elementenergy

Infrastructure in a low-carbon energy system to 2030:

Carbon capture and storage

Final report

for

The Committee on Climate Change

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The views and judgements expressed here are the opinions of the authors and do not reflect those of the CCC or the stakeholders consulted during the course of the project.

Contents

1 Introduction

The CCC's Fourth Carbon Budget suggests that the UK should target a 60% reduction of total greenhouse gas emissions relative to 1990 levels by 2030 in order to meet the 2050 target[1]. It is therefore expected that the power sector would be largely decarbonised by 2030, with significantly increased levels of electricity production and demand driven by wider electrification of the heat and transport sectors.

There are many different ways to decarbonise electricity supply; however, Carbon Capture and Storage (CCS) is currently unique as it is the only technology that could allow fossil fuels to remain in the UK generation mix while decarbonising the power sector. Flexible fossil fuel capacity with CCS is vital as it is able to respond to demand in the way that nuclear and wind cannot.[2] DECC's modelling for the Carbon Plan also showed that CCS can play a significant role in decarbonisation of the UK economy at least cost.[3]

In the UK, power plants fitted with CCS could contribute more than 10 GW by 2030[2]. If CCS is successfully deployed in the UK, CO_2 which would otherwise be emitted to the atmosphere will be captured from large power plants or industrial sites, transported onshore and offshore, mostly through new CO_2 pipelines, and permanently stored deep underground (e.g. in the depleted hydrocarbon fields and aquifers underlying the UK Continental Shelf). The UK will therefore need a significant investment for the CCS infrastructures including onshore and offshore pipelines, shoreline terminals, and offshore storage sites.

This report is the final deliverable from the CCS part of the Element Energy-led "cost and characterisation of infrastructure to 2030" study for the CCC and presents:

- Characterisation and cost of CCS infrastructure to 2030
- Timelines for CCS infrastructure deployment
- Feasibility of CCS deployment in the UK

Interim outputs from this study have been reviewed by key stakeholders, including DECC, ETI, the Crown Estate, National Grid and Imperial College.

The report is also accompanied by an appendix that provides further information on:

- Assumptions and methodology
- Onshore pipeline networks
- CCS infrastructure timelines

Conclusions and recommendations are those of Element Energy and not those of the stakeholders consulted.

[1] The CCC, 2010, The Fourth Carbon Budget
[2] DECC, 2012, CCS Roadmap
[3] DECC, 2011, The Carbon Plan

2 Characterisation and cost of CCS infrastructure to 2030

2.1 CCS deployment in the CCC scenarios

The CCC's Fourth Carbon Budget report suggests that the carbon intensity of power will need to fall to *ca*. 50gCO_2/kWh by 2030 with the deployment of a mixture of nuclear, renewables and CCS. The "core decarbonisation scenario" in this report represents the CCC's central scenario for the fourth carbon budget. Two additional scenarios were developed by the CCC for this study, namely, the "no climate action" and "delayed electrification" scenarios. Total installed capacities of electricity generation technologies in 2030 are shown in Figure 1 for the three CCC scenarios.

- **No climate action scenario:** It is assumed in this scenario that there is no climate change policy in the UK and Europe; therefore total installed capacity in the UK in 2030 is dominated by gas and coal-fired power plants. There are no CCS installations or grid intensity target for 2030 in this scenario.
- **Core decarbonisation scenario:** This is the CCC's central scenario for the fourth carbon budget. A wide mix to low-carbon technologies is installed by 2030. Coal CCS and gas CCS capacities are 9.2 and 3.6 GW, respectively. This scenario meets 50gCO_2/kWh of grid intensity by 2030.
- **Delayed electrification scenario:** This scenario is slightly different from the core decarbonisation scenario, reflecting 50% less deployment of heat pumps and electric vehicles (resulting in lower total electricity demand), and the power sector achieves around 100gCO_2/kWh by 2030. Coal CCS capacity in this scenario is 3.3 GW, which is slightly less than the capacity in the core decarbonisation scenario. However, gas CCS capacity (3.6 GW) is around a third of the gas CCS capacity in the core scenario.

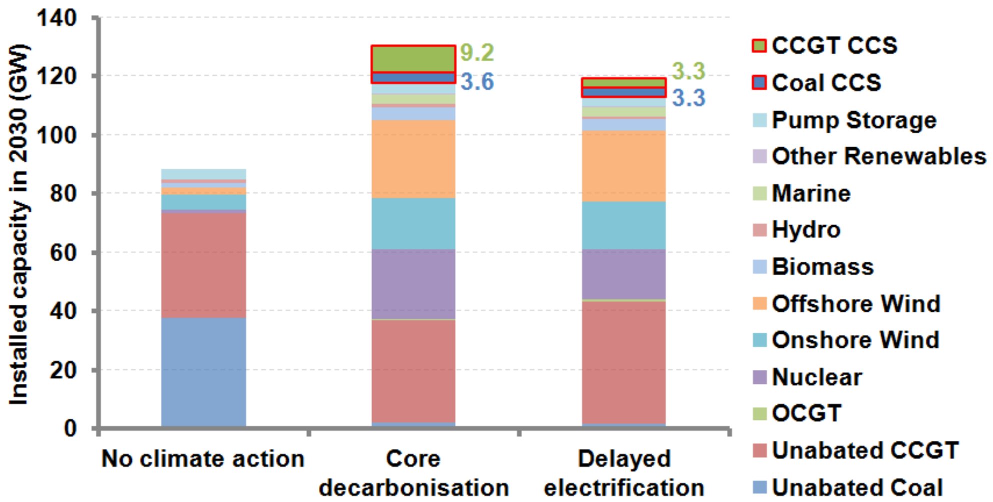

Figure 1: The UK's electricity generation mix in 2030 in the CCC scenarios

As shown in the figure above, the capacity of coal and gas power stations with CCS in 2030 is *ca*. 13 GW in the core decarbonisation scenario. Though lower than the capacities of onshore and offshore wind generation, this is nevertheless challenging given the current immaturity of CCS technology, with no end-to-end CCS projects under construction or in operation in the UK.

The Government is supporting the development of CCS in the UK through its CCS Roadmap. Importantly, this includes a "Commercialisation Programme", which comprises

£1 billion for capital subsidy and a Contract-for-Difference Feed-in Tariff for on-going support. Two preferred bidders in this CCS Commercialisation Programme were recently announced – it is anticipated these will proceed to studies this year. These projects are:

- **Peterhead Project**: A 340MW post-combustion capture retrofitted to part of an existing 1,180MW Combined Cycle Gas Turbine power station at Peterhead, Scotland, with the CO_2 transported by pipeline to the offshore Goldeneye Gas Condensate field. Led by Shell and SSE.
- **White Rose Project**: An Oxyfuel capture project at a proposed new 304MW fully abated supercritical coal-fired power station on the Drax site in Selby, Yorkshire. The project is led by Alstom and involving Drax, BOC and National Grid Carbon. The role of National Grid Carbon is to transport the CO_2 by pipeline to an aquifer storage site in the Southern North Sea.[4]

It is expected that the Front End Engineering Design (FEED) contracts will be signed in 2013, with final investment decisions for up to two projects being made by early 2015. There have been many challenges worldwide in funding CCS projects over the last decade. Therefore it is not certain that one or both the shortlisted projects will be funded. The earliest that these demonstration scale projects could be in commissioning would be 2018. Under the Electricity Market Reform arrangements, other power CCS projects in the UK could be underpinned by a combination of the CfD FiT and carbon pricing.

Two other CCS projects (IGCC-CCS projects in the Tees Valley and in Grangemouth) are formally "reserve" candidates. At least eight other CCS projects previously proposed in the UK are on hold or have been abandoned with various levels of detail. Given the long lead times for developing projects under the CCS Commercialisation Programme, the installed capacity of CCS in 2020 is therefore very unlikely to be more than the 650 MW representing the combined output of the two demonstration projects. A significant number of CCS projects will need to be commissioned from 2020 to 2030 for the levels of CCS deployment in the core decarbonisation and delayed electrification scenarios to be realised.

2.1.1 Core decarbonisation scenario

In the core decarbonisation scenario, CO_2 emissions of more than 20 large-scale CO_2 emitters including the two demonstration projects are captured by 2030. Figure 2 shows that CO_2 capture increases to 52 Mt/year in 2030, split 23 Mt/yr from 7 coal CCS projects, 23 Mt/yr from 11 gas CCS and 5 Mt/yr from four industrial sites. Clearly the locations for these capture sites are speculative; however, there are several arguments that suggest locations will be limited to locations of previously planned sites or in clusters, to take advantage of shared transport and storage networks.

[4] DECC, 2013, CCS Commercialisation Competition, Available at: https://www.gov.uk/uk-carbon-capture-and-storage-government-funding-and-support

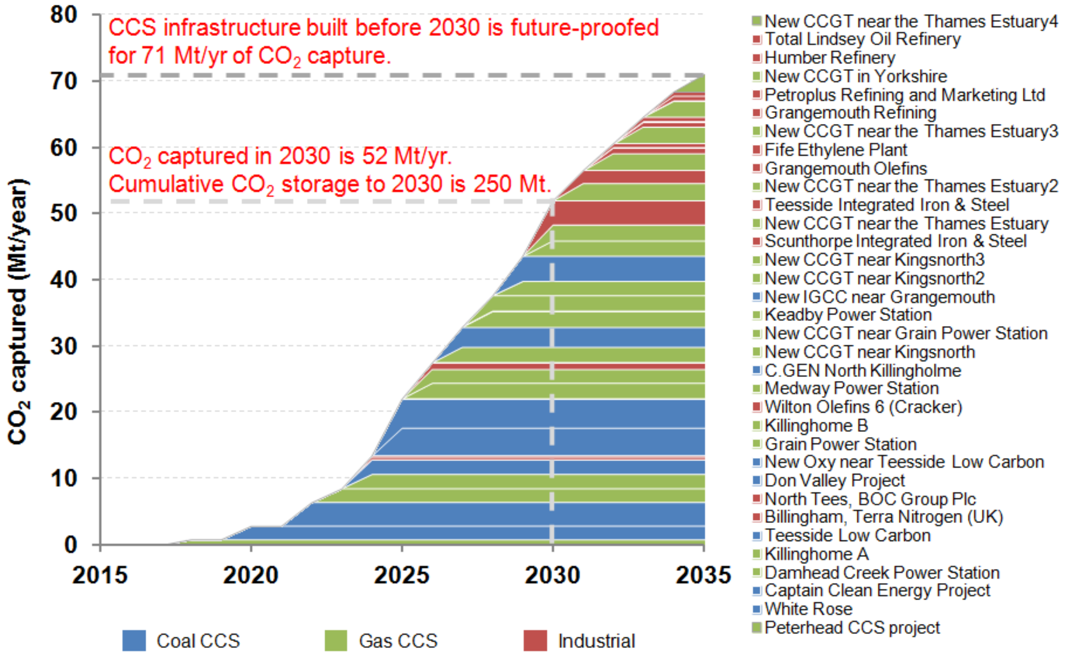

Figure 2: CO_2 capture in the core decarbonisation scenario[5]

There are significant economies of scale in CO_2 transport and storage infrastructure. Therefore, to better reflect the investment needs for infrastructure by 2030, around 20 Mt/yr of additional CO_2 capture post 2030 is also included in the analysis. The analysis assumes the CCS infrastructure built will be future-proofed to meet the modelled capacity required in 2035 of *ca.*70 Mt/year of CO_2 capture. Studies have shown the combined costs of each source developing its own transport and storage solution would be prohibitively expensive.

The analysis assumes that all CO_2 emitters shown above are connected via convergent networks to a limited number of shoreline terminals. The locations of these are speculative, but plausible candidates could be St. Fergus, Teesside, Yorkshire and Thames. Plausible offshore networks are then chosen based on nearby sinks. The CO_2Stored database produced in the UK Storage Appraisal Project[6] identifies many hundred potential storage sites with a wide range of storage capacities, risks, injectivities and costs. Of these a shortlist was identified as having sufficient theoretical injection capacity to meet the storage demand, and sufficient storage capacity to meet at least ten years of demand (see Appendix for description of transport and storage modelling).

CCS projects commissioned before 2030 will likely require several decades' worth of storage capacity beyond 2030 as "bankable" (equivalent to "proven reserves" in the language of oil and gas production) at the time of Final Investment Decision. The modelled "used" capacity in 2030 is 0.25 Gt, but there will be a need for potentially 1.25 Gt capacity

[5] The names and timings of the CCS projects shown in the graph are illustrative only.
[6] The CO_2Stored database is managed by the British Geological Survey, The Crown Estate and the Energy Technologies Institute. It is a web-enabled database containing the geological data, storage estimates, risk assessments and economics of the nearly 600 potential storage units identified by the project, covering both depleted oil and gas reservoirs and saline aquifers. See: http://www.eti.co.uk/news/article/storage_appraisal_project_web_enabled_database

as proven to support projects operational in 2030. In other words, decisions on CCS infrastructure for projects built before 2030 must reflect future capacity requirements. .

Figure 3 illustrates the modelled growth of the CCS network in the core decarbonisation scenario with snapshots of 2020, 2025, 2030 and 2035:

- **2020:** Two demonstration projects are successfully commissioned and operational. Up to 3 Mt of CO_2 is captured, transported and stored in the Central North Sea (CNS) and Southern North Sea (SNS) sinks.
- **2025:** CO_2 capture in the UK quickly ramps up to 22 Mt/year. Regional transport and storage networks are developed. In Scotland, CO_2 captured from Grangemouth is transported through a re-use onshore pipeline (i.e. Feeder 10[7]) to the St. Fergus shoreline terminal and stored in a CNS sink. CO_2 emitters with capture in Teesside, Yorkshire and Thames are connected to three SNS sinks through onshore and offshore pipelines.
- **2030:** Overall CO_2 capture is 52 Mt in the UK; therefore, additional sinks are connected to the CCS network. More than 40 Mt of CO_2 is stored in the SNS sinks.
- **2035:** Offshore infrastructure built by 2030 is assumed to be future-proofed; therefore, no new offshore pipelines or sinks are needed until 2035. Total CO_2 storage in 2035 is *ca* 70 Mt/yr.

[7] The Captain Clean Energy Project is proposing to re-use a National Grid gas pipeline (Feeder 10) for onshore transport between Avonbridge and St. Fergus. The viability of the onshore transport option was validated in Scottish Power's Longannet CCS demonstration proposal. See: CCEP Overview 2013, Available at: http://www.usea.org/sites/default/files/event-/2013%201%2023%20CCEP%20Overview.pdf

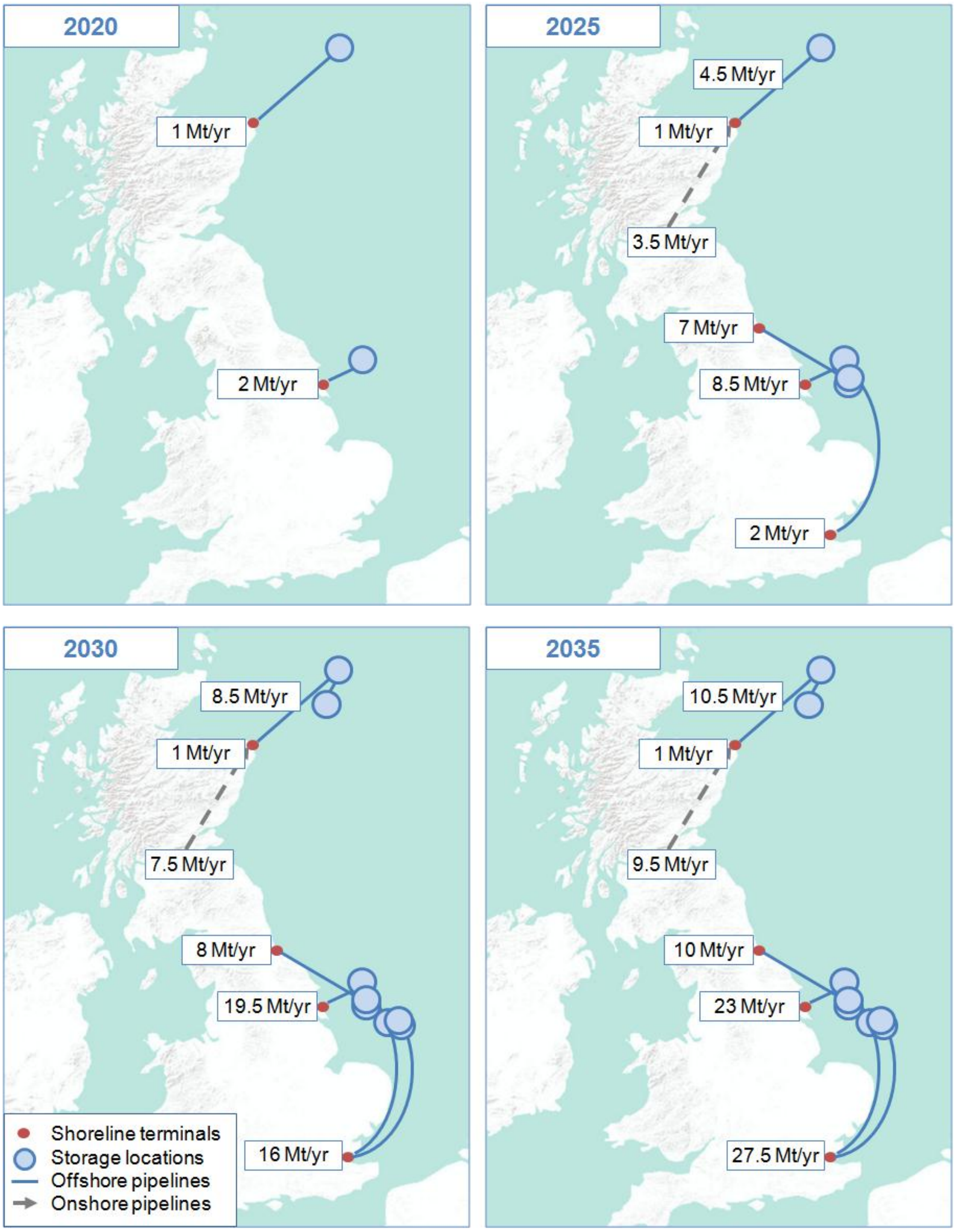

Figure 3 Snapshot maps of the CCS networks in the core decarbonisation scenario.[8]

[8] The selection of capacities, sources, sinks and transport routes are illustrative – there are a wide range of choices.

2.1.2 Delayed electrification scenario

In the delayed electrification scenario, total emissions of 35 $MtCO_2$ from seven coal-fired power plants, five gas-fired power plants and four industrial sites are captured in 2030. Similar to the core decarbonisation scenario, 11 Mt/yr of CO_2 capture post 2030 is also included in the analysis to allow future-proofing of the offshore infrastructure. Figure 4 shows the power plants and industrial emitters included in this scenario.

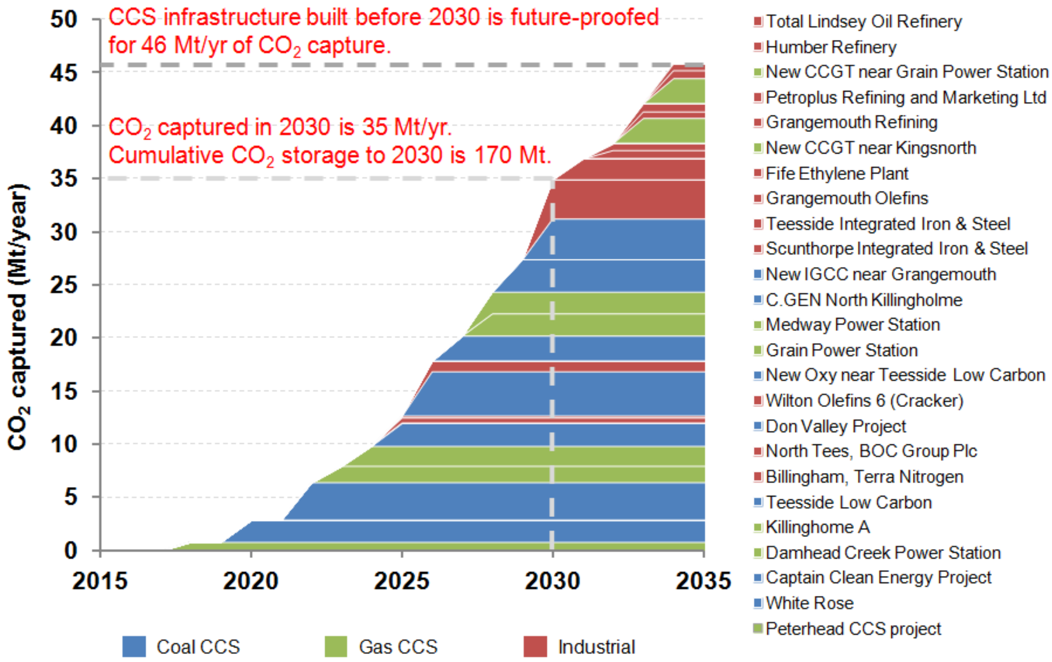

Figure 4: CO_2 capture in the delayed electrification scenario[9]

The CCS network growth in this scenario is illustrated in Figure 5. Following the commissioning of two demonstration projects by 2020, CO_2 capture rate ramps up to more than 12 Mt/yr in five years. The topography of the CCS network in 2030 is similar to the network in the core decarbonisation scenario except that fewer CO_2 pipelines and storage sites are required in this scenario due to the lower CO_2 capture rates.

CO_2 captured around Forth is transported through an onshore re-use pipeline and a new offshore pipeline and stored in the CNS, while CO_2 captured in Teesside, Yorkshire and Thames are stored in the SNS sinks. In 2035, CO_2 emissions of 25 emitters are stored in more than five sinks.

The maps shown in this section are illustrative only. Detailed characteristics of the CCS network shown in the maps are examined in the next section, "CCS infrastructure requirements by 2030".

[9] The names and timings of the CCS projects shown in the graph are illustrative only.

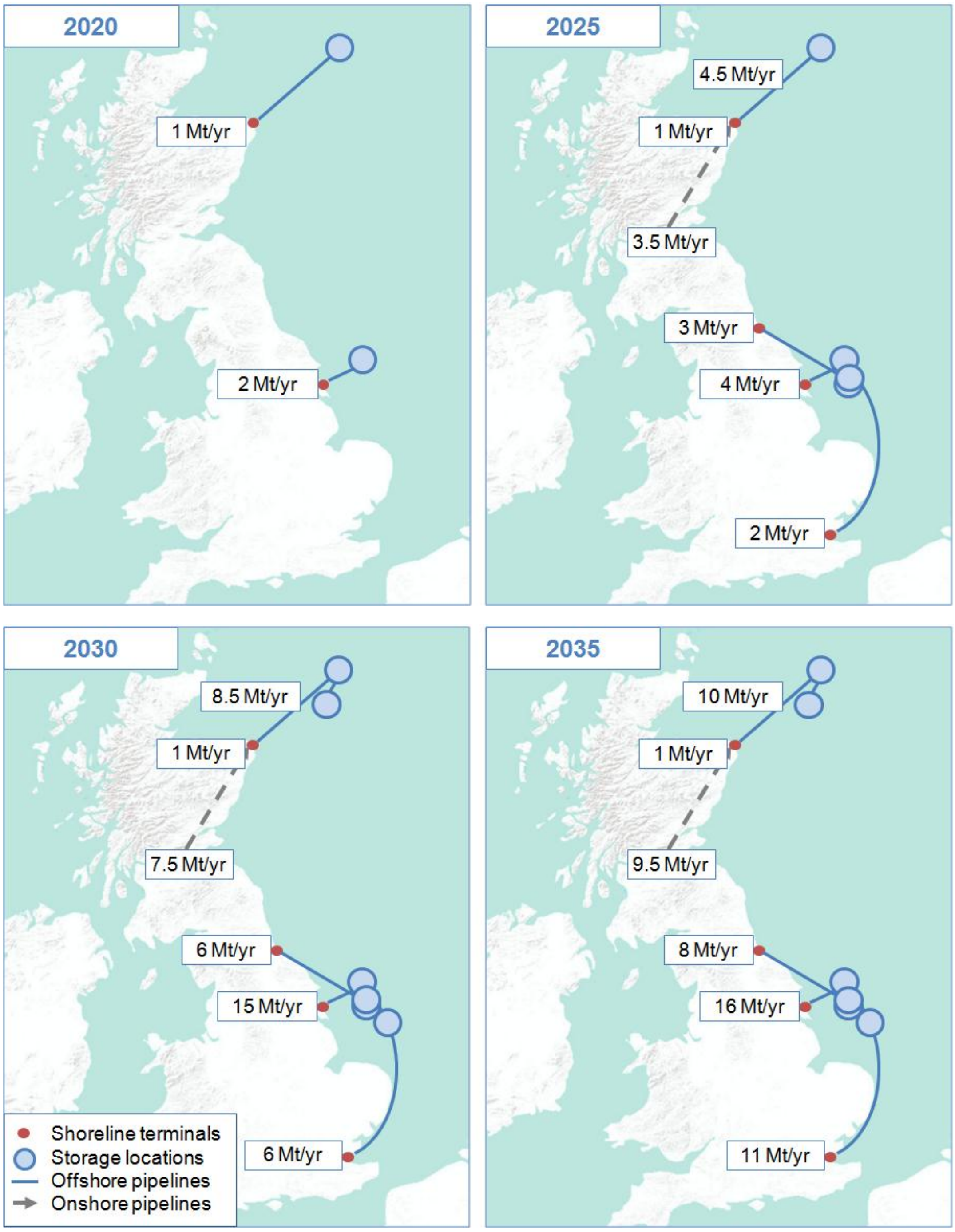

Figure 5: Snapshot maps of the CCS networks in the delayed electrification scenario[10]

[10] The selection of capacities, sources, sinks and transport routes are illustrative – there are a wide range of choices.

2.2 CCS infrastructure requirements by 2030

In the previous section, CCS deployments in the CCC scenarios were shown using illustrative maps. This section provides further characteristics of the designs and costs of the CCS infrastructure in the period to 2030. Figure 6 illustrates the different infrastructure elements of a typical CCS network with offshore storage.

As shown in the figure, several infrastructure elements are included in this study:

- Through onshore pipelines, power plants or industrial sites are connected to a shoreline boosting hub; where it is assumed that the CO_2 is delivered at 10 MPa at the required purity for offshore pipeline transport and geological storage and compressed to 25 MPa.
- CO_2 is then transported from shoreline terminals to storage sites through offshore pipelines with certain diameters depending on limiting pressure drops.
- Where offshore boosting is required, hubs are added to the network.
- Distribution pipelines are used for CO_2 transport from hub to CO_2 injection facilities, which are either sub-sea facilities or platforms.
- Finally, CO_2 is injected to the sink (i.e. aquifer or hydrocarbon fields) through CO_2 injection wells – the number of injection wells needed depends on CO_2 flow rates and pressure limits associated with injection.

The infrastructure model also includes costs for well remediation and appraisal:

- Appraisal costs include the cost of seismic assessment and appraisal wells for each sink.
- Well remediation costs are also included as existing wells drilled primarily for hydrocarbon production could provide a pathway for CO_2 to escape from a designated storage site, potentially to the seabed or atmosphere. Costs of re-abandoning a fraction of existing wells are therefore included.

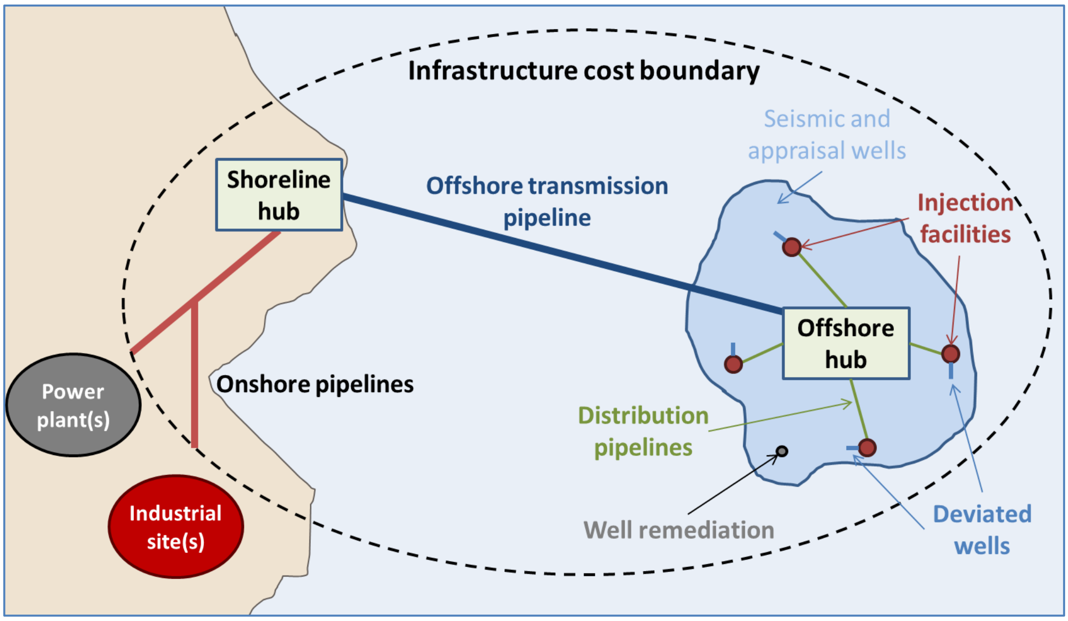

Figure 6: CCS infrastructure illustration

Costs and infrastructure elements associated with capture plants and onshore compressors outside the shoreline terminals are not included in this study as CAPEX for CO_2 compression units are usually included in the power plant CAPEX.[11]

Infrastructure characterisation analysis is carried out for both the core decarbonisation scenario and the delayed electrification scenario, and the results are summarised in Table 1. It is important to recognise that, alternate choices for sources, sinks and transport networks could give different outcomes. Furthermore there will be an inherent uncertainty and variability in subsurface performance that is very difficult to forecast in the absence of operational experience.

The number of shoreline terminals in 2030 is four in both scenarios; however, fewer CO_2 pipelines and storage sites are needed in the delayed electrification scenario for all other infrastructure elements.

Table 1: Characterisation of CCS infrastructure in 2030

Comparison	Core decarbonisation scenario (2030)	Delayed electrification scenario (2030)
CO_2 flow (Mt/year)	**52**	**35**
Number of shoreline terminals (cumulative)	**4**	**4**
Number of sinks in use (cumulative)	**8**	**6**
Number of injection facilities (cumulative)	**45**	**31**
Number of injection wells (cumulative)	**56**	**37**
Cumulative length of onshore pipelines (km)	**850**	**750**
Cumulative length of offshore pipelines (km)	**1,400**	**1,000**
Total length of onshore/offshore pipelines (km)	**2,250**	**1,750**

Under the scenarios outlined above 1,700–2,250 km of CO_2 pipelines and 31–45 injection facilities are needed by 2030. By comparison, there is a network of 14,000 km of pipelines linking more than 100 oil platforms and around 180 gas platforms and a substantial number of subsea installations in the UK, developed since the 1960s[12]. Therefore the offshore CO_2 transport and storage infrastructure is modest relative to the oil and gas infrastructure in the UK. The UK's extensive experience in offshore infrastructure suggests that the UK supply chain is capable of delivering the required CCS infrastructures by 2030, providing a compelling business case exists.

[11] PB for DECC, 2012, Electricity Generation Cost Model
[12] Oil & Gas UK, 2013, Key facts, Available at: http://www.oilandgasuk.co.uk/knowledgecentre/operations.cfm

2.3 Cost of CCS infrastructure by 2030

The changes in costs of various CCS infrastructure elements are shown in Figure 7 for both the core decarbonisation and delayed electrification scenarios (real and undiscounted). Cumulative costs in 2020 are around £2 billion in both scenarios. The differing levels of CCS rollout in the following decade between the delayed electrification and core decarbonisation scenarios leads to costs in 2030 of £5.5 and £7.7 billion respectively.[13] CO_2 transport and storage network costs could be significantly higher – for example if networks were chosen with less sharing of transport and storage among projects or if there was a need for additional work to manage subsurface risks and performance.

Offshore infrastructure costs dominate the cumulative CCS costs by 2030 in both scenarios. Cumulative CAPEX of offshore pipelines and storage are around £3 billion each in the core decarbonisation scenario. On the other hand, these costs are lower in the delayed electrification scenario (i.e. around £2 billion each). Total cumulative OPEX varies between £1.1 and £1.5 billion in the two scenarios.

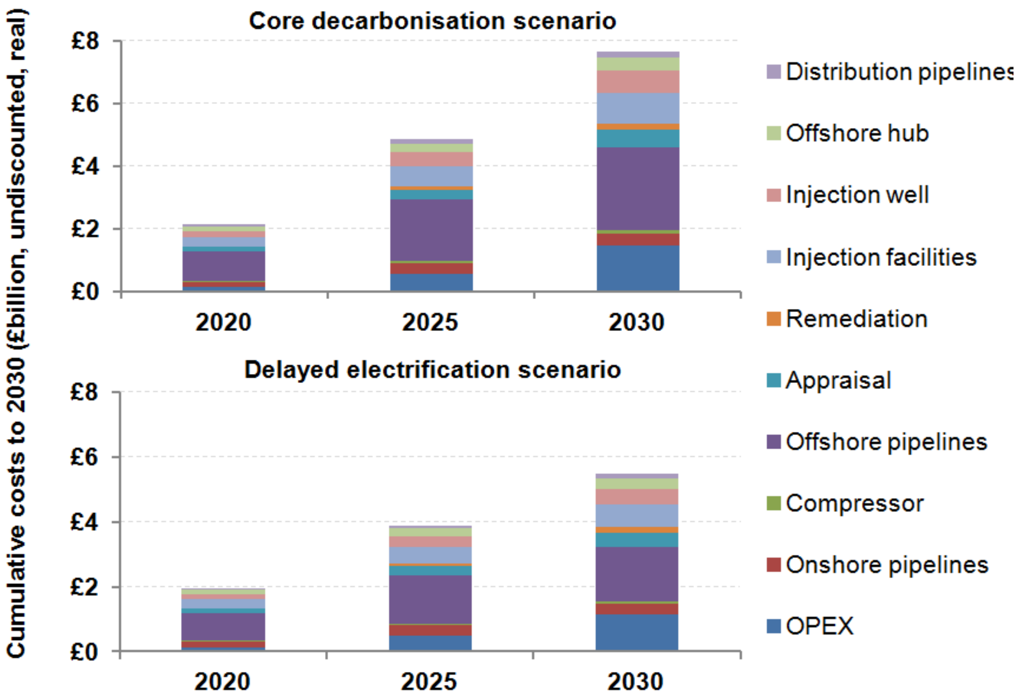

Figure 7: Undiscounted cost of CCS infrastructure by 2030 in the CCC scenarios

Onshore pipeline costs are much lower than the offshore infrastructure costs. This is primarily because the onshore emitters near the potential shoreline terminals are chosen in the scenarios. In addition, it is assumed that Feeder 10 natural gas pipeline is re-used for CO_2 transport between Forth and St. Fergus. Re-use CAPEX for this pipeline was estimated in the Longannet FEED study at around £80 million[14] (see the Appendix for detailed analysis of the onshore networks).

[13] The level of cost estimate is conceptual. For a given design, the uncertainties are +100%/-50%, which partially reflects inherent offshore cost volatility (due to market conditions) and variability (which reflects site issues).
[14] ScottishPower CCS Consortium, 2011, FEED Close Out Report - Summary of Estimated project Capital Costs at post-FEED stage

Although the absolute costs of the CCS infrastructure in the delayed electrification scenario are lower, unit costs of CO_2 transport and storage are higher compared to the core decarbonisation scenario. As Table 2 indicates, specific or unit costs are up to 20% higher in the delayed electrification scenario. The reason is that higher rates of CO_2 capture create more opportunities for shared infrastructure and network optimisation. The unit costs of both scenarios are within the range of European industry estimates of transport and storage costs identified in the Zero Emissions Platform (ZEP)[15] reports.

Unit costs for onshore and offshore pipelines in the ZEP report vary depending on the type of network (i.e. lower costs for large integrated networks and higher costs for point-to-point connections). Onshore costs in the CCC scenarios are in the middle of the ZEP's onshore pipeline cost range since both the integrated and point-to-point onshore pipelines are used in the scenarios. On the other hand, offshore pipeline costs are closer to the upper end of the range (i.e. point-to-point pipelines) of the ZEP costs as the majority of the offshore pipelines are point-to-point pipelines from shoreline terminals to the storage sites.

Table 2: Unit costs of CCS infrastructure elements[15]

Cost element	ZEP Point-to-point connections £/t	ZEP Large integrated networks £/t	CCC core decarbonisation scenario £/t	CCC delayed electrification scenario £/t
Onshore pipeline	£4.5/tCO_2	£1.3/tCO_2	£2.4/tCO_2	£3.0/tCO_2
Offshore pipeline	£7.8/tCO_2	£2.8/tCO_2	£6/tCO_2	£7/tCO_2
Storage	Span £2– 17/tCO_2 depending on site-specific issues.		£10/tCO_2	£11/tCO_2

Overall, almost £8 billion of investment (undiscounted) is needed over the period to 2030 in the core decarbonisation scenario. To put this in context, annual capital expenditure on the UKCS due to the oil and gas activities was almost £12 billion last year.[16] In other words, the total investment needed to deliver the levels of CCS in the core decarbonisation scenario by 2030 is equivalent to <70% of one year's investment in UKCS oil and gas activities. However, oil production generates billions of pounds of revenues each year for both the oil companies and the Government, resulting in significant commercial focus, innovation and policy support.

Whereas the main driver for CCS is Government-backed support including the CCS commercialisation programme, the electricity market reform and carbon pricing. The scale of investments and risks associated with the CCS projects are too large for the private sector to absorb; therefore, the main motivation for investing in the existing CCS projects appears to be strategic, rather than expected returns from the project. [17]

[15] Zero Emissions Platform (2011) Transport Report & Storage Report, Available at: http://www.zeroemissionsplatform.eu/library/publication/168-zep-cost-report-storage.html (Discount rate: 8%, £/€ = 1.19, pipeline length: 180 km, CO_2 transport rate: 2.5 to 20 Mt/yr)
[16] Oil & Gas UK, 2013, Activity Survey 2013
[17] Ecofin for ETI, 2012, Mobilising private sector finance for CCS in the UK

3 Timelines of infrastructure deployment

In this chapter, the timescales for the development of the main CCS infrastructure elements in the core decarbonisation scenario are examined in more detail. The figure below illustrates the timescales for the development of new power plants with capture, retrofit industrial sites with capture, aquifer storage, hydrocarbon storage and CO_2 pipelines. Blue areas show the period needed for pre-development and design, and green areas represent the construction period (installation period for pipelines). Please see Appendix for the detailed timelines for storage and pipeline development.

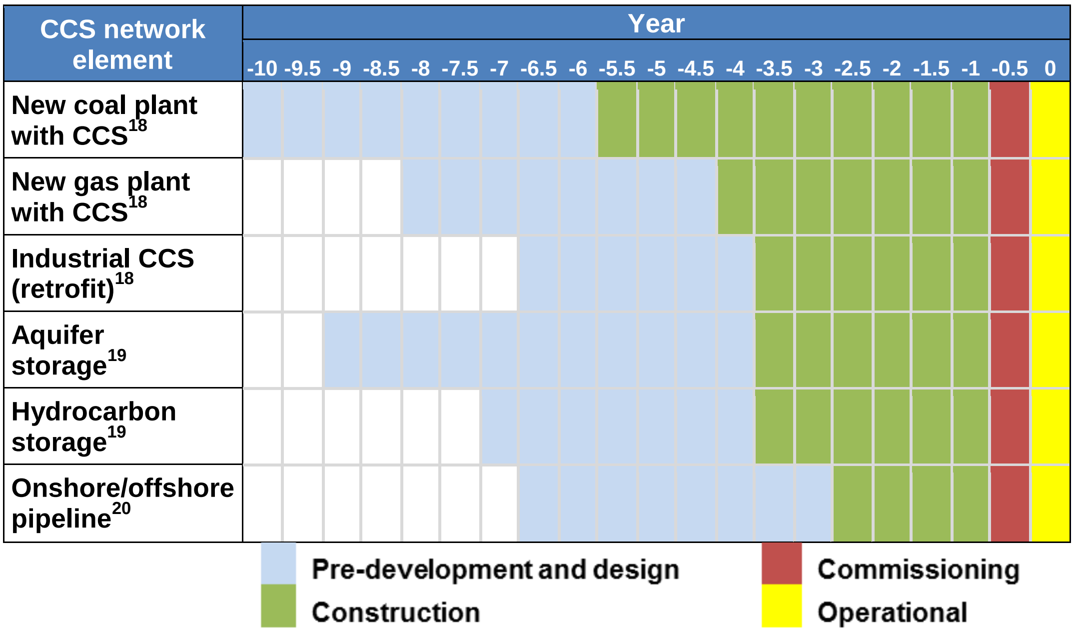

Figure 8: Timescales of the main CCS infrastructure elements

Storage development in the UK shares some analogies in terms of timescales and risks to the development of new basins for oil and gas. Power station, capture plant and pipelines also impact numerous stakeholders, and the first such projects will therefore need to spend considerable time and efforts to obtain buy-in.

Pre-development for new coal plants with CCS and aquifer storage should begin around ten years ahead of commissioning. Other elements seem to be less challenging in terms of the timescales with overall periods of six to eight years. The long periods required for the development of CCS projects represent a significant barrier for the CCS rollout in the core decarbonisation scenario as around 20 CCS projects would need to be commissioned following the demo projects, which are expected to be commissioned by 2018 at the earliest. The timescales of the CCS elements in the core decarbonisation scenario are discussed in more detail in the following sections.

[18] PB for DECC, 2012, Electricity Generation Cost Model - 2012 Update of Non Renewable Technologies – industrial CCS timeline is based on retrofit power plants
[19] Element Energy analysis for the CCC (2013) - see Appendix for detailed timelines
[20] ZEP, 2011, The costs of CO_2 transport - see Appendix for detailed timelines

3.1 CCS project timeline in the core decarbonisation scenario

As explained, development of a power plant with CO_2 capture takes from six to ten years depending on the plant type. Fortunately, more than a dozen UK sites have already been considered for CCS. The timeline below shows the development of the plants with CO_2 capture in the core decarbonisation scenario. The timeline suggests that pre-development of more than five post-demonstration CCS projects should be kick-started before CCS is proven successful in the UK (i.e. before 2018) for the levels of CCS deployment in the core decarbonisation to be realised. However, any pre-development work of this type is at risk since CCS may not be successfully demonstrated in the UK. The risks for the early commercial CCS projects could be shared by the Government.

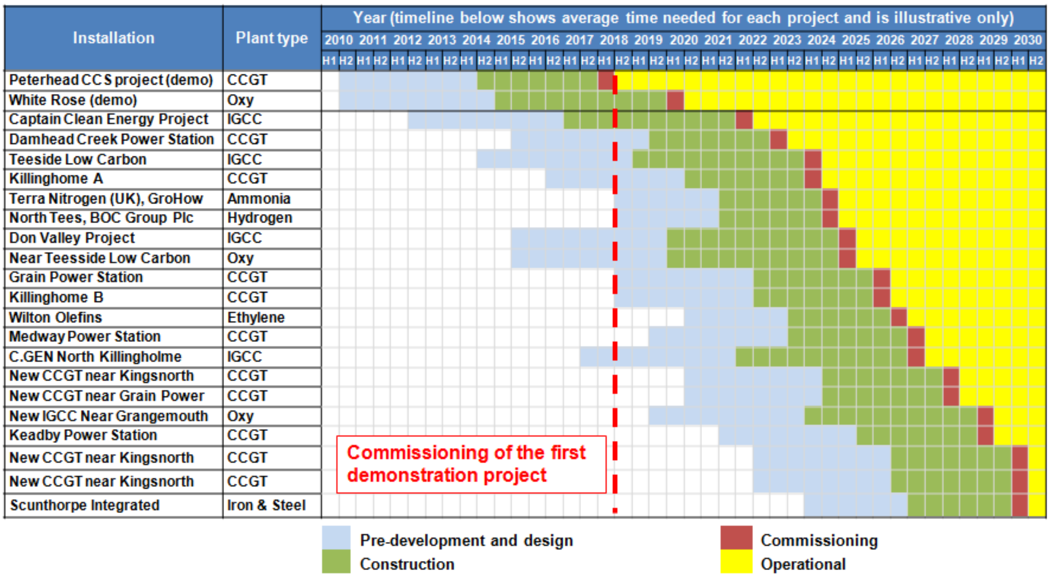

Figure 9: Timeline for the plants with CO_2 capture in the core decarbonisation scenario

If investors wait until CCS technology is demonstrated in the UK, it is unlikely that the CCS target for 2030 in the core decarbonisation scenario will be met. In such a case, almost 20 large-scale CCS projects would need to be commissioned in just four years from 2026 to 2030 (see Figure 10). A ramp up from two projects to more than 20 projects in a just a couple of years is unlikely; therefore, meeting the 2030 ambition for CCS in the core decarbonisation scenario would be delayed for at least five years. In order to avoid any delays in the CCS rollout, pre-development of several CCS projects should start soon. Therefore, favourable conditions for investment should be in place by 2015. These will be investigated in the next chapter, “Feasibility of CCS deployment in the UK”.

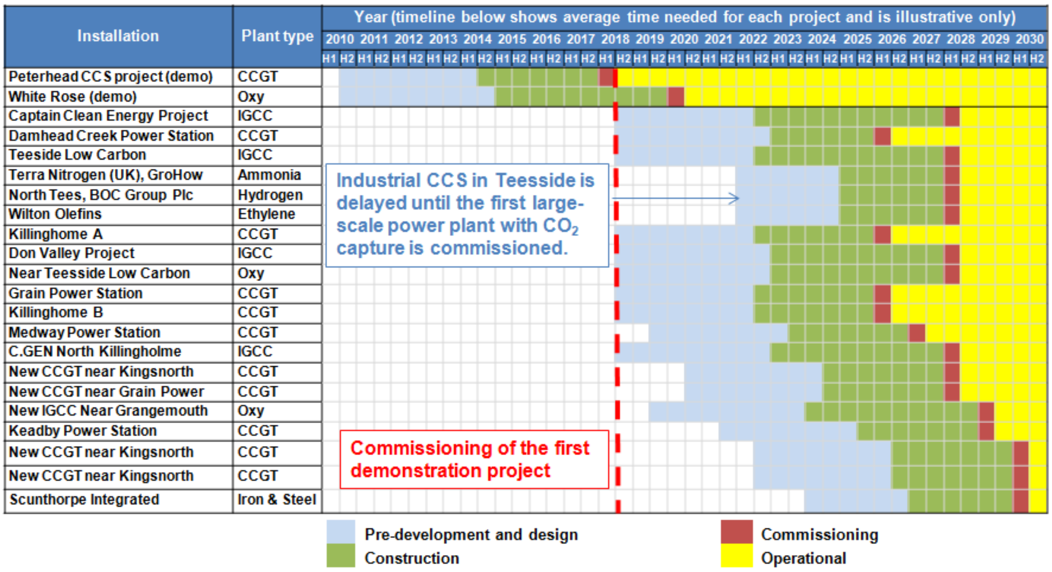

Figure 10: Delayed CCS project timeline

3.2 Storage timeline in the core decarbonisation scenario

Similar to the power plants, development of storage sites could also take up to almost ten years. Figure 11 indicates that planning and design of at least two large, or several small, storage sites should start prior to the commissioning of the demonstration projects. Although much of the UK Continental Shelf is well characterised for oil and gas production, CO_2 storage introduces novel challenges and numerous data gaps will need to be filled. There may need to be a “portfolio” approach to manage subsurface risks and performance uncertainties

Delays in the pre-development of the early post-demonstration storage sites could lead to delays in the overall timescales of CCS deployment in the core decarbonisation scenario (e.g. several years).

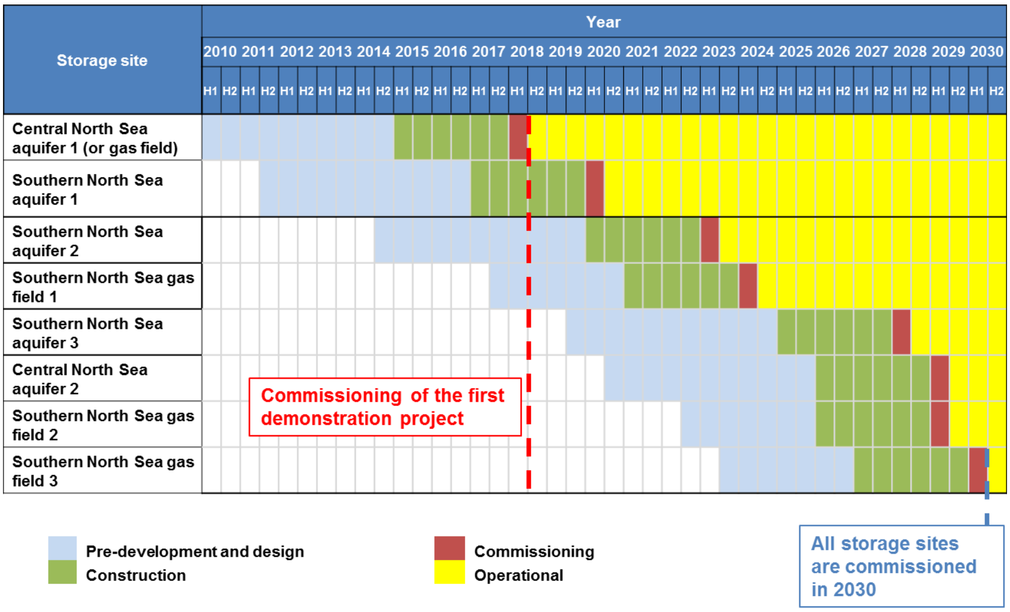

Figure 11: Storage development timeline[21]

Appraisal requirements also represent a barrier in terms of the timescales of storage development. Bankable capacity of a storage site should be available at final investment decision (FID) at least three years before the commissioning date. In order to deliver the bankable capacity, much more storage capacity should be appraised assuming several of these storage sites may fail. The ratio of bankable capacity to appraised storage capacity is however highly uncertain. As the graph below illustrates, appraisal requirement by 2030 could be as high as several gigatonnes in the core decarbonisation scenario.

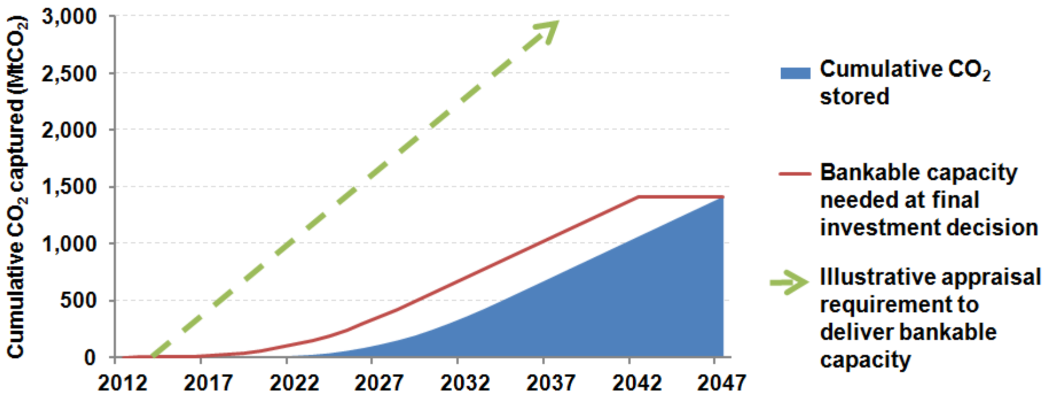

Figure 12: Appraisal requirement for the storage development

[21] Storage sites shown above do not represent any proposed storage sites. Sinks, which are nearest to the shoreline terminals with least costs, are selected within each phase.

4 Feasibility of CCS deployment in the UK

Building on the timelines developed for CCS deployment, this chapter investigates the feasibility of deployment. The main barriers to CCS deployment including political, regulatory, economic, commercial and technical constraints are identified. Key actions and recommendations linked to stakeholders (Government and/or industry) with illustrative deadlines are proposed.

The main barriers to deployment of CCS, identified in this study, are classified under three main groups:

- Political and regulatory barriers
- Economic and commercial barriers
- Technical barriers

Key actions proposed in this chapter are based on the team's experience and prior work including the final report of the CCS Cost Reduction Task Force.[22]

Political and regulatory barriers

1) The instability of the UK's low carbon policy agenda, and the lack of grassroots support from the public for CCS technology, poses a systemic threat to CCS investments, making it especially challenging to fund high capex first-of-a-kind projects.
   - **Key action proposed:** Continued efforts for a globally binding and robust climate deal.
     Deadline: 2015 **Responsibility:** UK Government with partners

2) The least cost CCS systems rely on significant demonstration to reduce the cost of finance and infrastructure sharing among projects. However the Government has refrained from detailing a clear vision for the amount, timing or location of CCS within the future energy mix. However, it takes up to ten years to plan, design and construct a full-chain CCS project, and the high asset specificity make it essential for investors to have clear, stable and strong signals for the period after the first CCS commercialisation projects.
   - **Key action proposed:** A clear vision for CCS, with credible location, time and capacity signals, is required.
     Deadline: 2015 **Responsibility:** Government and industry

3) The presence of a readily accessible transport and storage infrastructure significantly removes consenting risk and reduces complexity for subsequent projects. However, a focus on short-term cost reduction (and genuine uncertainties about overall deployment) may lead to a failure to develop CCS infrastructure with long-term potential even if the proposed CCS projects at Peterhead and Drax are funded. Government is currently focusing on making at least one demonstration scale project happen; no announcements have been made about funding multiple projects, despite the benefits this would bring in opening up diverse capture, transport and storage opportunities for future projects. There is a particularly high policy uncertainty associated with funding for post-demonstration projects.

[22] CCS Cost Reduction Task Force, 2013, Final Report

- **Key action proposed:** Encourage and guide developers of the follow-on UK CCS projects as to the incentive mechanisms in place that support transport and storage infrastructure, potentially ahead of the agreement of a Contract for Difference (CfD) Strike Price with individual sources.
  Deadline: 2015 **Responsibility:** Government

4) In order to meet the 2030 ambition for CCS in the core decarbonisation scenario, demonstration projects should be operational by 2020 and pre-development of around 5 post-demonstration projects should start. Government's CCS commercialisation programme could however be delayed if one or both of the projects fail to be successful following the FEED studies. Early commercial projects are also at risk as CCS may not be successfully demonstrated in the UK
   - **Key action proposed:** Ensure a robust pipeline of CCS projects, including development for reserve CCS projects. This could include funding for the FEED studies of the early commercial projects or support through planning process.
     Deadline: 2015 **Responsibility:** Government

5) Permits for onshore pipelines might involve multiple regulators and extensive consultation with a large and diverse list of potential statutory consultees and timescales are highly uncertain.
   - **Key action proposed:** Ensure effective planning and permitting process for pipelines and allow adequate time for these activities. Facilitate pipeline oversizing and other measures to minimise disruption to local stakeholders that may be impacted (to avoid issues of “Not in My Back Yard”).
     Deadline: 2015 **Responsibility:** Government and industry

6) Necessary regulatory frameworks for the transition from hydrocarbon production to CO_2 storage, third party infrastructure and storage site access, and financial security arrangements are not sufficient for future projects. This could include measures to improve storage readiness of aquifers and hydrocarbon fields, through processes for exchange of data and potentially choices for infrastructure abandonment.
   - **Key action proposed:** The regulatory framework for CCS in the UK needs to be finalised following the review of the EU CCS Directive in 2015.
     Deadline: 2015 **Responsibility:** Government and industry

7) Contracts, licences and leases might not be flexible enough to allow the most cost effective deployment via CO_2 injection into multiple stores in close proximity.
   - **Key action proposed:** Ensure contracts, licences and leases are structured to allow CO_2 to be injected into alternative stores, where this can be done safely.
     Deadline: 2015 **Responsibility:** Government

8) Due to the lack of investment return certainty, offshore pipelines of the early commercial projects might not be shared or future-proofed.
   - **Key action proposed:** Appropriate regulations and business models should be in place for shared pipelines and storage sites/hubs. At a minimum, ensure rights of way are in place to allow several parallel pipelines to use similar routes if pipeline “over-sizing” cannot be adopted.
     Deadline: 2020 **Responsibility:** Government and industry

Economic and commercial barriers

1) The industry lacks business models for widespread CCS adoption from demo projects.
   - **Key action proposed:** Develop business models and vision for development of CCS projects in the UK from demo projects to widespread adoption.
     Deadline: 2015 **Responsibility:** Government and industry

2) Future CCS projects need to build on lower cost transport and storage opportunities created by early projects; however, infrastructure of the demo projects might not be future-proofed.
   - **Key action proposed:** Conduct studies to identify optimum networks for the UK CCS transport and storage system for both early CCS projects and future CCS projects, in order to minimise costs.
     Deadline: 2015 **Responsibility:** Government and industry

3) Insurance and financing of CCS projects are challenging.
   - **Key action proposed:** Ensure that a variety of financial institutions and insurance companies better understand risk mitigation options of CCS.
     Deadline: 2015 **Responsibility:** Government and industry

4) Post-demonstration CCS projects might not be commercially viable without grants
   - **Key action proposed 1:** Ensure funding mechanisms and policy support for post-demonstration CCS projects are fit-for-purpose and sufficient for the projects that will mainly be supported by CfD contracts.
     Deadline: 2015 **Responsibility:** Government and industry
   - **Key action proposed 2:** Consider opportunities to develop low/negative cost storage sites, such as through tax-based incentives for early deployment of CO_2-enhanced oil recovery with CCS projects.[23]
     Deadline: 2015 **Responsibility:** Government and industry

5) A “core decarbonisation scenario" level of growth would see major UK energy infrastructure investment. The UK supply chain might have constraints given the ambition for CCS and other projects such as offshore wind or nuclear during the same period.
   - **Key action proposed:** Ensure effective supply chain planning (people, materials, equipment, capital).
     Deadline: 2020 **Responsibility:** Government and industry

6) Industrial CCS might fail to achieve cost-reduction as the industrial CCS market is immature and market conditions for industrial CCS are uncertain.
   - **Key action proposed 1:** Create necessary policy and financing regimes for industrial CCS.
     Deadline: 2020 **Responsibility:** Government and industry
   - **Key action proposed 2:** Consider incentivising the development of early industrial CCS projects.
     Deadline: 2020 **Responsibility:** Government

[23] See: Element Energy et al. for Scottish Enterprise (2012), Economic impacts of CO_2-enhanced oil recovery for Scotland, and
Element Energy et al. for SCCS (2013), CO_2-EOR in the UK: Analysis of fiscal incentives

7) Although two demonstration projects might be operational by 2020, multi-billion pound investments in developing CO_2 transport and storage solutions must begin while technologies and markets are still immature.
    - **Key action proposed 1:** Funding mechanisms and the cap on the Levy Control Framework should reflect immature market conditions of CCS for the commercial CCS projects.
    Deadline: 2020 **Responsibility:** Government
    - **Key action proposed 2:** Government and industry should continue to work in collaboration for cost reduction. Significant cost reduction should also be achieved by the late 2020s to levels competitive with other low carbon electricity generation (less than £100/MWh by 2030).
    Deadline: 2025 **Responsibility:** Government and industry

Technical barriers

1) Although hydrocarbon fields are better understood, storage at aquifers are not understood well enough and further investigations are required
    - **Key action proposed:** Conduct studies on leakage via natural faults, variability in seal quality, and unconstrained migration of CO_2 in open aquifers
    Deadline: 2015 **Responsibility:** Government and industry

2) Storage distribution in the UKCS is complex and heterogeneous, and significant characterisation/appraisal is needed several years ahead of the commissioning date of a storage site.
    - **Key action proposed:** Examine the options for characterisation of storage areas and specific storage sites in the UK in order to make storage sites bankable.
    Deadline: 2015 **Responsibility:** Government and industry

3) Many storage units span much larger areas than hydrocarbon fields, are stacked above each other, and have very unusual shapes – creating licensing/ leasing difficulties in scenarios with multiple storage companies. Reservoirs are also pressure connected and long-range CO_2 migration and leakage may be an issue.
    - **Key action proposed:** A regulatory or compensation regime needs to be in place reflecting complex geological realities (e.g. CO_2 migration) in order to avoid the risk that the value of a developer's investment in developing a particular store might be damaged by actions taken by the neighbouring stores.
    Deadline: 2015 **Responsibility:** Government

4) CO_2 from power and industrial sources is likely to be variable; however, common entry specifications for CO_2 pressures, temperatures, concentrations of impurities and phases would be needed.
    - **Key action proposed:** Conduct studies to estimate optimum/least cost entry specifications for CCS networks in the UK.
    Deadline: 2015 **Responsibility:** Government and industry

5) Long distance CO_2 transport likely to be close to challenging terrains (e.g. urban centres)
    - **Key action proposed:** Support modelling studies to identify the safest routes for CO2 pipelines, and ensure appropriate engineering, safety and regulatory guidelines are in place for CO_2 transport in the UK.
    Deadline: 2015 **Responsibility:** Government and HSE

6) There is limited experience in the UK with CO_2 capture, pipelines and storage.
   - **Key action proposed:** Ensure relevant authorities are provided appropriate guidelines for engineering, safety and regulatory aspects of CCS projects.
     Deadline: 2015 **Responsibility:** Government and HSE

7) Performances of the demonstration storage sites might fall below expectations.
   - **Key action proposed:** Ensure several storage sites are tested during the demonstration projects (e.g. Goldeneye gas field is part of the Captain aquifer and in close proximity to the Mey aquifer).
     Deadline: 2020 **Responsibility:** Government and industry

Summary of key actions

As identified in the previous sections, the deadlines for overcoming most of these barriers are 2015 since the pre-development of around five commercial CCS projects should start by 2015. There is currently significant uncertainty in the UK regarding the early commercial projects, which will come online after the demonstration projects. In order to attract investment without Government grants, almost all political, regulatory, economic, commercial and technical barriers must be overcome by 2015.

Figure 13 clearly shows that the scale of CCS infrastructure in place and the number of key actions that should be taken are inversely proportional. Although, there won't be any CCS projects in 2015 in the UK, a significant number of key actions should be taken. No key action is identified for the period after 2025, as CCS should be cost competitive with other technologies, and all necessary frameworks and guidelines should be in place by then.

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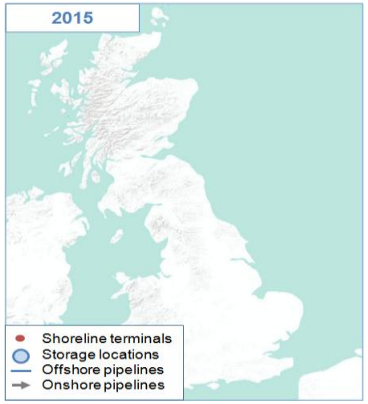
<tr><th>2015</th><th>2020</th><th>2025</th><th>2030</th></tr>
<tr>
<td>
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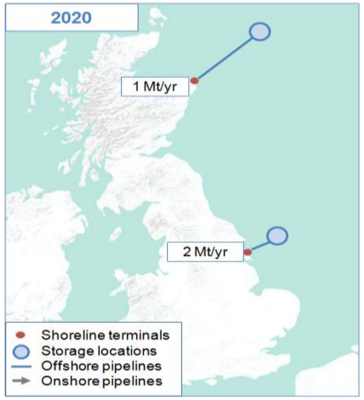
<td>
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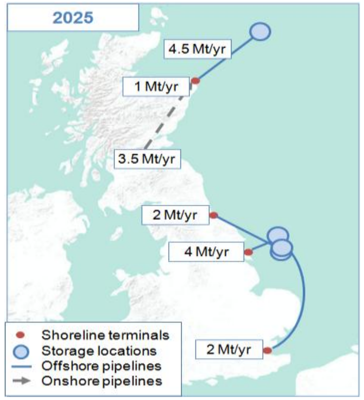
<td>
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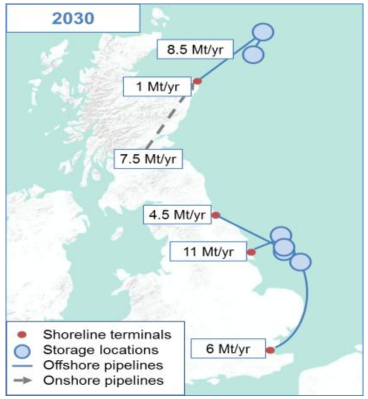
<td>
</td>
</tr>
<tr><th>Key actions by 2015</th><th>Key actions by 2020</th><th>Key actions by 2025</th><th>Key actions by 2030</th></tr>
<tr>
<td>• A clear vision for CCS by the Government
• Business models, funding mechanisms, guidelines for development of CCS projects from demo projects to widespread adoption.
• A regulatory framework reflecting complex geological realities
• Knowledge transfer from the demo projects
• Consider incentivising CO_2-EOR
• Engineering, safety and regulatory guidelines for pipelines
• Conduct various studies (e.g. optimum CCS networks, storage locations and pipeline entry specifications, and CO_2 migration)
• Examine the options for characterisation of storage areas/sites
• A variety of financial institutions and insurance companies should understand risk mitigation options of CCS better</td>
<td>• Necessary regulations and business models for shared pipelines and storage sites.
• Funding mechanisms and UK Levy cap should reflect immature market conditions of CCS
• Effective supply chain planning
• Ensure several storage sites are tested during the demo projects
• Necessary policy and financing regimes for industrial CCS</td>
<td>• Significant cost reduction by the late 2020s</td>
<td>• CCS is cost competitive with other technologies, and all necessary frameworks and guidelines are in place.</td>
</tr>
</table>

Figure 13: Timeline for key actions

5 Conclusions

Carbon capture and storage (CCS) is a unique technology, which could retain the flexibility of fossil-fuel based energy generation while materially reducing carbon emissions and providing flexible electricity generating capacity to balance other sources. CCS could also be applied to industrial plants to reduce carbon emissions.

CCS scenarios consistent with the CCC's core decarbonisation scenario requirements (50 $MtCO_2$/yr of capture in 2030) and delayed electrification scenario in 2030 (35 Mt/year of capture in 2030) are technically feasible. The engineering requirements for the infrastructure (i.e. pipeline lengths, numbers of wells, platforms and reservoirs) are less than or comparable to investments in North Sea oil and gas. However the existing oil and gas infrastructure in the UK Continental Shelf emerged over several decades with considerably stronger political and financial drivers compared to those currently envisaged for CO_2 transport and storage.

Overall, cumulative investment needed for the CCS infrastructure by 2030 in the core decarbonisation scenario is estimated to be almost £8 billion (undiscounted), which is less than the amount spent in one year on oil and gas activities (in 2012 the comparable figure was £12 billion). However it is important to note the absence of consensus on the preferred transport and storage network architecture and the paucity of actors interested in this space (for example hydrocarbon field operators engaging constructively to make their fields ready for CO_2 storage). There is also a very large uncertainty in costs due to inherent subsurface performance uncertainty and site variability, as well as the linkage between the offshore industry and volatile markets for oil, gas and other offshore infrastructure.

There are long lead times for storage assessment and high risks (as yet virtually unquantifiable) that specific storage sites or transport routes will fail to pass through all the consenting processes or meet other milestones. The current framework for post-commercialisation projects (negotiated strike price for power plants with capture) results in very weak incentives to coordinate infrastructure (to maximise capacity or minimise risks and costs), which could delay uptake. The commercial challenges are similar to the initiation of other networked solutions (e.g. district heating, offshore power grids), albeit exacerbated by the immaturity of CCS generally. These challenges have been successfully overcome in other sectors, but to date limited progress has been made in developing compelling business and regulatory models for CO_2 transport and storage.

The analysis carried out on the timelines of the CCS infrastructures reveals that, to meet the core decarbonisation scenario, pre-development of around five early commercial CCS projects with at least two large CO_2 sinks should start before the commissioning of the demonstration projects. If investors wait until CCS technology is demonstrated in the UK, the timelines suggest that meeting the 2030 ambition for CCS in the core decarbonisation scenario would be delayed by at least five years. Under the current framework, subsequent projects benefit primarily from a strike price negotiated at final investment decision, which will require detailed understanding of transport and storage infrastructure.

This study identifies the main barriers to deployment for CCS infrastructure and proposes some key actions to overcome each barrier with deadlines for actions. The analysis suggests that in order to attract investment in CCS infrastructure without Government grants in the UK, it is important to make progress in parallel on diverse political, regulatory, economic, commercial and technical barriers. Some of these will need to be completely resolved by *ca*. 2015 for a “second wave” of projects that need to make FID well before the operational performance of the first UK CCS projects is understood and any CCS infrastructure is in place in the UK (i.e. in the period 2015-2020).

This can best be achieved with a very clear vision for CCS from the UK Government, showing clearly the levels of CCS will be needed - rather than “may be needed” - in the UK in order to decarbonise, urgently, the power and industrial sectors. The industry, Government and regulators must continue to collaborate to overcome these barriers to meet the core scenario.

6 Appendix

6.1 Assumptions and methodology

Assumptions

Table 3: Key technical assumptions

Required data	Assumption/Source
Power plant specifications	• Source: Parsons Brinckerhoff
Gas and coal emissions factors	• Source: DEFRA
Load factors	• Estimated using Imperial's optimised network modelling
Location of power plants with capture in 2030	• Estimated using Imperial's optimised network modelling • 5 GW of CCGT post 2030 is included for over-sizing • Existing CCS project proposals and the demonstration projects are assumed to be operational by 2030*
Location of industrial sites with capture in the core decarbonisation and delayed electrification scenarios	• Ammonia, hydrogen, ethylene, large iron & steel and refinery (i.e. capture potential > 0.5 Mt/year) plants, which are near existing power plant clusters (i.e. distance < 100 km) are included in the analysis
Industrial CCS timeline	• Industrial CCS projects will likely need to access to shared transport and storage infrastructure. Industrial sites are therefore assumed to come online after offshore pipelines and storage sites are in place (i.e. around 2024)
Onshore pipeline diameter/length estimation	• Onshore pipeline diameters are estimated assuming a total pressure drop of 5 Mpa. Routing factor is assumed to be 2 for onshore pipelines and 1.2 for offshore pipelines.

Table 4: Key cost assumptions[24]

Cost Element	Unit	Cost (2020)
Onshore CAPEX 10"	£million/km	0.35
Onshore CAPEX 15"	£million/km	0.38
Onshore CAPEX 18"	£million/km	0.45
Onshore CAPEX 36"	£million/km	0.56
OPEX (%)	%	1.5%
Offshore infrastructure	Costs of shoreline terminals and all offshore infrastructure are based on in-house modelling	

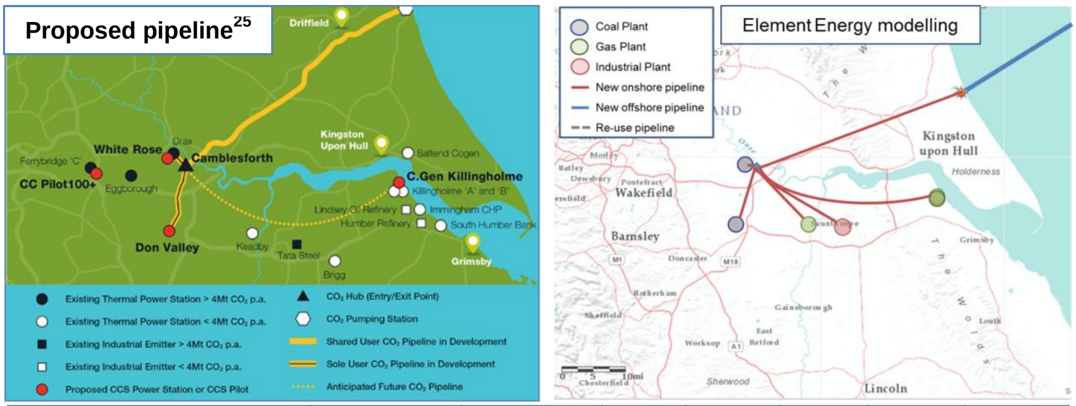
[24] CCS Cost Reduction Taskforce, 2013, Final Report

Source-sink matching methodology

- Element Energy CCS network modelling tool was used to estimate the offshore infrastructure costs of the CCS network in the core decarbonisation scenario.
- All CO_2 emitters are connected to the nearest shoreline terminals (i.e. St.Fergus, Teesside, Yorkshire and Thames) with possible onshore transport networks (see the onshore networks section for the onshore transport costs).
- Plausible offshore networks are then chosen based on the nearest sinks, identified in UKSAP*, having sufficient theoretical injection capacity to meet the storage demand, and sufficient storage capacity to meet at least ten years of demand.
- We have imposed some restrictions of storage selection, as per previous studies. For example, the availability of hydrocarbon fields for storage is limited to after their predicted Close of Production data (accurate to less than +/- 5 yrs). We avoided sites within close proximity to a producing hydrocarbon field. From the remaining potential sinks we chose those that were nearest to the shoreline terminals and had least costs (on a £/t basis).
- Offshore pipelines are over-sized (i.e. future proofed until 2035).
- All other offshore infrastructure are over-sized for 5 years.

6.2 Onshore networks

Yorkshire and Humber

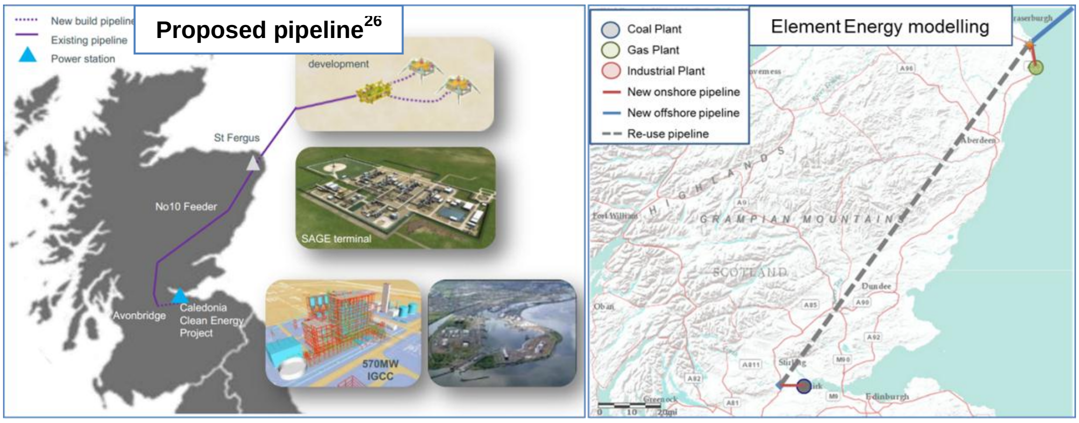


CO_2 source (2030)	Type	Connected to	CO_2 capture (Mt/year)	Pipeline diameter (inch)	Pipeline length (km)	CAPEX (£million)	OPEX (£million)
White Rose	Oxy	Hub near Drax	2.0	8	6	2	0.0
Don Valley Project	IGCC	Hub near Drax	4.2	14	31	12	0.2
Keadby Power Station	CCGT - Post	Hub near Drax	2.1	12	40	15	0.2
Killinghome cluster	IGCC and CCGT	Hub near Drax	7.3	18	93	52	0.8
Scunthorpe Integrated Iron & Steel	Iron & Steel	Forth hub	3.6	14	54	20	0.3
Hub near Drax	Hub	Humber		28	176	100	1.5
				Total	**400**	**200**	**3.0**

Figure 14: Onshore pipeline network in Yorkshire[25]

[25] CO_2 captured in the Yorkshire and Humber CCS cluster could be transported via a shared user CO_2 pipeline. See: http://www.offshore.no/international/article/21576_National_Grid_to_drill_for_North_Sea_CCS_project

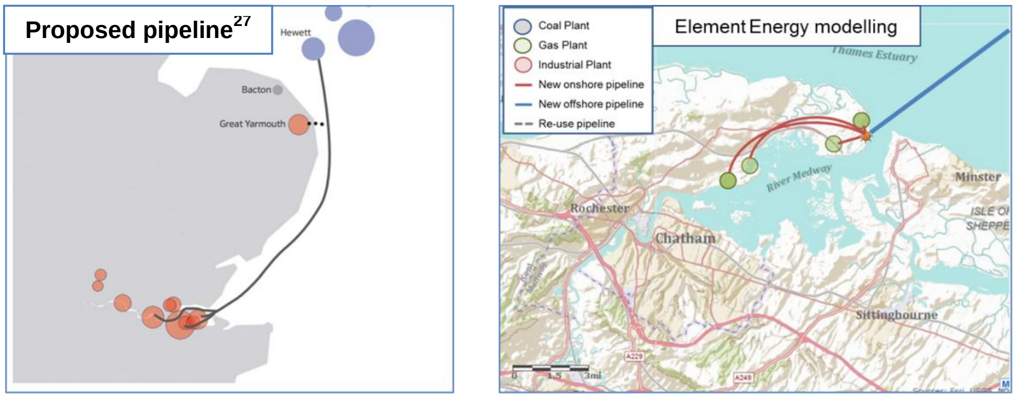
Scotland



CO_2 source (2030)	Type	Connected to	CO_2 capture (Mt/year)	Pipeline diameter (inch)	Pipeline length (km)	CAPEX (£million)	OPEX (£million)
Peterhead CCS project	CCGT - Post	St Fergus	0.8	6	23	8	0.1
Captain Clean Energy Project	IGCC	Forth hub	3.5	12	24	9	0.1
Near Grangemouth	IGCC	Forth hub	3.9	12	24	9	0.1
Feeder 10 (re-use pipeline)	Existing pipeline	St Fergus		36	280	80	1.2
				Total	**352**	**107**	**1.6**

Figure 15: Onshore pipeline network in Scotland[26]

Thames

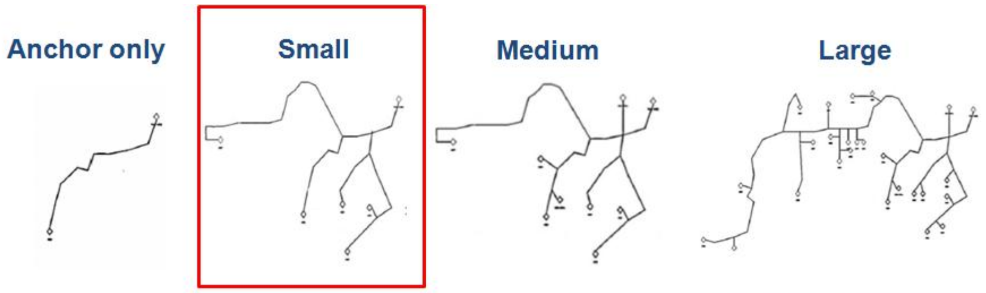


Installation (2030)	Type	Connected to	CO_2 capture (Mt/year)	Pipeline diameter (inch)	Pipeline length (km)	CAPEX (£million)	OPEX (£million)
Damhead Creek Power Station	CCGT - Post	Thames	2.1	10	12	5	0.1
Grain Power Station	CCGT - Post	Thames	2.4	8	4	1	0.0
Medway Power Station	CCGT - Post	Thames	2.4	8	1	1	0.0
Near Kingsnorth	CCGT - Post	Thames	2.4	10	15	6	0.1
Near Grain Power Station	CCGT - Post	Thames	2.4	8	4	1	0.0
Near Kingsnorth	CCGT - Post	Thames	2.4	10	15	6	0.1
Near Kingsnorth	CCGT - Post	Thames	2.4	10	15	6	0.1
				Total	**67**	**25**	**0.4**

Figure 16: Onshore pipeline network in Thames[27]

[26] National Grid's Feeder 10 pipeline could be re-used for onshore CO_2 transport from Forth to St Fergus (~10 $MtCO_2$/year capacity) See: http://www.usea.org/sites/default/files/event-/2013%201%2023%20CCEP%20Overview.pdf
[27] See for example: http://www.eon-uk.com/Thames_cluster_report_-_April_2009.pdf

Teesside



Network description	Anchor-only	Small	Medium	Large
Number of sources	1	5	8	37
Peak capacity (Mt/yr)	5	14	22	26
Onshore pipeline distance	5 km	19 km	22 km	37 km
Capital cost for onshore pipeline(s)	£7.5 m	£46 m	£48 m	£60 m

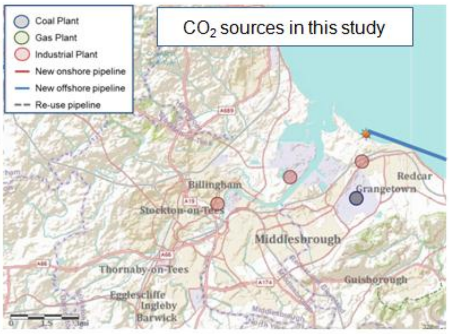


Figure 17: Onshore pipeline network in Teesside[28]

6.3 Detailed infrastructure costs

Table 5: Summary of onshore pipeline costs

Core decarbonisation scenario Cumulative real costs by 2030	Pipeline length (km)	CAPEX (£million)	OPEX (£million)
Scotland	352	107	1.6
Teesside	19	46	0.7
Yorkshire	400	200	3
Thames	67	25	0.4
Total	**838**	**378**	**5.7**
Delayed electrification scenario Cumulative real costs by 2030			
Scotland	352	107	1.6
Teesside	19	46	0.7
Yorkshire	360	174	2.6
Thames	17	6	0.1
Total	**748**	**333**	**5.0**

[28] Potential onshore pipeline networks were examined in detailed before. Source: One North East, Developing a CCS network in the Tees Valley Region Report

Table 6: Cumulative costs to 2030 by cost element

Cost element	Cumulative costs to 2030 (£billion, undiscounted, real)	
	Core decarbonisation scenario	Delayed electrification scenario
Distribution pipelines	£0.20	£0.10
Offshore hub	£0.40	£0.30
Injection well	£0.70	£0.50
Injection facilities	£1.00	£0.70
Remediation	£0.20	£0.20
Appraisal	£0.50	£0.40
Offshore pipelines	£2.70	£1.70
Shoreline terminals	£0.10	£0.10
Onshore pipelines	£0.40	£0.30
OPEX	£1.50	£1.10
Total	**£7.70**	**£5.50**

6.4 Detailed timelines

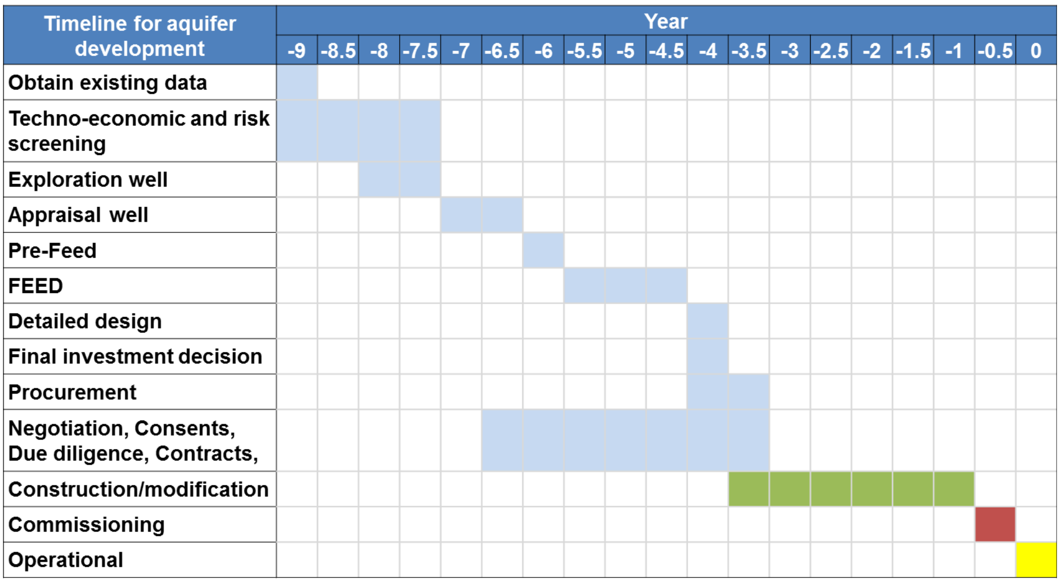


Figure 18: Illustrative timeline for aquifer development

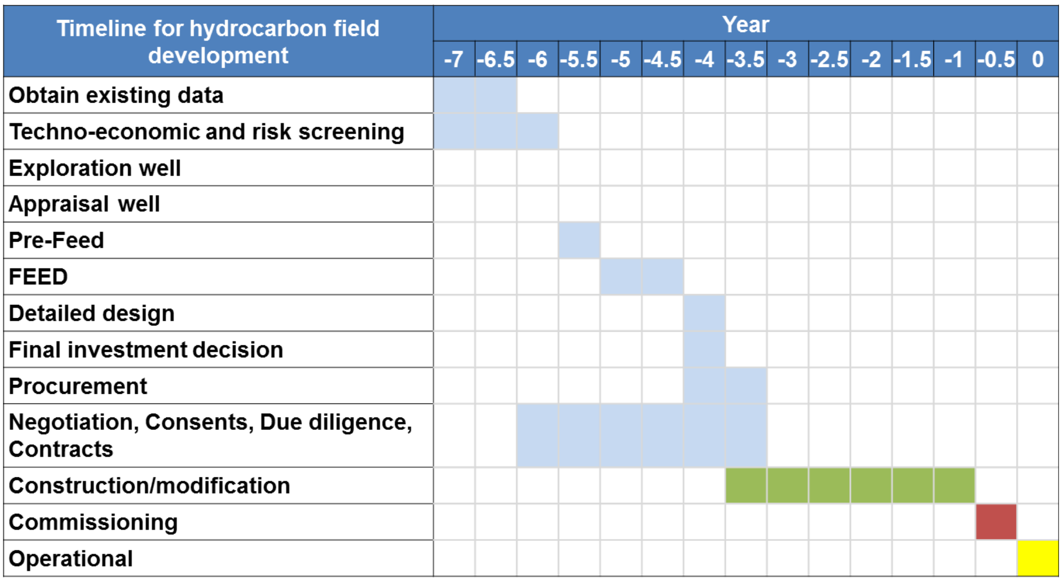


Figure 19: Illustrative timeline for hydrocarbon field development

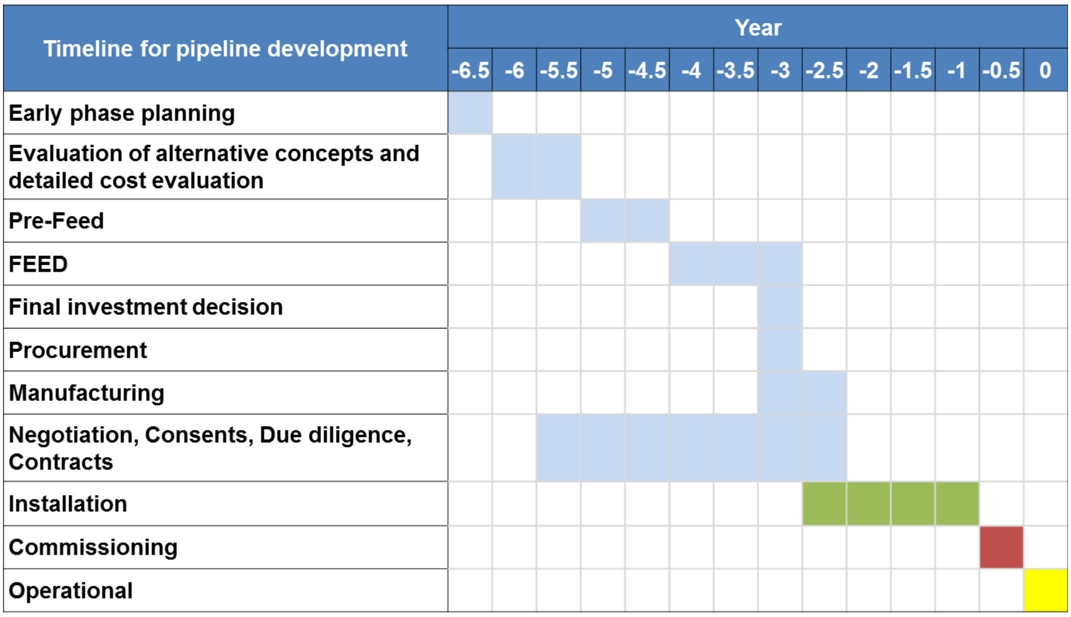


Figure 20: Illustrative timeline for pipeline development

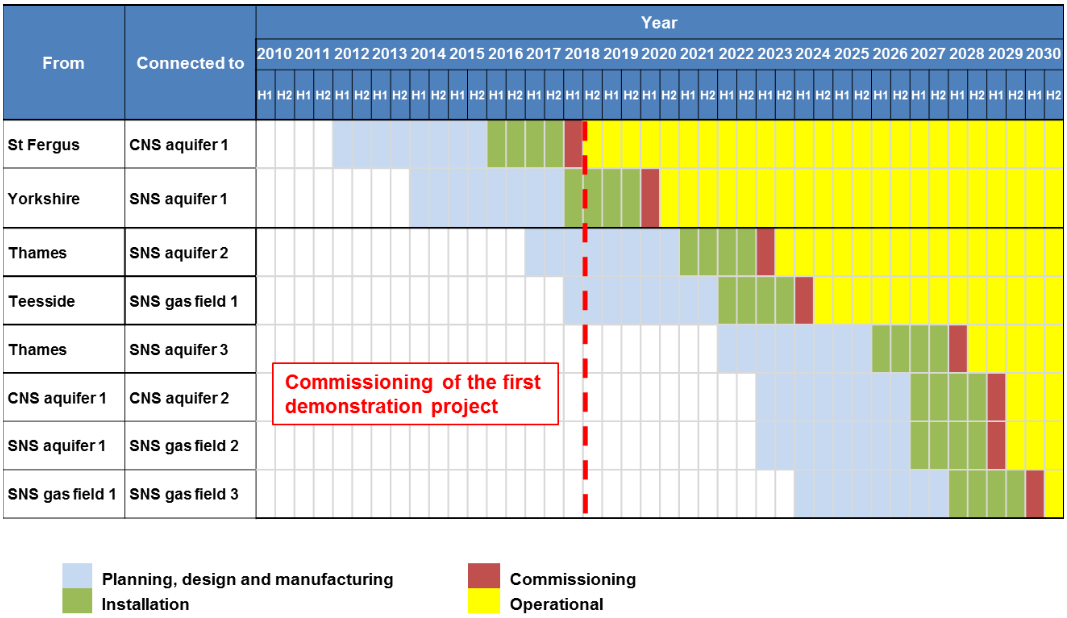


Figure 21: Offshore pipeline development in the core decarbonisation scenario

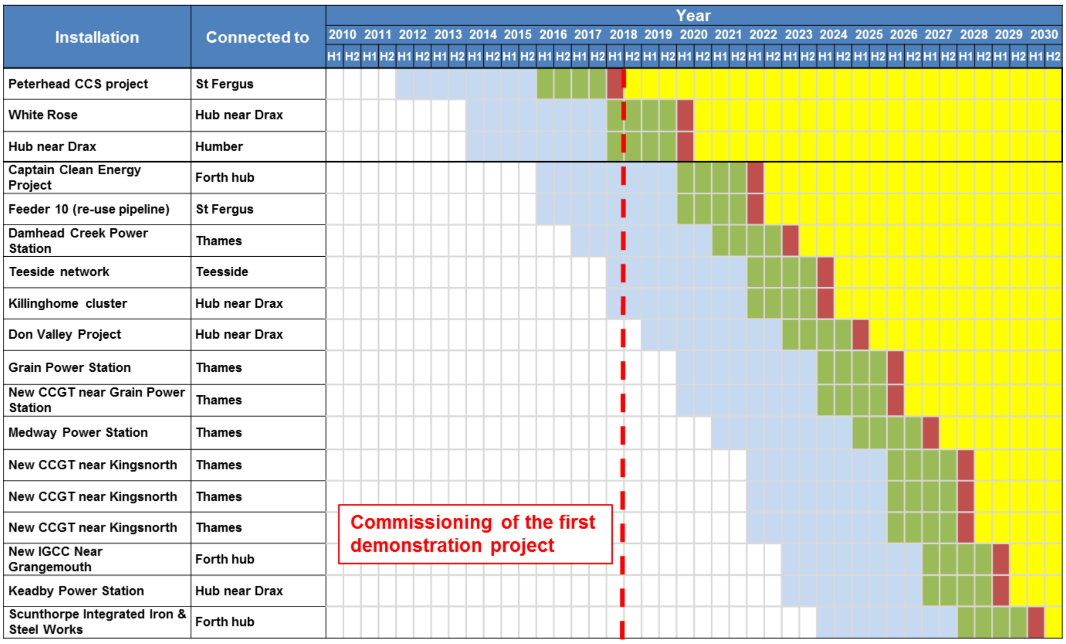


Figure 22: Onshore pipeline development in the core decarbonisation scenario

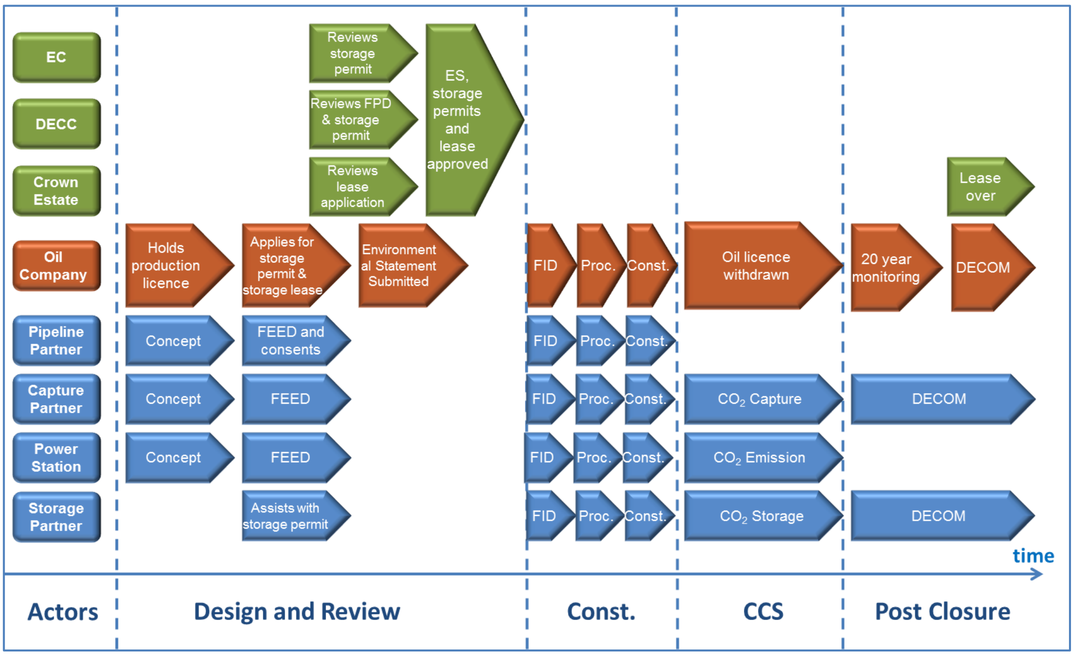


Figure 23: Illustrative regulatory pathway for CCS projects