The development of UK CCUS strategy and current plans for large-scale deployment of this technology

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For over 20 years, carbon capture utilisation and storage (CCUS) has been recognised as a useful tool to help reduce UK national emissions. Over this period the target reduction in greenhouse gas emission rates for 2050 has increased, from 60% to 100%, i.e. net zero. This has led to change in the role envisaged for CCUS, from initially just cutting emissions on coal power plants by around 50%, to the point where capture and secure sequestration of all fossil CO_2 emissions is required, either directly at source or indirectly via carbon dioxide removal from the air (CDR). Additional CDR, either through the use of biomass energy with carbon capture and storage (BECCS) or direct air carbon capture and storage (DACCS), will also be required to compensate for other UK greenhouse gas emissions. Potentially over 100 $MtCO_2$/yr of CCUS is needed by 2050. Current UK plans are to establish four CCUS clusters by 2030, capturing and storing a minimum of 10 $MtCO_2$/yr from industry, power, hydrogen production and, potentially, CDR. The UK has a large amount of secure storage capacity for CO_2 in geological formations a kilometre or more below the sea bed in the North Sea and the Irish Sea.

The development of UK CCUS strategy

CCUS studies in the UK date back nearly forty years, to a study on using post-combustion carbon dioxide (CO_2) capture with amines on coal power plants to supply CO_2 for enhanced oil recovery (EOR) (Roberts, 1983). Serious plans, however, started in 2002, when the Royal Commission on Environmental Pollution (RCEP, 2002) recommended that UK 2050 annual CO_2 emissions be reduced by 60% compared to 1990 and suggested that "there is considerable potential for disposing of carbon dioxide in deep geological strata with minimal environmental impact... Disposal in geological formations beneath the sea-bed may be safer and more secure than in those below dry land".

The 60% reduction target was accepted by the UK government in an Energy White Paper in 2003 (DTI, 2003). Consistent with the relatively modest emission reduction target, this also discussed CCUS mainly in the context of coal power generation: "CCS offers the potential to deal with the carbon emissions from using fossil fuels in electricity generation or from other large CO_2 sources (such as chemical plants and refineries). In coal plant it could be achieved either by capturing the CO_2 from flue gases or technically more easily by gasifying the coal prior to electricity generation (in an integrated gasification combined cycle – IGCC – plant)".

The statement that IGCC is the preferred technology for CO_2 capture from coal is an example of a fundamental error that afflicted world-wide CCUS practice for several decades, culminating in the failed $7.5bn Kemper County IGCC project in the USA (Kelly, 2018). It is indeed relatively cheap to capture CO_2 when using a gasifier to produce hydrogen (H_2), a combination known as pre-combustion capture. But IGCC plants have higher capital costs, so that the overall cost of electricity is higher than for a conventional coal plant with post-combustion capture (PCC). The overall cost and efficiency penalty for pre-combustion capture vs. PCC is even larger for natural gas (e.g. IEAGHG, 2006; IEAGHG, 2012; Wood, 2018).

This initial misapprehension about pre-combustion capture and H_2 led to a rash of early studies on IGCC projects by UK utilities interested in new coal plants, although these were put aside at the pre-feasibility study stage and replaced with conventional coal plus PCC projects. More seriously, BP persisted in taking a project for a new H_2-fired power plant at Peterhead through a full, self-funded, front-end engineering design (FEED) study (Macalister, 2007). Anecdotal evidence suggests this was based on an argument that can be summarised as "oil companies want to sell molecules, not regulated electricity". However, it seems at least possible that if BP had followed advice to use the cheaper PCC option on the already-existing natural gas power plant at Peterhead then the project would have attracted the necessary government support – and UK CCUS deployment would be about 15 years ahead.

The UK government launched its 1st CCUS Competition following the 2007 Energy White Paper (DTI, 2007). With a budget of £1bn, this was limited to funding demonstration-scale PCC projects on new pulverised coal power plants. Coal with CCUS was a high political priority at the time; under the pressure of very high natural gas prices UK utilities were planning to build many new coal plants and this was the subject of major protests from environmentalists e.g. (Guardian, 2008). Nonetheless, as noted above, the BP Peterhead gas power CCUS project might still have attracted government support as a useful and cost-effective technology demonstration, if it had used PCC.

Two projects were selected, for PCC retrofits at new coal power plants at the Longannet (Scottish Power, then Iberdrola) and Kingsnorth (EON) power plant sites. These both went through full FEED studies but were cancelled by the UK Government in October 2011. This was despite strong political support for CCUS; the main purpose of the 2010 Energy Act (HMG, 2010) was to authorise an £11bn CCS Levy on all electricity consumers. But, over the period of the 1st CCUS Competition, the 2007-2009 depression led to significant reductions in UK electricity demand and natural gas prices, plus a reluctance to invest. This was followed by the "shale revolution" in the USA, which, together with growing renewable generation capacity, led to a perception that any new power capacity should be unabated natural gas power plants, at a much lower cost. EON's new Kingsnorth power plant was cancelled in late 2010, although the FEED study was continued to generate further information. The Longannet study appeared to include only a demonstration unit (curiously comprising two identical small units) attached to an old existing power plant with a short remaining life. Both FEED studies, with some redactions, are still available (DECC, 2011).

But the need to develop CCUS on other applications had also increased since the start of the 1st Competition. In 2008 the UK adopted a legally-binding 2050 greenhouse gas (GHG) emission reduction target of 80% (HMG, 2008; CCC, 2008), effectively halving the amount of CO_2 that could be emitted then, and also set up an independent body, the Climate Change Committee, to monitor and advise on progress against the target. This new target meant that natural gas power plants would also need CCUS, as well as other large emitters. A 2nd CCUS Competition with a £1bn budget was therefore launched in April 2012. This resulted in two projects undertaking FEED studies:

- a PCC retrofit, led by Shell, to one of the three units on the existing Peterhead gas power plant, linked to the same decommissioned Goldeneye gas production platform as used for the Longannet study;
- a new coal-fired oxyfuel plant study, known as White Rose, led by Alstom (subsequently GE), on the Drax site, with a new pipeline to a storage site in an offshore aquifer.

By mid-2015, however, it was apparent that the Levy Control Framework, a cap on total subsidies for low-carbon electricity, was going to be exceeded even before CCS projects were funded. In late 2015 the 2nd Competition was also cancelled when the FEED studies were largely completed, although again partially-redacted documents were made publicly available (BEIS, 2015). This decision was reported to have been made collectively by the Cabinet (Liaison Committee, 2016). The main factors influencing the result appear to have been perceived high cost, partly caused by cross chain multiplication of risks and the expectation that these two single source to sink projects should develop the CO_2 transport and storage infrastructure of subsequent CCS projects, and lack of relevance. It was stated by the Prime Minister, David Cameron (Liaison Committee, 2016) that "even after you've spent that £1 billion, that doesn't give you carbon capture and storage that is competitive in the market… you get some carbon capture and storage capacity and it would cost you, at the current estimate, something like £170 per megawatt-hour".

At the same time, however, the Paris Agreement in 2015 made the case for CCUS stronger, as noted by the Climate Change Committee in a letter to the government (CCC, 2016): "significantly, the Agreement aims… to reach net zero global emissions of greenhouse gases in the second half of the century. This is more ambitious than the basis of the UK's statutory target for 2050, which was a global path to hold the temperature rise close to 2°C". The same letter then went on to comment on the recent CCUS project cancellation, "CCS has a crucial role to play… The recent funding decision must not and does not exclude CCS permanently from playing a significant role in reducing UK emissions…"

CCUS in the UK therefore needed to make a fresh start in 2016, taking into account both the need to be more cost-effective and also the need to achieve net-zero emissions. To assist with this the UKCCSRC organised a series of regional meetings to promote clusters with a range of CO_2 sources sharing CO_2 transport and storage (T&S) infrastructure (UKCCSRC, 2016). The simple formula to deliver cost-effective CCS with offshore storage was summarised as:

Cost-effective CCS	=	Multiple Sources (>5 units per cluster)	+	Large-scale Pipeline & Storage (>10MtCO2/yr)

In 2018 the cluster theme was developed further by the CCUS Cost Challenge Taskforce, established by BEIS with extensive stakeholder participation, with the following main conclusions in its final report (BEIS, 2018):

- potentially over 100 $MtCO_2$/yr of CCUS is needed by 2050 and time is short to deliver this. The first projects should become operational in the mid-2020s;
- CCUS covers a wide range of activities, including "low carbon industrial products, decarbonised electricity and gas, a hydrogen economy, greenhouse gas removal, and new industries based around utilising CO_2";
- "we need viable business models to move the technology to a sustainable commercial footing";
- CCUS can already be deployed at a competitive cost by using clusters.

CCUS also received a major boost when the UK adopted a net zero GHG emission legal target for 2050 in 2019 (BEIS, 2019). As the Climate Change Committee noted in a study on how net zero could be delivered (CCC, 2019), "CCS is a necessity not an option".

Current plans for large-scale CCUS deployment in the UK

Current UK plans for CCUS deployment are based on clusters in the areas shown in Figure. Unlike France's two largest industrial clusters in the Rhone Valley and the Paris Basin, all UK clusters benefit from direct access to offshore geological storage, either via pipeline or, in the case of the South Wales cluster, by ship. With access to the favourable geology of the Northern North Sea, clusters on the East Coast of Great Britain may emulate the ambition of the Northern Lights cluster in Norway, and also store CO_2 from Europe. Other CCUS clusters in the South of England, notably at Southampton and on the Thames/Medway estuaries, are also likely in the longer term.

Weeks before COP26, the UK government increased its target for CCUS deployment, from 10 $MtCO_2$ per year by 2030 (HMG, 2020), to a new target of "deliver[ing] four carbon capture usage and storage (CCUS) clusters, capturing 20-30 $MtCO_2$ across the economy, including 6 $MtCO_2$ of industrial emissions, per year by 2030" (HMG, 2021).

This is being financially supported through:

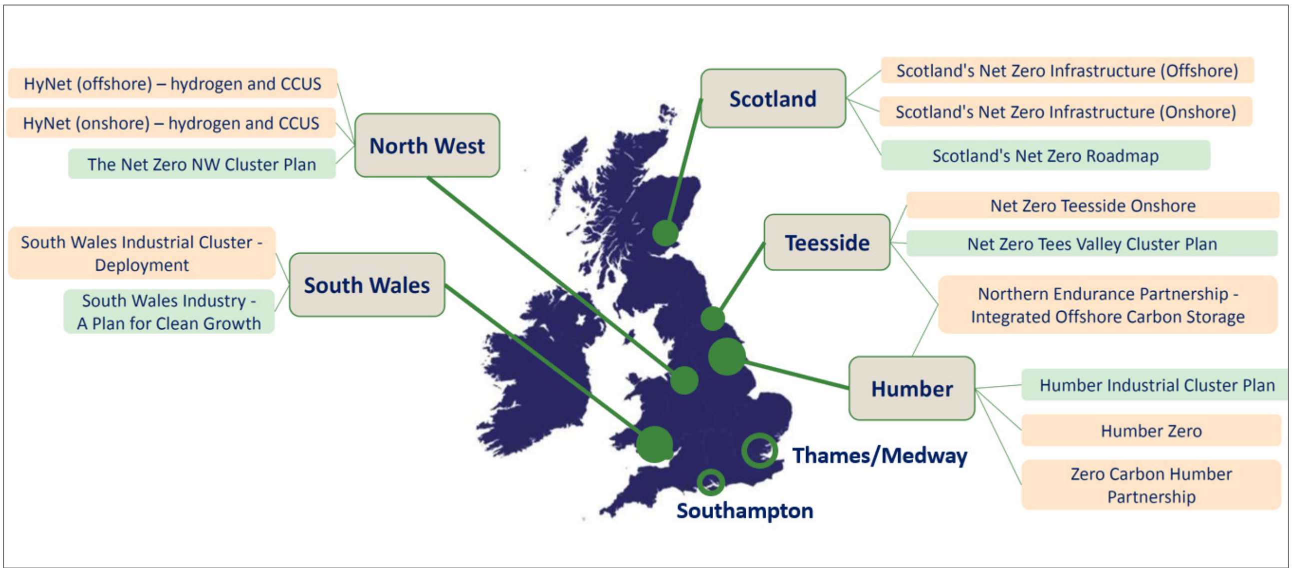
- the Industrial Decarbonisation Challenge (IDC, UKRI, 2021), which principally is co-funding FEED studies, with smaller amounts for research and cluster planning (Livesey, 2021);
- £1bn CCS Infrastructure Fund (CIF; BEIS, 2021a), which will primarily support capital expenditure on CO_2 Transport and Storage networks and industrial carbon capture projects;
- business models being developed to provide market-based support for CO_2 Transport and Storage, power, and industrial carbon capture (BEIS, 2021e), also for all types of low carbon H_2 (BEIS, 2021d).

Following a call for proposals with the five prospective clusters in Figure (BEIS, 2021c), a formal Cluster Sequencing Process was begun in October 2021 (HMG, 2021) to divide them into two 'tracks':

- Track 1 clusters made up of projects making Final Investment Decision (FID) in 2022, or soon after, and in operation by the 'mid-2020s' ;
- and Track 2, clusters with projects making FID in 2024 and operational from 2027 onwards.

Negotiations with the individual T&S and capture projects to establish the final cluster rollout arrangements are now beginning to take place within the Cluster Sequencing Process.

Further developments beyond initial cluster projects will be supported by the six research projects in the IDC's "Decarbonisation of industrial clusters: cluster plan" programme, which will examine how additio-



UK CCUS clusters in the Industrial Decarbonisation Challenge (solid circles, areas show relative industrial emissions) and potential additional clusters (open circles) – Based on LIVESEY, 2021.

nal CCUS and other decarbonisation activities can be applied to eventually deliver net zero clusters (Livesey, 2021).

Overview of proposed UK CCUS Clusters

The Phase 1 of the Cluster Sequencing Process includes the Hynet Cluster in the NorthWest of England and the East Coast Cluster as the Track 1 clusters, with the Scottish cluster as a reserve cluster (HMG, 2021). The final form of the Track 2 clusters is therefore undefined at time of writing. Some reported features of the clusters in the Cluster Sequencing Process are as follows:

Track 1 Clusters in operation by the 'mid-2020s'

Hynet Cluster (Hynet 2021)

HyNet North West is a CCUS and hydrogen project in the North West region of England and North Wales. CO_2 will be captured from existing industrial sites near Ince and the Stanlow refinery, and from a new low-carbon H_2 plant at Stanlow. Total potential capture is reported to be 10 $MtCO_2$/yr by 2030, with up to 4GW of hydrogen. CO_2 will be transported via an onshore network and a 30 km offshore pipeline. Eni plans to repurpose depleted hydrocarbon reservoirs in Liverpool Bay for permanent CO_2 storage (Offshore, 2020).

East Coast Cluster (East Coast Cluster, 2021)

This is a collaboration between two large onshore cluster projects, Zero Carbon Humber (ZCH) and Net Zero Teesside (NZT), and the offshore Northern Endurance Partnership. CO_2 would be stored in the Endurance aquifer in the Southern North Sea, via a 145 km pipeline from Teesside and an 85 km pipeline from the Humber. A wide range of CO_2 sources are envisaged, potentially including natural gas power plants, blue hydrogen, energy-intensive industries and energy-from-waste plants. ZCH aims to capture at least 17 $MtCO_2$/yr and to supply up to 10 GW of H_2 by the mid-2030s. NZT aims to capture up to 10 $MtCO_2$/yr. Regional H_2 pipelines and salt cavern storage are also included.

Possible Track 2 clusters operational from 2027 onwards

Scottish Cluster (Storegga, 2021)

The Scottish Cluster is planned to serve nine CO_2 sources by 2030, including industrial sites, power generation plants, a new hydrogen generation plant and Direct Air Capture ("DAC") technology, storing 6.7 $MtCO_2$/yr by 2030, and over 23 $MtCO_2$/yr in the longer term. H_2 production is predicted to reach 1.3 GW by 2030 and 3.7 GW by 2050. Repurposing existing infrastructure from the oil and gas industry is expected to save cost and time. CO_2 imports via shipping to Peterhead Port are envisaged from 2026, with around 3 $MtCO_2$/yr from UK sources by 2030 and up to 9 $MtCO_2$/yr in the long term.

DelpHYnus (Neptune, 2021)

The DelpHYnus proposal is for a CO_2 T&S network using existing natural gas production facilities where feasible, accessed from the Theddlethorpe pipeline terminal and with 1.8 GW of hydrogen production facilities also located there. It would also serve the South Humber Industrial area, via existing onshore pipelines.

V Net Zero (Humber Zero, 2021)

This cluster, on the south bank of the river Humber, is centred around the Lindsey and P66 Humber oil refineries and the associated VPI Immingham CHP plant. With added H_2 production facilities it is predicted that up to 8 $MtCO_2$/yr would be captured by 2030. CO_2 is to be transported, via existing pipelines, to the Theddlethorpe terminal and onward to depleted gas fields. This cluster is adjacent to the Humberside onshore elements of the East Coast Cluster.

Conclusions

Current UK plans for CCUS deployment are very different from what has gone before, although previous initiatives, even though unsuccessful, have generated much useful experience. The proposed CCUS clusters offer reduced cost and risk, as well as facilitating CCUS for many of the emission sources that must now be addressed to deliver net-zero. Comprehensive plans are in hand to deliver at least four operating UK CCUS clusters by 2030, capturing and storing over 20 $MtCO_2$/yr.

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