Department for
Business, Energy
& Industrial Strategy

Carbon Capture & Utilisation Demonstration Programme

Phase 1 Final Study Report

Document Number: 13414-8820-RP-005 Revision: 3A

Date: April 2019

Department for Business, Energy & Industrial Strategy

CCU Demonstration Programme

Phase 1 Final Study Report

13414-8820-RP-005, Rev. No. 3A

Report for

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Document revisions

No.	Details	Date
01	For Comment	20th Nov 2018
1A	Final	17th Jan 2019
2A	Final + 150 kTPA Extension	8th March 2019
3A	Minor Comments Added	17th April 2019

Cover Photograph

Image courtesy of Suzie Ferguson

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1 Introduction

The Department for Business, Energy and Industrial Strategy (hereinafter BEIS) has launched a Carbon Capture and Utilisation Demonstration (CCUD) programme to support the design, construction and demonstration of carbon dioxide capture and utilisation technologies from industrial sources.

The programme is divided into three phases. Phase 1 of the programme was designed to assess the techno-economic feasibility of applying carbon capture technologies at a range of potential host sites. The results were used by BEIS to seek approval of funds for Phases 2 and 3 [1], and to inform BEIS on the range of UK-led technologies under development.

Within Phase 1, three Work Streams were envisaged. The aims of Work Stream 1 were to engage potential host sites and technology suppliers, to review technical submissions and to develop a short-list of potential projects to assess.

Work Stream 2 covered the production of site and technology specific cost estimates that can be used by host sites to consider the commercial viability of projects at a scale of 30-70 thousand tonnes per annum (kTPA) CO_2 and which may be used as evidence to apply for funds for Phases 2 of the demonstration programme. Work Stream 3 was established to conclude reporting of the outcomes from Work Streams 1 and 2, and to generate grading criteria for BEIS to use in assessment of applications for Phase 2 and Phase 3 funding.

The primary target of the study was to establish the viability of a 30-70 kTPA plant at selected host sites. This included consideration of both the technical and economic feasibility of the project. It was realised during the study that whilst many technologies were technically feasible the economics may not be as favourable as desired for plants at this (small) scale. To determine whether projects may benefit from economies of scale, the study was extended to consider larger plants at a scale of 150 kTPA. This size was selected to be large enough to determine the economic benefit but small enough to be considered a demonstration of the technology.

Two final study reports have been generated within Phase 1. The first report, 13414-8820-RP-004, included full confidential details of potential host sites and capture technologies and hence was issued for BEIS internal use only. This second report summarises non-confidential elements of the work performed by Wood for publication on the BEIS website.

A typical block flow diagram for a solvent-based post-combustion carbon capture process with purification and liquefaction for food grade export is shown below.

[1] Further details of the £20m CCUD programme can be found at this link: https://www.gov.uk/guidance/funding-for-low-carbon-industry#carbon-capture-and-utilisation-demonstration-ccud

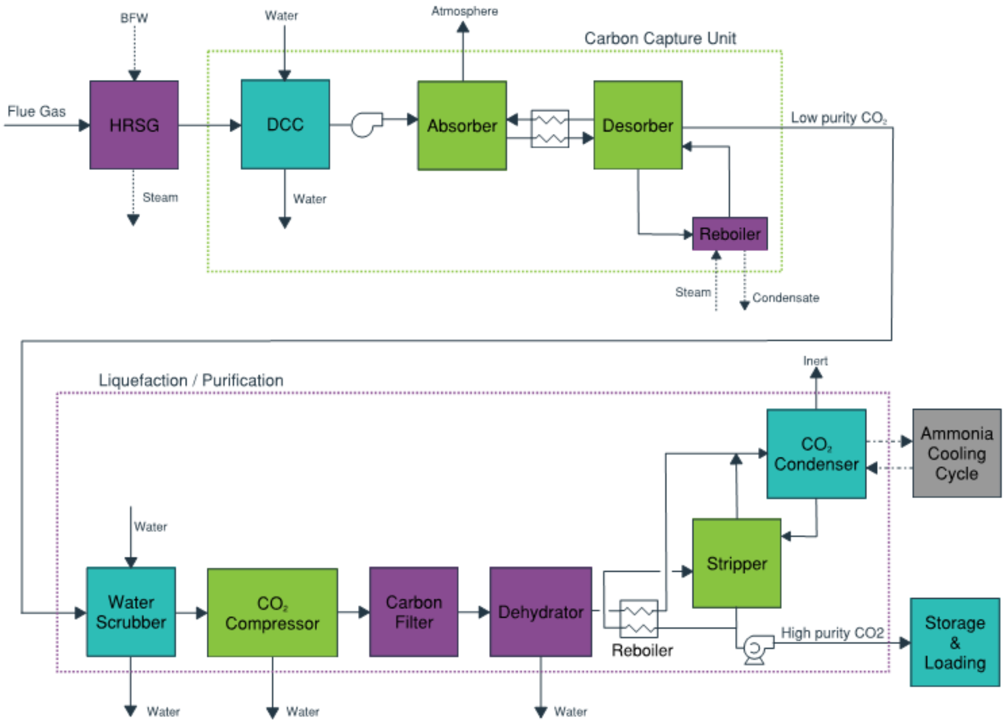


Figure 1-1: Typical Block Flow Diagram for Carbon Capture and Liquefaction Facility

BFW = Boiler Feed Water. HRSG = Heat Recovery Steam Generator. DCC = Direct Contact Cooler.

2 Abbreviations and Acronyms

AACE	American Association of Cost Engineers
ACCE	Aspen Capital Cost Estimator
BEIS	Department for Business, Energy and Industrial Strategy
BFW	Boiler Feed Water
CAPEX	Capital Expenditure
CCU	Carbon Capture and Utilisation
CCUD	Carbon Capture and Utilisation Demonstration
CO_2	Carbon Dioxide
DCC	Direct Contact Cooler
EIGA	European Industrial Gases Association
EIA	Environmental Impact Assessment
EPC	Engineering, Procurement and Construction
FEED	Front End Engineering Design
FID	Final Investment Decision
GBP	British Pound
HRSG	Heat Recovery Steam Generator
IEAGHG	International Energy Agency Greenhouse Gas R&D Programme
ITT	Invitation to Tender
kTPA	Thousand Tonnes per Annum
LP	Low Pressure
MP	Medium Pressure
MWh	Mega Watt Hour
NG	Natural Gas
ONS	Office for National Statistics
P&ID	Piping and Instrumentation Diagram
RFSU	Ready for Start-up
RPI	Retail Price Index
TPA	Tonnes per Annum

3 Basis of Design

The following data were used to provide a basis for designing all of the capture units on a consistent basis and can be applied to all of the host site locations.

The site is a generic brownfield industrial location in the North of England. Previous industrial units have been cleared, leaving a level, obstruction free (both above and below ground) site, without the need for any special civil works.

3.1 Climatic Conditions

The following climatic conditions marked (*) shall be considered reference conditions for plant performance evaluation. If required, site specific conditions will be considered on a case-by-case basis.

Atmospheric pressure:	1013 mbar (*)	
Relative humidity:	average:	80% (*)
	maximum:	100%
	minimum:	10%
Ambient temperature:	average:	9°C (*)
	maximum:	30°C
	minimum:	-10°C

3.2 CO_2 Product Specification

The product CO_2 stream specification is dependent on the utilisation method and proximity to the source of production. For sites where the product is intended to be sold to food and drink manufacturers, it should be prepared to food grade quality for transportation using refrigerated road tankers. The quality specification should be aligned with the European Industrial Gases Association (EIGA) standard 'Carbon Dioxide Food and Beverages Grade, Source Qualification, Quality Standards and Verification' EIGA Doc 70/17, Appendix A.

Unless the technology provider could justify an alternative CO_2 recovery in order to optimise operations, it was requested that 90% of the CO_2 entering the capture plant is delivered as product. It should be noted that while Wood requested 90% CO_2 capture, a CO_2 flow rate slightly deviating from this was given by some technology providers.

Product storage and loading facilities will be sufficient for 5 to 6 road tankers per day for most cases (dependant on final throughout of each case) with storage of 4 days of production for the smaller scale plant. Loading facilities suitable for 30 to 40 tankers per day and CO_2 bulk storage of 4 days has been considered for the larger 150 kTPA plant.

Note that where tanker transportation of the product is required, the EIGA standard has been adopted for this study, even if the utilisation process itself is not related to food and drink manufacture. It is assumed that road tanker operating companies will not be willing to risk contaminating dedicated CO_2 transport containers with off-spec products, nor to absorb the cost and time to clean tankers after use.

For CO_2 product transported via pipeline, the product must be compressed and dried for conditions covering the full range of pipeline operation. Otherwise, the product specifications are as specified for the nominated end-user.

4 Industrial Engagement Day

In order to raise awareness of the programme, BEIS and Wood hosted an Industrial Engagement Day in Westminster on 19th April 2018. The day was attended by a range of UK-led carbon capture technology suppliers and owners of potential sites who might be willing to trial these technologies.

A targeted invitation list was developed using existing contact lists from both BEIS and Wood. This then extended naturally to other potential partners via professional networks and industry groupings such as the UK Petroleum Industry Association, Chemical Industry Association, and the Mineral Products Association.

After a series of short presentations by BEIS and Wood, describing the programme and its aims, nine technology providers were given ten-minute slots to highlight some of the advantages of their carbon capture and utilisation processes. This gave the host sites an opportunity to see what processing opportunities exist and to encourage discussion during the lunch break.

In the afternoon, BEIS and Wood personnel hosted round-table discussions on opportunities and barriers for deployment of carbon capture technologies in the UK. The major concerns regarding CCU deployment by companies raised during the round-table sessions were:

- Economic uncertainties. The CO_2 market within the UK may change rapidly if CCU was deployed extensively. Brexit was also flagged as a risk to the economy.
- Technical risks. Using unproven novel technologies, or proven technologies in novel applications presents a technology risk. Project developers and engineering contractors wish to avoid these risks.
- Support by the Government. Companies would like guarantees that the Government will keep helping CCU to be developed in the UK.
- Lack of standards / policies. Legislation may need to be refined in order to sell new carbon products on the market.

With respect to the last bullet point above, it is worth noting that until carbon capture has been commercially deployed on several reference industrial sites, the exact conditions that the UK environmental regulators will place on the early sites is an unknown.

On the other hand, most of the attendees were positive about the deployment of CCU in the UK:

- Firstly, for the host sites, reducing their carbon footprint would generally give a positive impact on public opinion, which is important to consumer-facing businesses.
- Secondly, the early-adopter companies would start learning lessons at an early stage, giving them an advantage against those that are outside the market.
- Finally, they will be the first to develop low carbon products, a market that is yet to be discovered and expected to grow in the future as more companies might tend to prefer the lower carbon products. Media pressure on plastics manufacturers arising from the BBC's Blue Planet series and its focus on plastic accumulation in the oceans was highlighted.

Regarding the support by BEIS and the UK Government in general, many propositions were made that could be summarised in the following:

- Economic. Both with financial incentives and profit assurance. (Concern was also raised regarding long-term liabilities for CO_2 storage, although this is not specifically related to the CCU demonstration programme.)
- Business Environment. New policies that would promote the use of carbon products or carbon free certifications.

A full list of attendees and the presentation slides cannot be provided in this version of the report. However, a summary of the types of organisations represented at the Industrial Engagement Day is provided below.

Table 4-1: Source of Attendees at Industrial Engagement Day

Type of Organisation	Number of Attendees
Organisers (BEIS & Wood)	9
Host Sites / Project Developers	10
Technology Suppliers	16
Engineering Contractors (other than Wood)	4
Industry Associations / Government (not BEIS)	6
Total Attendees	45

Following the Industrial Engagement Day, Wood emailed Host Site Enquiry and Technology Supplier Enquiry Forms to companies that had attended the day and had shown a willingness to become engaged during Phase 1. Copies of these two Enquiry documents are included within Attachment 1.

5 Current UK CO_2 Market

The aim of the current programme is to encourage small to medium size CO_2 emitters [2] to capture their carbon dioxide for use in existing UK markets, rather than sending CO_2 for sequestration or generating specific new markets for utilisation. Carbon dioxide is used to a limited extent in some petrochemical processes, for soda ash manufacture and for use in fire extinguishers, but its primary use in the UK is within the food and drink sector.

The CO_2 distribution market within the UK is dominated by three main players: BOC, Air Products and Air Liquide. Between them, these three companies cover approximately 90% of annual sales of around £200m (Ref. IBISWorld Industry Report C20.110 'Industrial Gas Manufacturing in the UK'.) Typical prices for sale of carbon dioxide to industrial gas distributors are in the range £30-40 per tonne, whilst for resale, these companies may charge upwards of £70 per tonne.

Supply of carbon dioxide for industrial uses is currently dominated by companies that need to remove CO_2 from their processes, for example, fertiliser manufacture and bioethanol production. A small proportion (5-10%) of the UK industrial gas supply is imported from Europe. Recent shortages in supply of CO_2 within the UK for beer and soft drinks have highlighted that fertiliser manufacture is a seasonal process and it seems likely that an increase in the number of reliable UK-generated sources of carbon dioxide would be welcomed by the market.

Since carbon dioxide is a relatively low value industrial gas, long distance transport via road tanker is difficult to justify. Target outlets for CO_2 should ideally be found within 100 km of the point of production. Therefore, it is important to match up potential suppliers with a range of potential sales outlets.

IBISWorld advises that the UK regions with the largest demand for industrial gases, including carbon dioxide, are North West England, Scotland (particularly the central belt) and South East England. North East England also presents a moderate-sized market, although there is believed to be a surplus in this region due to the presence of several large producers.

Whilst it remains the responsibility of project developers to identify potential sales outlets for their carbon dioxide product, the general information above was used in part to short-list potential host sites for assessment in Phase 1 of the programme.

[2] The original Phase 1 ITT (TRN1393/11/2017) issued by BEIS proposed a range of 30,000 – 70,000 tonnes CO_2 per annum.

6 Cost Estimating and Economic Modelling Assumptions

6.1 Capital Cost Estimating

Where sized equipment lists were available from technology suppliers, capital cost estimates were prepared using an approach aligned to AACE Class 4. This will typically give an estimate accuracy of around ±30%. However, some of the technology suppliers only provided overall costs for the carbon capture unit. For these elements, the accuracy is likely to be closer to ±40%.

The CAPEX estimates are largely based on a Wood 'Indexed' version of the Aspen Capital Cost Estimator (ACCE) computer programme. The ACCE programme includes 'in-built' P&ID (Piping & Instrumentation Diagram) models and is used to generate the base equipment & bulk material costs and direct labour manhours. The ACCE output was checked against in-house costs and statistical data from a variety of sources.

All costs are provided in British pounds (GBP), fixed at the end of Q1 2018.

Reference costs provided in Euro were converted to GBP at the spot rate for 31st March 2018, as published by the Bank of England, as follows:

- €1 = £0.87936

All capital costs are assumed to be incurred during the two years prior to first start-up, with costs allocated in the following percentages:

- 2019 50%
- 2020 50%

Plant commissioning is assumed to occur at the end of the last year before operation and thus no reduction in plant capacity is taken during year 1.

Costs have been split between different cost elements as shown in the figure below. Costs for non-standard processes were allocated to the closest matching cost element.

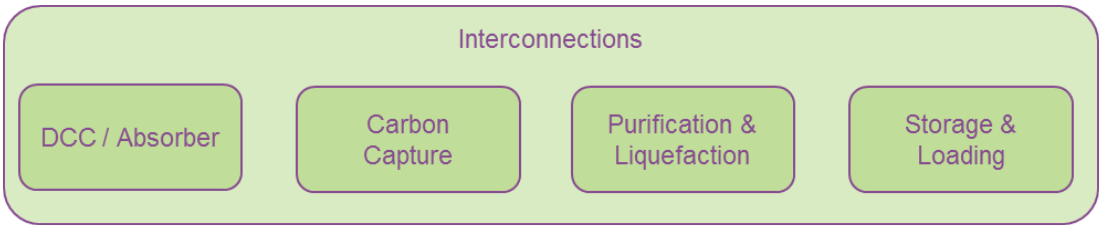


Figure 6-1: Cost Breakdown Structure

The DCC / Absorber is treated as a block separate from the main carbon capture unit because the equipment items are typically large and are shipped loose, rather than being included within the pre-fabricated module. Separating these items also allowed Wood to scale the cost of these items in proportion to the actual volumetric flow of flue gas, rather than the mass flow rate of carbon dioxide captured, which was used to scale the carbon capture, purification and liquefaction systems. This enabled BEIS and the host site to get a feel for how the cost of the DCC / Absorber and Carbon Capture scale with volumetric flow of flue gas.

The Interconnections cost takes into account the tie-in to the flue gas system, ductwork to and from the carbon capture plant, service lines for LP steam, cooling water, demineralised water, air and electric power, lines between the systems shown above and pipe racks / supports for all these items.

The submissions from the technology suppliers were for plants of approximately 30-40 kTPA and so it was determined that the larger, 150 kTPA, plant economics should be examined using scaled-up versions of the submissions. Capital costs for the generic larger scale case were adapted from the Generic Case with Tanker Export using a scaling index of 0.66 at the unit level. A cross check was undertaken with other cases to ensure the economics gave an appropriate representation. Capital costs calculated using unit scaling are typically accurate to +/- 40%.

6.1.1 EPC Contract Cost

The Engineering, Procurement and Construction (EPC) contract costs provided in this report refer to new-build facilities tied-in to existing industrial process plant. They are assumed to be awarded as a single lump sum contract through a competitive tendering process or through conversion from Front End Engineering Design (FEED) to lumpsum EPC using open-book estimates.

Direct Material costs have generally been built-up from equipment costs estimated via Wood's indexed version of ACCE. Factors for Piping, Control & Instrumentation and Electrical bulks are built into our version of ACCE, based on configurations for each type of equipment item. First-fill quantities for solvents, catalysts and other consumables have been estimated and costed based on past project experience.

Typical EPC project factors for Shipping & Freight, Third Party Inspection and Spare Parts have been applied to the Direct Materials cost.

Materials and Labour Contract costs were developed using in-house factors on the total Materials cost. The factors for these elements vary greatly from unit to unit, depending on the relative quantities of rotating equipment, static equipment, piping elements, control elements and analysers. These factors cover contracts for Civils, Steelwork & Buildings, Mechanical, Electrical & Instrumentation, and Scaffolding, Lagging & Rigging.

The EPC Contractor cost for services includes engineering design, project management, procurement, construction management and commissioning. It also includes for the EPC Contractor's recovery for corporate overheads, project contingency and profit. Naturally, the cost for services and profit margin may vary greatly in different locations and from year to year depending on the level of activity in the region and the degree of competitiveness between contractors. A higher percentage of the Materials and Construction cost has been assumed for interconnecting facilities since no large equipment costs exist for this unit.

6.1.2 Pre-Licensing, Technical & Design Costs

The EPC costs discussed above reflect the contractor costs that occur from the point of the project developer making its Final Investment Decision (FID). However, most projects proceed through a series of stages from early conceptual design or feasibility studies, through pre-FEED, and FEED that demonstrate the bankability of the project at increasing levels of detail.

A rule of thumb is that each design stage requires an order of magnitude more effort than the previous phase, culminating in the cost for engineering services in the EPC phase. For this study, the developer's costs for this phase of the work have been estimated at 1% of the EPC contract value.

6.1.3 Regulatory, Licensing & Public Enquiry Costs

In order to construct any new facility, approvals are required from the Local Authority and other statutory agencies. Costs for internal staff to manage this process are included under Owner's Costs below, but costs can also arise through the need to hire:

- Planning and consenting specialists to manage the process and guide the preparation of the applications;
- Consultants to provide the strategy for engagement and to run the consultation activities;
- An environmental consultancy to prepare the preliminary EIA;
- Technical support to liaise between the project designers and the above.

For all cases, we have assumed costs for Regulatory requirements and public enquiries of 2% of the onsite EPC cost.

6.1.4 Owner's Costs

This element covers the Project Developer's internal costs for developing the project concept through to start-up, including direct-hire personnel, technology licence fees, taxes and insurances. Clearly, there may be huge variability in these elements. Land purchase costs have been excluded for this study, on the assumption that the new facilities will be built on land that already belongs to the Owner.

Owner's costs are assumed to be 7% of the EPC Contract Cost.

6.2 Operating Cost Estimating

Operating and Maintenance costs are generally allocated as fixed and variable costs.

Fixed costs are made up from the following categories:

- Direct labour
- Administrative and general overheads
- Maintenance

Variable costs assessed for this study are:

- Power
- Steam
- Cooling Water
- Solvent make-up costs
- Replacement catalysts, chemicals and consumables.

6.2.1 Direct Labour

Specific data for host site employees was not available to the study team. Labour costs are based on the IEAGHG Report 2012/08 [3], which based personnel costs on an annual average salary of € 60,000 pa. The UK Office for National Statistics (ONS) indicates that between February 2012 and

[3] IEAGHG 2012/08, "CO2 Capture at Gas Fired Power Plants", July 2012.

February 2018, UK average weekly earnings rose from £465 to £513 [4]. Applying a similar rise in salary and converting to GBP at the exchange rate in Section 6.1 leads to an equivalent 2018 salary of £58,200 pa.

A social burden equivalent to 30% has been added to the salary cost to account for social security payments, pension contributions, medical insurance and other in-company benefits.

It is assumed that each facility already has a full complement of operations and maintenance staff to manage the primary production plant, and that the burden of operating the carbon capture facilities will be spread across the same team. For conventional solvent-based post-combustion capture processes, an allowance of one additional full-time equivalent person has been made, reflecting the need to maintain rotating machinery, take and analyse samples of solvent and manage the CO_2 truck loading station. Other processes are assessed on a case-by-case basis.

6.2.2 Administrative, General Overheads, Insurance and Local Taxes

These costs include all other Company services not directly involved in the operation of the complex, such as Management, Personnel Services and Clerical staff. These services vary widely from company to company and are also dependent on the type and complexity of the operation.

For this study, an allowance equivalent to 0.1% of the EPC Contract Cost has been assigned for annual Administrative and General Overheads.

A further 0.2% of EPC Contract Cost is included to account for insurance and local taxes. This percentage is lower than typically used for grassroots projects, reflecting that the addition of carbon capture equipment is relatively minor compared to scale of the overall facilities.

6.2.3 Maintenance

Maintenance costs have been assessed as a percentage of the EPC Contract Cost. Rotating machinery typically has a higher maintenance cost than static equipment and there are a significant number of pumps, blowers and compressors within the unit.

An allowance of 1.5% of EPC Contract Cost has been made for Maintenance costs.

6.2.4 Electricity, Steam and Cooling Water Costs

Utility demands have been estimated based on the technology supplier submissions and Wood estimates of power demand from simulating the purification and liquefaction processes. For the larger scale cases at 150 kTPA, utility demands were scaled linearly from the smaller-scale cases.

Electricity costs have been assumed at a rate of £ 40 / MWh, which is the UK average spot price for industrial electricity purchase across the first 3 months of 2018 [5].

LP and MP Steam costs are based on the assumption that if the owner was not using the steam to regenerate solvents, they would instead feed the steam to a steam turbine to generate electricity. Thus, the steam price is taken as the cost of electricity equivalent to the thermal energy used by the process, allowing for an assumed steam turbine efficiency of 80%. The thermal energy is taken

[4] https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/earningsandworkinghours

[5] http://www.wrap.org.uk/content/electricity-spot-prices

as the enthalpy drop between the superheated steam at delivery conditions and the bubble point condensate. This results in costs of £ 19.0 / tonne for LP steam and £ 19.4 / tonne for MP steam.

Cooling water costs have been estimated at £ 0.05 / m^3, based on a typical open-loop, evaporative cooling tower arrangement, taking into account make-up water, purge rates of industrial waste water, chemical additives and electric power for fans and pumps.

Where site-specific electricity, steam or cooling water costs were provided by the host sites, these were substituted into the economic model for that case.

6.3 Economic Modelling Factors

The required sales price per tonne of food grade carbon dioxide has been calculated using a simple, spreadsheet-based economic model. All cases assume full equity-financing by the project development company, hence interest payments, capital loan phasing and contingency release are all excluded. Since the model calculates a sales price that assumes the plant breaks even over its entire life, the model indicates that the company never earns enough to pay corporation tax, which also simplifies the model.

6.3.1 Discount Factor / Hurdle Rate and Inflation

A discount factor of 8% has been used to reduce the price of future costs and sales income. All costs are in real terms, based of 2018Q1, hence no inflationary effects have been included within the analysis. 8% represents a relatively low return on investment for an operator. This reflects the underlying assumption that the Owner is considering a project for the environmental benefits and positive public image and is not primarily seeking a large direct return on investment. Operators that wish to price in an element of risk related to the future carbon dioxide supply market may wish to use a higher discount factor. In Wood's experience, the discount factor used by different companies can vary from 5% for state-run utilities, to as high as 12% for independent development companies, working in more uncertain markets.

Over the seventeen years since the turn of the century, the European Power Capital Cost Index provided by IHS, has shown an average rise of 3.5% per annum, although the rate was significantly higher in the period to 2008 and has averaged zero growth since the recession. Over the same period, the UK Retail Price Index (RPI) has averaged 2.8% per annum. Within the accuracy of this analysis, capital costs are rising in line with inflation and hence the assumption of zero real terms escalation is appropriate for future capital costs.

6.3.2 Plant Availability

Plant availability represents the proportion of an average year that both the flue gas source plant and the carbon capture facilities are operating at their rated capacity. This value takes account of both scheduled maintenance and downtime due to equipment failure / emergency repairs.

All of the host sites' processes operate year-round with no seasonal variations or extended downtime. It is likely that the host process will continue operation when the carbon capture plant is offline or running at reduced capacity.

For the relatively simple process configurations considered, using conventional technologies, an overall availability of 90% has been assumed.

7 Summary Results

Wood received a range of submissions for companies willing to use their sites or capture technologies as a basis for Phase 1. Seven host sites and five carbon capture processes were selected for techno-economic assessments. These were combined to create 14 discrete cases covering natural-gas, waste and biomass fired industrial heaters / boilers, anaerobic digestion, glass manufacture and brewing.

Whilst technologies for direct utilisation of carbon dioxide into products such as building materials were submitted for assessment, it was not possible to match these with host sites within the time allowed for Phase 1. Host sites prefer to concentrate their efforts on their core products and were resistant to incorporating aggregate production into their facilities.

Due to confidentiality restrictions, protecting both host sites and technology suppliers, specific results cannot be reported in this public-domain version of the final study report. Therefore, a generic case has been created for this report, based on an industrial fired heater with 7 vol% CO_2 in its flue gas and producing 30 kTPA of food-grade CO_2. An alternative set of results is also presented below, based on the same case, but with the product CO_2 compressed and dehydrated for export to a local user via pipeline at 10 barg. The third case presented is for a larger-scale plant producing 150 kTPA of food-grade CO_2 for tanker export. Estimated utility demands for these three generic cases are shown below.

Table 7-1: Generic Case Utility Demands

		Generic Case Tanker Export **30 kTPA**	Generic Case Pipeline Export **30 kTPA**	Generic Case Tanker Export **150 kTPA**
Power	kWe	570	310	2850
LP Steam	kg/h	2870	2870	14300
MP Steam	kg/h	34	34	170
Cooling Water	m^3/h	540	540	2700

Capital costs for the generic case have been scaled from site-specific cases. This produces a capital cost estimate with an accuracy of +/- 40%. The capital cost of the Purification & Liquefaction unit has been re-estimated from a modified in-house equipment list.

The pipeline export case assumes compression and dehydration to an export pressure of 10 barg (i.e. no liquefaction). A capital cost allowance of 20% has been added to the Interconnections unit cost in this case, to allow for an export line to the battery limit and a metering package.

Table 7-2: Capital Costs for Generic Cases

All figures in GBP thousands	Generic Case Tanker Export **30 kTPA**	Generic Case Pipeline Export **30 kTPA**	Generic Case Tanker Export **150 kTPA**
Pre-Licensing, Technical & Design	163	130	424
Regulatory, Licensing, etc.	327	261	849
EPC Contract Cost	16,335	13,033	42,441
DCC / Absorber	5,972	5,972	17,277
CO_2 Capture Balance	2,418	2,418	6,995
CO_2 Purification & Liquefaction	5,366	3,005	11,768
CO_2 Storage & Loading	1,214	-	2,452
Interconnects and Tie-ins	1,365	1,638	3,949
Owners Costs	1,143	912	2,971
Total Project CAPEX	17,968	14,336	46,685
Specific Project CAPEX (GBP/TPA CO_2 product)	599	478	311

For post-combustion capture processes, both capital and operating costs create barriers to small scale implementation of carbon dioxide capture. Taking into account the equipment for carbon dioxide capture, solvent regeneration, interconnections, CO_2 treatment and liquefaction, storage and tanker loading facilities, capital costs for a typical facility exporting approximately 30 kTPA ranged from £ 15 – 19m, excluding Owner's costs. This equates to a specific project CAPEX of £ 500 – 630 / tonne per annum product CO_2.

For a typical post-combustion capture process with CO_2 liquefaction producing a larger rate of 150 kTPA food-grade CO_2, the specific project CAPEX reduces to £ 300 – 350 / tonne per annum product CO_2.

Economic evaluations have been developed in line with the methodology outlined in Sections 6.2 and 6.3. Results are shown in Table 7-3 below.

For all cases, the sales price for product CO_2 has been calculated that provides a zero net present value (break even cost) with two base assumptions:

- Development is fully-funded by the host site, or;
- BEIS providing 50% of the EPC cost through grant-funding.

Note that no agreement has been made on the level of BEIS grant-funding for Phase 3 and each applicant will need to justify the level of BEIS involvement. The figures provided below are indicative of the impact that grant-funding will make to the economics. The interactive spreadsheet developed as part of the Phase 1 study allows the level of BEIS funding to be adjusted as a variable.

Table 7-3: Economic Assessment for Generic Cases

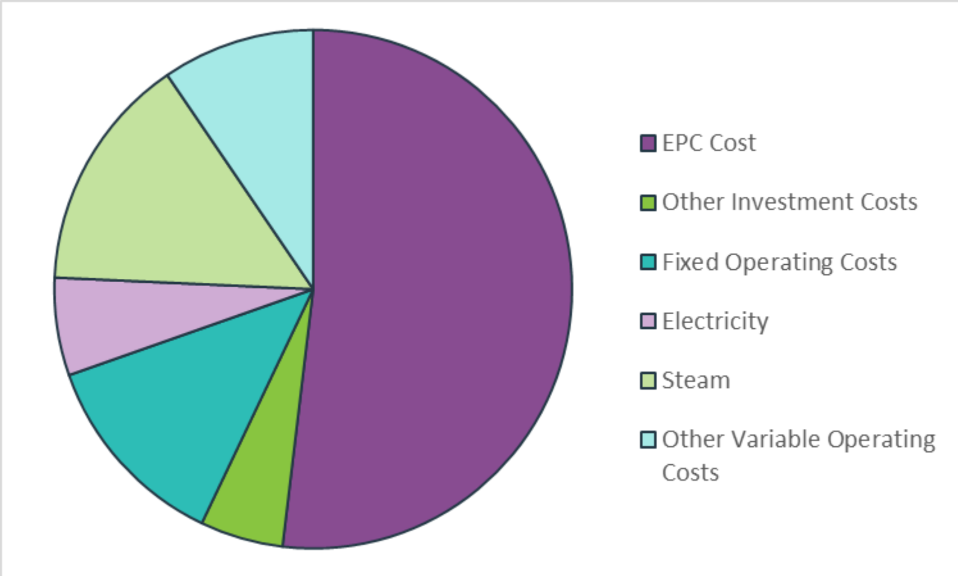
	Generic Case Tanker Export **30 kTPA**	Generic Case Pipeline Export **30 kTPA**	Generic Case Tanker Export **150 kTPA**
Total Project CAPEX (GBP k)	17,968	14,336	46,685
Fixed Operating Costs (GBP k pa)	370	310	840
Variable Operating Costs (GBP k pa)	896	814	4,379
CO_2 Product Rate (kTPA)	30	30	150
Life of Plant	25 years	25 years	25 years
Discount Rate	8%	8%	8%
Fully-funded Results			
CO_2 Sales Price (GBP / tonne)	98	82	64
Income from Sales (GBP k pa)	2,949	2,467	9,592
Part-BEIS Funded Results			
BEIS Funding of EPC Contract	50%	50%	50%
BEIS Contribution (GBP M)	8.167	6.517	21.221
CO_2 Sales Price (GBP / tonne)	73	62	51
Income from Sales (GBP k pa)	2,184	1,857	7,604

Spreading capital and operating costs across a 25-year plant life at a discount rate of 8%, a sales price of around £ 100 / tonne CO_2 is required to balance to a net present value of zero. 57% of the costs are related to capital expenditure, with the balance due to operating costs as shown in Figure 7-1 below. BEIS grant-funding towards the capital cost will reduce the required sales price, but not to within the typical cost of buying CO_2 from an industrial gas supplier.

If it is possible to export via low pressure pipeline, then some of the capital and operating costs at the operating site are decreased. Thus, a lower sales price can be tolerated.

Increasing the scale of capture and export process significantly reduces the capital cost per tonne of product, with a subsequent reduction in the sales price per tonne of CO_2 exported.

Figure 7-1: Relative Contribution of Different Cost Elements to CO_2 Sales Price



For processes that are fired on solid materials, such as biomass, the carbon dioxide concentration in the flue gas is significantly higher than for flue gas from a natural-gas boiler (typically 10 – 14 vol%, compared to 7 – 9 vol% for NG). Thus, for the same CO_2 loading, the flue gas volumes are significantly reduced and hence the main absorber and any other pre-treatment equipment (e.g. waste heat boiler, direct contact cooler, etc.) have a lower cost. However, the rest of the new equipment and the operating costs are essentially the same as for the natural gas cases, with similar economics.

The bulk of carbon dioxide that is currently traded within the UK arises from processes such as bioethanol fermentation, where the CO_2 is removed as a high-purity by-product. These processes do not require solvent-based absorbers, nor regeneration systems and the associated energy-intensive regeneration loads. The study examined two high-purity CO_2 streams arising from anaerobic digestion and brewing. For these systems, the additional treatment and liquefaction systems can be constructed and operated at a cost that allows the sale of CO_2 at an achievable price of £ 30 – 40 per tonne. However, this is dependent upon both the scale of the plant and the degree of site preparation / tie-ins required. Larger proposed projects benefit from economy of scale. Sites generating less than 10-15 kTPA may struggle to justify the investment cost although this may be overcome depending on the level of grant funding available from BEIS.

8 Project Implementation Schedule

A Level 1 implementation schedule has been developed for a typical project development aligned with retrofit of a solvent-based carbon dioxide capture process, purification and liquefaction for road tanker export. This includes activities from the start of Front End Engineering Design (FEED), through design, procurement and construction to the point where the plant is Ready for Start-up (RFSU). The schedule is provided as Attachment 1.

The schedule has been developed with achievable durations and sufficient float to allow the developer an 80% chance of meeting the RFSU date. Depending on the site preparation required and flexibility to perform installation of modules and tie-ins on an operating site, different contractors may be able to offer alternative schedule proposals.

Key durations are as follows:

- Licensor selection — prior to start of FEED
- FEED Phase — 8 months
- Engineering & Procurement (E&P) — 13 months
- Construction and Commissioning (C&C) — 13 months
- Overall – Start of FEED to RFSU — 26 months (note overlap between E&P and C&C)

The schedule shows only working months, rather than specific dates. If, for example, a project commenced FEED at the start of January 2019, the plant would have a good probability of being ready for start-up by March 2021.

Key assumptions underlining this schedule are described below.

Technology Selection and Process Design Package

The schedule assumes that technology selection for the Carbon Capture process has been completed prior to the start of FEED, particularly for projects that are bidding for BEIS Phase 2 funding. Hence, development of the Process Design Package (PDP) by the technology licensor can commence on Day 1 of the FEED.

Where technology selection has not been completed, Wood suggests that a 6-month pre-FEED phase is added at the front end of the schedule.

Site Survey

A survey of underground obstructions and geotech has been allowed within the FEED schedule. Some existing sites may have good knowledge of the proposed plot and be confident that a geotechnical investigation is not required. This activity is not on the critical path for the schedule presented, but may prevent acceleration of engineering design if a shorter project duration is desired.

Contracting Strategy

Various contracting strategies are available, each with its own advantages and disadvantages. For this schedule, Wood has assumed that the contract with the FEED contractor rolls-over into a Detail Engineering and Procurement contract following the Final Investment Decision (FID) by the Owners. In addition, a separate Construction contract will be awarded by the Owner to manage on-site preparation and installation.

A different contracting strategy could be adopted, involving award of a lumpsum, turnkey Engineering, Procurement & Construction (EPC) contract following completion of FEED. This approach tends to produce a lower procurement and construction cost, but can extend the schedule by 4-6 months, due to the EPC bidding process.

FID and BEIS Grant-Funding

This schedule indicates that a Class 2 capital cost estimate (typically +/-10%) would be available at the end of seven months, in preparation for a Final Investment Decision (FID) at the end of month 8. If the Owner is seeking BEIS funding under Phase 3 of the Carbon Capture and Utilisation Demonstration Programme, then an additional application / approval period may be appropriate between the estimate and FID.

Procurement

The procurement period has been set assuming a longest lead time of 9 months for fabrication and delivery of equipment: this is for the Direct Contact Cooler and Absorber in the front section of the plant.

Projects using novel capture or utilisation technologies that feature unusual or proprietary equipment should consult with suppliers to confirm the lead time between placement of an order and delivery of the equipment.

9 Conclusions & Recommendations

Five different carbon capture technologies have been assessed at the 30-70 kTPA scale at five host sites to provide a range of twelve combined cases that require a capture system. Due to confidentiality, these cannot be reported here, but similar results are reflected by the two generic cases presented in Section 7. The analysis indicates that none of the proposed 30-70 kTPA scale projects at these sites meet economic criteria for investment. BEIS grant funding at up to 50% of the EPC Contract cost was not sufficient to make an investment attractive for these host sites.

The first five main sites examined all considered low pressure post-combustion flue gases, covering a CO_2 concentration range of 4 – 12 mol% (dry basis) and product rates in the range 28 – 44 kTPA. The large size of the coolers and absorbers for these streams results in a high capital cost and the large solvent regeneration load results in large operating costs.

Comparing the five technologies at one site, there was a reasonable degree of consistency within the capital cost estimates for four of the five, with one outlier technology. Costs for the main four technologies ranged between £ 15 – 19m for Engineering, Procurement and Construction, excluding Owner's costs. Whilst lower EPC costs than those reported here may be offered by contractors or technology suppliers, these are unlikely to be low enough to significantly change the outcome of the study.

In order to make a demonstration project attractive at a scale of 30 – 70 kTPA, ongoing financial support in terms of carbon credits or Contract for Difference would be required. If the captured CO_2 was being permanently stored, then a carbon credit may be available to these projects. The economics for this case would be similar to the Generic Case with Pipeline Export, as shown in Section 7, but with an additional transport and storage charge applied. The 2016 Leigh-Fisher Report [6] assessed a central cost projection of £ 19 / tonne for transport and storage by an independent operator. Using this figure, a carbon price of £ 80 – 100 per tonne would be needed to provide positive economics. Based on the central UK projection for traded carbon emissions prices [7], this might occur in the early 2030s.

It has been suggested that direct-capture utilisation technologies with a lower cost-base might make CO_2 capture cost-effective in a shorter time-frame than this. Whilst this is possible, the data for these technologies that was provided to BEIS for Phase 1 did not contain the necessary level of detail for feasibility assessment.

Some sites may benefit from a combination of low-cost (or zero cost) utility supplies, readily-available labour and an on-site (or neighbouring) outlet for the CO_2 product. Under these circumstances, a viable project is conceivable and this should be supported by BEIS during Phase 2 and Phase 3 of the programme.

Two additional sites assessed in Phase 1 use industrial processes that generate much higher concentration sources of CO_2, approaching 95% in the outlet stream. For these sites there is a reasonable possibility of installing CO_2 purification and liquefaction equipment to produce food grade CO_2 at a competitive price. However, the scale of production needs to be significant in order to reduce the capital costs per unit of production. Production rates in excess of 10 – 15

[6] Table 64, 'Electricity Generation Costs and Hurdle Rates, Lot 3: Non-Renewable Technologies', LeighFisher Ltd for Department of Energy and Climate Change, August 2016.

[7] Refer to tables found via website https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

kTPA liquid CO_2 product are recommended to make this approach economic and the specific conditions faced by each facility must be examined. Phase 3 grant-funding from BEIS may be critical for these companies when deciding whether to invest in CO_2 capture.

To reduce the selling price of the CO_2, there may be some benefit to build and operate the capture at a larger scale. This was examined for the Generic Case with Tanker Export to produce a nominal 150 kTPA of CO_2 product. Whilst it is clear that the selling price of the CO_2 was significantly reduced, it was not low enough to make the case economic as a standalone facility. This would probably only be feasible for power stations, refineries or the very largest manufacturing plants and it is not clear that the existing market for food-grade CO_2 would support larger volumes of additional product.

It will be challenging for new UK-led technologies to justify investment in a small-scale demonstration project, within a sensible scale-up ratio from pilot facilities, based on income generated from sales of food grade CO_2. Wood recommend that BEIS continue to support development of truly novel processes through to demonstration level, supporting a proportion of both capital and operating costs, since these new technologies hold the potential to provide a step-change in performance for large-scale carbon capture plants.

Novel direct utilisation processes face additional hurdles with respect to the need to transport solid materials to and from the production site. These additional truck movements are not automatically welcomed by all operators and may be considered as a diversion away from core manufacturing. Not all of the host sites were negative about direct utilisation, and BEIS may continue to act as a broker between technology providers and welcoming host sites.

Attachment 1 Host Site and Technology Supplier Enquiry Documents

BEIS Carbon Capture & Utilisation Demonstration

Host Site Opportunity Document

BEIS Carbon Capture & Utilisation Demonstration

Host Site Opportunity Document

WOOD DOCUMENT NO.: 13414-8110-PS-002

Document Revisions

No.	Details	Date	By	Approved
O	For Comment	23rd April 2018	Nigel Fletcher	Tony Tarrant

Contents

wood.

1 Introduction

The Department for Business, Energy and Industrial Strategy (BEIS) has engaged Wood to carry out a study to assess the potential for installing a demonstration plant to capture carbon dioxide (CO_2) at one or more host sites.

The aim of this study is to evaluate which UK-led CO_2 capture technologies can be financially supported at demonstration plant scale with a view to further development to full scale operation for UK Industry. The programme will also provide information for future UK innovation spending programmes and CCS policy.

BEIS is seeking interest from companies with UK sites who are prepared to host these developing CO_2 capture technologies for a minimum, agreed demonstration period. Financial assistance may be provided from the UK Government to install the capture technology on the site. The host site will normally be expected to operate the technology as part of its own operations. Note: Operational assistance may be given where the technology is very small or still in need of development – this will be agreed between the host, the supplier and BEIS.

To become a host site there will be certain requirements that need to be met as a part of the application. This document outlines the initial data that needs to be determined by the host site for the installation of a demonstration unit. To determine the site's suitability and the most appropriate technology for the demonstration will require as much of the requested information as can be gathered and this will help to accelerate the project.

If the requirements in this document are unclear, or you wish to talk through the BEIS CCU Demonstration Programme further before submitting a response, then let us know: we may be able to arrange a meeting to discuss your host site's specific needs.

2 Scope

This document defines the information that the host site should aim to assemble to accompany the application for installation of the CO_2 capture technology. Host sites wishing to be considered should aim to supply as much of the requested information as possible, together with any limitations. Where information is incomplete or unavailable then this should be stated, and suggestions should be provided as to how any deficiencies might be addressed.

The detailed data requirements are listed in Section 4.

3 Basic Requirements

Before considering whether a site is suitable for CO_2 capture technology, it must meet a few basic requirements:

3.1 Source(s) of CO_2

Although obvious, the source of CO_2 is important and its quality (other gases/contaminants in the stream) – it may come from a number of different sources including:

- Boilers - gas, solid or liquid fuel fired
- (Internal combustion) Engines
- Processes that react fossil fuels or biomass with air/oxygen
- Processes that produce CO_2 as a normal part of their operation (e.g. fermentation)

These sources should have vents/exhausts that are confined to vent stacks/ducts, chimneys or similar and can be adapted to route the stream to the capture technology. A site may have multiple sources. The sources need to be measured/quantified as outlined in section 4

3.2 CO_2 Source Availability

Most CO_2 capture technologies operate continuously so the flow of gas(es) containing CO_2 should, ideally, be continuous (24/7) but if this is not possible then the intermittency and flow variation needs to be quantified as part of the application. It should be noted that a site with an intermittent flow of CO_2 might not be suitable for this demonstration but if there is sufficient benefit to be gained then intermittent availability might not be an objection to selecting the site for further consideration.

3.3 Captured CO_2 Reuse

The intent of the BEIS work is to determine the means by which captured CO_2 is reused. Where the CO_2 can be reused internally, this should be identified in response to this enquiry. However, we understand that many host sites do not have obvious routes to reuse or sell the CO_2 for third party reuse. In this situation, BEIS and its consultants will assist the host to find suitable routes to send CO_2 for reuse/sale although any final commercial agreement will be between the host site and the third party to agree and manage.

3.4 Available Utilities Capacity

Capture technologies require utilities to operate and each technology requires a different balance, but the host site should have available capacity in most of the following utilities or identify a suitable source/supply to be installed in parallel with the CO_2 capture technology:

- Fuel Gas (natural gas from the UK Gas grid)
- Cooling Water
- Steam and Condensate recovery
- MV Electric Power (11 kV or higher)
- Nitrogen from cylinders/bulk store (TBC)
- Instrument air and plant air
- Raw water, demineralised water and/or potable water
- Liquid and Solid Waste Disposal
- Emergency Power Supply and supply for ‘Black-start’ if required
- Water treatment facilities
- Fire-fighting facilities

3.5 Environmental Considerations

The purpose of the work is to reduce CO_2 emissions to the environment; however, it must be appreciated that the capture process will give rise to wastes (other than the CO_2 stream). These may be new or existing waste streams altered in composition and/or quantity. Where the host site may have limitations on discharges then it should raise this point with BEIS and the technology supplier to determine if the new technology can be installed.

4 Information to be provided by the Host Site

Hosts are requested to provide the following information to allow the site to be assessed for suitability:

a. List of all potential sources for CO_2 capture including a brief description of each source;

b. Description of the source of the CO_2 whether from natural gas, biomass, by-product from chemical production, etc.;

c. Analysis of stream for each source including: flowrate, temperature, pressure, nitrogen, NOx, CO_2 concentration, other contaminants (esp. sulphur compounds), particulates, etc.;

d. CO_2 source availability (see section 3.2);

e. Available power and utility capacity (see section 3.4) together with any ‘unavailable’ utilities;

f. Opportunities for heat and/or power integration into existing site operations;

g. Site plan showing CO_2 sources, access roads and infrastructure;

h. Any confidentiality requirements;

i. Any special restrictions applying to the site e.g. environmental;

j. Any other limitations (e.g. staffing limitations) or opportunities (e.g. neighbouring site);

Any documents containing commercially sensitive data should be clearly marked “Confidential”.

BEIS Carbon Capture & Utilisation Demonstration

Enquiry for Carbon Capture Technology Submissions

BEIS Carbon Capture & Utilisation Demonstration

Enquiry for Carbon Capture Technology Submissions

WOOD DOCUMENT NO.: 13414-8110-PS-001

Document Revisions

No.	Details	Date	By	Approved
1	For Comment	26th April 2018	Nigel Fletcher	Tony Tarrant

Contents

1 Introduction

The Department for Business, Energy and Industrial Strategy (BEIS) has engaged Wood to carry out a study to assess the potential for installing a demonstration plant to capture carbon dioxide (CO_2) at one or more host sites.

Thus, the aim of this study is to evaluate which UK-led CO_2 capture technologies can be financially supported at demonstration plant scale with a view to its further development to full scale operation for UK Industry and provide information for future UK innovation spending programmes and CCS policy.

BEIS is seeking interest from UK-led companies developing CO_2 capture technologies that may provide enhanced performance or provide lower cost alternatives to established technologies and support UK commitments to move towards a decarbonised economy.

This enquiry document defines the data to be submitted by interested parties that wish to develop their technology by the installation of a demonstration unit at a host site. To ease the selection of a technology, the supplier is requested to provide as much information as possible to allow BEIS and Wood to evaluate the technology and its suitability for selection.

2 Scope

This document defines the information required to complete the technology evaluation exercise, which should accompany the application from the supplier. Companies wishing to submit their technologies for consideration should aim to supply as much of the requested information as possible. Where data is incomplete this should be stated together with any limitations that this may imply.

The scale of CO_2 capture (kg/h) for the demonstration is not important but the supplier must remember the installation will be in an industrial situation so the capture rate of CO_2 must be ‘credible’. For small rates of capture (< 10 kg/h) the supplier may be required to provide 24/7 support for the operation.

The detailed data requirements are listed in Section 4.

3 Design Basis Information

3.1 Target Host Plant Location & Site Conditions

Until a host site is selected the supplier is to assume: The site is a greenfield, coastal location in the North East of England. A clear, level, obstruction free (both above and below ground) site, without the need for any special civil works.

The actual site location will be determined later as a result of a selection procedure between technology suppliers, hosts, BEIS and their consultants.

3.2 Climatic Conditions

The following climatic conditions marked (*) shall be considered reference conditions for plant performance evaluation.

Atmospheric pressure:		1013 mbar (*)
Relative humidity:	average:	80% (*)
	maximum:	100%
	minimum:	10%
Ambient temperature:	average:	9°C (*)

maximum:	30°C
minimum:	-10°C

3.3 Battery Limits

Typical streams that may be assumed to cross the plant battery limits, include the following:

- Fuel Gas (natural gas)
- Electric Power
- CO_2 product
- Treated exhaust gas
- Closed loop cooling water supply and return
- Steam and condensate
- Nitrogen from cylinders/bulk store (TBC)
- Instrument air and plant air
- Raw water, demineralised water and/or potable water
- Liquid and Solid Waste Disposal
- Emergency Power Supply and supply for 'Black-start' if required
- Water to water treatment facilities
- Fire-fighting facilities
- Chemicals & catalysts
- Industrial waste water

Other streams may be specified, as required by the specific process.

3.4 Utilities

Fuel Gas

Where the unit requires natural gas, the UK National Grid gas specification should be assumed as the basis:

Characteristic	Value
H_2S Content	Assume 3 ppm (molar)
Total Sulphur Content	Not more than 50 mg/m^3
Hydrogen Content	Assume 0.1% (molar)
Oxygen Content	Assume 0.001% (molar)
Hydrocarbon Dewpoint	Not more than -2°C, at any pressure up to 85 bar(g)
Water Dewpoint	Not more than -10°C, at 85 bar(g)
Wobbe Number (real gross dry)	Between 48.14 MJ/m^3 and 51.41 MJ/m^3 (at standard temperature and pressure)
Gross Calorific Value (real gross dry)	Between 36.9 MJ/m^3 and 42.3 MJ/m^3 (at standard temperature and pressure)
Delivery Temperature	Between 1°C and 38°C

Cooling Water

Cooling will be provided by mechanical draught open-circuit cooling towers using an approach temperature of 7°C to the wet bulb temperature and a temperature rise of 11°C.

Cooling Water Supply = 14°C

Cooling Water Return = 25°C

Steam and Condensate

Where the process either requires steam for heating purposes, or generates steam in order to utilise excess heat, then the developer should include these streams in the heat & material balance.

The developer should define the pressure, temperature and degree of superheat in the steam and the operating conditions for the returning condensate stream.

Power

The supplier can assume that power is available for start-up and continuous operation. Assume a grid connection at 275kV (UK 50 Hz, 3 ph) will be available and higher voltage levels may be specified, if required. Developer to advise specific power requirements (voltage etc.)

4 Information to be provided by the Technology Supplier

Suppliers are requested to provide the following information for the technology evaluation exercise.

a. Statement of maximum single train capacity that can be achieved using existing technology and what equipment limits the capacity;
b. Details of process development to date, including references for any operating units at any scale together with a statement of current challenges in the development of the technology;
c. CO_2 absorption efficiency;
d. Typical Block Flow Diagram;
e. Process description with key operating conditions;
f. Heat & material balance (including all information for streams crossing the unit's battery limits);
g. Sized list of major equipment within scope, indicating proprietary items;
h. Energy and utility consumption (and production);
i. Catalyst, chemicals and consumables: initial charge and annualised replacement rate, plus estimated costs;
j. Details of any chemicals used that may pose a risk to health, safety or the environment;
k. Summary of effluents and emissions;
l. Budget cost estimate for proprietary items, ex-works;
m. Budget total installed cost for unit at existing scale;
n. List of assumptions and exclusions (technical, cost);
o. List of relevant pilot, demonstration and commercial scale references;
p. Technology development roadmap;

Any documents containing commercially sensitive data should be clearly marked "Confidential".

Attachment 2 Project Implementation Schedule

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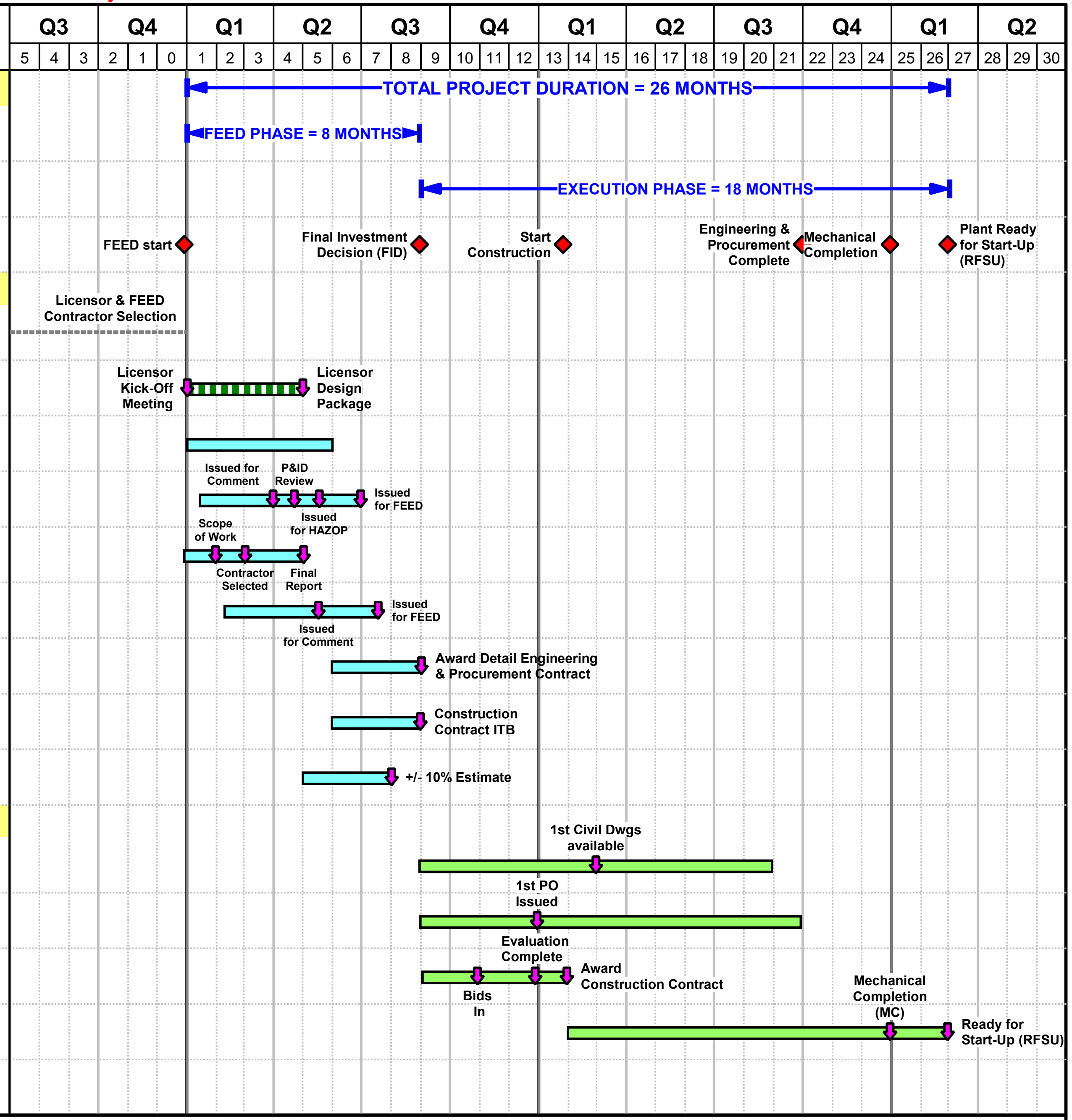
CO2 Capture & Utilisation Demonstration Programme

Level 1 Project Schedule

For Feasibility Assessment

CLIENT: BEIS
PROJECT: CCU Demonstration Programme
LOCATION: TBC, UK
CONTRACT: 13414

		Duration (Months)
1	**PROJECT PHASES**	
2	FEED Phase (up to Final Investment Decision)	8
3	Execution Phase (FID to Ready for Start-Up)	18
4	Key Project Milestones	
5	**Front-End Engineering Design (FEED) Phase**	
6	Licensor and FEED contractor selection	
7	Technology Licensor PDP development	4
8	FEED Contractor Interfaces	5
9	Develop P&IDs	5.5
10	Site Survey	4
11	Engineering Deliverables	6
12	Proposal & Negotiation for Detail Engineering & Procurement Contract	3
13	ITB for Construction Contract	3
14	Prepare Cost Estimate & Schedule (+/-10%)	3
15	**Project Execution Phase**	
16	Detail Engineering	12
17	Procurement (material supply & fabrication)	13
18	Tender & Award Construction Contract	5
19	Construction & Commissioning	14
20		



Project Phases | Key Project Milestone | Project Milestone | Licensor Design Activity | FEED Phase Activity | Execution Phase Activity

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