route to achieving net negative emissions. You can see just how essential this path is by flicking through the recent IPCC Special Report on global warming of 1.5 degrees, (IPCC, 2018).
- Achieving net negative emissions through CO_2 sequestration, provides us with a possible offset solution for some of those sectors where we struggle to find alternative decarbonisation solutions such as aviation.
- We can also partner CCS with electricity production where fossil fuels are still being used to generate electricity.

Back in 2008 the CCC was established to give independent advice to Government and Parliament. Our first piece of advice was on the level for the UK's long-term ambition. We advised that by 2050, emissions should have fallen by 80% from their level in 1990, (Committee on Climate Change , 2008). Ten years on, and, the governments of the UK, Scotland and Wales have again asked the CCC to provide advice on our long-term targets for greenhouse gas emissions, in light of the UK's responsibilities under the Paris Agreement. We are now considering whether it is time for the UK to name the date for its full transition to a net zero carbon economy, (UK Government, 2018).

It is increasingly obvious that we will need as broad a range of technologies and solutions as we can find if we are to turn around our thirst for unabated fossil fuels. So, the materials presented through this ACT Acorn programme are highly topical.

Every future scenario we consider rests on the development of commercial CCS, so I am pleased to see the publication of this report, which brings that outcome one step closer. I hope the ACT Acorn research provides new impetus for CCS deployment in the UK.

Figure 1-1: Chris Stark, CEO of the CCC delivers the closing keynote address for the ACT Acorn Final Event. Image credit: Indira Mann, SCCS

2.0 About ACT Acorn

2.1 Accelerating CCS Technologies (ACT)

ACT is an ERA-NET Cofund - a tool established by the European Commission under the Horizon 2020 programme to support research and innovation. The ACT programme was established with 13 funding partners all with a clear ambition to fund research and innovation projects that could lead to safe and cost-effective CCS technology and accelerated CCS deployment, (ACT, 2019).

ACT Acorn, project 271500, is the first of the ACT funded projects to conclude its detailed research programme.

2.2 ACT Acorn

ACT Acorn received funding from the UK Government Department for Business, Energy and Industrial Strategy (BEIS), the Research Council of Norway (RCN) and The Netherlands Enterprise Agency (RVO), and is co-funded by the European Commission under the ERA-NET instrument of the Horizon 2020 programme. ACT grant number 691712.

2.2.1 Project Partners

The ACT Acorn programme was a close collaboration between eight European partner organisations, led by Pale Blue Dot Energy in the UK, as shown in Figure 2-1. In addition to these eight key contributing organisations, ACT Acorn drew on support from Axis Well Technologies, CO_2DeepStore, Costain, Guangdong CCUS Centre, GeoRes, MJ Design, North Sea Midstream Partners, Robert Gordon University and The University for Texas at Austin.

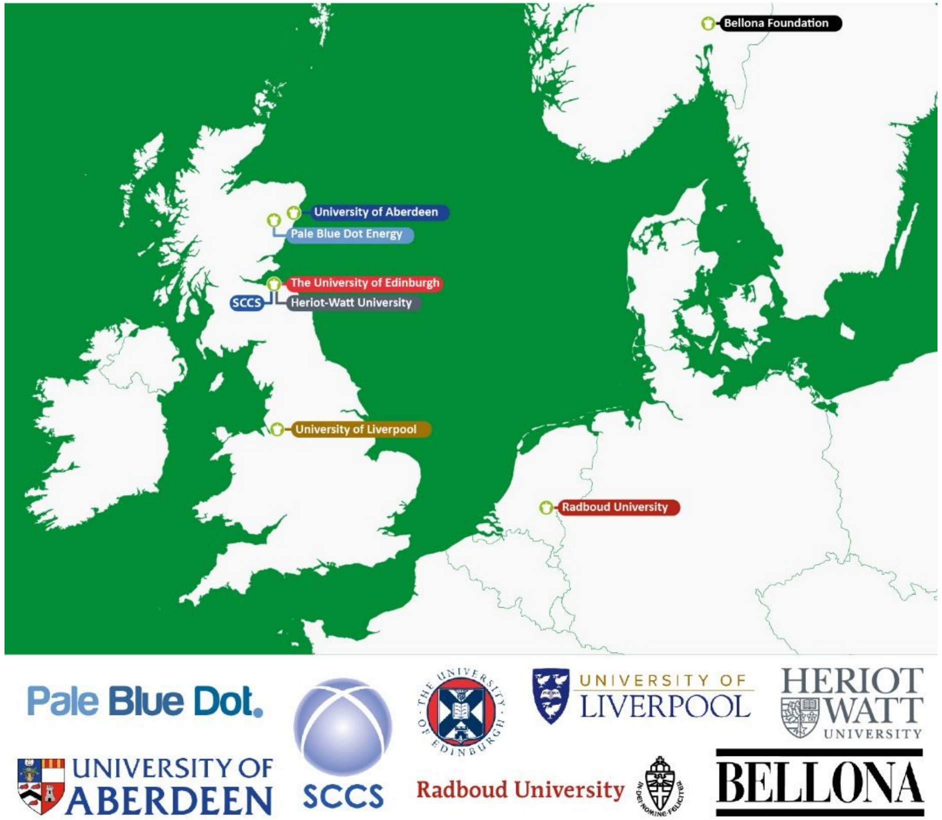


Figure 2-1: The ACT Acorn consortium partners

2.2.2 Accelerating CCS in the UK and Europe

Figure 2-2: Alan James, Managing Director, Pale Blue Dot Energy, introducing the 'Acorn Options' at the ACT Acorn Final Event. Image credit: Kirsty Lynch, Pale Blue Dot Energy

"What I'd like to reinforce here, is just how transformational this ACT programme has been for this project" ***(www.actacorn.eu/about-act-acorn/acorn-options)***

ACT Acorn was specifically designed to accelerate CCS deployment through development of the Acorn CCS project in the UK, and to support learning and knowledge dissemination with other CCS initiatives across Europe.

The project was delivered over a 19-month period, concluding on the 28th February 2019. During this time, the multi-disciplinary project team created and published 21 detailed 'Deliverables' covering a broad suite of both technical and non-technical activities, as well as leading edge scientific research.

Specific objectives of the project were to:

- Produce a costed technical development plan for a full-chain CCS hub that would capture CO_2 emissions from the St Fergus Gas Terminal in North East Scotland and store the CO_2 at an offshore storage site (to be selected) under the North Sea;
- Identify technical options to increase the storage efficiency of the selected storage site based on scientific evidence from geomechanical experiments and dynamic CO_2 flow modelling thereby driving scientific advancement and innovation in both these areas;
- Explore build out options including interconnections to the nearby Peterhead Port, other large sources of CO_2 emissions in the UK region and CO_2 utilisation plants;
- Identify other potential locations for CCS hubs around the North Sea region, develop policy recommendations to protect relevant infrastructure from premature decommissioning and for the future ownership of potential CO_2 stores;
- Engage with CCS and low carbon economy stakeholders in Europe and worldwide to disseminate the lessons from the project and encourage replication.

The completion of the detailed feasibility studies undertaken during ACT Acorn, in combination with the transport infrastructure studies that the Acorn CCS project is about to complete with the support of the Connecting Europe Facilities (CEF) fund, mean that Acorn CCS will soon be ready to enter front end engineering and design (known as FEED studies). This is the very detailed technical and commercial assessment that come prior to a final investment decision and, ultimately, construction.

With the right set of circumstances, Acorn CCS could be operating in the early 2020s, helping the UK meet its climate targets and providing a valuable blueprint for the decarbonisation of regions dependent on the fossil fuel industry and its products.

All the detailed findings from ACT Acorn are publicly available on the project website, www.actacorn.eu/, along with a suite of accessible communication resources, (infographics, factsheets, short video files and a webinar), to help share learning from the project with the widest possible audience.

2.3 Acorn CCS

Acorn CCS is a low-cost, low-risk carbon capture and storage project specifically designed to make best use of existing oil and gas infrastructure and a well understood offshore CO_2 storage site to unlock large-scale CO_2 transport and storage solutions for the east coast of the UK and beyond.

The project being developed by Pale Blue Dot Energy, is recognised as a European Project of Common Interest, (European Commission, 2019), and is located at the St Fergus Gas Terminal in North East Scotland, an active industrial site where around 35% of all the natural gas used in the UK comes onshore.

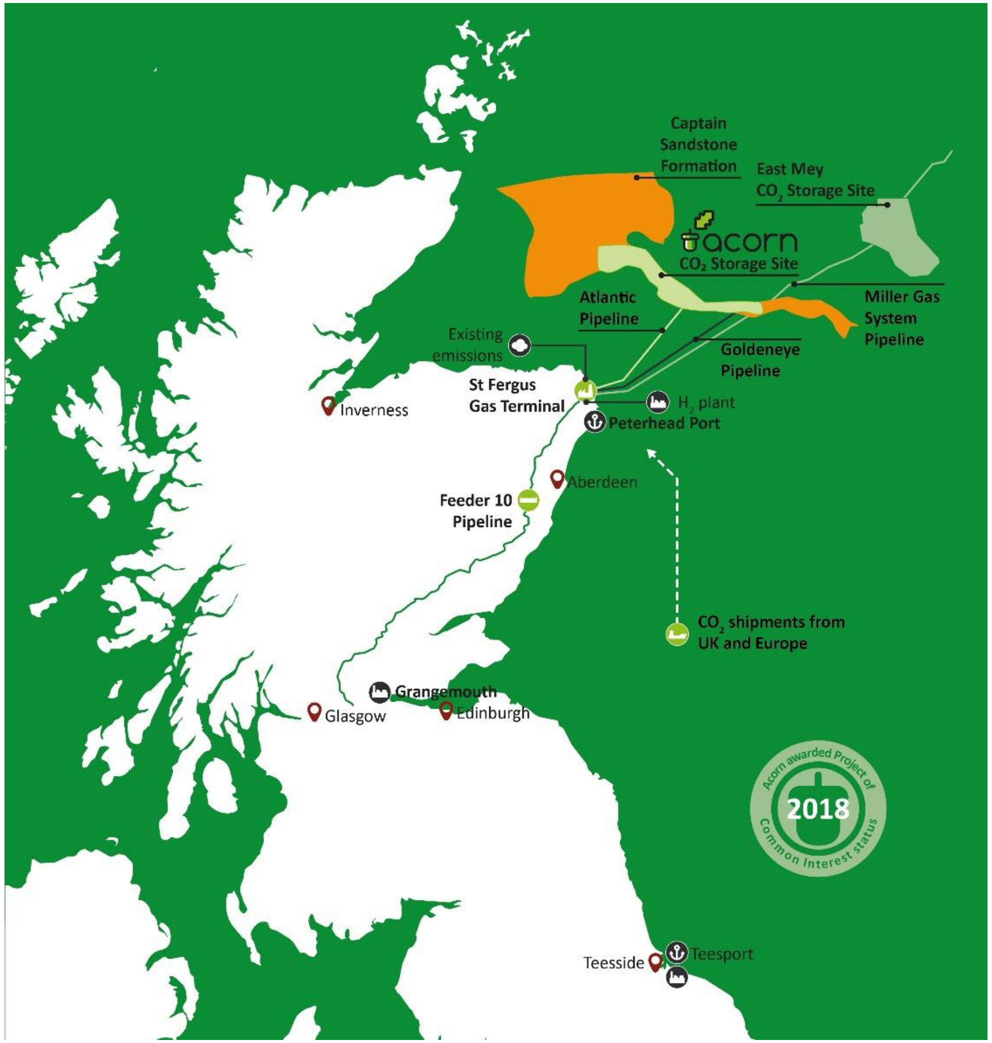


Figure 2-2: The Acorn CCS Project

2.3.1 The Acorn Development Concept: Mighty Oaks from Little Acorns Grow

Acorn CCS has been specifically designed to tackle one of the acknowledged major blockers to carbon capture usage and storage (CCUS) deployment in the UK, the high capital costs involved in getting CCUS started.

In the past, many CCS projects have been burdened with immediately achieving "economies of scale" to be deemed cost effective. This inevitably increases the initial cost hurdle to achieve a lower life cycle unit cost, be that £/MWh or £/t, which raises the bar from the perspectives of initial capital requirement and overall project risk.

Acorn CCS attempts to buck this trend, by designing a full-chain CCS development of industrial scale, which minimises or eliminates the scale-up risk, but at the lowest possible capital cost, accepting that the initial unit cost for the project may be high for the first small tranche of CO_2 stored.

By reusing suitable oil and gas infrastructure and the very large, well-characterised storage sites that exist in the Central North Sea, Acorn CCS is quickly able to establish millions of tonnes worth of CO_2 transport and storage infrastructure using a relatively small quantity of captured CO_2.

A successful seed project will improve confidence for further low-cost growth and incremental development, accelerate CCS deployment on a commercial basis and will provide cost-effective CO_2 transport and storage infrastructure from which to grow a regional cluster and an international CO_2 hub.

This makes Acorn CCS an important catalyst for clean growth in the north east of the UK and beyond. The detailed feasibility studies carried out during this ACT Acorn programme, in combination with other ongoing Acorn research initiatives, have indicated the potential for Acorn CCS to kick start:

- A major hydrogen and CCS hub at St Fergus;
- An economic opportunity for CO_2 import at the deep-water port at Peterhead;
- The repurposing of a large onshore natural gas pipeline, known as Feeder 10, to transport Scotland's Central Belt emissions to St Fergus;
- An international CO_2 storage hub in the Central North Sea that unlocks CO_2 transportation and storage solutions for other carbon capture usage and storage (CCUS) clusters across the UK and potentially Europe.

2.3.2 Current Status

On publication of this report, the ACT Acorn programme is now complete and has certainly achieved the objective of accelerating CCS in Europe. In June 2018, Acorn CCS became the first CCUS project in Europe to have been awarded funding support from the European Commission's CEF fund. In November 2018, Acorn was able to announce match funding from the UK Government, the Scottish Government, Pale Blue Dot Energy and Total Exploration and Production (UK) for the CEF work programme on Acorn's CO_2 transport infrastructure development project, known as the CO_2-SAPLING project (Pale Blue Dot Energy, 2018).

Acorn CCS has also been awarded the Oil and Gas Authority's first CO_2 appraisal and storage licence and Crown Estate Scotland's first lease option for CO_2 storage for the Acorn CO_2 Storage Site, (Pale Blue Dot Energy, 2018).

The next stage of development for Acorn CCS is to move towards Option Selection and FEED. At the time of writing, details for the funding and work programme for these stages were being defined (Pale Blue Dot Energy, 2019).

2.4 The ACT Acorn Themes

Figure 2-3: The ACT Acorn Navigation Tree

In order to set the individual ACT Acorn Deliverables in context, they have been clustered together under five major themes, plus the 'ACT Acorn' explanation of the project. The navigation tree graphic, Figure 2-3, has been created as a signpost for all website visitors towards the key thematic areas explored during the ACT Acorn project, https://actacorn.eu/. On the website all the final ACT Acorn deliverable materials are housed under one of the five themes:

The Acorn Options

This theme sets out the different development options open to the Acorn CCS project, with key deliverables including: a full-chain development plan and budget for the initial Acorn project; detailed analysis of the various build-out opportunities for Acorn; an economic model; and an outline environmental impact assessment.

Infrastructure Reuse and Decommissioning

This is an important theme, which considers the potential for reusing existing oil and gas infrastructure in Acorn and for other projects across Europe. It examines both the technical and cost-saving elements of infrastructure reuse and provides a set of policy recommendations for infrastructure reuse and decommissioning, with a focus on the importance of pipeline preservation.

CCS and a Just Transition

This research theme explores the role of CCS in providing a just energy transition for areas that remain highly dependent on fossil fuel resources, with stakeholder panels held in the UK, the Netherlands and Norway.

Understanding Underground CO_2 Storage

This section contains a detailed examination of two critical themes concerning CO_2 storage for Acorn CCS:

1. The CO_2 storage site selection processes and creation of the Storage Development Plans for two selected storage sites.

2. Understanding the geomechanics and petrology of the two Acorn storage sites.

Life Cycle Assessment

This research uncovers the full life cycle assessment of the Acorn CCS project, confirming that even capturing only a small volume of CO_2 initially can make a significant impact on overall CO_2 emissions.

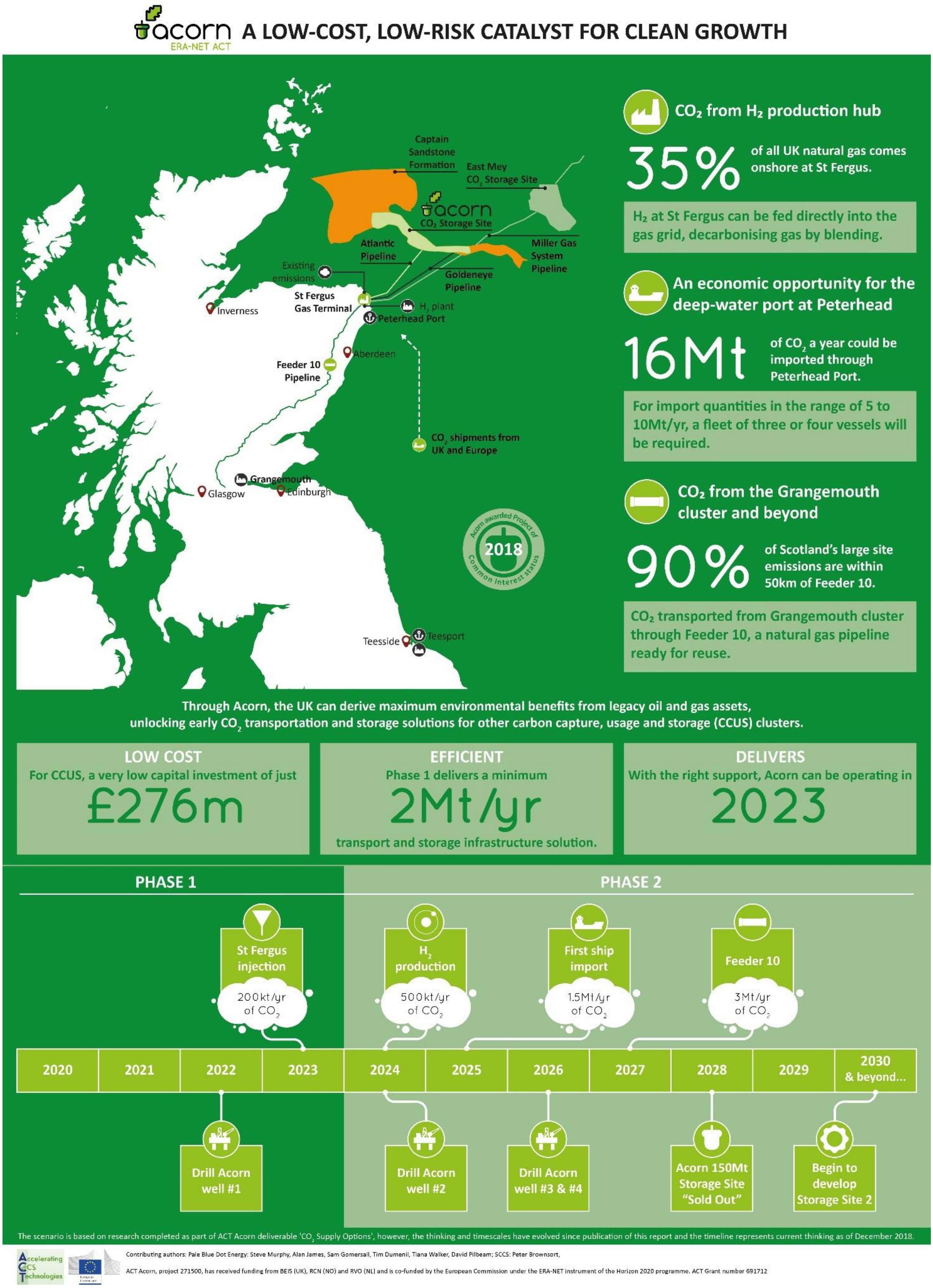
2.5 Using the Final Report

This Final Report is intended to be used as a navigation document, providing a brief overview of the content included within each of these themes, highlighting key reports and findings, and signposting readers to sources of further information.

The report concludes with a collection of key findings from the ACT Acorn programme, which were explored more fully during the ACT Acorn Final Event, (ACT Acorn Consortium, 2019). The filmed presentations and discussion panels from this event are included under the individual theme sections of the ACT Acorn website and are worth viewing for people keen to source the most current information and findings from the ACT Acorn programme. As the programme was providing live knowledge sharing over a 19-month period, assumptions and findings evolved throughout the life of the project. This should be borne in mind when accessing information from early reports.

Sharing knowledge and learning was a critical component of the ACT Acorn project, which included a comprehensive programme of communication and knowledge exchange to a wide variety of audiences. An excellent summary of this programme is included in the ACT Acorn Knowledge Dissemination Report (ACT Acorn Consortium, 2019) stored in the ACT Acorn section of the project website. Although a summary of this work is not specifically included within this Final Report, examples of the ACT Acorn communication materials are included throughout.

Figure 2-4: A tour of the Rock Deformation Lab at University of Liverpool to share learning across the ACT Acorn Consortium. Image credit: Indira Mann, SCCS


acorn ERA-NET ACT
A LOW-COST, LOW-RISK CATALYST FOR CLEAN GROWTH
Captain Sandstone Formation
East Mey CO_2 Storage Site
acorn CO_2 Storage Site
Atlantic Pipeline
Miller Gas System Pipeline
Goldeneye Pipeline
Existing emissions
St Fergus Gas Terminal
H_2 plant
Peterhead Port
Inverness
Aberdeen
Feeder 10 Pipeline
CO_2 shipments from UK and Europe
Grangemouth
Glasgow
Edinburgh
Acorn awarded Project of Common Interest status 2018
Teesside
Teesport
CO_2 from H_2 production hub
35% of all UK natural gas comes onshore at St Fergus.
H_2 at St Fergus can be fed directly into the gas grid, decarbonising gas by blending.
An economic opportunity for the deep-water port at Peterhead
16Mt of CO_2 a year could be imported through Peterhead Port.
For import quantities in the range of 5 to 10Mt/yr, a fleet of three or four vessels will be required.
CO_2 from the Grangemouth cluster and beyond
90% of Scotland's large site emissions are within 50km of Feeder 10.
CO_2 transported from Grangemouth cluster through Feeder 10, a natural gas pipeline ready for reuse.
Through Acorn, the UK can derive maximum environmental benefits from legacy oil and gas assets, unlocking early CO_2 transportation and storage solutions for other carbon capture, usage and storage (CCUS) clusters.
LOW COST
For CCUS, a very low capital investment of just
£276m
EFFICIENT
Phase 1 delivers a minimum
2Mt/yr
transport and storage infrastructure solution.
DELIVERS
With the right support, Acorn can be operating in
2023
PHASE 1
PHASE 2
St Fergus injection
200kt/yr of CO_2
H_2 production
500kt/yr of CO_2
First ship import
1.5Mt/yr of CO_2
Feeder 10
3Mt/yr of CO_2
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030 & beyond...
Drill Acorn well #1
Drill Acorn well #2
Drill Acorn well #3 & #4
Acorn 150Mt Storage Site "Sold Out"
Begin to develop Storage Site 2
The scenario is based on research completed as part of ACT Acorn deliverable 'CO_2 Supply Options', however, the thinking and timescales have evolved since publication of this report and the timeline represents current thinking as of December 2018.
Accelerating CCS Technologies
Contributing authors: Pale Blue Dot Energy: Steve Murphy, Alan James, Sam Gomersall, Tim Dumenil, Tiana Walker, David Pilbeam; SCCS: Peter Brownsort,
ACT Acorn, project 271500, has received funding from BEIS (UK), RCN (NO) and RVO (NL) and is co-funded by the European Commission under the ERA-NET instrument of the Horizon 2020 programme. ACT Grant number 691712

3.0 The Acorn Options

This theme includes eight detailed reports that together establish a reference case for the first phase of the Acorn CCS project that assumes a modest supply of initial CO_2 captured directly from the site at St Fergus Gas Terminal. This then goes on to give the most comprehensive assessment to date of the different development or 'build-out' options open to Acorn CCS if key CO_2 transport and storage infrastructure can be established.

3.1 Deliverable Summaries

3.1.1 ACT Acorn CO_2 Supply Options

This Deliverable brings together current information on existing, planned and possible future CO_2 emissions at St Fergus and Grangemouth, and on CO_2 emissions that could be imported to Peterhead Port.

It is an important piece of analysis that establishes a reference case and two further scenarios for CO_2 supply to Acorn CCS at the St Fergus Gas Terminal; these are used as the basis for subsequent analysis in a variety of the ACT Acorn Deliverables:

- **Reference Case**
  Assumes a flat rate of 0.2Mt/yr CO_2 can be captured from the gas processing Terminal at St Fergus, starting in 2022.
- **Scenario A**
  A conservative profile representative of a slow decarbonisation effort. The maximum CO_2 rate is 8.6Mt/yr, with cumulative emissions captured of 255Mt from 2022 to 2060.
- **Scenario B**
  A more optimistic decarbonisation pathway for the UK with a more rapid uptake of hydrogen as an energy vector and CCS for industry. The maximum CO_2 rate 16Mt/yr, with cumulative emissions captured of 450Mt from 2022 to 2060.

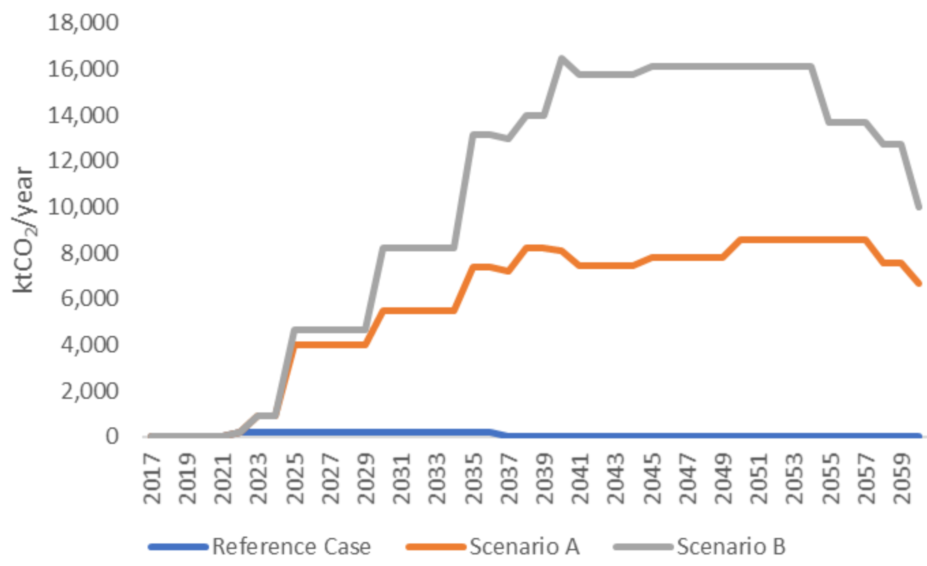


Figure 3-1: A comparison of three potential CO_2 supply options for Acorn CCS.

Assessing Likely CO_2 Supplies

There are high levels of uncertainty regarding the future energy landscape and therefore what emissions sources are likely to exist, so a scenario-based approach provides a way to describe a range of potential future context for the ACT Acorn project.

This Deliverable includes an inventory of existing emissions sources, based on data from the Scottish Pollutant Release Inventory (Scottish Environmental Protection Agency, 2017). The inventory was compiled and screened for those sites with capture potential of over 100,000t/yr within 50km of Feeder 10.

This portfolio of existing emitters was then overlain with known planned emissions sources and possible new emissions sources. These future emissions include those within Scotland, at St Fergus and Grangemouth, as well as those that could be imported by ship from Teesside and Rotterdam via Peterhead Port, as detailed in the CO_2SAPLING PCI bid, (Pale Blue Dot Energy, 2017).

The CO_2 supply options established in this Deliverable are the ones used for the design of the St Fergus capture facilities, the storage development plans, the economic analysis for the project, the build out vision and the life cycle assessment of ACT Acorn.

Deliverable Direct Link:

ACT Acorn CO_2 Supply Options Report

3.1.2 ACT Acorn Basis of Design for St Fergus Facilities

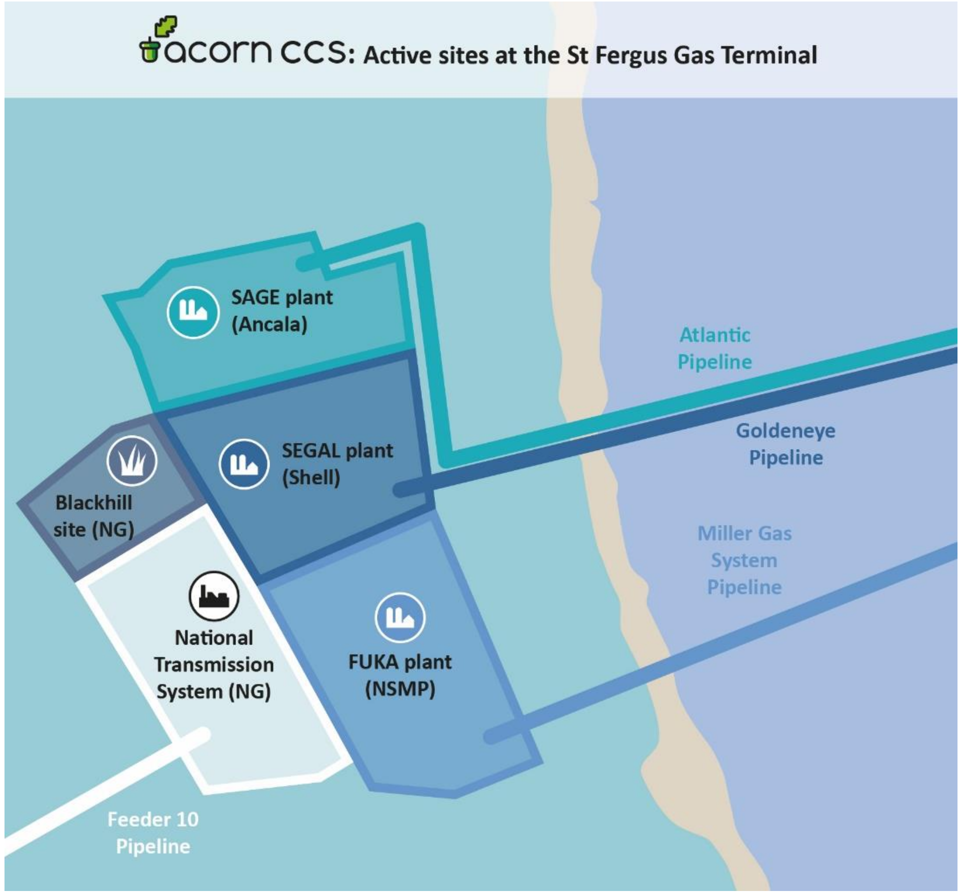


Figure 3-2: The Active Sites at the St Fergus Gas Terminal (NG is National Grid and NSMP is for North Sea Midstream Partners)

The St Fergus Gas Terminal contains four key terminal sites that emit around 570,000t/yr of CO_2 from burning natural gas for heating and power generation during the gas processing operations. This makes St Fergus one of the largest emissions locations in Scotland.

This Deliverable considers the potential for capturing around 200,000t/yr of CO_2 emissions from the St Fergus Gas Terminal, making a useful contribution to reducing existing CO_2 emissions in Scotland, but even more importantly, using this modest quantity of CO_2 to initiate a 2Mt/yr CO_2 transport and storage infrastructure hub at St Fergus which can be used by other, much larger CCS projects well into the future.

This Deliverable is a relatively technical document, establishing the design basis and conceptual design options for the capture and compression facilities required to capture CO_2 from major point sources at the St Fergus Gas Terminals, and to condition that CO_2 for offshore transport and injection.

Interestingly, at St Fergus there is an existing gas sweetening plant that has been separating CO_2 from natural gas at the SAGE terminal for 20 years. Within the next few years it will no longer be required for this purpose, and so this Deliverable considered the potential for reusing the SAGE CO_2 plant for separating CO_2 from flue gases for Acorn CCS, but at this point it looks a lot more likely that a new build capture facility would be required. Space exists to build a standalone capture plant, which would have the advantage of being purpose built, new and in a location to optimise collection of CO_2 emissions from multiple sites.

Deliverable Direct Link:

ACT Acorn Basis of Design for St Fergus Facilities Report

3.1.3 ACT Acorn Plan and Budget for FEED

All the detailed studies that have been completed under the ACT Acorn work programme were designed to progress components of the Acorn CCS project through the feasibility stages of project design, in preparation for the next phase of major activity known as FEED.

This Deliverable outlines the activities, resources and effort required to deliver the FEED stage. It also covers the remaining feasibility level activities outside the scope of the ACT Acorn work programme that must be completed before FEED can commence.

Additional Concept Phase Activity

The ACT Acorn work programme has allowed for approximately 5% project definition, (AACE International, 2016), for Acorn CCS. Additional work is required before the project can commence FEED. In particular, the preferred options for CO_2 capture and storage must be selected, several key commercial agreements must be put in place and a more comprehensive plan for FEED completed. This Concept Stage activity would increase the project definition to around 15–20%. It is estimated to require 12,300 man-hours of activity and cost around £1.6million.

FEED Activity

The FEED programme will add considerable definition to the project and by the time the programme is completed the project definition deliverables should be at 80-90% maturity. The FEED programme is estimated to require 66,000 man-hours of activity and cost approximately £15.3million.

Illustrative examples of the project organisation required for FEED and an outline execution strategy are proposed within this Deliverable. Key roles have been identified. A notable element of the Concept stage work is to finalise the plan for FEED.

Deliverable Direct Link:

ACT Acorn Plan and Budget for FEED Report

3.1.4 ACT Acorn Feeder 10 Business Case

National Grid's National Transmission System (NTS) No. 10 Feeder for gas is a 280km long 900mm (36") diameter buried steel pipeline which currently runs from the onshore natural gas terminal facilities at St. Fergus to the existing compressor station at Avonbridge, near Bathgate . It is more commonly known as Feeder 10, (ScottishPower CCS Consortium, 2011).

The Feeder 10 pipeline has been studied by two previous Scottish CCS projects looking to change the pipeline use to transport CO_2 from Scotland's industrial Central Belt to St Fergus for offshore storage.

The FEED study from the first UK CCS Demonstration Competition, known as "Demo1", (ScottishPower CCS Consortium, 2010), and analysis completed for Captain Clean Energy Project (CCEP) in the second UK CCS Demonstration Competition, known as "Demo 2", (Captain Clean Energy Limited, 2012), were both reviewed and refreshed for this report.

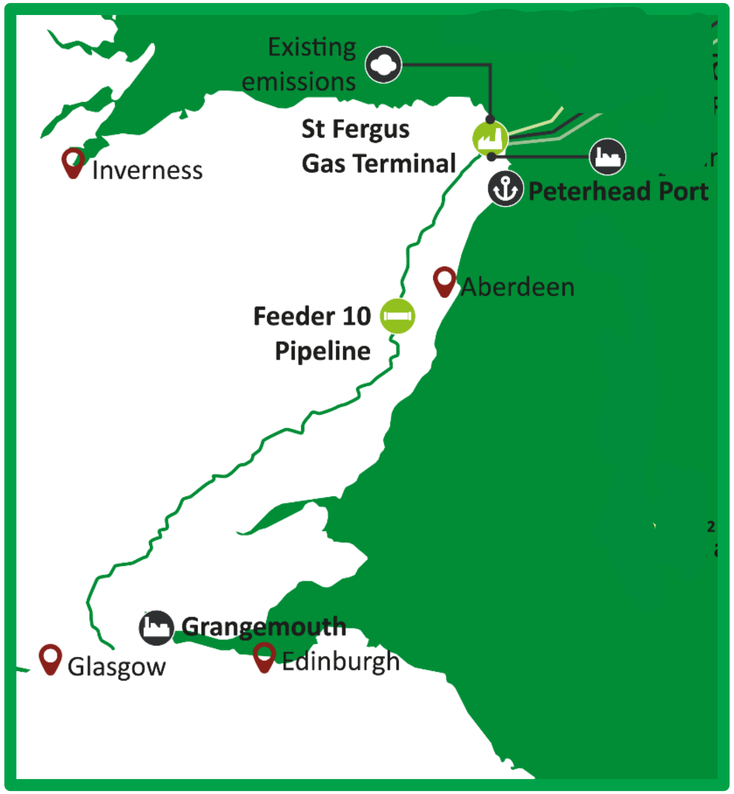


Figure 3-3: The Feeder 10 pipeline linking Avonbridge and the St Fergus Terminal

This Deliverable provides the following key insights:

- A summary of the Feeder 10 pipeline status including its current ownership and potential for reuse;
- An outline functional specification;
- A summary assessment of the cost associated with change of use of Feeder 10;

- An outline value proposition and preliminary economics for CO_2 transport through the line;
- An outline of potential alternatives for changes of use and ownership;
- A summary of the key issues, risks and challenges to the repurposing of the pipeline;
- Recommendations for further work and next steps in the transition process.

Preliminary studies conducted by National Grid for the CCEP showed that Feeder 10 could transport up to 6Mt/yr CO_2. With additional in line compression along Feeder 10, the potential exists to increase capacity to around 10Mt/yr with CO_2 remaining in gas phase and within operating limits of the pipeline, (CO2DeepStore, 2012).

Deliverable Direct Link:

ACT Acorn Feeder 10 Business Case Report

3.1.5 ACT Acorn Economic Model Documentation

This Economic Model Documentation Deliverable should be read together with the Acorn Full Chain Development Plan and Budget where all the cost assumptions for Acorn Phase 1 are documented, it also builds on a lot of the analysis completed in other ACT Acorn reports to populate and run the economic model in different scenarios.

The Deliverable consists of an overview report that provides a detailed rationale for the Acorn CCS economic model along with the key results and analysis from the model and a few supplementary documents:

- A decision focussed economic model built in Excel that is capable of being run in probabilistic or deterministic mode and of running multiple scenarios;
- A user guide for the economic model, contained within the Annex of the summary report;
- A data input book, which explains the calculation of a range of value metrics, contained within the Annex of the summary report.

The Key Figures

Phase 1 requires a capital investment of £276 million and an estimated operating expenditure of £341 million over the 20-year evaluation horizon. To cover this investment and the cost of capital, a payment of £629 million (spread over 20 years) from Government has been assumed in Phase 1, along with a service fee of £30/t charged to the CO_2 emitter. In total, this equates to approximately £184/t during Phase 1.

In Phase 2, a transport and storage fee of £19/t enables the build out of Acorn CCS to achieve an 8% rate of return and the Government to recover its investment from Phase 1 via a clawback mechanism.

The transport and storage fee required for Phase 2 to achieve the economic return is heavily influenced by the assumed level of Government cost recovery. This ranges from £19/t for 100% recovery to £12/t if there is no cost recovery.

The timing, pace and cost of this expansion phase are synchronised with the speed and scale of decarbonisation in the UK – Acorn CCS is designed to grow on a "just-in-time basis. The capital and operating costs for Phase 2 are highly dependent upon the level of CO_2 supply and demand for transport and storage services. One sensitivity examined a scenario in which demand was 73% less than the reference case and this resulted in a 69% reduction in the costs.

For ACT Acorn, the overall commercial model adopted is one of a utility type service with a capped rate of return. The modelling assumes an 8% cost of capital and nominal discount rate.

Deliverable Direct Link:

ACT Acorn Economic Model and Documentation Report

3.1.6 ACT Acorn Full-chain Development Plan and Budget

This Deliverable draws together several strands of analysis from other ACT Acorn Deliverables in order to complete a detailed reference case, development plan and cost estimate for the first phase of Acorn CCS.

Acorn Phase 1

The plan and budget for Phase 1 of Acorn CCS include the following pieces of infrastructure:

- A new amine-based CO_2 capture, conditioning and compression system with an initial capacity of up to 280kt/yr CO_2;
- Reuse of the offshore Atlantic pipeline with a throughput capacity of up to 5-6Mt/yr CO_2 in dense phase;
- A new infield pipeline to optimise the injection well location;
- A new subsea umbilical and manifold to provide power, control and connections for additional wells;
- A new subsea well capable of injecting at rates ranging from 0.2Mt/yr to 2Mt/yr to cover the requirements of Phase 1 as well as subsequent phases.

The capital investment required for Phase 1 is estimated to be between £193 - 387 million, with a reference figure of £276 million, including contingency.

The schedule in Figure 3-5, shows a final investment decision (FID) in 2020, enabling commercial operations to commence in 2023.

The schedule also shows that the engineering and design phase, appraisal and contracting activities required before FID will take slightly more than 2 years to complete. Procurement and construction follow FID and take place over a 2.5 year period.

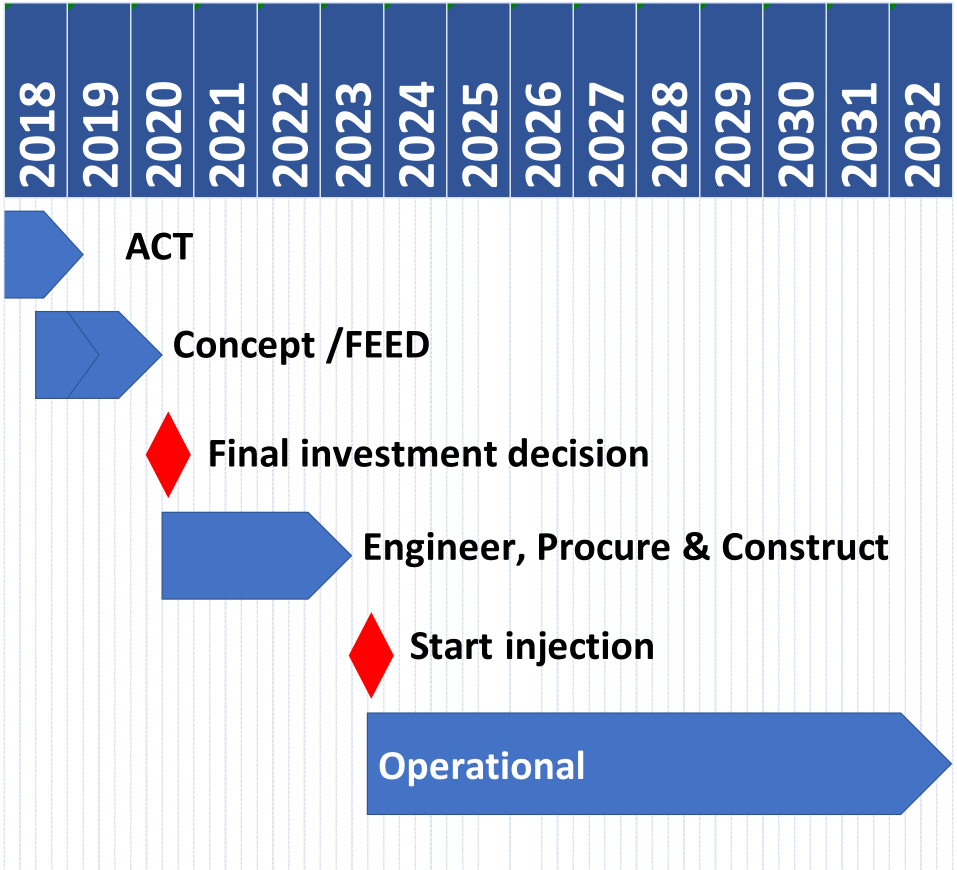


Figure 3-4: The Acorn CO_2 Storage Site project schedule

The key technical risks associated with Phase 1 at the time of writing this Deliverable were:

- Integration with the existing onshore operations;
- Managing pipeline operations during start up and shut down;
- Demonstrating pipeline integrity for the life of the project;
- The need for CO_2 filtration at the injection site;
- Operation of the second phase including additional well(s).

The timing of additional quantities of CO_2 for the build-out phase of Acorn CCS, will depend on the decarbonisation route taken by the UK. However, the work undertaken in the CO_2 Supply Options, see Section 3.1.1, indicates that additional CO_2 should arrive at St Fergus by 2024. Further details of the likely expansion opportunities open to, and created by, Acorn CCS are available in the ACT Acorn Expansion Options Deliverable described below.

Deliverable Direct Link:

ACT Acorn Full Chain Development Plan and Budget Report

3.1.7 ACT Acorn Expansion Options Report

The ACT Acorn Expansion Options Report is focused on the future phases or 'build-out' opportunities for the Acorn CCS project. This Deliverable contains the detailed analysis and research that has allowed Acorn CCS to articulate an exciting, but also realistic vision for developing the project, including CO_2 ship import, hydrogen generation, bioenergy and CO_2 utilisation.

This Deliverable provides the detailed thinking that sits behind the 2025 vision for Acorn CCS presented in the ACT Acorn Webinar, (ACT Acorn, 2018), and the recent discussions around build-out potential during the Final Event presentation and Q&A session, (ACT Acorn, 2019).

Key Findings

The St Fergus Gas Terminal is an ideal location for a CCS hub, with a rich oil and gas heritage, continuous gas throughput, access to suitable, reusable pipelines for CO_2 transportation offshore, and proximity to world class CO_2 storage. St Fergus will most likely be one of three or four key coastal hub locations for CCS across the UK.

Although the first phase of Acorn CCS is only likely to involve modest CO_2 emissions captured directly from the St Fergus site, by enabling the rapid commissioning of approximately 5-6Mt/yr of offshore CO_2 transport and storage infrastructure, Acorn CCS becomes an exciting enabler for much wider decarbonisation efforts:

Hydrogen Generation: Acorn enables the potential for hydrogen manufacture at St Fergus as an initial step in decarbonising gas in the UK. Natural gas would be used in Steam Methane Reformers to produce hydrogen whilst capturing the CO_2. Hydrogen can then be exported in the gas transmission system or used locally, whilst the CO_2 created during the process is transported and stored offshore. As an important natural gas import facility, with access to nearby CO_2 storage facilities and three redundant (but reusable) offshore pipelines, St Fergus is a great location to initiate hydrogen production by decarbonising natural gas.

Importing CO_2 by Ship: The report lays out initial details for importing CO_2 by ship via Peterhead Port and transferring it by pipeline via Peterhead Power Station to St Fergus in a new pipeline designed for carrying liquid phase CO_2 at around 120bar.

The power station is included to provide land for facilities, access to waste heat for warming the imported CO_2 and provision of power and utilities.

Peterhead Port has plenty of capacity for the import quantities of CO_2 envisaged for the early build out phases of Acorn CCS, and a maximum practical capacity of 16.2Mt/yr. For import quantities in the range of 5 to 10Mt/yr, a fleet of three or four tankers of 30,000 to 50,000 deadweight tonnage (equivalent to 24,000 to 40,000 tonnes CO_2) size will be required to service routes from CO_2 export hubs within the North Sea area.

Decarbonising Scottish Industry: The ACT Acorn Feeder 10 Business Case Deliverable confirmed that Feeder 10 was a viable route to transport CO_2 emissions from Scotland's industrial Central Belt to St Fergus for offshore transportation and storage. Analysis has shown that 90% of Scotland's large-site CO_2 emissions are located within 50km of the Feeder 10 pipeline. The emission intensive area of Grangemouth presents the best location in Scotland for developing carbon capture and usage (CCU) opportunities, with the potential link to higher volumes of CO_2 captured and transported through Feeder 10 to the Acorn project.

Bioenergy: The opportunities for physical linkage of bioenergy projects with Acorn CCS are limited bar a handful of existing large-scale bioenergy plants in the Grangemouth Region. However, considerable opportunity exists for development of synergies and the development of bioenergy as part of the integrated energy mix, which includes consideration of CO_2 emissions and new energy vectors such as hydrogen.

Deliverable Direct Link:

ACT Acorn Expansions Options Report

3.1.8 ACT Acorn Outline Environmental Impact Assessment

The ACT Acorn Outline Environmental Impact Assessment (EIA) Deliverable provides a brief assessment of the possible environmental impacts of Acorn CCS and a summary of relevant permits and consents likely to be required by the project.

Understanding whether an EIA was likely to be required from Aberdeenshire Council was an important outcome from this work. The provisional view from Aberdeenshire Council is that an EIA will be necessary, which will require the EIA and respective Onshore Environmental Statement and Offshore Environmental Statement to be completed during the FEED stage of project development.

The current assessment of both the onshore environmental impact and offshore environmental impact for Acorn CCS indicates minimal impact beyond current activities.

The reuse of the Atlantic pipeline for the transportation of CO_2 for Acorn CCS Phase 1 will result in a lower environmental impact when compared to the need to install a new pipeline.

This Deliverable draws heavily on a previous CCS study commissioned by CO_2DeepStore, (Pefrofac Engineering Limited, 2012), and the EIA completed by BG for the Atlantic and Cromarty Decommissioning Programme, (BG Group, 2016). For readers interested in the most up-to-date work in this area, since the publication of this Deliverable, Pale Blue Dot Energy have undertaken further studies on behalf of the Scottish Government to understand and map out more details behind the various consents and permits influencing Acorn CCS and CCS in Scotland. The executive summary of this work should be available on the Scottish Government website soon.

Deliverable Direct Link:

ACT Acorn Outline Environmental Impact Assessment

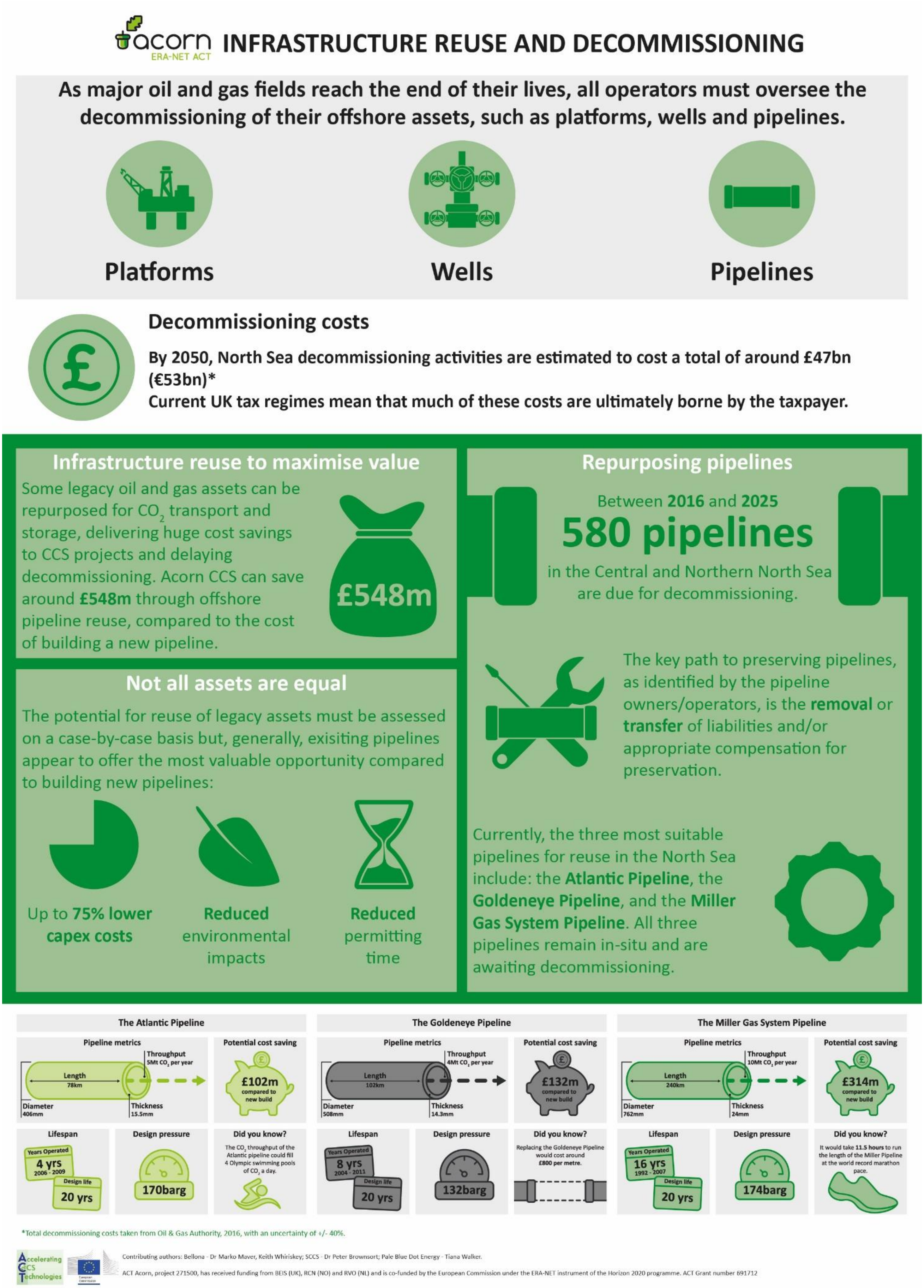
3.2 Useful Links

The Acorn Options Web Section

The Acorn Options Video Presentation

The Acorn Options Infographic

ACT Acorn Webinar: Acorn 2025: A pathway to decarbonising the UK


acorn
ERA-NET ACT
INFRASTRUCTURE REUSE AND DECOMMISSIONING
As major oil and gas fields reach the end of their lives, all operators must oversee the decommissioning of their offshore assets, such as platforms, wells and pipelines.
Platforms
Wells
Pipelines
Decommissioning costs
By 2050, North Sea decommissioning activities are estimated to cost a total of around £47bn (€53bn)*
Current UK tax regimes mean that much of these costs are ultimately borne by the taxpayer.
Infrastructure reuse to maximise value
Some legacy oil and gas assets can be repurposed for CO2 transport and storage, delivering huge cost savings to CCS projects and delaying decommissioning. Acorn CCS can save around £548m through offshore pipeline reuse, compared to the cost of building a new pipeline.
£548m
Repurposing pipelines
Between 2016 and 2025
580 pipelines
in the Central and Northern North Sea are due for decommissioning.
The key path to preserving pipelines, as identified by the pipeline owners/operators, is the removal or transfer of liabilities and/or appropriate compensation for preservation.
Not all assets are equal
The potential for reuse of legacy assets must be assessed on a case-by-case basis but, generally, exisiting pipelines appear to offer the most valuable opportunity compared to building new pipelines:
Up to 75% lower capex costs
Reduced environmental impacts
Reduced permitting time
Currently, the three most suitable pipelines for reuse in the North Sea include: the Atlantic Pipeline, the Goldeneye Pipeline, and the Miller Gas System Pipeline. All three pipelines remain in-situ and are awaiting decommissioning.
The Atlantic Pipeline
Pipeline metrics
Throughput 5Mt CO2 per year
Length 78km
Diameter 406mm
Thickness 15.5mm
Potential cost saving
£102m compared to new build
Lifespan
Years Operated 4 yrs 2006 - 2009
Design life 20 yrs
Design pressure
170barg
Did you know?
The CO2 throughput of the Atlantic pipeline could fill 4 Olympic swimming pools of CO2 a day.
The Goldeneye Pipeline
Pipeline metrics
Throughput 4Mt CO2 per year
Length 102km
Diameter 508mm
Thickness 14.3mm
Potential cost saving
£132m compared to new build
Lifespan
Years Operated 8 yrs 2004 - 2011
Design life 20 yrs
Design pressure
132barg
Did you know?
Replacing the Goldeneye Pipeline would cost around £800 per metre.
The Miller Gas System Pipeline
Pipeline metrics
Throughput 10Mt CO2 per year
Length 240km
Diameter 762mm
Thickness 24mm
Potential cost saving
£314m compared to new build
Lifespan
Years Operated 16 yrs 1992 - 2007
Design life 20 yrs
Design pressure
174barg
Did you know?
It would take 11.5 hours to run the length of the Miller Pipeline at the world record marathon pace.
*Total decommissioning costs taken from Oil & Gas Authority, 2016, with an uncertainty of +/- 40%.
Accelerating CCS Technologies
Contributing authors: Bellona - Dr Marko Maver, Keith Whiriskey; SCCS - Dr Peter Brownsort; Pale Blue Dot Energy - Tiana Walker.
ACT Acorn, project 271500, has received funding from BEIS (UK), RCN (NO) and RVO (NL) and is co-funded by the European Commission under the ERA-NET instrument of the Horizon 2020 programme. ACT Grant number 691712

4.0 Infrastructure Reuse and Decommissioning

The reuse of suitable legacy oil and gas infrastructure can offer substantial cost and time savings for CCUS deployment, both in the UK and across Europe. This important research theme for the ACT Acorn programme examines where the most value can be achieved from infrastructure reuse and delayed decommissioning, as well as the policy frameworks and structures needed to help support and incentivise a serious, European wide approach to identification and preservation of valuable infrastructure.

A more detailed examination of the cost and technical issues around the reuse of three offshore pipelines for Acorn CCS is also presented under this theme. These findings allow Acorn CCS to be used as a case study to raise awareness amongst infrastructure owners and governments of the huge potential value of these three pipelines and other assets that may soon be available across the North Sea.

4.1 Deliverable Summaries

4.1.1 ACT Acorn Policy Options

The ACT Acorn Policy Options Deliverable first considers the potential and rationale for the reuse of existing infrastructure, concluding that while the potential for reuse must be considered on a case-by-case basis, generally, the use of existing oil and gas pipelines can offer the greatest value to future CCS projects. In the case of Acorn CCS, the project can save approximately £548m by reusing three offshore pipelines compared to the cost of building these pipelines as new.

Assessing Infrastructure Value

Recognising the huge quantities of legacy infrastructure in the North Sea that are currently, or soon will be, up for decommissioning, the Deliverable provides a useful methodology for valuing infrastructure for potential use in the CO_2 value chain, including existing wells, topsides, and pipelines.

The Deliverable also tabulates the risks associated with infrastructure reuse, including technical reuse specifications, mothballing requirements, timing of future use and liability transfer, and contrasts this with illustrative costs of new infrastructure to replace decommissioned infrastructure, including development costs, timelines and permitting requirements.

Recommendations

Short, helpful assessments of the current infrastructure preservation and build-out options in the UK, the Netherlands and in Norway, help to highlight current ‘at risk’ infrastructure and provide estimated decommissioning timelines. Two critical issues frequently brought up in relation to infrastructure reuse are considered:

- The different options for CO_2 transport and storage operator ownership by Public Private Partnership (PPP) as compared to a direct State Contractor;
- Management of liability in CO_2 transport and storage networks.

Detailed discussion and practical examples from both these areas can be found in the annex of the Policy Options Deliverable.

Whilst the authors recognise that there is no one-size-fits-all business model for developing CO_2 transport and storage infrastructure in Europe, and that different models are effective for different stages of development and national and regional contexts, they conclude that significant state underwriting, and possible intervention to identify and retain valuable existing infrastructure is required.

A strong policy recommendation that emerged from this work was the support for a collection of, most likely state owned, CO_2 Development Organisations (CDO's) to take the lead in developing CO_2 transport and storage infrastructure in different regions across Europe. Recognising that development of strategic infrastructure in a cost-effective manner requires close cooperation between governments and industry (Zero Emissions Platform, 2015), the Deliverable recommends some type of CDO, in the form of state backed/owned companies, as offering the best way to remove counter-party risks that have previously impeded CCS development in Europe.

Deliverable Direct Link:

ACT Acorn Policy Options Report

4.1.2 ACT Acorn Infrastructure Reuse

This Deliverable is particularly focused on providing the rationale for the preservation of the three offshore pipelines currently under consideration for use on the Acorn CCS project: the Atlantic, Goldeneye, and Miller Gas System pipelines, all of which are currently under an Interim Pipeline Regime awaiting decommissioning.

Case Studies

The report presents each of these pipelines as a detailed case study, exploring their operating envelopes and technical specifications, repurposing requirements, estimated repurposing costs and key risks, as well as the views and needs of key stakeholders. The report concluded that these three pipelines currently offer three of the most suitable pipelines for reuse in the North Sea.

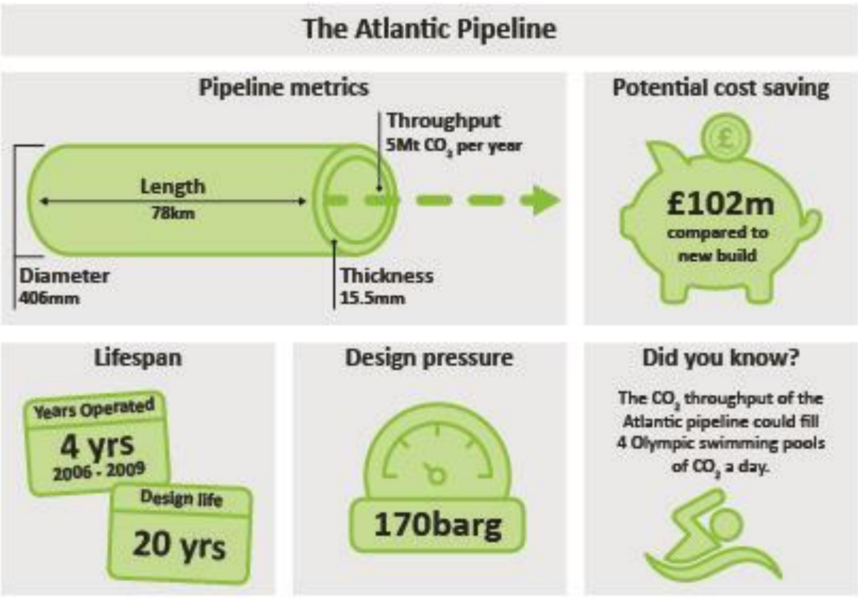


Figure 4-1: The vital statistics of the Atlantic pipeline, one of the three most suitable pipelines in the North Sea for reuse as CO_2 transport infrastructure

Literature Review

A literature review on the infrastructure reuse opportunity helps clarify some of the parameters around the economics of reuse and infrastructure preservation, set in the context of the enormous decommissioning programmes already underway in the North Sea. It also reveals some encouraging studies on the potential value of pipeline reuse which demonstrate that the reuse of pipeline can be worth five times, or more, the scrap value of the steel, if reusing the pipelines means that new ones do not have to be built (Benton, 2015).

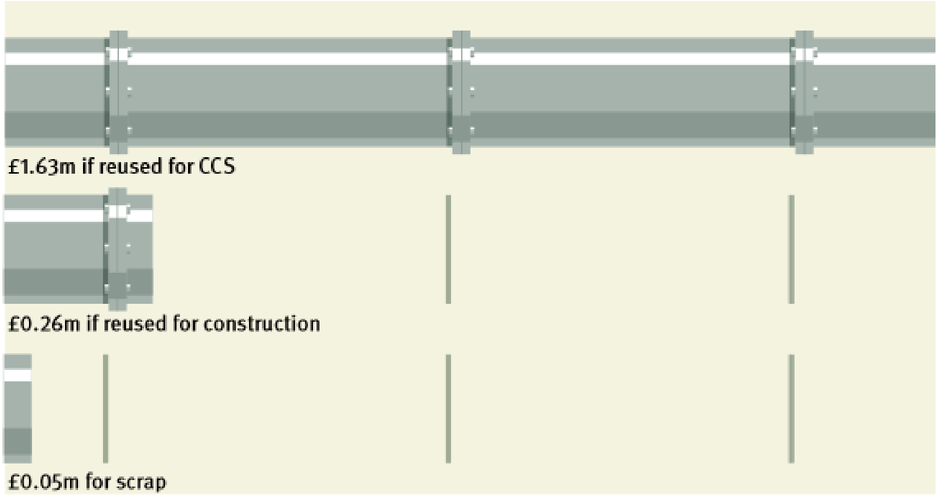


Figure 4-2: Reusing pipelines, (values per km): (Benton, 2015)

Risks and Liability

The potential for reuse of existing pipelines as compared to building new ones for CCS projects is usually determined by a cost versus risk trade-off. While the risks appear higher with existing pipelines, the costs are lower. Corrosion is identified as the largest potential technical risk. This could be an issue when CO_2 from multiple sources is combined. It will be critical to ensure that capture plants meet the required CO_2 purity levels, and this will need reconfirmed before CO_2 is transported through the existing pipeline. When pipelines are deemed suitable for reuse, the risks are believed to be manageable, which together with the lower associated repurposing costs should outweigh the higher costs of building new pipelines and infrastructure.

Delaying decommissioning and reusing existing infrastructure offers deferral of decommissioning costs and significant cost savings to CCS project developers. In addition, it can enable smaller industrial players that might otherwise not be able to justify stand-alone projects, to take up CCS. However, preservation of infrastructure is not likely to occur without government support and appropriate compensation to the asset owners for costs incurred due to prolongation of asset life.

Clarity on liability provisions, particularly when ownership of assets is transferred is key. PPP has been identified as the best suited model, whereupon assets are transferred into public ownership, with the government taking on all the associated risks and liabilities. Investments in repurposing and modifications would be paid for by the private sector, with investments incentivised, for example, by making them tax deductible.

Deliverable Direct Link:

ACT Acorn Infrastructure Reuse Report

4.2 Useful Links

The Infrastructure Reuse Web Section

The Infrastructure Reuse Video Presentation

The Infrastructure and Reuse Infographic

ACT Acorn Webinar: Acorn 2025: A pathway to decarbonising the UK

ACT Acorn Well Reuse Factsheet

ACT Acorn Facilities Reuse Factsheet

ACT Acorn Pipeline Reuse Factsheet

Figure 4-3: ACT Acorn Final Event participants encouraged #PipeUp4Reuse by special guest Chair Kirsty Blackman MP. Image credit: Indira Mann, SCCS

CCS AND A JUST TRANSITION

What role, if any, do stakeholders and citizens think carbon capture and storage (CCS) has in helping achieve a more environmentally sustainable future in regions where workers and economies rely on carbon intensive industries?

Achieving a 'just transition' to 2050

Data collected from a combination of in-depth stakeholder interviews and wider citizen and stakeholder focus groups.
Three high-emitting industrial areas bordering the North Sea with the potential for CCS.

North East Scotland findings

Benefits and public interest
Questions around who benefits from CCS and how to manage CCS developments in the public interest.

Respect for workers
Strong sense of identity and history comes from the oil and gas industries that needs to be valued.

Infrastructure reuse
Infrastructure reuse can help transform an area, stakeholders instantly make connections with decommissioning.

Wider implications for other regions

Role for local government
Expectation that city/regional governments should take the lead in setting out local pathways for a just transition.

Lack of understanding
In carbon-intensive regions with limited connection to subsurface oil and gas activities, understanding of the role of CCS in a just transition is less apparent.

Site-specific infrastructure
Although CCS is a very flexible technology, there were strong feelings in the Netherlands that the equipment is highly site-specific and will not help establish a just transition in every carbon-intensive region.

Acorn CCS in context

Developing Acorn CCS to become an open CO_2 transport and storage hub reduces risks and improves the business case for Acorn CCS itself and wider European CCS projects.

Acorn CCS and a European CCS Network will facilitate the creation of climate-proof industrial clusters that can withstand growing political and financial pressures associated with climate concerns of the 21st century.

By promoting a cross-sectoral just transition, Acorn CCS helps transform a key fossil fuel industry into an essential part of the zero carbon economy.

Accelerating CCS Technologies

Contributing authors: Bellona - Jan-Justus Andreas; Radboud University - Floris Swennenhuis; Robert Gordon University - Dr Leslie Mabon, Yi-Chen Huang

ACT Acorn, project 271500, has received funding from BEIS (UK), RCN (NO) and RVO (NL) and is co-funded by the European Commission under the ERA-NET instrument of the Horizon 2020 programme. ACT Grant number 691712

5.0 CCS and a Just Transition

This research theme explores the role of CCS in addressing climate change and sustainability challenges in cities and regions that remain heavily reliant on carbon intensive industries for employment and as an economic base.

The Deliverable for this theme draws on multiple sources of data collected from a combination of in-depth stakeholder interviews and wider citizen and stakeholder focus groups, held in three high emitting industrial areas bordering the North Sea with the potential for CCS.

5.1 A Just Transition

The concept of a ‘just transition’ has been adopted in a variety of ways, depending on the stakeholders and geographies involved. For the purposes of the ACT Acorn research we were keen to explore how stakeholders with a growing interest in a ‘just transition’ for carbon intensive regions understood CCS. We also explored understanding of the role that CCS could play in helping ensure locations and workers traditionally dependent on carbon intensive activities are not left behind in the transition to clean energy and a more sustainable economy.

5.2 Research Methods

The three carbon-intensive regions bordering the North Sea that were assessed were: Aberdeen and North East Scotland, the Rijnmond and Rotterdam Harbour area in the Netherlands; and some emission-intensive areas of Norway.

The small European research team used in-depth interviews with key stakeholders from the relevant regional and national governments, trade unions, environmental organisations, industry, and research, development and innovation organisations spread over the three locations. There were also focus groups with stakeholders and informed citizens in North East Scotland; and stakeholder workshops in Europe.

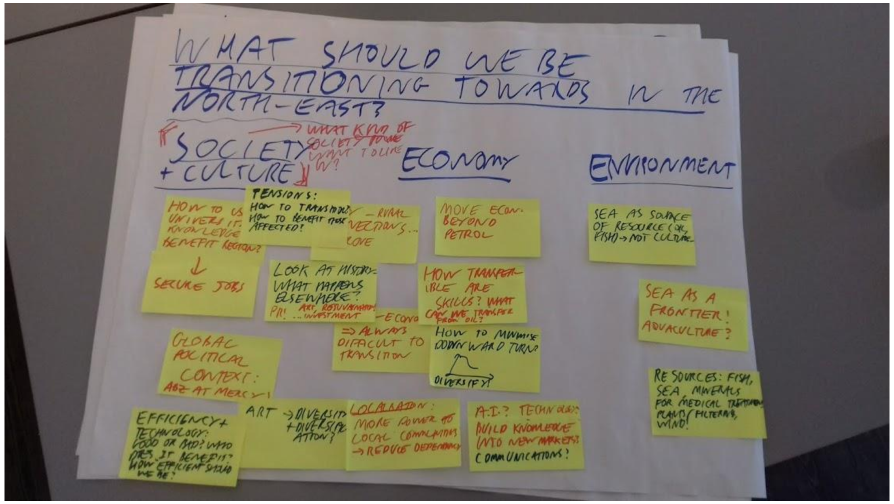


Figure 5-1: Identifying common themes and issues during a Scottish stakeholder focus group. Image credit: Leslie Mabon, Robert Gordon University

5.3 Key Findings

There was some variation in results across the different regions. This highlights a key discussion point raised in the Dutch studies: that CCS was a relatively site-specific technology that might not help establish a just transition in every carbon-intensive region. However, there was also particularly useful learning for future CCS project development:

- Consistent feedback was expressed on the need for a stronger empirical evidence base and much clearer articulation of how existing skills within carbon-intensive industries can be matched with those required for large-scale CCS deployment. The need for improved engagement and communication with key stakeholders such as trade unions and environmental/civil society organisations was evident, particularly in the Scottish sessions.
- The importance of a public interest case for CCS was a relatively consistent theme, also the belief that local or regional government should be the key stakeholder taking the lead in setting out local pathways towards a just transition.
- Suggestions that CCS could be framed positively in terms of being just one part of a wider suite of measures, which could help to transition society to a more sustainable format. This goes beyond carbon reduction to also consider how to govern energy infrastructure in a way that brings benefit to society.
- On a related theme, in workshops it was very clear that many stakeholders draw a strong sense of identity and history from the carbon-intensive industries that have been so fundamental to their region. The importance of recognising and valuing this was evident, but also presents an opportunity for climate change mitigation via CO_2 storage to leverage the existing local pride and identity associated with having developed the North Sea.
- Concerns around technological / scientific risk seemed much less relevant for CCS in the north east of Scotland given the established strengths of subsea and subsurface oil and gas operations. However, apathy towards CCS in relation to renewables and/or suspicion of the motives of private sector operators may prove to be bigger barriers than concerns over the risks associated with the technology.
- Smaller scale initiatives such as Acorn CCS have a significant role in proving the viability of CCS to reach deployment and form part of a just transition.

Deliverable Direct Link:

ACT Acorn Societal Acceptance Report

5.4 Useful Links

CCS and a Just Transition Web Section

CCS and a Just Transition Video Presentation

CCS and a Just Transition Infographic

ACT Acorn Webinar: Acorn 2025: A pathway to decarbonising the UK

UNLOCKING UNDERGROUND CO_2 STORAGE

CO_2 storage site selection

574

In the CO_2Stored database, the UK has 574 possible storage sites offering 78Gt or 200 years of the UK's total CO_2 emissions at 2016 levels.

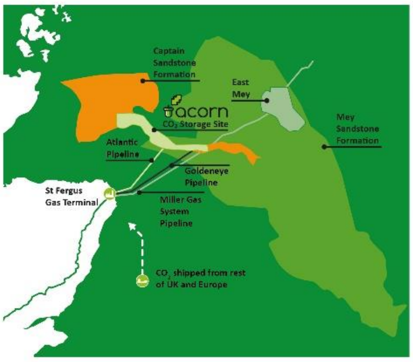
113

113 sites (23.8Gt) are within 50km of existing target pipelines.

Acorn CO_2 Storage Site preselected based on previous Energy Technologies Institute (ETI) screening process
www.eti.co.uk/programmes/carbon-capture-storage/strategic-uk-ccs-storage-appraisal

20
Site shortlist

5
Site portfolio, including the Captain Sandstone

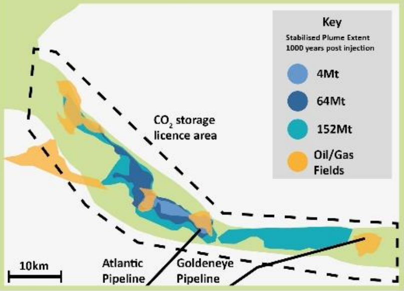


Additional Acorn CCS store required as a back-up and to allow the project to grow.

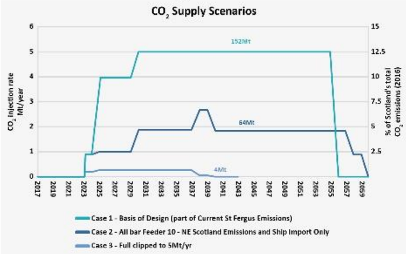
16
Sites passed screening criteria

6
Top sites ranked against screening criteria

Acorn CO_2 Storage Site

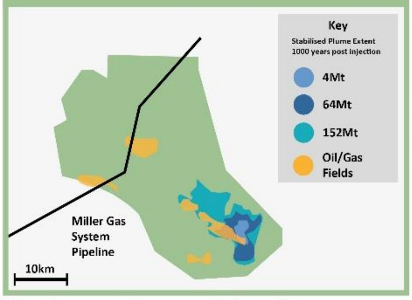


Detailed static and dynamic modelling of both sites



Each supply scenario considered can be accommodated in either storage site.

East Mey Storage Site



Geomechanics and petrology - the structure and chemistry of each CO_2 store and caprock (seal)

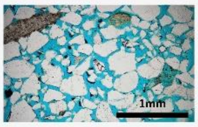
Acorn Caprock/seal: Rodby Shale

Average porosity: 13.8%

Average permeability: 0.00023mD

High content of swelling clay called smectite

Acorn CO_2 Store: Captain Sandstone



Average porosity: 27.6%

Average permeability: 2114mD

Tensile strength of 2 ± 0.19bara

Pore space

Key findings:

- Both storage sites are highly suitable for the injection and long-term storage of CO_2.
- Both the Captain and Mey Sandstones are highly porous and permeable, with rock chemistry that is stable in CO_2-rich conditions.
- The Mey Sandstone has a greater rock strength than the Captain Sandstone due to its lower overall porosity.
- All the samples tested are strong enough to withstand expected pressures/stresses during CO_2 injection operations and long-term storage.

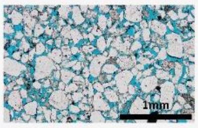
East Mey Caprock/seal: Lista Shale

Average porosity: 15.7%

Average permeability: 0.00026mD

High content of swelling clay called smectite

East Mey CO_2 Store: Mey Sandstone



Average porosity: 24.3%

Average permeability: 471mD

Tensile strength of 3 ± 0.4bara

Pore space

Storage development plan

Acorn CO_2 Storage Site

A low-cost and highly flexible storage solution due to valuable pipeline reuse options, flexible well design and a large, secure CO_2 storage resource with plenty geological data that can be used far beyond Phase 1 of the project.

Storage site area	Secure storage resource	Offshore capital investment
971km²	152Mt CO_2 at 5Mt/yr	£177m
Pipeline	**Well**	**Injection start date**
Reuse of 78km of the Atlantic Pipeline and new 8km pipeline	Initially 1 subsea dual completion well (0.1Mt to 2Mt/yr injection rate)	2023

East Mey CO_2 Storage Site

A large and low-cost storage resource that is accessible by existing infrastructure, which could be developed during the 2020s as another, flexible and scalable storage site to allow Acorn CCS room to grow.

Storage site area	Secure storage resource	Offshore capital investment
1,124km²	500Mt CO_2 at 5Mt/yr	£372m
Pipeline	**Well**	**Injection start date**
Reuse of 180km of the Miller Gas System and new 27km pipeline	Initially 1 subsea dual completion well (0.1Mt to 2Mt/yr injection rate)	Possible within the 2020s as a second Acorn CCS store

Contributing authors: Heriot-Watt University: Prof Eric MacKay, Dr Saeed Ghanbari; Pale Blue Dot Energy: Alan James, Hazel Robertson; University of Aberdeen: Dr Clare Bond, Dr Juan Alcalde; University of Edinburgh: Prof Stuart Haszeldine, Dr Niklas Heinemann; University of Liverpool: Prof Richard Worden, Dr Mike Allen

ACT Acorn, project 271500, has received funding from BEIS (UK), RCN (NO) and RVO (NL) and is co-funded by the European Commission under the ERA-NET instrument of the Horizon 2020 programme. ACT Grant number 691712

6.0 Unlocking Underground CO_2 Storage

This theme encompasses a huge body of ACT Acorn work, designed to select, test and develop two underground CO_2 storage sites for the Acorn CCS project.

The work was carried out by technical specialists from four separate research institutions, (University of Aberdeen, Heriot-Watt University, University of Edinburgh and University of Liverpool) together with the Acorn CCS Project Developer, Pale Blue Dot Energy.

The Acorn CO_2 Storage Site (occasionally referred to as Captain X in some early ACT Acorn documentation) was pre-selected as the first Acorn CO_2 store, based on a rigorous site selection process previously carried out by the Energy Technologies Institute, (ETI, 2016). The selection process of the second CO_2 store (required both as a back-up store and to allow the Acorn project room to grow) is fully documented as part of the ACT Acorn programme and forms an important set of Deliverables within this research theme.

The area of the Central North Sea where both the Acorn CO_2 stores are located, benefits from a rich oil and gas legacy, providing the ACT Acorn project access to a long list of potential CO_2 stores, but also valuable data and rock samples to allow the rapid development of the stores once selected.

The programme has made best use of this wealth of data and materials to understand and test the micro structures and minerals present within the different rocks that make up both the CO_2 stores for Acorn (Geomechanics Deliverable), and to create highly detailed 3D models of each store, allowing the simulation of lots of different scenarios of CO_2 injection over time and at different quantities and pressures.

This modelling data and the detailed geomechanics results are combined to make decisions on how to create, manage and monitor each of the Acorn CO_2 storage sites. All this learning then culminates in the creation of a Storage Development Plan (SDP) for each store.

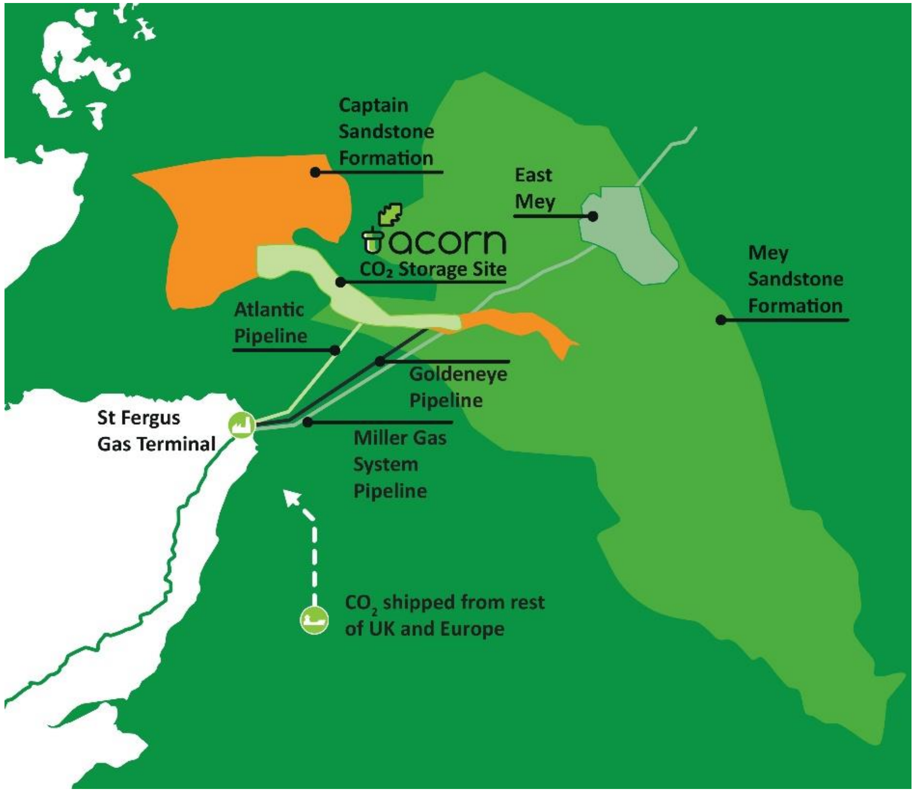


Figure 6-1: The two Acorn CO_2 storage sites highlighted within the wider Captain and Mey Sandstone rock formations

In addition to the five Deliverables summarised here, the Unlocking Underground CO_2 Storage page on the ACT Acorn website contains a treasure trove of supporting files and annexes containing detailed technical data and modelling from the two selected stores. Links to these files are included at the end of this chapter.

6.1 Deliverable Summaries

6.1.1 ACT Acorn Site Screening Methodology Report

This Deliverable outlines the methodology used to create the initial shortlist of possible CO_2 storage sites for the second Acorn store.

The process starts with an examination of the CO_2 Stored database, www.CO2stored.co.uk. This fantastic public resource is a database that contains detailed information on nearly 600 potential CO_2 storage sites currently identified around the UK. When added together, all these possible storage sites offer around 78Gt of CO_2 storage, which is approximately 200 years of the UK's total CO_2 emissions at their 2016 levels.

Perhaps even more impressive, is that 113 of these sites (totalling almost 24Gt) are all located within 50km of the three existing pipelines identified for CO_2 transportation on the Acorn CCS project.

This initial long list of 113 potential CO_2 stores was put through a qualification check which made use of IEAGHG criteria for containment, capacity and injectivity, (IEA Greenhouse Gas, 2009), as well as checking potential sites against the storage objectives from the basis of design such as cost and data availability.

16 sites emerged as promising CO_2 stores from this qualification check, including three different types of store, all complimentary to the original Acorn CO_2 Storage Site (an open aquifer). There was one other open saline aquifer, six confined saline aquifers and three structural/stratigraphic traps.

Deliverable Direct Link:

ACT Acorn Site Screening Methodology

6.1.2 ACT Acorn Site Selection Report

This Deliverable builds on the outputs of the Methodology Report, recording the ranking and reassessment process on the 16 potential CO_2 stores, including a summary of the Site Selection Workshop held with various project team members and external stakeholders to validate the selection process/methodology and a shortlist of six identified sites.

All six shortlisted sites were considered strong candidates for CO_2 stores. A detailed poster, (including seismic sections, well logs, stratigraphic columns and maps), has been published for each potential store; these are accessible via the direct links included at the end of this chapter.

In order to select the final site from the shortlist of six, each site was put through a process of due diligence analysis. The due diligence took account of other data sources independent of the CO_2 Stored database, this included original well log data, technical papers from researchers and oilfield operators, selected analogues and the Petroleum Geo-Services seismic MegaSurvey dataset (PGS, 2017).

This Deliverable concluded with the selection of the East Mey CO_2 Storage Site as the second Acorn CO_2 store. East Mey was deemed to be an excellent CO_2 store because it offers:

- Significant capacity as the storage reservoir can hold very large volumes (in excess of 500Mt) of CO_2
- Excellent injectivity (over 1.5Mt/y per well) as the storage rock is very porous and permeable, so the CO_2 can move easily through it;
- A secure storage site as the cap or sealing rock above the sandstone where the CO_2 is being stored is high quality, proven caprock, there are lots of other sealing layers or secondary containment, and there are good well abandonment practices in the area;
- Access to data, including dynamic data through oil field development in the area;
- De-risked aquifer development, through combining oil field structural traps with the Mey aquifer.

Deliverable Direct Link:
Site Selection Report

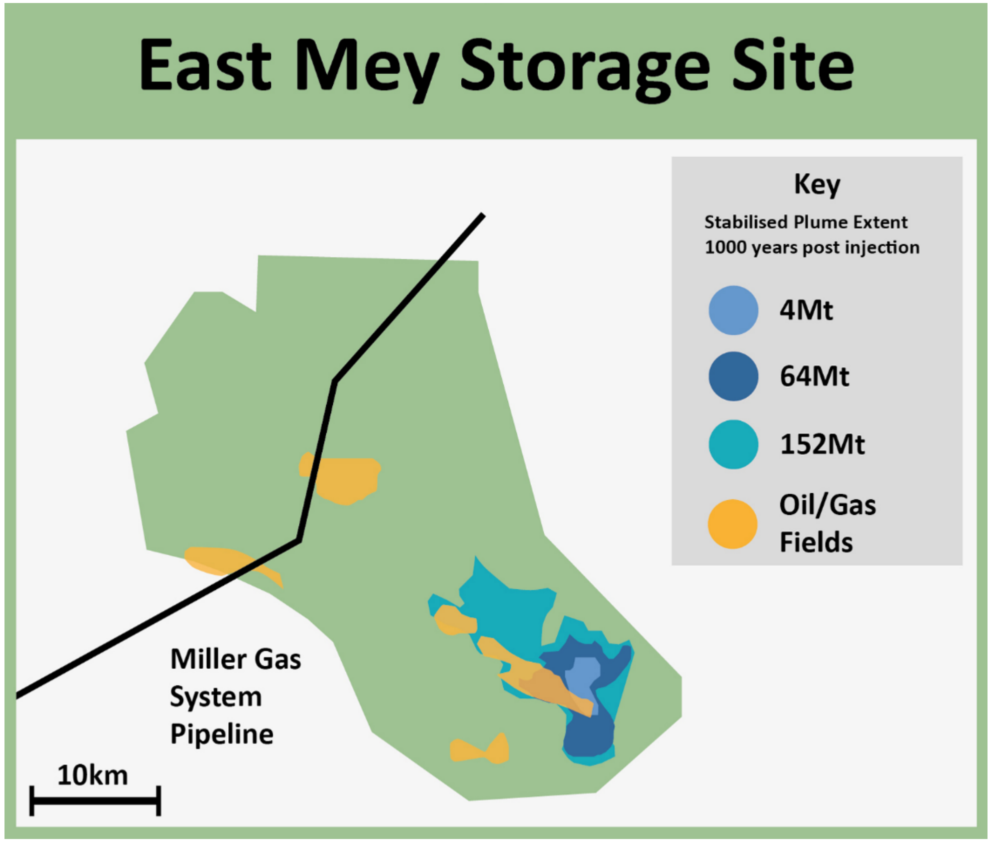


Figure 6-2: The East Mey CO_2 Storage Site - with the different blue plumes showing where different levels of injected CO_2 will be 1000 years after injection ends

6.1.3 ACT Acorn Geomechanics

This Deliverable was completed by the Rock Deformation Laboratory at the University of Liverpool. The team ran experimental geomechanical and petrological investigations on the storage or reservoir rock and the caprock samples from both the Acorn CO_2 Storage site (Captain Sandstone and

Sola/Rodby Shale) and the East Mey CO_2 Storage Site (Mey Sandstone and Lista Shale).

These tests were looking to understand:

- The porosity and permeability of the different rocks - how easily a gas or liquid can move through the rock pores;
- The strength of the rocks;
- The different minerals and chemistry present in the rocks and how they would react to CO_2;
- How the rocks respond to increasing and decreasing pressures over time.

The geomechanical and petrological analyses on the samples obtained from the Acorn CO_2 Storage Site and East Mey CO_2 Storage Site confirmed the following:

Both storage sites are highly suitable for the injection and long-term storage of CO_2.

Both the Captain and Mey Sandstones are highly porous and permeable, with rock chemistry that is stable in CO_2 rich conditions.

The Mey Sandstone has a greater rock strength than the Captain Sandstone due to its lower overall porosity.

All the samples tested are strong enough to withstand expected pressures/stresses during CO_2 injection operations and long-term storage.

The University of Liverpool has taken a novel approach to some of the testing by directly measuring rock strength at different fluid pressures and combining this data with detailed and quantitative rock characterisation data, which was then linked directly to routine, subsurface wireline log measurements.

The aim with this research was to develop a universal best practice for rock strength determination and upscaling, as well as providing valuable inputs into both the Acorn CCS Storage Development Plans.

Deliverable Direct Link:

ACT Acorn Geomechanics Report

6.1.4 Acorn CO_2 Storage Site Development Plan

A Storage Development Plan (SDP) was created for both Acorn CCS CO_2 stores. The SDP is the ‘how-to manual’ for developing each store. The SDP records all the findings from the storage team’s intensive mapping and modelling activities, combined with the detailed knowledge of the rock microstructure and minerals from the geomechanics reports. The SDP also sets out decisions on how we will create, manage and monitor each CO_2 storage site.

The SDPs are living documents that will evolve and develop with the Acorn CCS project, however, the two ACT Acorn SDP Deliverables provide very detailed appraisals of the current plans for development of both the Acorn CO_2 Storage

Site and the East Mey CO_2 Storage Site (see Section 6.1.5), including the budgets and timescales involved for developing both stores.

In the case of the Acorn CO_2 Storage Site SDP, the report draws heavily on the work from the Strategic UK CO_2 Storage Appraisal Project, (ETI, 2016), as a foundation of knowledge around the CO_2 store. For the ACT Acorn CCS programme additional development plan refinement, option evaluation, fundamental work and research has been carried out.

The proposed storage complex for the Acorn CO_2 Storage Site covers an area of 971km^2, extending from the west of the Blake oilfield, to the east of the Goldeneye gas field in the Outer Moray Firth, approximately 80km from St Fergus.

The work undertaken for the ACT research study has confirmed that the Acorn CO_2 Storage Site offers a low-cost and highly flexible storage solution due to the following factors.

Pipeline Optionality: Two existing and redundant pipelines, Atlantic and Goldeneye, both run from St Fergus to the Acorn CO_2 Storage Site. These can be reused and offer significant cost savings over a new build pipeline. Initially, reuse of the Atlantic pipeline is the reference case for getting started on the Acorn CCS Project.

Low Cost Flexible Well Design: A single dual completion subsea injection well provides lower capital cost than a platform well and is designed to handle a range of injection rates, from 0.1Mt to 2Mt/yr, meaning it can be used in subsequent phases of the project.

Scalable Storage Resource: It has been demonstrated through careful dynamic modelling of the reservoir that up to 152Mt can be securely stored within the Acorn CO_2 Storage Site storage complex, providing scalability and additional storage resource, far beyond the initial Phase 1, 0.2Mt/yr, of the project

Deliverable Direct Link:

ACT Acorn - Acorn CO_2 Storage Site Development Plan

6.1.5 East Mey CO_2 Storage Site Development Plan

After the rigorous selection process to confirm the East Mey site as the second CO_2 store for the Acorn CCS project, the ACT Acorn storage team have produced some incredibly detailed research to confirm East Mey's suitability as a CO_2 store and complete a comprehensive SDP with supporting annexes.

The proposed storage complex for the East Mey CO_2 Storage Site covers an area of 1,124km^2, in the Central North Sea, extending from west of the MacCulloch field, to east of the Balmoral field, approximately 180km from St Fergus.

The work undertaken for the ACT Acorn programme has confirmed that the East Mey CO_2 Storage Site offers the following benefits.

Significant Storage Resource: This arises due to high quality reservoir properties and injectivity potential. The largest simulation that the project ran for both sites was injection of 152Mt, or 5Mt of CO_2 per year. However, because the East Mey site is so significant, we also ran an additional simulation for East Mey where the model injected up to 500Mt and the results showed that the site would comfortably hold this volume.

Secure Storage: East Mey has a demonstrated working caprock, which is the primary caprock for several large hydrocarbon fields in the Central North Sea. As a mature oil producing reservoir, current well abandonment standards are designed to eliminate the escape of oil and gas from the Mey reservoir. This is helpful in retaining high CO_2 integrity.

Access to Data: Since hydrocarbon fields exist within the Mey formation, there is both plentiful high quality reservoir data and good access to it. This includes reservoir and caprock core and dynamic data such as reservoir pressure variation during production.

De-risked Aquifer Development. The development site can be located close to a depleted oilfield. This provides additional structural trapping security and containment for buoyancy-injected CO_2 as well as residual trapping in the body of the underlying aquifer.

Deliverable Direct Link:

ACT Acorn East Mey Storage Development Plan

6.2 Useful Links

Unlocking Underground CO_2 Storage Web Section

Unlocking Underground CO_2 Storage Video Presentation

Unlocking Underground CO_2 Storage Infographic

ACT Acorn Webinar: Acorn 2025: A pathway to decarbonising the UK

6.2.1 Direct links to detailed supporting data

ACT Acorn Site Selection Posters

ACT Acorn East Mey CO_2 Storage Site SDP Annexes

ACT Acorn Eclipse Model Files Report

acorn ERA-NET ACT LIFE CYCLE ASSESSMENT

Key task

Assess the carbon footprint of three Acorn CCS scenarios:

Reference case 0.2Mt/yr CO_2	Conservative build-out case up to 8.6Mt/yr CO_2	Optimistic build-out case up to 16Mt/yr CO_2
		
1 facility	12 facilities	29 facilities

Damage indicators

- Human health
- Ecosystems
- Resource scarcity

Timescale

Assuming full system operations, between 2022 - 2089 for build-out scenarios

	Reference case	Conservative build-out case	Optimistic build-out case
Carbon footprint	Greenhouse gas emissions reduced by 3Mt (↓50%) between 2022-2036	Greenhouse gas emissions reduced by 268Mt (↓69%) between 2022-2089	Greenhouse gas emissions reduced from 470Mt (↓68%) between 2022-2089
Impact on health	↓ 25%	↓ 52%	↓ 54%
Impact on ecosystems	↓ 35%	↓ 54%	↓ 56%
Impact on resource scarcity	↑ £19 per tonne of CO_2 captured and stored	↑ £21 per tonne of CO_2 captured and stored	↑ £21 per tonne of CO_2 captured and stored

Key findings

In every scenario, Acorn CCS causes a net reduction of greenhouse gas (GHG) emissions between 2022 and 2089 of between 50% (reference case) and 69% (conservative case) compared to no carbon capture and storage (CCS).

Generally, as the Acorn CCS system scales up, the net reduction of GHG emissions improves.

The more CO_2 that is captured and stored, the lower the damage to human health and ecosystems.

The largest GHG footprint of the CCS process is caused by the heat requirement of the CO_2 capture process - this accounts for approximately 80% of the GHG emissions for the full-chain CCS system.

Acorn CCS leads to major reductions in carbon footprint at all scales and in all scenarios, and consequently leads to lower predicted impacts on human health and ecosystems.

There are opportunities to reduce the carbon footprint of the CCS process further by capture process innovation, minimising heat requirements through engineering optimisation and capturing any emissions associated with that heat requirement.

Contributing authors: Radboud University - Dr Rosalie van Zelm and Frans Brands

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7.0 Life Cycle Assessment

This research theme uncovers the carbon footprint of several development scenarios for the Acorn CCS Project using the standard methodology of life cycle assessment (LCA).

The LCA compared the total amount of greenhouse gas (GHG) emissions, before and after installing a CCS hub. This calculation of net reduction in GHG emissions includes the GHG emissions created by implementing such a system, such as greater use of fuel and materials.

7.1 CO_2 Supply Scenarios

The baseline scenario assumes no implementation of CCS and provides a benchmark for comparison with the different CCS implementation scenarios.

The three CCS implementation scenarios outlined in Section 3.1.1 were used for the LCA:

- The Reference Case Scenario involves the capture of 200kt/yr, roughly a third, of the CO_2 emissions from the St Fergus Gas Terminal;
- Scenario A represents a conservative build out scenario with the capture, transportation and storage of up to 8.6Mt/yr of CO_2. The CO_2 in this scenario comes from emission sources within 50km of the Feeder 10 pipeline. These sources include gas processing plants; power generation plants; petrochemical plants; a hydrogen reformation plant and limited CO_2 import;
- Scenario B represents an optimistic build-out scenario with storage of up to 16Mt/yr of CO_2. The CO_2 in this scenario includes those in Scenario A plus future potential emission sources such as redeveloped power plants, bioenergy plants, widespread implementation of hydrogen reformation at St Fergus and Grangemouth and large-scale import of CO_2 into Peterhead Port.

7.2 Resource Inventory of Scenarios

An inventory of the resources that would be consumed in each of the scenarios was compiled, based on the major elements of CCS infrastructure required in each scenario.

The principle resources likely to be consumed were steel, concrete, sand, diesel, electricity, heat and chemicals.

Key components of infrastructure are CO_2 capture plant, compression facility, injection and storage facility and pipelines.

The main activities in each scenario are construction, drilling, CO_2 capture and transport.

A key source of data and information was the Ecoinvent database (Ecoinvent Database, 2019). This provides a wide range of data and estimating norms such as the resource requirements for different construction activities.

7.3 Analysis

The LCA was performed using the ReCiPe 2016 methodology and is summarised in Figure 7-1

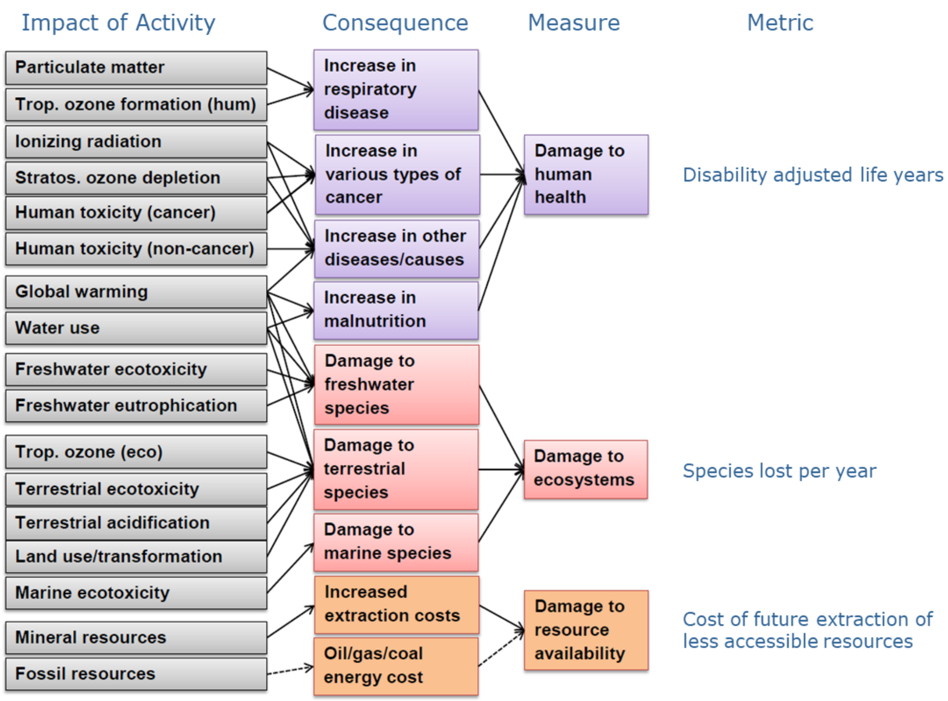

Figure 7-1: Life Cycle Assessment Methodology and Metrics. Image Credit Rosalie van Zelm, Radboud University

7.4 Results

This early attempt to apply a comprehensive LCA to CCS proved to be a complex, but very important, area of work. The results have been instructive for understanding the carbon footprint of the Acorn CCS project, homing in on key areas where process improvements are required and describing some of the wider environmental, health and resource impacts of the project.

The results confirm that even capturing a small volume of CO_2 can make a significant impact on overall CO_2 emissions. The metrics for each of the scenarios are tabulated in the infographic at the beginning of this chapter.

Deliverable Direct Link:

ACT Acorn Lifecycle Assessment Report

7.5 Useful Links

Life Cycle Assessment Web Section
Life Cycle Assessment Video Presentation
Life Cycle Assessment Infographic

8.0 Key Findings

The UK's existing North Sea oil and gas transport infrastructure coupled with an impressive natural CO_2 storage resource offers significant benefits and value.

Careful screening around just three strategically important pipelines reveals at least 16 suitable storage sites, with the most promising two potentially providing a storage resource for over 650 million tonnes (Mt) of CO_2, with injection into storage feasible from as early as 2023.

The deep-water port at Peterhead can import CO_2 by ship from the UK and Europe. With a maximum throughput of 16Mt of CO_2 annually, this facility could enable carbon capture in many other regions around the UK and the North Sea Basin.

This early start to decarbonising high-emitting regions can then be expanded in a phased and low-cost manner, building on national and European CCS networks.

The reuse of legacy oil and gas infrastructure as part of the Acorn CCS project will save around £548 million compared to the cost of new build. This brings a significant saving to the taxpayer in decommissioning alone.

Decarbonisation of the UK gas grid – for heat and transport – is possible by producing hydrogen from natural gas with CCS, particularly at St Fergus, where 35% of all UK natural gas comes onshore.

Citizens in high-emitting industrial areas look to governments (and local government in particular) to enable a just transition from a fossil-fuel based economy to an environmentally sustainable future.

In all three life cycle assessment scenarios the Acorn CCS project is predicted to bring major carbon reductions and lower the impact of greenhouse gas emissions on health and ecosystems.

Knowledge derived from the ACT Acorn project will be invaluable for similar developments in other North Sea regions and further afield where legacy oil and gas operations are in place.

9.0 References

AACE International. (2016). *18R-97 Recommended Practice Cost Estimation in Process Industires.* Association for Advancement of Cost Engineering International.

ACT. (2019, February 01). *ACT homepage*. Retrieved from http://www.act-ccs.eu/about-us/

ACT Acorn. (2018, June 20). *Webinar 1 Acorn 2025: A Pathway to Decarbonising the UK.* Retrieved from ACT Acorn: https://www.actacorn.eu/webinar-1-acorn-2025-pathway-decarbonising-uk

ACT Acorn. (2019, January 23). Retrieved from ACT Acorn Options: https://www.actacorn.eu/about-act-acorn/acorn-options

ACT Acorn Consortium. (2018). *ACT Acorn Site Selection Report.* ACT Acorn Consortium.

ACT Acorn Consortium. (2019, January 23). Retrieved from http://actacorn.eu/news/act-acorn-catalyst-low-cost-low-risk-clean-growth

ACT Acorn Consortium. (2019). *ACT Acorn Knowledge Dissemination.* Edinburgh: Pale Blue Dot Energy.

Ahmadi, Z., Sawyers, M., Kenyon-Roberts, S., Stanworth, B., Kugler, K., Kristensen, J., & Fugelli, E. (2003). Chapter 14: Paleocene. In D. Evans, C. Grahan, A. Armour, & P. Bathurst, *The Millennium Atlas: petroleum geology of the central and northern North Sea* (pp. 235-259). London: The Geological Society of London.

BG Group. (2016). *Atlantic & Cromarty Decommissioning Programme: Environmental Impact Assessment.*

Captain Clean Energy Limited. (2012). *Captain Clean Energy Project CCS Proposal to DECC.* Aberdeen: CCEP.

CO2DeepStore. (2012). *Proposal for the DECC 2012 CCS Commercialisation Programme.*

Committee on Climate Change . (2008, October 07). Retrieved from https://www.theccc.org.uk/publication/letter-interim-advice-from-the-committee-on-climate-change/).

Committee on Climate Change. (2018, June 28). Retrieved from CCC: https://www.theccc.org.uk/publication/reducing-uk-emissions-2018-progress-report-to-parliament/

Det Norsk Veritas. (2012). *DNV-RP-J203 Geological Storage of Carbon Dioxide.* (D. N. Veritas, Ed.) Retrieved from http://www2.dnvgl.com/dnv-rp-j203

Ecoinvent Database. (2019). Retrieved from Ecoinvent: https://www.ecoinvent.org/database/database.html

ETI. (2016). *Strategic UK CCS Storage Appraisal.* Retrieved from www.eti.co.uk/programmes/carbon-capture-storage/strategic-uk-ccs-storage-appraisal

European Commission. (2019, February 01). *European Commission*. Retrieved from https://ec.europa.eu/energy/en/topics/infrastructure/projects-common-interest

IEA Greenhouse Gas. (2009). *CCS Site Characterisation Criteria.* IEA GHG R&D Programme.

IPCC. (2018). Retrieved from Intergovernmental Panel on Climate Change: https://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf

ISO 27914. (2017). *Carbon dioxide capture, transportation and geological storage - Geological Storage.* Geneva: ISO copyright office. Retrieved from http://www.standard.no/nyheter/nyhetsarkiv/energi-og-klima/2017-nyheter/internasjonale-standarder-for-transport-og-lagring-av-co2-lansert/

Pale Blue Dot Energy & Axis Well Technology. (2016). *Captain X Storage Development Plan - Strategic UK CO2 Storage & Appraisal Project.* Energy Technologies Institute.

Pale Blue Dot Energy. (2017). *CO2 SAPLING Transport Infrastructure Project: Project of Common Interest Application.*

Pale Blue Dot Energy. (2018, November 28). Retrieved from Pale Blue Dot Energy: https://pale-blu.com/2018/11/28/government-and-industry-join-forces-to-support-acorn-ccs-investment/

Pale Blue Dot Energy. (2018). *CO2 Transportation and Storage Business Models Summary Report.* UK Government: BEIS.

Pale Blue Dot Energy. (2018, December 06). *News.* Retrieved from Pale Blue Dot Energy: https://pale-blu.com/2018/12/06/acorn-co2-storage-site-receives-carbon-capture-storage-licence/

Pale Blue Dot Energy. (2019, January 24). *CO2 SAPLING.* Retrieved from Pale Blue Dot Energy: https://pale-blu.com/2019/01/24/notification-from-the-eus-connecting-europe-facility-fund/

Pale Blue Dot Energy and SCCS. (2017). *ACT Acorn CO2 Supply Options.* ACT Acorn Consortium.

Parliamentary Advisory Group. (2016b). *Lowest Cost Decarbonisation for the UK: The Critical Role of CCS.* CCSa.

Pefrofac Engineering Limited. (2012). *Caledonia Clean Energy Project Conceptual Study Report (Internal report for CO2DeepStore).*

PGS. (2017). *PGS North Sea Mega Survey.* Retrieved from www.pgs.com: https://www.pgs.com/data-library/europe/nw-europe/north-sea/

Scottish Environmental Protection Agency. (2017, October 5). *Scottish Pollutant Release Inventory.* Retrieved from Scottish Environmental Protection Agency: http://apps.sepa.org.uk/spripa/Search/Options.aspx

ScottishPower CCS Consortium. (2010). *Longannet ScottishPower CCS Consortium Front End Engineering and Design (FEED).*

ScottishPower CCS Consortium. (2011). *Demo 1 KT: SP-SP 6.0 - RT015 Feed Close Out Report.*

UK Government. (2018, October 15). Retrieved from Gov.uk: https://www.gov.uk/government/publications/uk-climate-targets-request-for-advice-from-the-committee-on-climate-change

Zero Emissions Platform. (2015). *An Executable Plan for Enabling CCS in Europe.* ZEP.