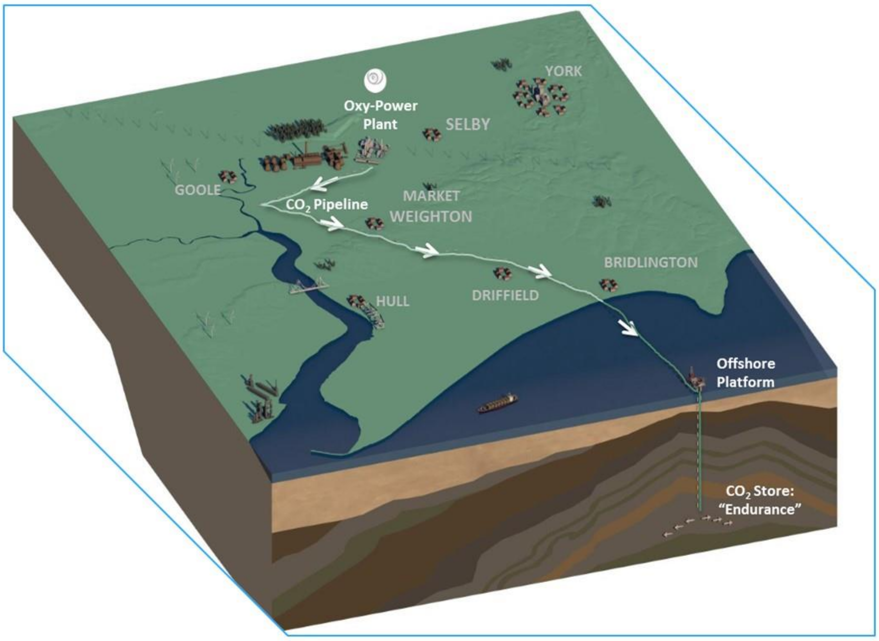
March 2016

K.01 Full Chain FEED Summary Report

Commercial; Project Management



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Key Words

Key Word	Description
Air Separation Unit	A unit whose function is to separate oxygen from the air for use in the oxyfuel process
Air Separation Plant	Collective term for two ASU units
Authority	The Department of Energy and Climate Change (DECC) as defined in the FEED Contract between DECC and Capture Power Ltd.
Carbon	An element, but used as shorthand for its gaseous oxide, Carbon Dioxide, CO_2.
Carbon Dioxide	A greenhouse gas produced during the combustion process, the chemical symbol for which is CO_2.
Carbon Capture and Storage	A technology which reduces carbon emissions from the combustion based power generation process and stores it in a suitable location
Capture	Collection of CO_2 from power station combustion process or other industrial facility
Financial Close	The point at which the final investment decision is taken and the Notice to Proceed with the Implementation Phase is issued
Full Chain	Reports described as “full chain” would cover the complete process including the OPP and T&S.
Gas Processing Unit	Unit in which the processing and compressing of CO_2 gas takes place before transportation to storage
Interconnections	Links for supply between existing Drax and OPP facilities
Implementation Phase	Stage of CCS project that covers construction
Key Knowledge	Information developed and provided in Deliverables
Lessons Learnt	Key insights into learnings specific to Carbon Capture and Storage, as a result of undertaking FEED
Operating Mode	The method of operation of the OPP, which can operate in air or oxy-firing mode
Oxyfuel	The technology where combustion of fuel takes place with a mixture of CO_2 and oxygen replacing air as the oxidant for the process, with resultant flue gas being high in CO_2
Oxy Power Plant	A power plant using oxyfuel technology
OPP Process	The flow of input and output streams through the Oxy Power Plant
Pipeline	The long pipe used for conveying CO_2 from the power plant to the storage facilities
Plot Plan	Layout of main items of equipment and buildings
Storage	Containment of CO_2 in suitable pervious rock formations located under impervious cap rock formations usually under the sea bed
Transport	Transfer of processed CO_2 from the capture and process unit by pipeline, to the permanent storage
White Rose	The White Rose Carbon Capture and Storage project

Executive Summary

The Full chain FEED summary report was generated as part of the Front End Engineering Design (FEED) contract with the Department of Energy and Climate Change (DECC) for White Rose, an integrated full-chain Carbon Capture and Storage (CCS) Project. This summary report provides a narrative made up of sections covering the full chain as well as its constituent parts including the Oxy Power Plant (OPP), transport and storage, each section is covered in more detail in one of the series of Key Knowledge Deliverables (KKD) from White Rose to be issued by DECC for public information.

White Rose comprises a new coal-fired ultra-supercritical OPP of up to 448 MWe (gross) and a Transport and Storage (T&S) network that will transfer the carbon dioxide from the OPP by pipeline for permanent storage under the southern North Sea. The OPP captures around 90% of the carbon dioxide emissions and has the option to co-fire biomass.

Delivery of the project is through Capture Power Limited (CPL), an industrial consortium formed by General Electric[1] (GE), BOC and Drax, and National Grid Carbon Limited (NGC), a wholly owned subsidiary of National Grid.

This summary report provides an overview of the FEED largely by taking information included in more detail in other KKDs, further more detailed information can be obtained by referring to these separate KKDs as listed below:

- K.02 – Full chain basis of design
- K.03 – Full chain operating philosophy
- K.04 – Full chain FEED lessons learnt
- K.05 – Full chain FEED decision report
- K.06 – Full chain FEED risk report
- K.09 – Full chain project programme
- K.10 – Full chain FEED programme
- K.11 – Full chain consents register
- K.12 – Full chain health and safety report
- K.13 – Full chain environmental reports
- K.14 – Full chain project cost estimate report
- K.20 – Project Implementation Phase project execution plan
- K.22 – Full chain process flow diagrams
- K.23 – Full chain heat and material balances
- K.25 – Full chain externally supplied utility summary

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[1] CPL was formed in December 2013 between Drax, BOC and Alstom UK Holdings Limited. In November 2015 General Electric acquired the energy businesses of Alstom including its interests in CPL.

- K.26 – Full chain effluent summary
- K.27 – Oxy-power plant process description
- K.30 – Storage process description
- K.38 – Subsurface wells report
- K.39 – Subsurface production technology report
- K.40 – Subsurface geoscience and production chemistry report
- K.41 – Reservoir engineering field report
- K.42 – Storage risk assessment, monitoring and corrective measures reports
- K.43 – Field development report

Her Majesty's Government (HMG) Spending Review was set out on 25 November 2015 outlining its capital budget and priorities. A market announcement on the same day indicated that the £1 billion ring-fenced capital budget for the Carbon Capture and Storage Competition was no longer available, the Spending Review accordingly did not include such budget. This meant that the Competition could not proceed as originally envisaged. Following this decision, a notice of termination was issued on 23 December 2015 under the White Rose FEED Contract, which terminated accordingly on 25 January 2016, prior to the expected completion date of FEED. The Government, CPL and National Grid are committed to sharing the knowledge from UK CCS projects, and this Key Knowledge Deliverable represents the learning achieved up to the cancellation of the CCS Competition and termination of the FEED Contract and therefore does not necessarily represent the final and completed constructible project.

1 Introduction

1.1 Background

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

The OPP is a new state-of-the-art ultra-supercritical power plant with oxyfuel technology of up to 448 MWe gross electrical output that will capture around 90% of carbon dioxide emissions and is also designed to have the option to co-fire biomass.

The first large scale demonstration plant of its type in the world, White Rose aims to prove CCS technology at commercial scale as a competitive form of low-carbon power generation and as an important technology in tackling climate change. The OPP will generate enough low carbon electricity to supply the equivalent needs of over 630,000 homes.

White Rose is being developed by Capture Power Limited (CPL), a consortium of GE, BOC and Drax. The project will also establish a CO_2 transportation and storage network in the region through the Yorkshire and Humber CCS pipeline being developed by National Grid Carbon Ltd (NGC). CPL and NGC together form the White Rose Consortium (WRC).

1.2 Summary report

The report comprises a narrative describing the full chain and its constituent parts, made up of the OPP (including oxy boiler, power generation, air quality control systems, Air Separation Unit (ASU) and Gas processing Unit (GPU)) and T&S (including pumping station).

1.2.1 Full chain

The following sections are included relating to the full chain and its constituent parts:

1. Full chain description and design basis including:
    - Description of new and existing assets
    - Sizing point specification (flow rates, operating conditions and limitations)
    - Design life
    - Tie-in points/ battery limits
    - Metering and monitoring philosophy
    - Heat integration between the ASU and the power plant
    - Composition of CO_2 stream
    - OPP plot size
2. Full chain block flow diagram and key stream data
3. Operating philosophy including:
    - operating hours based on design life
    - design availability
    - CO_2 venting requirements
    - Line packing

4. External utility summary, including raw water consumption from OPP, duty of compressor and pump station
5. Effluent and emissions summary
6. Consents register
7. Milestones for FEED and project
8. Project cost estimate including:
    - date of cost baseline
    - accuracy
    - CAPEX and OPEX (for overall CCS chain and its constituent parts)
9. Project execution plan
10. Top 10 risks from the project risk register at the start and at the end of FEED specific to CCS
11. Summary of key findings from CCS-specific EHS reviews
12. Summary of key decisions specific to CCS
13. Top 10 FEED lessons learnt specific to CCS
14. Summary of commercial arrangements

1.2.2 OPP operation with CCS

In addition to the relevant sections in the full chain sections above, the following sections are included specific to the OPP operation with CCS:

- Type of power plant
- Capture technology
- Fuel specifications
- CO_2 capture rate
- Net power output
- Air emissions (with and without CCS application)

1.2.3 T&S

In addition to the relevant sections in the full chain sections above, the following sections are included specific to the T&S:

1. Pipeline description
    - Length and diameter
    - Material
    - Metering (location, number accuracy)
2. Booster station description
3. Oversizing of infrastructure and clustering potential
4. Criteria relating to offshore facilities including:
    - Location, type, capacity and site conditions
    - Leases
    - Interpretation of geochemical, geophysical and hydrographical data and modelling
    - Interpretation of storage studies including:
        a. injectivity
        b. integrity

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    c. leakage
- Subsurface wells selection and proposal
- Proposed annual CO_2 injection rate, duration and total to be stored
- Storage licence summary
- Storage development concept
    a. Storage risk assessment
    b. Storage monitoring and reporting
    c. Corrective measures
    d. Decommissioning / abandonment plan
    e. Development concept and wells

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2 Full Chain Description and Design Basis

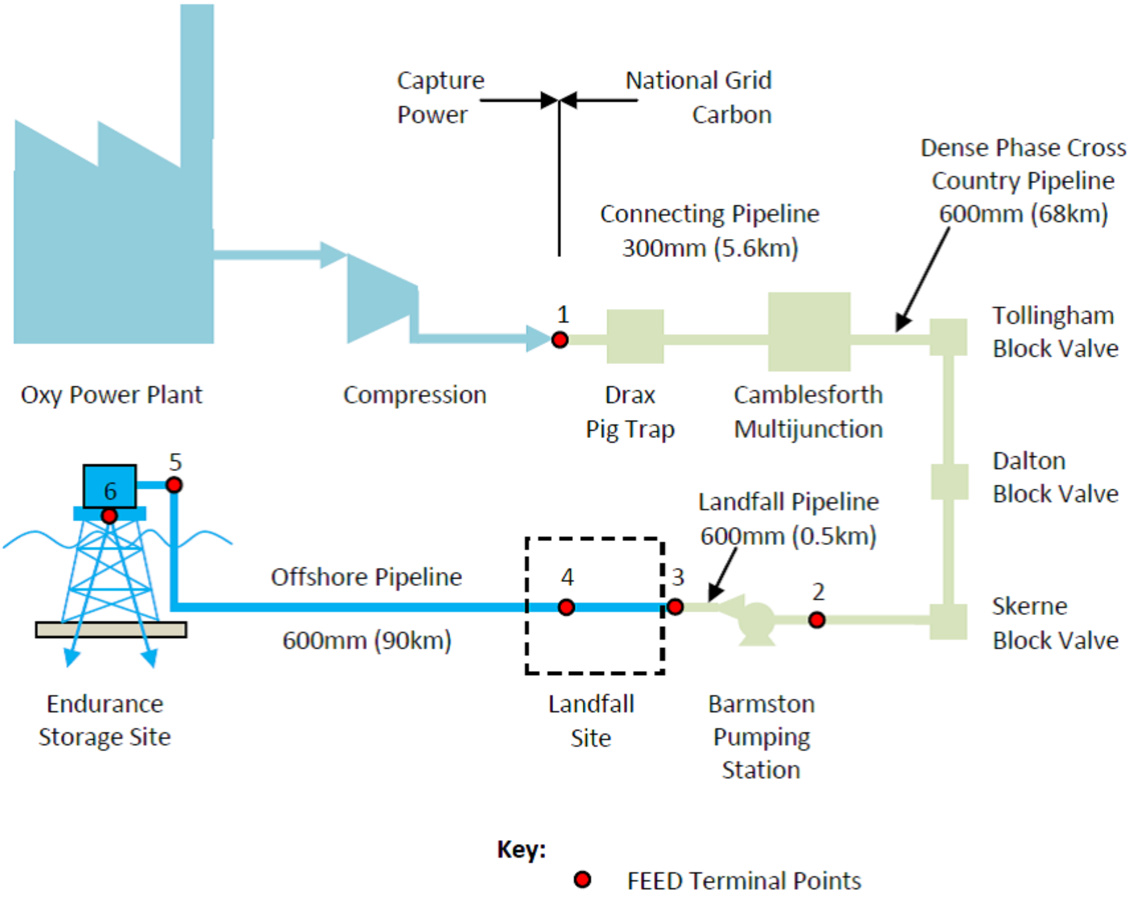
The White Rose Carbon Capture and Storage Project is an integrated full-chain CCS project comprising a new coal-fired Oxy Power Plant (OPP) and a Transport and Storage (T&S) network that will transfer the carbon dioxide from the OPP by pipeline for permanent storage under the southern North Sea.

The OPP is a new ultra-supercritical power plant with oxyfuel technology of up to 448 MWe gross output that will capture around 90% of carbon dioxide emissions and also have the option to co-fire biomass.

The project will also establish a CO_2 transportation and storage network in the region through the Yorkshire and Humber CCS pipeline being developed by National Grid Carbon Ltd (NGC).

The Full Chain and its component parts are designed to be operated such that the target of two million tonnes of CO_2 per year can be safely stored.

Figure 2.1: Full Chain Overall Schematic



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2.1 OPP Overview

The standalone OPP will be located to the northeast of the existing Drax Power Station site near Selby, North Yorkshire within the Drax Power Limited (DPL) landholding and benefits from fuel import and power transmission infrastructure currently in place. The plant will generate electricity for export to the Electricity Transmission Network while capturing approximately 2 million tonnes of CO_2 per year, some 90% of all CO_2 emissions produced by the plant. The CO_2 will be transported by pipeline for permanent undersea storage beneath the North Sea.

Figure 2.2: White Rose CCS Project Artist Impression

The OPP includes the following main components:

- Oxy-fuel boiler, steam turbine generator and other power block components;
- Air Separation Unit (ASU) that provides the oxygen for the oxy-fuel combustion process;
- Air Quality Control Systems (AQCS) that clean the flue gas to reduce atmospheric pollutants arising from combustion, the main components of which are the Electrostatic Precipitator (ESP);
- Flue Gas Desulphurisation (FGD) unit; and
- Gas Processing Unit (GPU) to process and compress the CO_2 rich flue gas to achieve the required CO_2 specifications and pressure for onward transport and storage.

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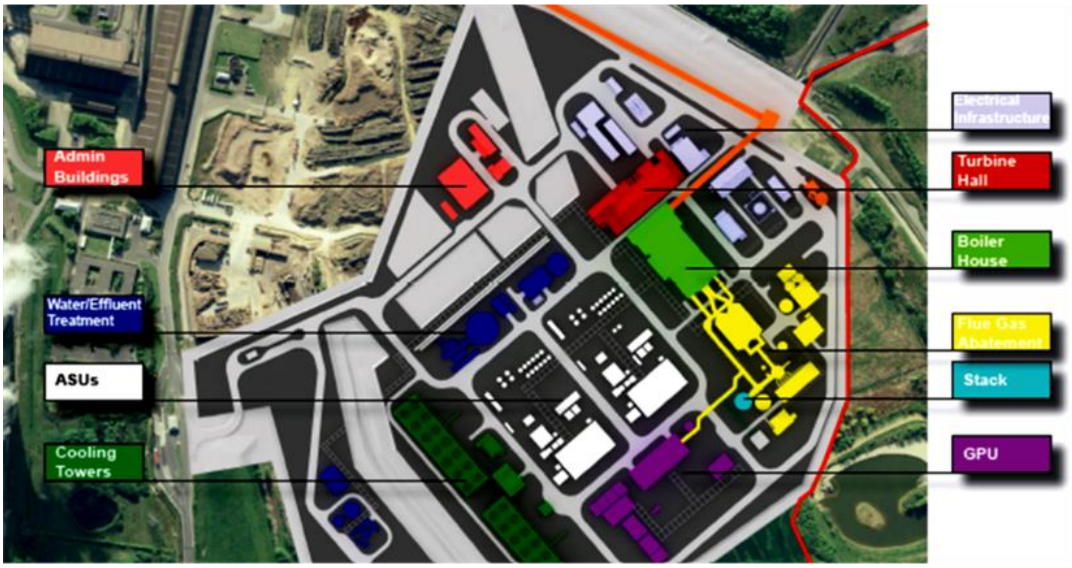
The general layout for the OPP components is shown in below.

Figure 2.3: OPP Layout



The OPP site is located on land adjoining the existing Drax Power Station in North Yorkshire and occupies an area of approximately 27 hectares. Further details of the layout is given in K.28 – OPP Plot Plan.

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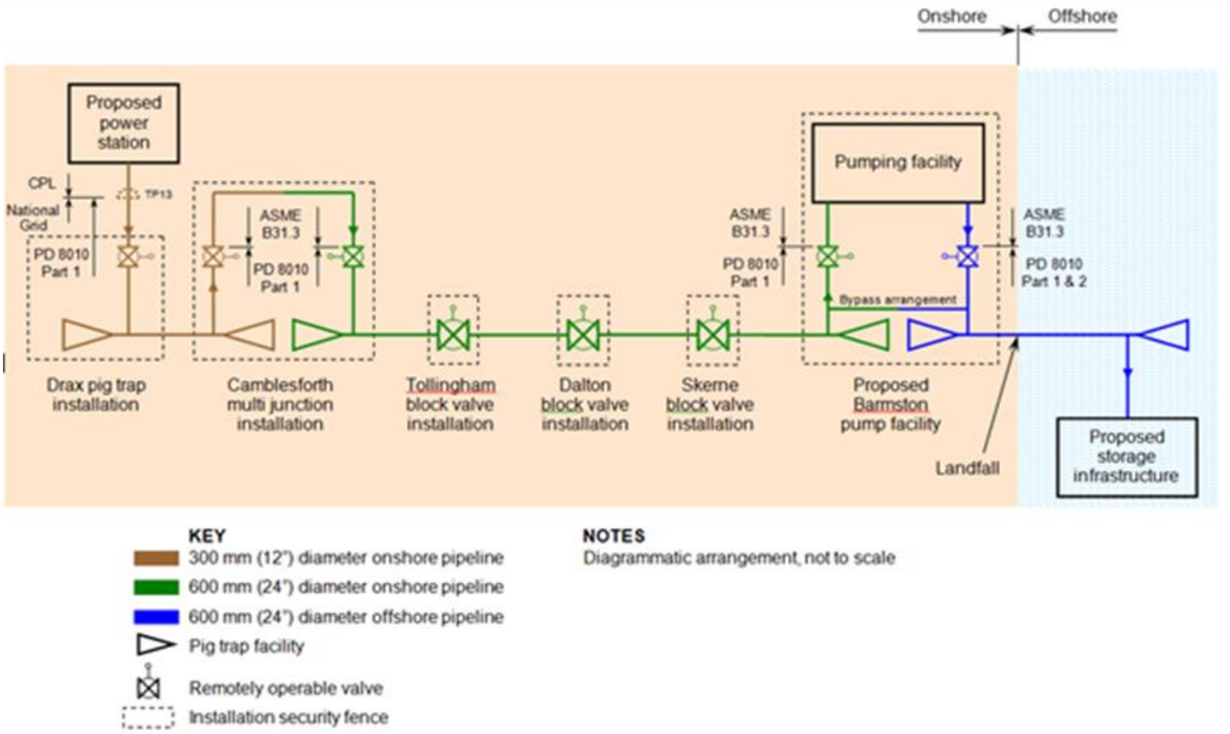
2.2 Transport & Storage System Overview

The figure below provides a schematic diagram of the Transport & Storage (T&S) system for the White Rose CCS Project.

Figure 2.4: Overall Schematic Diagram of the T&S System



2.2.1 Onshore Transport Facility

The new onshore transport facility comprises a pipeline from the OPP to the coast at Barmston and includes a number of installations to provide control and safety functions as well as access to the system for future emitters and pressure boosting.

2.2.1.1 Drax AGI

The Drax Above Ground Installation (AGI) is located adjacent to the OPP site and will include a 300mm (12”) diameter pipeline from the OPP, a Pipeline Inspection Gauge (PIG) launcher, valves, pipework with local and remote control and monitoring systems to enable on-going operations and maintenance of the transportation system, including the internal inspection of the proposed onshore pipeline.

A 300mm (12”) diameter underground pipeline will run approximately 6km from the Drax AGI to the Camblesforth Multi-Junction Installation.

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2.2.1.2 Camblesforth Multi-Junction Installation

The Camblesforth Multi-Junction Installation allows connection of potential future pipelines from other regional carbon capture sources to White Rose transport and storage system.

Current provision is for three additional pipelines, along with isolation valves and PIG facilities. It is also the starting point for the 600mm (24") diameter underground cross country pipeline extending 69km the proposed pumping facility near Barmston, South of Bridlington (Barmston Pumping Facility).

2.2.1.3 Block Valve Stations

Along the length of the pipeline between the Camblesforth Multi-Junction Installation and the Barmston Pumping Facility are three Block Valve Stations (BVS), spaced at approximately 20km intervals, at Tollingham, Dalton and Skerne. The block valve stations enable the isolation of discrete sections of pipeline.

2.2.1.4 Barmston Pumping Facility

At the Barmston Pumping Facility, CO_2 pumps boost the pressure of the CO_2 as required for transportation to the saline formation storage site located approximately 90 km away from the pumping facility.

Space is set aside within the facility for additional pumps to accommodate the full range of requirements from the initial load from the OPP to the future full flow design case (17.0 MTPA). The facility also includes PIG receiving and launching facilities.

2.2.2 Offshore Pipeline and Storage Facilities Description

2.2.2.1 Offshore Pipeline

The CO_2 is transported from the Barmston Pumping Facility to the offshore storage facility via a 600mm (24") diameter subsea pipeline which has a nominal length of 88 km.

2.2.2.2 Offshore Facilities

The White Rose offshore storage facility is a wellhead injection platform supporting three CO_2 injection wells which dispose of the CO_2 into the saline formation site located in the Southern North Sea. It is designed so that in the future, the numbers of injection wells can be increased.

2.3 OPP Description

The OPP will be a new ultra-supercritical coal fired power plant consisting of a pulverised coal boiler designed for operation with either air or a mixture of CO_2 and oxygen aspiration, a steam turbine generator unit, air quality control systems (AQCS), ASU, CO_2 processing and compression unit (GPU). The OPP has been designed to allow for the future potential co-firing of up to 10% biomass.

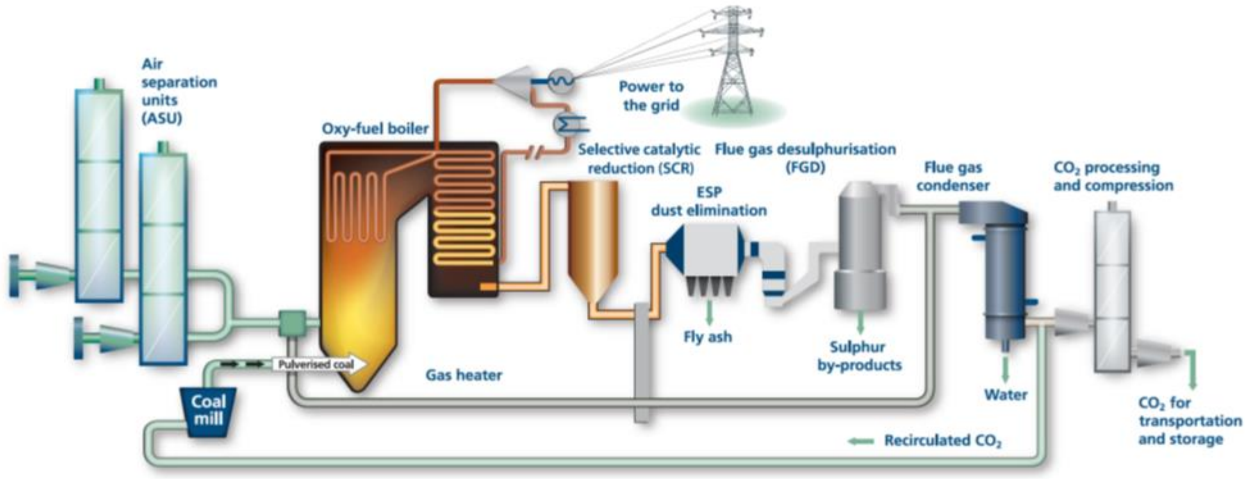
The basic oxy-firing concept uses a mixture of oxygen and recirculated flue gas, rich in CO_2, to replace combustion air, which after combustion produces a flue gas comprised of mainly CO_2 and water vapour and much smaller amounts of oxygen, nitrogen, argon, sulphur dioxide, etc.

The flue gas leaving the boiler is cooled and cleaned of the particulates, SOx and NOx in the AQCS.

The GPU is designed to capture approximately 90 % of the CO_2 produced, first removing the water vapour from the flue gas, before the remaining CO_2 is further processed to meet the specification required for the T&S system. CO_2 will be delivered in dense phase to the CO_2 pipeline header for onward transportation.

The main components of the OPP are shown in Figure 2.5.

Figure 2.5: Oxy Power Plant Diagram



Source: CPL

The OPP includes the following major facilities:

- Balanced draft, sliding pressure, supercritical, once-through type boiler, utilizing a low NOx firing system, and including Selective Catalytic Reduction (SCR);
- AQCS including wet Flue Gas Desulphurisation (FGD), limestone handling/preparation, gypsum dewatering and Electrostatic Precipitator (ESP) removal equipment;
- Steam Turbine generator and auxiliaries;
- Water and Steam Cycle equipment;
- Cooling towers (mechanical draft low plume cooling towers);
- Closed cooling system ;
- Light Fuel Oil storage and supply;
- Ash Handling;

- Water Supply (Demineralised water treatment and cycle makeup, Waste water);
- Water / Steam cycle chemistry;
- Polishing Plant;
- Dosing equipment;
- Steam cycle sampling and analysis;
- Auxiliary steam;
- Compressed air system; and
- Plant electrical system and Control System.

The boiler is capable of producing full load in either the air or oxy-fired mode of operation from a wide range of pulverised coals and is designed with the option to co-fire biomass along with the coal. The boiler provides steam (both high pressure and reheat pressure streams) to the steam turbine (ST) at the specified flow rate, temperature and pressure.

To allow operation in oxy mode some modifications to the power plant itself, versus a conventional unit, are necessary, in particular:

- Partial recirculation of the flue gas in order to maintain appropriate temperature and heat absorption in the furnace and convection pass;
- Removal of the water from the flue gas before treatment in the GPU in the Flue Gas Condenser;
- Minimisation of leakage of air into the boiler;
- Sizing of equipment (e.g. cooling and electrical systems), taking into account the additional needs of ASU and GPU; and
- Injection/mixing of oxygen in the flue gas path.

2.3.1 Gas Processing Unit

The GPU conditions and compresses the CO_2 rich flue gas to achieve the required purity, pressure and temperature specification for the transportation system. The CO_2 rich flue gas undergoes the following steps in the GPU:

- Bulk water removal in a Direct Contact Cooler (DCC);
- Compression in the Flue Gas Compressor;
- Final drying in molecular sieve adsorber beds;
- Mercury removal;
- Purification in a cryogenic section; and
- Compression to the required pressure required for onward transfer to the T&S infrastructure.

2.3.2 Air Separation Unit

Gaseous oxygen to the boiler is supplied at low pressure from two identical ASUs each sized to produce up to about 3,145 tonnes per day of oxygen.

For each unit, air is filtered, compressed, cooled and dried before being separated through cryogenic distillation in a cold box to produce the oxygen product stream. The nitrogen by-product is used for regeneration of the molecular sieve units which dry and remove CO_2 from the air before it enters the cold boxes, and also to produce chilled water used to pre-cool the air.

As well as producing gaseous oxygen, the ASU has been designed to liquefy oxygen during off- peak power periods (e.g. night time).

The liquid oxygen (LOX) produced is stored in two systems:

- a back-up system where LOX from dedicated storage vessels can be vaporised in the steam heated vaporisers to maintain the oxygen flow to the boiler in the event of an ASU outage sufficient to allow the boiler to ramp down to 50% load without tripping ; and
- a system to inject LOX, from a separate storage vessel, to the ASU during peak power demand in order to reduce the ASU load (the load of the ASU's main air compressor) and thereby increase the net power output of the OPP to the grid.

Heat is recovered from the ASUs into the boiler by using the heat of compression from the main air compressors to pre-heat a condensate stream which is returned to the boiler.

Steam is imported from the boiler to each ASU to provide the heat needed for regeneration of the pre-purification units and for the LOX vaporisers.

2.3.3 Interfaces with Drax Power Plant

Fuel is delivered via the existing DPL coal yard, with the coal imported to the yard via rail. A new conveying system will supply to silos located at the OPP boiler house.

The cooling water system will consist of mechanical draft low plume cooling towers. Raw water, used for make-up will be supplied from the existing DPL facilities.

Industrial liquid effluents including flue gas desulphurisation effluents will be treated within the OPP before discharged to the River Ouse through DPL's existing discharge line under their current consent.

The OPP includes all facilities required for an independent electric power generating unit, excluding those facilities specifically provided by DPL.

The following services from the existing DPL Facility will be supplied to the OPP:

- coal;
- raw limestone;
- dry gypsum return;
- raw water;
- water return (to include treated process waste water and rain water as well as cooling tower blow down);
- sanitary sewage treatment;

- pulverised fly ash (PFA) disposal; and
- furnace bottom ash disposal.

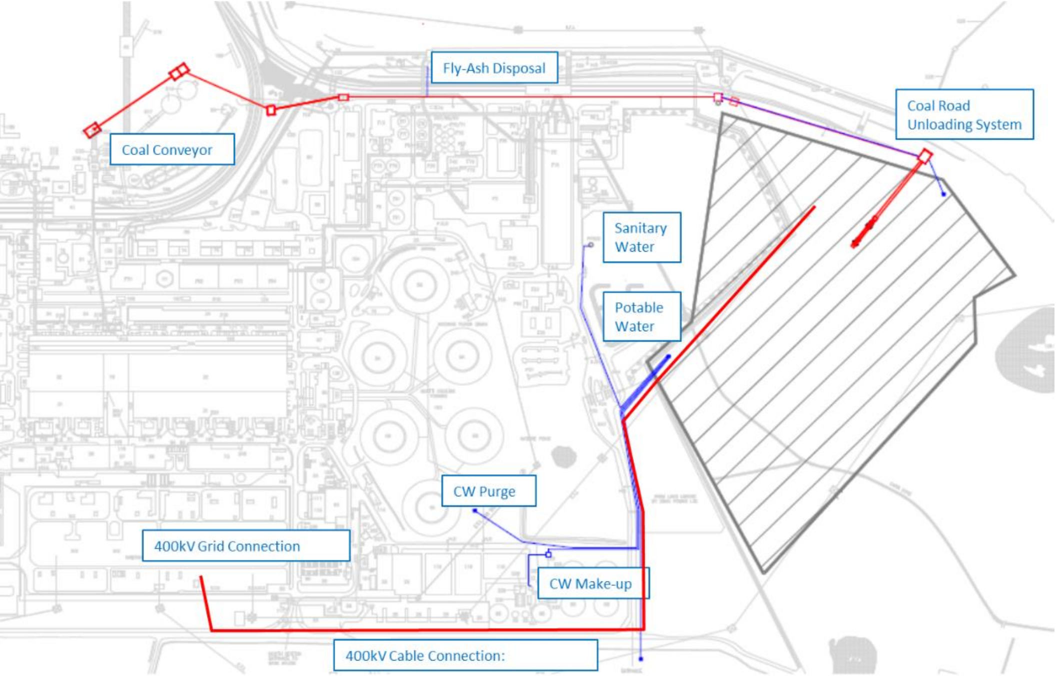
The interface between the OPP and DPL control systems will be via hard wired and serial.

Batch flows, e.g. transfer of coal to the OPP from DPL or transfer of PFA from the OPP to DPL, will be initiated from the OPP sending a “request coal delivery” or “request to empty PFA” signal to DPL. Permissive signals between the two control systems will ensure all systems are operational before transfer begins and also stop the system in the case of plant failures or safety issues.

The consumption rate of coal will be approximately 160t/h and it is expected that the coal conveyors will run 2 or 3 times a day.

The figure below shows the interconnections between the OPP and DPL facilities.

Figure 2.6: Interconnections with the DPL Facilities



Source: CPL

The table below summarises the interfaces design parameters for the OPP.

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Table 2.1: Interconnection Process Details

Terminal Point Description	From	To	Pressure / Temp (design)	Design Flow	Comments
Coal Supply	Drax	OPP	N/A	2x 320 t/h	Batch supply by 2x100% conveyors OPP normal usage: 140 t/h
Biomass Supply (future potential)	Drax	OPP	N/A	1x 80 t/h	Batch supply by conveyor
Cooling Water (CW) Make-up	Drax	OPP	4 bar / 30°C	1600 m^3/h	Normal flow: 1200 m^3/h
Potable Water	Yorkshire Water	OPP	6 bar / 20°C	10 m^3/h	
CW Purge	OPP	Drax	4 bar / 30°C	1,650 m^3/h	Max flow including rain water discharge. Normal flow of treated waste water (excluding rainwater): 533 m^3/h
Sanitary Water	OPP	Drax	4 bar / 30°C	10 m^3/h	
Pulverised Fly Ash	OPP	Drax	N/A	100 t/h	Batch flow to DPL. Normal PFA production from OPP: 20 t/h
11 kV Connection	Drax	OPP	N/A	9 MVA	
CO_2	OPP	NGC	135 barg	306 t/hr	Normal CO_2 flow rate: 264 t/h Minimum CO_2 flow rate: 66 t/h
400 kV	OPP	NGET	N/A	400 MVA	

Source: CPL

2.3.4 Grid Connection

The electrical output from the plant will be exported to the National Grid Electricity Transmission (NGET) 400kV network. A new connection will be made from the OPP to a bay in NGET's existing switchyard at DPL.

2.3.5 Heat Integration with ASU

Heat integration between the ASUs and the oxy boiler allows for the recovery of a large portion of the heat of compression from the ASUs' main air compressors back into the water steam cycle loop.

Cold condensate from the ST condenser passes to the condensate pumps and is then divided into two streams. The first stream goes to the first LP heater within the boiler for reheating, while a second stream, around 30% of the total cold condensate flow, goes to the ASUs for reheating before being returned upstream of the last LP heater. This approach reduces the amount of steam extracted from the ST to heat-up the cold condensate, thereby improving the cycle efficiency.

In order to maximise the amount and temperature of the heat recovered, an axial flow main air compressor is selected with no intercooling and the heat is recovered in a spiral wound heat exchanger in order to achieve a close approach temperature and low pressure drop. The cold condensate is heated from around

30°C to about 145°C in the ASU exchangers and the heat integration recovers up to 40 MW of thermal heat.

A more detailed description of the OPP processes can be found in KKD 27 – Oxy Power Plant Process Description.

2.3.6 CO_2 Capture Rate

When operating in oxy mode, the OPP is designed to capture at least 90% of the CO_2 generated from the combustion of its fuel.

2.3.7 Composition of CO_2 Stream

The pipeline entry specification below provides the permitted limits for each component having considered safety design, integrity design and hydraulic efficiency criteria. This specification will also apply to the offshore storage system.

Table 2.2: CO_2 Entry Specification

Component	Specification
CO_2	Min 96%vol
H_2S	Max. 20 ppmv
CO	Max. 0.2%vol
NO_x	Max.100 ppmv
SO_x	Max.100 ppmv
O_2	Max. 10 ppmv
H_2	Max. 2%vol
N_2 +O_2 +H_2 +CH_4 +Ar (non-condensable components)	Max. 4%vol
H_2O	Max. 50 ppmv

The three limiting criteria (safety, integrity and hydraulic efficiency) which set the overall specification, as well as further notes on the values selected for each component, are provided in Table 16.5.

CO_2 stream from the OPP will have a CO_2 content of ~ 99.9%vol, much higher than the minimum required by the pipeline entry requirements.

2.4 Net Power Output

When operating in oxy mode, the OPP has a net output >300 MW.

2.5 Fuel Specification

2.5.1 Coal

The Performance Coal is SC Ravenstruther SC01.

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Table 2.3: Coal Range

Coal Range	Min	Max	Performance Coal
Proximate Analysis (wt%)			
Moisture	9.10	15.00	15.00
Volatile Matter	27.80	35.30	3.38
Fixed Carbon	41.00	48.20	1.09
Ash	5.72	18.00	14.70
Ratio Fixed Carbon / Volatile Matter	1.27	1.56	1.40
Ultimate Analysis (wt%)			
Moisture	9.10	15.00	15.00
Hydrogen	3.38	4.28	3.38
Carbon	57.35	67.68	57.35
Sulphur	0.37	2.00	1.09
Nitrogen	1.05	1.80	1.12
Oxygen (diff)	3.77	10.86	7.29
Chloride	0.01	0.18	0.07
Ash	5.72	18.00	14.70
HHV, kJ/kg	23,517	26,810	23,517
kg Moisture/10^6 kJ	3.50	20.32	19.31
kg Sulphur/10^6 kJ	0.15	0.85	0.46
kg Ash/10^6 kJ	2.26	7.56	6.25
kg Nitrogen/10^6 kJ	0.41	0.68	0.48
Hardgrove Grindability Index	45	63	51
Ash Analysis (wt%)			
SiO_2	46.18	61.14	51.85
Al_2O_3	18.65	30.84	30.84
Fe_2O_3	0.12	9.64	0.12
CaO	0.9	10.01	10.01
MgO	1	2.8	1.19
Na_2O	0.07	3.48	0.07
K_2O	1.52	2.5	1.59
TiO_2	0.83	1.6	1.09
Mn_3O_4	0.04	0.3	0.3
P_2O_5	0.1	0.8	1.1
SO_3	0.6	10.75	1.83
Ash Fusion Temperature (C)			-
Initial Deformation	1163	1482	1390
Softening	1207	1482	1480
Hemisphere	1232	1500	1500
Flow	1310	1520	1520

2.5.2 Biomass

The co-firing of 10% (heat content) biomass from the start of operations was considered in FEED but not adopted. However it remains a future potential option.

The primary biomass fuel is expected to be timber pellets but a range of agricultural by-products and energy crop miscanthus were also considered in the design. Biomass would be pelletised.

Table 2.4: Biomass Range

	Timber Pellet		All biomass sources including: Agricultural By-products and Energy Crop Miscanthus	
	Min	Max	Minimum	Maximum
Proximate Analysis				
Total moisture (% a.r.b.)	5.2	10.1	5.2	21.7
Ash (% a.r.b.)	0.4	2.5	0.4	13.7
Volatile matter (% a.r.b.)	74.2	80.7	52.2	80.7
CV Net MJ/kg (H det. A.r.b.)	15.9	18	13.5	18
CV Gross MJ/kg (a.r.b)	17.9	19.3	15	19.3
Ultimate Analysis				
Chlorine (% a.r.b.)	0	0.03	0	0.47
Sulphur (% a.r.b.)	0	0.1	0	0.46
Nitrogen (% a.r.b.)	0	2.4	0	6
Carbon (% a.r.b.)	44.8	48.3	38.24	48.3
Hydrogen (% a.r.b.)	5.3	5.7	4.1	6.5
Oxygen (% a.r.b.)	38.2	41.3	27	41.3
Ash Analysis				
SiO_3 (%)	4.9	22.4	2.9	74.2
Al_2O_3 (%)	2.2	7.6	0.18	24.5
Fe_2O_3 (%)	2.9	8.3	0.3	23.45
TiO_2 (%)	0.14	0.97	0.03	3.26
MnO (%)	2.1	5	0.1	5
CaO (%)	30.3	45.4	2.41	45.4
MgO (%)	7.2	11.5	1.18	12.4
Na_2O (%)	0.58	3.6	0.06	3.6
K_2O (%)	12.8	20.3	1.06	29.2
P_2O_5 (%)	2.9	5.3	0.15	42.4
SO_3 (%)	1.4	3.1	0.66	10.3
Ash Fusion Reducing (C)				
Initial Deformation	1130		800	1390
Softening Temperature	1170		900	1400
Hemispherical Temperature	1190		930	1250
Flow Temperature	1200		1100	1260

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2.5.3 Liquid Fuel Interface Data

The start-up fuel will be Light Fuel Oil BS 2869:2010 – Class A2 – Sulphur free. Light Fuel Oil will also be used for the auxiliary boiler.

2.6 Emissions to Air

Emissions to air for both air and oxy mode operation are detailed in section 6.

2.7 Design life

The OPP will be designed for a 30 year design life.

The T&S facilities will be designed for a 40 year design life when practical. Some facilities, subject to obsolescence (e.g. control systems) or wear (e.g. wells choke valves), may have a shorter design life and require upgrade or replacement.

2.8 Tie-in points / battery limits

The tie-in point conditions for the Full Chain are given below. Information on the CO_2 flowrates and CO_2 composition are provided in tables 16.3 and 16.4.

2.8.1 Onshore Pipeline and AGIs

The pressure and temperature conditions for the onshore pipelines and the AGIs are given below and these represent the conditions for CO_2 entering the pipeline from the OPP or any future entrant.

Table 2.5: Onshore Pipeline and AGIs Pressure and Temperature Conditions

Parameter	Units	Max	Min
Pipeline Maximum Allowable Operating Pressure (MAOP)	barg	135	-
Pipeline Design Pressure	barg	135	
Pipeline Normal Operating Pressures	barg	135	90
AGI Design Pressure	barg	148.5	-
AGI Design Temperature	°C	50	-46
Pipeline Design Temperature	°C	25	0
Pipeline Normal Operating Temperatures	°C	20	5
Buried Pipeline Temperature	°C	15	4

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2.8.2 Pumping Station

The pressure and temperature conditions for the pumping station inlet/ outlet are given below.

Table 2.6: Pumping Station Pressure and Temperature Conditions

Parameter	Units	Max	Min
Design Pressure	barg	148.5	-
Normal Operating Pressure	barg	135	90
Design Temperatures	°C	50	-46
Normal Operating Temperatures	°C	18	4.5
Design Pressure[1]	barg	281.5	-
Normal Operating Pressure[1]	barg	182	138
Design Temperatures	°C	50	-46
Normal Operating Temperatures	°C	30	4.5

Notes:

1. Following Year 10 operation there may be a requirement to up-rate the pumps at Barmston (therefore avoiding the requirement for additional pumping and associated recycle cooler at the offshore platform), to transport CO_2 via the offshore hub to remote storage sites. The offshore pipeline and riser will be mechanically designed to be suitable for an increased MAOP of 235 barg (and MIP 250.5 barg, limited to the platform piping 1500# class limit at 50°C). The equipment, piping and instrumentation at the pumping station installed for Year 1 operation should have its suitability assessed for the increased pressure (class limits for increased pressures and temperatures, testing and certification requirements including hydrotest pressures, etc).

2.8.3 Design Conditions Offshore Pipeline

Key design and operational parameters for the offshore pipeline are provided below.

Table 2.7: Offshore Pipeline Operating and Design Conditions

Parameter	Units	Max	Min
Offshore Pipeline Design Pressure		235	
Pipeline MAOP[1]	barg	182	-
Pipeline Normal Operating Pressures	barg	182	90
Pipeline Normal Operating Temperatures[2]	°C	29.3	1
Pipeline Design Temperature	°C	40	0
Riser Design Temperature	°C	50	-46

Notes:

1. The offshore pipeline and riser will be mechanically designed to be suitable for an increased MAOP of 235 barg (and MIP of 250.5 barg, limited to the offshore platform 1500# piping class limit at 50°C). This is to facilitate future potential for up-rating the pumps at Barmston Pumping Station (therefore avoiding the requirement for additional pumping and associated recycle cooler at the offshore platform) post Year 10 operation to transport CO_2 via the offshore hub to remote storage sites.
2. The maximum operating temperature at the pump discharge pressure of 235 barg has been estimated as 33.4°C.

2.8.4 Offshore Facilities Design Conditions

The pressure and temperature conditions for the platform are given below.

Table 2.8: Offshore Facilities Pressure and Temperature Conditions - Process

Parameter	Units	Max	Min
Design Pressure[1]	barg	200	-
Normal Operating Pressure[1]	barg	182	90
Design Temperatures	°C	50	-46
Normal Operating Temperatures	°C	16	1

Notes:

1. Post Year 10 operation, the design pressure may require up-rating to 250.5 barg (1500# piping class limit at a design temperature of 50°C. The corresponding MAOP will be 235 barg) to facilitate up-rated pumps at Barmston Pumping Station (therefore avoiding the requirement for additional pumping and associated recycle cooler at the offshore platform), to transport CO_2 via the offshore hub to remote storage sites.

2.9 Metering & Monitoring Philosophy

The Metering & Monitoring philosophy is summarised below. Further detail is provided in K.02 – Full Chain Basis of Design.

2.9.1 Metering and Monitoring Objectives

The CCS chain is made up of separate installations each with its own requirements for metering and monitoring driven by its specific safety, operational, regulatory and commercial requirements.

2.9.1.1 Safety and Operational

- Sufficient instrumentation, metering and monitoring systems must be included in the plant design to allow the plant to operate safely in all routine and foreseeable upset conditions. Such systems should be sufficiently robust as to give an adequate level of confidence in the long term safe operation of chain elements and the Full Chain; and
- Similarly, sufficient metering and monitoring systems must be in place to allow proper control of the plant for optimum performance and output.

2.9.1.2 Regulatory

- Power generators will be required to be party to a Contract for Difference (CfD) contract;
- Storage facilities require a permit under the Geological Storage Directive (GSD);
- Each operator within the CCS Chain is required to be permitted under the European Union Emissions Trading Scheme (EUETS); and
- Power generation is captured under the EU Industrial Emission Directive (EU IED) which is transposed into UK law by the Environmental permitting regulations.

2.9.1.3 External Commercial

- CfD requires monitoring of a range of electrical power volumes and measurement of Carbon and CO_2 contents and volumes to establish revenue from clean electricity;

- T&S Operators will generate revenue based on the mass of CO_2 transported and stored; and
- The purchase of Carbon Credits is required for all CO_2 emitted to the atmosphere from any part of the CCS Chain.

2.9.1.4 Internal Commercial

- Each Chain Element Operator will be commercially responsible for the performance, reliability and availability of its own chain element; and
- Sufficient instrumentation, metering and monitoring will be required of both the Chain Elements and the interfaces between them to allow correct allocations of responsibility and risk to be determined.

2.9.2 OPP Metering

Table 2.9: OPP Metering Requirements below summarises the key metering requirements for the OPP.

Table 2.9: OPP Metering Requirements

Main parameter to be measured	Maximum system measurement uncertainty	Measurement Location
Mass flow of coal	Class 0.5 (+/- 0.25%)	Belt weigher
Net calorific value of coal	0.5%	Laboratory analysis samples taken from main coal feed conveyor belt
Mass fraction of total carbon in coal	0.5%	Laboratory analysis of representative samples taken from main coal feed conveyor belt
Mass flow of total ash in coal	0.5%	Laboratory analysis of representative samples taken from main coal feed conveyor belt
Mass fraction of total carbon in bottom ash	0.5%	Laboratory analysis of representative samples taken from bottom ash conveyor belt
Mass flow of fly ash	0.5%	Fly ash pneumatic conveyor flow meter
Mass fraction of carbon in fly ash	0.5%	Representative online sampling in fly ash pneumatic conveyor and laboratory analysis
Mass flow of auxiliary fuel (liquid or gaseous form)	1%	Flow meter in fuel intake at nearest practicable point(s) immediately prior to combustion
Mass fraction of carbon in auxiliary fuel	0.5%	Representative sampling at nearest practicable point(s) immediately prior to combustion
Gross electrical energy	Class 0.2S (0.2%)	Generator terminals
Export (net) electrical energy	Class 0.2S (0.2%)	At NGET switchyard
Auxiliary electrical energy (11kV and 3.3kV)	Class 0.2S (0.2%)	At interface point

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Main parameter to be measured	Maximum system measurement uncertainty	Measurement Location
Mass flow of pure CO_2 injected into pipeline	1%	Venturi flow element at inlet to onshore pipeline
Mass fraction of CO_2 in fluid injected into pipeline	0.1%	On-line analyser at inlet to onshore pipeline
Mass flow of vent gas from GPU	1%	Venturi flow element before vent stack
Mass fraction of uncaptured CO_2 in vent gases	0.1%	On-line analyser before vent stack

2.9.3 Transport - Onshore Metering

- CO_2 volumetric and mass flow rates shall be measured to a fiscal standard prior to their entry into the offshore pipeline. Orifice plate metering is the proposed method of flow measurement;
- CO_2 metering devices shall be to an appropriate international standard which ensures that the uncertainty levels can be determined with the metering device in situ. The required uncertainty level is +/- 2.5%; and
- It shall be possible for nominated independent parties to validate the outputs from the CO_2 flow metering system.

2.9.4 Offshore Metering

The total CO_2 mass arriving to the platform will not be measured, however each platform injection well inlet arrangement would be provided with an orifice plate for metering.

CO_2 metering would be provided on each well flow line for allocation purposes. The flow meters would be orifice plate or Venturi tube with an anticipated uncertainty of better than +/- 2.5%.

The mass of CO_2 vented to atmosphere through planned interventions will be calculated (i.e. not metered) based on the measured temperature, pressure and equipment inventories.

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2.9.5 Subsurface Monitoring

All wells will have meters, temperature and pressure sensors to accurately measure injection rates, tubing head pressure, surface casing pressure and bottom-hole injection pressure in order to increase the understanding of the behaviour of the CO_2 plume injected into the reservoir. It is expected that fibre optic cables will be used to measure both temperature and acoustic readings. The table presents the injection wells instrumentation requirements.

Table 2.10: Injection Wells Instrumentation Requirements

Activity	Frequency
Tubing Head Pressure (THP)	Continuous
Tubing Head Temperature (THT)	Continuous
Injection Flowrate	Continuous
Permanent Down-Hole Gauges (PDGs)	Continuous
Temperature Measurement along well bore with Distributed Temperature Sensors (DTS)	Continuous
Acoustic Measurement along well bore with Distributed Acoustic Sensors (DAS)	Continuous
Well Sampling	Sporadic
Saturation Profile	Sporadic

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3 Full Chain Block Flow Diagram

For further detail see K.22 – Full Chain Process Flow Diagrams.

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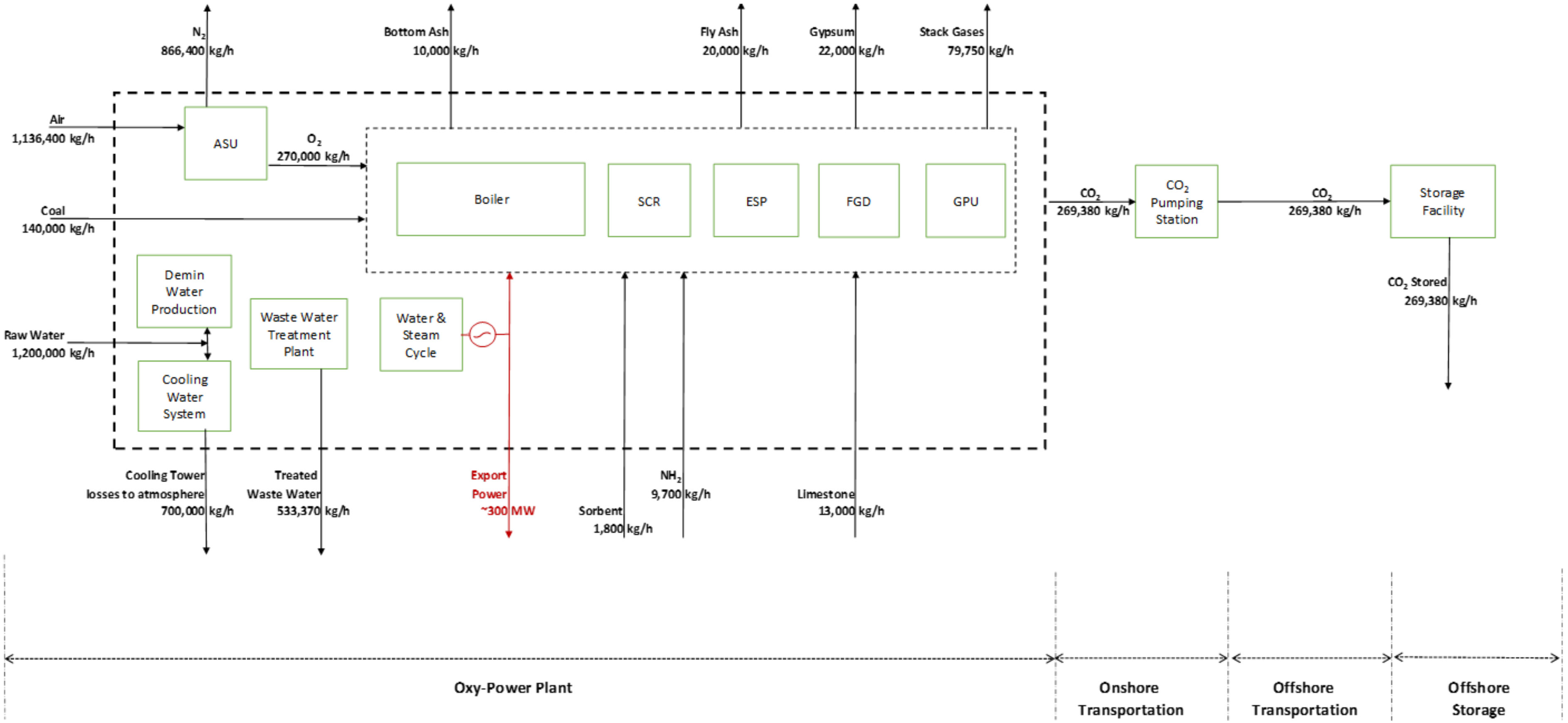
Figure 3.1: Full Chain Block Flow Diagram and Overall Stream Summary



Source: CPL

4 Operating Philosophy

4.1 Full Chain Operation

The operating modes for both the OPP and the T&S system will be start-up, part load, base load and shutdown.

- OPP: On start-up, the flue gases will be directed to the OPP main stack until the flue gas is within the limits acceptable to the GPU. The flue gas will then be admitted to the GPU. When the processed CO_2 meets the required specification it will be directed to the inlet of the T&S system once the system is confirmed to be ready to accept CO_2.
- T&S system: On start-up, the CO_2, with confirmation of within composition limits, will proceed through the pipeline, passing the Drax AGI, Camblesforth Multi-Junction, and Tollingham, Dalton and Skerne Block Valve Stations. The booster pump station at Barmston will increase the operating pressure and the CO_2 which will be pumped to the offshore facility, where it will be filtered and injected into the saline formation.

The OPP can operate in either air or oxy firing modes. Oxy mode (i.e. with CO_2 to T&S network) is normal operation.

Air mode is only for:

- initial commissioning of the power plant;
- start-up and shutdown; and
- as a temporary back-up in case of unavailability of the ASU, GPU or T&S network.

The design and operational intention is to run the plant continuously (minimising the number of starts).

4.1.1 Normal Operation

Base load is expected to be the main operating mode. The plant would be able to ramp up and down with a normal loading and unloading ramp rate of 2% per minute.

In normal operation, the most efficient operation of the plant is expected to be between 80% and 100% load. This is due to the ASU and GPU compressors operating ranges. Below about 75% to 80% load the GPU compressors are in recycling mode. In base load operation the boiler uses the ASU oxygen production with no production of Liquid Oxygen (LOX) and no use of the stored LOX.

Dense phase CO_2 would be produced by the OPP at Drax up to a design flowrate of 306 tonnes per hour (tph) (or 2.68 million tonnes per annum (MTPA)).

Base load for each element of the chain is defined as follows:

- OPP: the plant is operating at its rated gross output and providing CO_2 to the T&S system at an outlet pressure of up to 135 barg;
- Pumping Station: a number of pumps operating at full load; and
- 3 injection wells.

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4.1.2 Flexible Operation

As this is a demonstration project, there is a requirement for the plant to prove its ability to respond to market conditions through flexible operation. Therefore the Full Chain has been designed to have the capacity to allow flexible operation in each element of the system.

Possible variations have been established as follows:

- OPP: The power plant is designed for flexibility, allowing the net output to be adjusted:
    - A “flexibility concept” which mimics traditional “2-shifting day/night” operation. During this operating regime, for periods of weeks or months or a season (up to 100 days/yr), the CO_2 production can be reduced to 35% for a period of up to approximately 8 hours on a daily basis. In this mode the plant moves to a position that results in export of no power to the grid while still generating the clean power needed to operate the ASUs and the GPU. By doing this, the plant can operate without shutting down and CO_2 is provided continuously, at a reduced rate, to the T&S system;
    - A “normal ramping” range set by turndown limits of ASU and GPU while compliant with Stable Export Limit (SEL). The CO_2 output is expected to vary in the range 100-75% during “normal ramping”;
- CO_2 Pumping Station: The CO_2 pumps at Pumping Station can modulate to adjust to the CO_2 production rate and the process requirements of the pipeline;
- Injection wells:
    - The combination of injection wells in use will change the range of injection rates to accommodate the full range of CO_2 from the OPP;
    - The overall injection rate range will vary as the reservoir pressure increases over the injection period; and
    - The wells maximum supply pressure of up to 182 barg and minimum of 90 barg to prevent phase separation occurring within the pipeline.

In addition, the plant could on occasions be required to turn down to 50-60% SEL in order to comply with the electrical Grid Code requirements. The OPP operating regime is presented in Table 4.1.

Table 4.1: OPP Operating Regime

Operating Mode	Net MW	CO_2 Production	Comment
Normal Operation	Approx. 300 – 220	100%-75%	continuous ramp rate 2%/min
Flexibility Concept			
High Load	Approx. 310	100%	~ 13 hours operation
Min Load	~	35%	~ 5.5 hours operation
			1.5 hour transition between modes

Based on the above, the OPP is designed for a yearly production profile as shown in **Table 4.2**.

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Table 4.2: OPP Yearly Production Profile

Yearly duration	Load
65%	100% load
10%	75% load
10%	<50% load
15%	off line

This allows for 100 days per annum of flexible operation as well as 3-6 hours per day “normal ramping” between 100 % - 75 %.

For design, the number of starts is assumed to be as shown in **Table 4.3**.

Table 4.3: OPP Number of Starts

	Cold	Warm	Hot	Cycling 100 % <> 40 % or 25%
Typical number of starts	2 p.a	4 p.a	6 p.a	100 p.a

The types of start are defined as:

- Hot start: after <=8 hours shutdown;
- Warm start: after > 8h, but <= 48h shutdown (e.g. after a weekend shutdown); and
- Cold start: after > 48h shutdown (e.g. start-up from ambient temperature after maintenance overhaul).

4.1.3 OPP Turndown

The minimum CO_2 turndown rate is 0.81 MTPA.

4.1.4 Well Turndown

The minimum CO_2 turndown rate is less than the rate at which the CO_2 starts to flash downstream of the wellhead choke for 5.5” diameter well tubing. However the FEED has demonstrated the likelihood of flashing across the valve is small and that the risks are acceptable**.** Therefore all platform wells are 5.5” diameter.

The Reliability, Availability and Maintainability (RAM) of the Full Chain are in accordance with the overall targets.

It is recognised that the desired reliability and availability may not be achieved immediately but would progressively improve in the first few years of operation.

Reliability and availability will be calculated and reported in accordance with Institute of Electrical and Electronics Engineers (IEEE) 762 for the OPP, and according to a discrete event driven simulation for the onshore transportation system. A compatible method for the offshore storage system shall be used.

The following are the project availability and reliability targets for the Full Chain.

4.2 Design Availability

Full Chain availability target, including planned outages and unplanned outages, is 85 %.

For the OPP the availability target is based on an average availability over a six year maintenance cycle. It was assumed that planned maintenance of the T&S system would be performed during the period of the planned maintenance for the OPP. Therefore, the reliability target for the T&S system is 99%.

Reliability and availability assessments have been undertaken during FEED to confirm the required redundancy and to determine the provisions necessary to achieve the overall availability target including planned and unplanned outages for the Full Chain. The availability target was confirmed by a detailed RAM study.

The RAM study will be repeated during subsequent design phases of the project incorporating the final design and actual vendor data to confirm the expected plant availability and to determine the level of redundancy required across the Full Chain in more detail.

Availability of the transportation system will be dependent on maintenance requirements and be influenced as much by the storage element (the wells) as by the emitter.

The operating philosophy of the full well chain would be dictated by injection performance and water production performance of the specific wells in each of the injection hubs. Wells that are not required to maintain injection or water production rates would be isolated from service in order to provide redundancy throughout the life of the Full Chain.

The downhole and surface monitoring (pressure/temperature/flow rates) systems would be used to manage the well chain along with the overall reservoir monitoring system. As the life of the Full Chain advances the monitoring would be used to determine whether any additional injection or production wells are required for the system.

4.3 CO_2 Venting

Venting of CO_2 from the Full Chain is required for safety, process, operating and maintenance reasons.

The overall requirements of the venting systems are to:

- Support start-up and shutdown of the Full Chain;
- Prevent out-of-specification CO_2 entering the T&S system;
- Provide a means for removing out-of-specification CO_2 from the T&S;
- Support maintenance activities;
- Provide overpressure/thermal relief;
- Provide a means for controlled system depressurisation;
- Support the isolation of high pressure systems (e.g. using double block and bleed arrangements); and
- Support commissioning of the Full Chain.

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Additionally, the venting system will be designed to meet a number of objectives, namely:

- Maintain operation of the OPP during loss of T&S service, whenever possible, to minimise start-up or transition times between operating modes and maintain availability at the OPP;
- Minimise the quantity of CO_2 released into the atmosphere; and
- Prevent/ minimise/ withstand adiabatic cooling effects.

The venting strategy and the required venting system performance should satisfy the needs of:

- Health and safety;
- Plant protection (avoidance of damage);
- Plant operability and maintainability (both routine and in upset conditions);
- Minimising fiscal loss due to loss of CO_2; and
- Environmental impact.

The venting system must achieve a high standard of health, safety and environmental and engineering performance while complying with UK regulations and legislation and with operating organisations' policies and procedures.

In the event of a small CO_2 release, e.g. leak, the relevant section of the system will be isolated, depressurised and replaced in accordance with company procedures. In-line and visual inspections of the pipeline will be frequently conducted to detect any defects so they can be addressed before a CO_2 release occurs.

Further details of the co-ordination, facilities, circumstances and consideration associated with CO_2 venting are provided in K.03 – Full Chain Operating Philosophy

4.4 Line Packing

The compressibility of the CO_2 in the dense phase is significantly less than for traditional gas pipelines. However, it is possible that 'line-packing', the ability to compress the fluid, in the pipeline by a small additional margin, could be used, to a very limited extent, to manage abnormal conditions and small transients due to time lags between balancing supply and demand.

CO_2 inventory may be held "packed" in a pipeline within the operating pressure range to allow resumption of its transportation on an immediate basis. The CO_2 could be "line packed" if there were to be a need to suspend transport.

The transportation system has been sized to accommodate multiple emitters. During early operation, when there is only one emitter connected to the system, the extra pipeline capacity provides additional "line-pack". The extent of this additional "line-pack" is subject to further analysis, however due to the limited compressibility of dense phase CO_2 it is expected that the "line-pack" will not be of the same magnitude as seen within natural gas pipeline systems.

5 External Utility Summary

This section provides a summary of the externally supplied utilities for the Full Chain, further details are provided in K.25 - Full chain - Externally supplied utility summary.

5.1 OPP

The main external supplies to the OPP are shown below:

Table 5.1: OPP Utility Summary

Utility / consumable	Consumption
Coal Supply	Typical 140 t/h
Light Fuel Oil (LFO)	Normally zero / 40 m^3/h max.
Raw Limestone	Typical 13 t/h
Raw Water	Typical 1,200 m^3/h / max. 1,650 m^3/h
Potable Water	Typical 13 m^3/h / max. 20 m^3/h
11 kV connection	Normally zero / max. 10 MVA

5.2 Transport System

The main external supplies to the normally unmanned Barmston Pumping Facility are shown below:

Table 5.2: Barmston Pumping Facility

Utility / consumable	Consumption
Potable Water	8 m^3 per visit
Electricity	66 kV connection 1,200 kW per CO_2 Booster Pump

5.3 Offshore Storage

Power for the platform is provided by diesel generators:

Table 5.3: Offshore Storage Utility Summary

Utility / consumable	Consumption
Diesel	40 l/h manned / 12 l/h unmanned operation.
Seawater	1000m^3/day during well water wash injection
Potable Water	3.6 m^3/h max. (unattended platform - normally zero)

6 Effluent and Emissions Summary

6.1 OPP Emissions to Air

There are three points of emissions to air from the OPP, exhaust from the main stack, from the auxiliary boiler stack and from the FGD.

The OPP has two modes of operation:

- oxy mode which represents the normal operating conditions for the Project;
- air mode which represents the operational conditions during start-up, shut down and during loss of availability of the T&S system.

The full load emissions to air for each case are shown below:

Table 6.1: OPP Main Stack emissions in oxy mode and air mode

Emissions	Unit	Air Mode BMCR	Oxy Mode BMCR
Sulphur Dioxide	g/s	50.830	0.606
Nitrogen Dioxide	g/s	45.830	1.260
Particulates Matter (PM10)	g/s	3.477	0.250
Carbon monoxide	g/s	83.61	15.00
Hydrogen chloride	g/s	1.769	0.001
Hydrogen fluoride (as F)	g/s	0.110	0.001
Arsenic and compounds (as As)	g/s	0.016	0.008
Cadmium and its compounds (as Cd)	g/s	0.001	0.0005
Chromium, chromium(II) compounds and chromium(III) compounds as Cr	g/s	0.007	0.003
Chromium(IV) compounds as Cr	g/s	0.001	0.0005
Copper dusts and mists (as Cu)	g/s	0.007	0.004
Lead	g/s	3.008	0.004
Mercury and compounds, except mercury alkyls (as Hg)	g/s	0.001	0.0001
Nickel (total Ni compounds in PM10 factor)	g/s	0.020	0.009
Selenium and compounds except hydrogen selenide (as Se)	g/s	1.773	0.082
Vanadium	g/s	0.178	0.006
Ammonia	g/s	0.233	0.139

Stack emissions during air mode operation will be in compliance with EU Directive IED 2010/75/EU, but this is not a meaningful metric for oxy mode and it is proposed that emission limits for oxy mode should be expressed on an energy input basis, as milligrams per Mega-Joule (mg/MJ).

The auxiliary boiler will be in operation only during start-up of the OPP, and its emissions must also comply with the limits in the EU Directive.

A gaseous stream is emitted from the Flue Gas Desulphurisation (FGD) which contains some CO_2 generated in the FGD's sulphur removal process.

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6.2 OPP Liquid Effluents

There are two liquid effluent discharge points from the OPP.

The primary discharge point combines the effluent streams from the OPP as well as rain water collected from the north of the OPP site which is returned to the river Ouse via Drax's existing system and in compliance with the requirements of Drax's existing Environmental Permit. The characteristics are shown below:

Table 6.2: Characteristics of Primary Discharge of Liquid Effluents from OPP

Parameter	Units	Continuous
Flow	m3/h	468 (normal) / 650 (max) effluent 1,650 (max – including rainwater return)
pH	-	6 to 9
Temperature	°C	Max 30
Total Ammonia (as Nitrogen)	mg/l	0.5
Cadmium (Cd)	mg/l	0.01
Mercury (Hg)	mg/l	0.005

The secondary discharge point returns rain water to Carr Dyke from the part of the OPP site to the south of Carr Dyke. The flowrate varies up to a maximum of 130 m^3/h.

6.3 OPP Solid By-products & Waste

A number of solid by-product and waste streams are produced by the OPP and summarised below:

Table 6.3: OPP Solid Wastes

Solid Waste	Production rate	Comment
Furnace Bottom Ash	Nominal 10.9 t/h	Non-hazardous. Saleable as building aggregate
Fly Ash	Nominal 19.6 t/h	Non-hazardous. Saleable for cement production
Gypsum	Nominal 22.5 t/h	Classed by EA as a by-product Exported for production of plaster board
Sludge from waste water treatment plant	Approx. 18 m^3/day	Hazardous waste Taken by truck for offsite treatment and disposal
Activated Carbon – mercury removal	90 t/year	Stable non-reactive hazardous waste Taken off site for potential recovery
Desiccant – flue gas driers	55 t (every two years)	Non -hazardous waste Taken off site for potential recovery
SCR catalyst	~180 t (every 5 years)	Hazardous waste Taken by truck for offsite treatment and disposal
Membranes Filters & Resins from raw and demin water systems	Periodic replacement	Non- hazardous. - taken off site for disposal

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6.4 Transport System Effluents & Emissions

There are no effluent or emission streams from the Transport System.

6.5 Offshore Storage Effluents & Emissions

The only source of emissions from the offshore platform is the exhaust gases from the diesel generators, which deliver power to the platform.

6.6 Transport & Storage Solid Waste

Total solid waste production from the onshore pipeline installations and offshore platform is estimated to be around 2.5 tonnes per year on average.

From this the non-hazardous waste will be recycled or sent to landfill and the hazardous waste disposed of using a suitable waste management contractor.

7 Consents Register

The key environmental consents for the full chain are summarised below.

A full list is contained in K.11 - Full chain consents register.

Table 7.1: Key Environmental Consents

Consent	Description
Development Consent Order for the Oxy-Power Plant	As a Nationally Significant Infrastructure Project (NSIP) the White Rose OPP requires grant of a Development Consent Order (DCO). The DCO provides consent for a project and means that a range of other consents, such as planning permission and listed building consent will not be required. A DCO can also include provisions authorising the compulsory acquisition of land or of interests in or rights over land which is the subject of an application.
Environmental Permit (EP) for Oxy-Power Plant	A generating station requires a 'permit to operate'. In addition to setting limits for emissions to air and water, the permit has requirements for a range of environmental issues including energy efficiency, use of raw materials and waste management. It also sets out monitoring and reporting on environmental performance.
Electricity Generation Licence for OPP	The OPP requires an Electricity Generation Licence to export power to the grid.
Development Consent Order for the Onshore Pipeline	The Yorkshire and Humber CCS Cross Country Pipeline is a NSIP and requires grant of a DCO. The DCO provides consent for a project and means that a range of other consents, such as planning permission and listed building consent will not be required. A DCO can also include provisions authorising the compulsory acquisition of land or of interests in or rights over land which is the subject of an application.
CO_2 Storage Permit (inclusive of Offshore Environmental Statement)	The CO_2 Storage Permit is required for the storage of carbon dioxide in a geological formation.
Pipeline Works Authorisation for the Offshore Pipeline	Pipeline Works Authorisation (PWA) must be in place before construction of the offshore pipeline can begin.
EU Greenhouse Gas Emissions Trading Scheme (ETS) Permits	Each element of the full chain, OPP, transport & storage will require a permit under the EU ETS to operate, and must report its CO_2 emissions to atmosphere

8 Milestone Dates for FEED and the Project

The following tables set out a summary of the milestones for the FEED and the project. Those for the FEED represent the actual dates up to the point of withdrawal of grant funding from the competition. Beyond that point in FEED the dates were as forecast at that point. Further detail can be found for the FEED in K.10 – Full chain FEED Programme, and for the project in K.09 – Full chain Project programme.

Table 8.1: FEED milestones

Milestone	Month/year
FEED Contract Signing	12-2013
Start of FEED	01-2014
Initial OPP Design Envelope Agreed For Preliminary Environmental Impact Report (PEIR)	05-2014
Final Sign-off & Submission of PEIR	06-2014
Submission of Development Consent Order (DCO) Application for Onshore Pipeline	06-2014
Adoption by the EC of the NER300 Award Decision	07-2014
Full Chain Design Requirements Available	09-2014
Submission of OPP Technical FEED to the Authority	10-2014
Submission of DCO Application for the OPP	11-2014
PC First Draft Issued by the Authority	12-2014
Power Plant Cost Estimates from Subcontractors Complete	01-2015
Initial Supply Chain HoTs Agreed	05-2015
Submission of OPP Capex Cost Estimate Report – Initial to the Authority	08-2015
Submission of Onshore Transport Technical FEED to the Authority	08-2015
Submission of Offshore Transport Technical FEED to the Authority	08-2015
Removal of Grant Funding from Competition	
Submission of RRP Submission (final bid) to the Authority	12-2015
OPP Environmental Permit Issued	03-2016
OPP DCO Awarded	04-2016
Onshore Pipeline DCO Awarded	05-2016
Storage Permit Granted	06-2016
End of FEED	08-2016

Table 8.2: Project milestones

Activity Name	Months from NTP
Pre NTP Works Earliest Commencement	-14
Access to Site Granted on Vacant Possession and Enabling Works Commenced	-12
Start of Site Raising & Soil Consolidation Works	-7
Notice to Proceed (NTP)	0
Site Raising (Power Block) - Power Block Access Available	5
Piling Works Start	5
Site Raising Complete	13
Start First Steel Structure Erection (Boiler)	14
Start Bolier Erection	20
Start Steam Turbine Erection	22
Start Cold Commissioning (to Enable Start of Back Energisation)	24

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Activity Name	Months from NTP
Onshore Pipeline Construction Started	27
Back Energisation	28
Boiler First Firing (LFO)	36
Offshore Topsides Construction Complete	38
1st Steam to Turbine	38
Camblesforth MJ Mechanically Complete	38
1st Synchronization	38
Energy Export Air Mode	40
Rig in Position and Ready to Drill	46
Offshore Control Centre - Construction Complete	46
Compete Jacket & Topsides Hook-Up & Pre-Commissioning	46
Offshore Pipeline - Completed	46
Trial Air Mode Run Started	47
Completion in Air Mode	47
Onshore Pipeline Mechanically Complete	47
Barmston Pumping Station - Construction Complete	49
Onshore Transportation Facilities Complete	49
All Wells Drilled	50
Commercial Operation Date - Oxy Mode Completion	53
CfD Commences	53
Completion of T&S Commissioning	62
Full Chain Testing Complete	63
End of Commercial proving Period	89

9 Project Cost Estimate

For further details, refer to K.14 – Full chain project cost estimate report.

9.1 Estimation Basis

Estimation of the Full Chain project costs has been undertaken by the Key Sub-Contractors: GE, BOC, Drax and NGC for their respective areas of responsibility. The Key Sub-Contractors have estimated the vast majority of the costs meaning that a market enquiry has been undertaken for over 90% of the project costs. Therefore costs are assessed to be at an equivalent stage to an Association for the Advancement of Cost Engineering (AACE) cost estimate Level 2 for the majority of capital expenditure items (typical accuracy of +12.5% to +35% and -7.5% to -21%). Costs provided to CPL were based on a Notice To Proceed (NTP) date of April 2016 and on exchange rates of the day. Costs presented in the table below have been adjusted to the assumed NTP date and exchange rates as at 30 November 2015.

Each Key Sub-Contractor has identified their costs within a specific Cost Breakdown Structure (CBS) on a much more detailed basis than presented within this report. Each cost has been estimated as a specific cost distribution which has been used to generate an uncertainty band for each cost item. Calculation of uncertainty bands has been through Monte Carlo analysis, whereby a large number of simulations for each cost element are undertaken giving an overall probability distribution. This analysis generated a: p50 cost which is equivalent to the cost that is likely to be sufficient with 50% certainty, a p10 value which is the cost that will be sufficient with a 10% probability; and a p90 value which is the cost that will be sufficient with a 90% probability. The cost presented in Table 2.1 has been built up from the results of the detailed Key Sub-Contractor Monte Carlo analyses through importing the cost distribution for twenty-eight line items and subsequently re-running for the six cost elements shown. The basis of FEED was to reduce risk and associated uncertainty this led the Key Sub-Contractors to include the cost of risks within their base estimates. This has had the effect of increasing the p50 estimate and narrowing the uncertainty band on certain of the chain elements.

Commercial arrangements both between CPL and Key Sub-Contractors and between CPL and DECC have not been completed leading to uncertainty over ownership of risk and likely final cost. Commercial risk for the full chain has therefore not been fully included within the interim project cost estimate.

9.2 Implementation Phase Capex

Table 9.1 presents the expected implementation phase capex for the project. This shows CPL's expected value for each cost (p50) and the percentage decrease or increase in cost to p10 and p90 respectively.

Table 9.1: Expected Implementation Phase Capex (Nominal Costs, NTP September 2017)

Cost Element	Notes	p50 value (£m)	p10	p90	Drivers of Uncertainty
1. Externally supplied utilities	Interconnections for coal, limestone, water and power	49	-3%	+3%	Commodity prices and labour prices

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Cost Element	Notes	p50 value (£m)	p10	p90	Drivers of Uncertainty
2. Oxyfuel boiler, Air Separation Unit (ASU) and Gas Processing Unit (GPU)		455	-2%	+3%	Commodity prices, labour prices, new technology risks
3. OPP Generation Equipment and Balance of Plant (BoP)	Excludes costs for site raising, laydown areas and commissioning/ testing. Includes turbine, generators, environmental control equipment, transformers, switchgear, water systems (including raw, treatment, heating, cooling and waste), coal, limestone and ash handling systems, auxiliary systems, erection costs, project management costs and plant civil costs.	471	-3%	+4%	Commodity prices and labour prices
4. Onshore CO_2 pipeline and associated costs	includes multi- junction, CO_2 pumping station, the land, meters and monitors, and NGC business costs	358	-6%	+6%	Commodity prices and labour prices
5. Offshore pipeline and associated costs	includes pipeline, landfall metering and monitoring and, NGC business costs	225	-11%	+11%	Commodity prices, labour prices and offshore risk
6. Storage facilities	includes the platform, the wells and any monitoring/ metering and NGC business costs	344	-17%	+21%	Commodity prices, labour prices, offshore risk, storage risk
TOTAL		1,902	-6%	+7%	

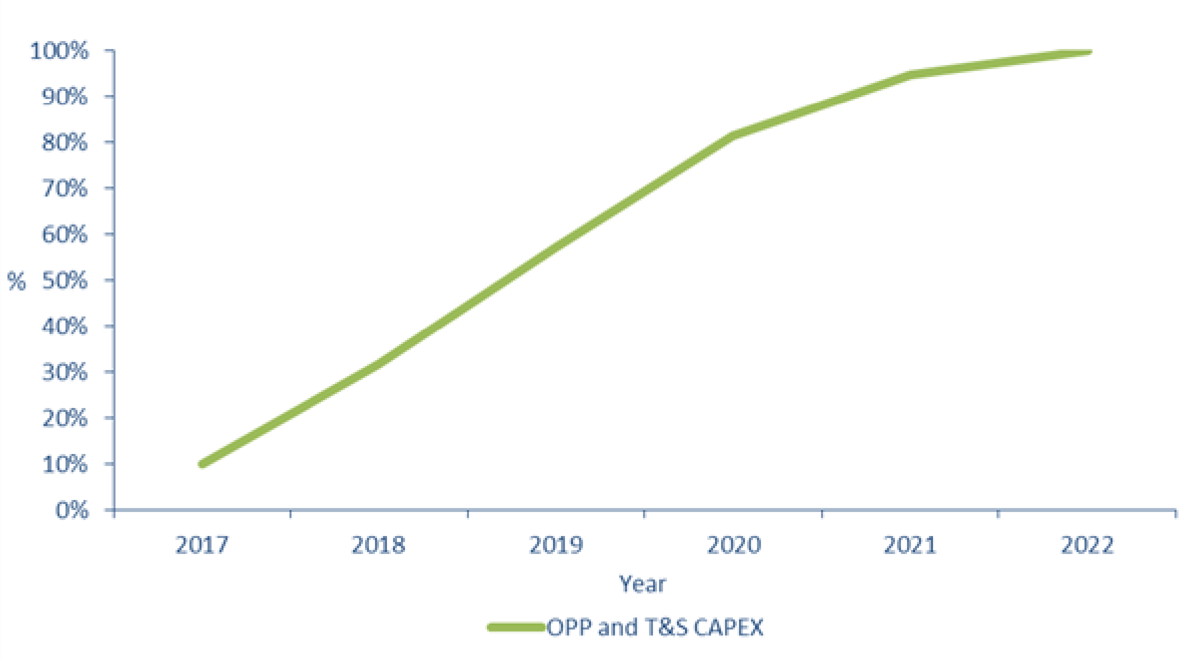
Capex for White Rose for FEED purposes has been estimated on a complete basis for the specific equipment configuration, participants and location. This included costs that would not necessarily be incurred or incurred to the same extent if a similar oxy-fired CCS project was to be implemented at a different site, in a different country or by a different type of client. To try to ensure consistency of presentation with reports on oxy-technology internationally, capex in this report has been presented on the basis of:

- Costs for elements 2 and 3 have been amended to a US Gulf Coast basis to be consistent with the majority of international reports on CCS costs. Localisation to the UK would require uplift of 29% and 34% respectively;
- The site identified in the UK required significant preparation, in particular for flood protection. These site preparation costs have been excluded;
- Costs for testing and commissioning of the project, including labour, consumables and utilities have been excluded as these will depend on the local cost of labour, fuels and utilities; and
- Owner's costs for developing the project including project management, administration, development, insurance and hedging have been excluded as these will depend on the nature of any existing client/developer organisation.

Capex for Transport and Storage has been estimated on the basis of sizing the infrastructure to enable further projects to be accommodated. This is due to the limited additional capex that would be required to future proof the investment in comparison to the expenditure that would be required to increase capacity at a later date. The decrease in cost for sizing the infrastructure only for White Rose would be £110m. Commercial charging arrangements between NGC and White Rose would have ensured that this additional capex would not have been borne by the White Rose project.

Figure 9.1 presents a simplified total expenditure S-curve for capex spend. The S-curve applies for all three levels of certainty.

Figure 9.1: Simplified S-Curve



Source: CPL

9.3 Operation (Annual Opex)

The annual cost of operation for the Full Chain is shown in nominal terms for the first full year of operation for the project in Table 9.2. Uncertainty bands have been provided for the opex costs based on the variability for both time and cost and the lower maturity of opex cost estimation compared to capex.

Table 9.2: Annual Opex

Cost Element	Notes	Expected Cost (£m per annum)	Uncertainty Band	Drivers of uncertainty
1. Projected fuel costs	Coal cost (including transport)	60	+/-25%	International coal market price
2. Projected externally supplied utility costs	Includes: water, power import, costs for start-	11	+/-25%	Costs will be agreed under long term contracts that will

Cost Element	Notes	Expected Cost (£m per annum)	Uncertainty Band	Drivers of uncertainty
	ups, chemical costs and landfill costs			reflect market forces at the time they are let
3. Projected operation and maintenance costs for OPP	Operation and maintenance costs for OPP, including ASU, GPU and BoP	67	+/-20%	Costs will be driven mainly by labour market and commodity prices
4. Projected operation and maintenance costs for T&S	Includes full costs of onshore and offshore transport and storage.	47	+/-27%	Costs will be driven mainly by labour market, commodity prices and insurance requirements

9.4 Decommissioning Costs

Decommissioning costs for the off-shore facilities are estimated to be £64.5m in real (2014) terms. This cost includes removal of jacket and topsides and abandonment of wells.

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10 Project Execution Plan

For further detail refer to KKD K.20 Project Implementation Phase project execution plan.

10.1 Project Scope

CPL are responsible for management of the full chain through to and including commissioning including provision of the OPP site and for the design, construction and operation of the OPP.

CPL are partnering with NGC who will be responsible for the construction and operation of the CO_2 transport pipeline and the permanent CO_2 undersea storage facilities in the Endurance storage formation (formerly 5/42) in the North Sea.

10.2 Division of Work

The Enabling Works EPC Contractor will execute those works required to ensure the OPP site is handed over to the OPP EPC Contractor free from obstructions and constraints to facilitate efficient mobilisation and start of construction activities. These works include improvements and extensions to existing main site access, diversion of existing utilities and services where these impact on the OPP site or laydown areas, (including 11kV overhead power line, footpaths and woodyard) and installation of temporary/permanent fencing.

The OPP EPC Contractor will engineer, procure, construct and commission the OPP under a turnkey EPC Contract. Their scope will interface with Drax Power Limited (DPL) who will execute the Interconnections on Drax operating land between the existing Drax Power Station and the OPP, also under a turnkey EPC Contract. The OPP EPC Contractor will be responsible for any interconnections scope within the OPP site, and will also be responsible for the coal conveyor and fly ash disposal systems which cross the site boundary and which will be constructed on Drax operational land by Drax. OPP EPC Contractor scope will also include procurement of a temporary heavy lift crane facility adjacent to the existing DPL jetty. The 400 kV connection to the NETS also crosses the OPP site boundary. The OPP EPC Contractor will contract with National Grid Electricity Transmission (NGET) for connection of the 400 kV cable in the NGET switchyard, while the Interconnections EPC Contractor will dig the cable trench on Drax operating land to interface with the trench on the OPP site. The 400 kV cable and termination in the NGET sub-station will be installed by an NGET approved sub-contractor to the OPP EPC Contractor.

The OPP EPC Contractor will also cooperate with NGC who will be responsible under a Transport and Storage Services Agreement (TSSA) for engineering, procurement and construction of the Transport and Storage (T&S) system from the OPP to the offshore platform and storage facility. These interfaces include providing access and laydown areas for NGC to construct their Above Ground Installation (AGI) at the OPP site and the CO_2 pipeline, and subsequent connection to the pipeline for filling and commissioning of the system.

The overall integrated control of the T&S system will be by NGC and is anticipated to be similar to that of the National Grid natural gas pipeline network. Local operating procedures will be developed with individual parties to cover all operational aspects including start-up, normal and abnormal operation, controlled and emergency shutdowns. The procedures will include a hierarchy of operation, responsibility, communication procedures and protocols.

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10.3 Environment, Health and Safety (EHS)

CPL’s Environmental Health Safety and Quality (EHSQ) policy and guidelines will govern the project’s management of all EHS matters.

The CPL EHSQ policy includes the following principles which will form the basis for the execution of the project:

- Safety, health, quality and care for the environment are foundational principles of our business;
- The safety and health of our colleagues, customers, business partners and communities in which we do business are paramount and are at the forefront of our business objectives;
- Visible leadership and personal accountability for EHSQ exist at all levels in the business.

Within the CPL team there will be a senior manager responsible for EHSQ who will report directly to CPL’s Chief Executive Officer (CEO).

Given CPL’s contracting strategy, the implementation of EHS management will be largely in the hands of CPL’s supply chain both in the Implementation Phase and in the transition to Operations. The performance of CPL’s EPC Contractors in respect of EHS will be overseen by the Project Management Contractor (PMC) and by the CPL team with respect to all other aspects.

Whilst CPL, and all other project participants, have general responsibilities for Health and Safety (H&S) under the Health and Safety at Work Act 1974 and for environmental management under the Environmental Protection Act 1990, the key legislation that provides the framework for H&S is, for the parts of the project which are the main responsibility of CPL (i.e. the OPP), the Construction Design and Management Regulations 2015 (CDM) and the Control of Major Accident Hazards Regulations 2015 (COMAH). With respect to the environment, the key regulatory controls for CPL’s compliance are provided through the Development Consent Order (DCO) with its various requirements and the Environmental Permit and its conditions.

10.4 Quality Management and Assurance

Quality Assurance (QA) will be undertaken to ensure that project activities are planned, controlled, performed, verified and documented in such a way that all specified contractual requirements are met.

All parties shall apply their own Quality Management System (QMS) for the areas of the project for which they are responsible.

The EPC Contractors will be required to demonstrate compliance with CPL’s QA requirements, based on the International Organisation for Standardisation (ISO) Management Systems and the expectations described in the respective EPC Contracts. A fundamental principle of the CPL quality system is for the EPC Contractors to monitor and approve their own work, including that of any of their sub-contractors, and implementation of the quality systems. The PMC will monitor the EPC Contractors’ ability to follow approved plans and procedures throughout the entire project, i.e. design, construction, commissioning and completion, and handover, and CPL will undertake a reasonable number of QA audits in order to confirm that activities are being performed in accordance with contract requirements.

Each EPC Contractor will be required to prepare and submit an Inspection and Test Plan (ITP) covering, as appropriate, design, construction, manufacture, installation, testing and commissioning. The PMC, on behalf of CPL, will verify EPC Contractors' performance against the ITPs.

10.5 CPL Project Management

The basic CPL structure for the Implementation Phase consists of four main elements that will manage all aspects of project delivery up to handover into operation. These four elements are:

- CPL, comprising security, EHS, quality, legal and secretariat, and finance;
- CPL Delivery Team;
- Sponsors' office;
- Asset management.

The CPL organisation reports to the Chief Executive Officer (CEO).

The CPL Delivery Team will be responsible for all aspects of delivery of the full chain system, including compliance with all applicable EHS regulations and standards, quality assurance, stakeholder management, engineering management including technical change control and assurance, contract and change management, commissioning management, readiness for operations and project and financial controls.

The CPL Delivery Team will appoint a PMC to manage the EPC Contracts on CPL's behalf with an appropriate Delegation of Authority (DOA).

The Sponsor function covers two key areas for project success: maintaining the integrity of the business case and administration of contracts with DECC as well as any third party equity providers and lenders.

Asset Management will be accountable for the operation of the OPP and will be engaged during the delivery phase to provide operations input into OPP design, testing and commissioning and subsequent plant handover. Asset management also includes trading.

Project governance anticipates a CPL Board structure, a CPL Executive Committee and a supervisory meeting chaired by DECC.

Project management also includes Project Controls and Project Coordination.

10.6 Stakeholder Management

Stakeholder management aims to take control of the external influences that may impact on project success by developing relationships with stakeholders who will support the project at every interface.

The requirements of stakeholder management activities will feed into project requirements in terms of systems, standards and processes, and will form an integral part of project execution by the CPL Delivery Team.

10.7 CPL Project Delivery

10.7.1 Engineering

CPL's strategy is to maximise the amount of full chain engineering work performed within the EPC contracts for the OPP and similarly for the T&S assets under the responsibility of NGC. However, it is recognised that there may be some scope or activities which cannot be so included. The CPL Engineering Manager, reporting to the CPL Delivery Director, will fulfil CPL's obligations with regards to the full chain and will have lead responsibility for the chain integration and co-ordination of full chain reviews.

All EPC Contractor scope will comply with the relevant codes and standards in force at Contract award, and with safety, legal and other regulations (local and national), acts and legislation in force in the United Kingdom.

The OPP will be designed in accordance with Good Industry Practice (GIP) to enable it to be constructed, installed, commissioned, operated and maintained in a prudent and safe manner, compliant with UK regulations and legislation. The CDM Regulations 2015 shall govern onshore construction works, including the OPP, onshore pipeline and beach crossing, with the CPL Delivery Team providing the Principal Designer (PD) and NGC providing the PD for the onshore transport system.

The CPL Delivery Team will implement a formal engineering change management process to ensure that a safe and operationally robust design is achieved that allows the project to be executed in accordance with the project programme, within budget and to meet its operational performance objectives. Respective EPC Contractor engineering changes will be managed by the PMC on behalf of the CPL Engineering Manager, with changes that impact the full chain programme, budget or operational performance referred in the first instance to the CPL Engineering Manager for approval/endorsement and subsequent elevation to the CPL Project Sponsor if required by the DOA.

The CPL Engineering Manager is accountable for assuring design quality for the OPP and interfaces across the full chain. The PMC will undertake assurance of the OPP on behalf of the CPL Engineering Manager.

A Value Engineering process will be implemented with the OPP and Interconnections EPC Contractors targeting improved profitability.

10.7.2 Supply Chain Management

The contracting strategy of CPL, as a special purpose company, is typical of a project financed independent power producer (IPP) project. The objective of the CPL contracting strategy is to transfer as great a risk as possible from the special purpose company, its shareholders and creditors into the supply chain through contracts that are typically fixed price, and which deliver to a pre-defined programme schedule.

The CPL Commercial Manager, reporting to the CPL Delivery Director, will be responsible for the placement and administration of all contracts, including trading services agreements for the CPL corporate organisation, supply-side services and works for the CPL Delivery Team and the Operations and Maintenance (O&M) Contract for Operations.

The contract strategy is split into two distinct sections:

- Key Sub-Contracts (including the EPC Contracts)
- Non-Key Sub-Contracts.

All the Key Sub-Contracts will be executed contemporaneously with the Principal CCS Contracts at or around Financial Close (FC), and the non-Key Sub-Contracts will be let in the Implementation Phase.

The Key Sub-Contracts anticipated are:

- Pre-Notice to Proceed (NTP) Works
- PMC
- Supply-Side Services
- Supply-Side Works
- Power Offtake Services
- CO_2 Offtake Services
- Emissions Trading Services
- Insurance

In addition, there will be a number of service contracts let by CPL including Lenders' advisors (technical, legal, insurance and market), technical facilitation and assurance, audit and accountancy services, public relations and communications, courier services, graphics consultant and legal support.

10.7.3 Commissioning and Start-up

CPL's commissioning strategy, embedded in the EPC Contracts, is designed to minimise the commissioning interfaces between the EPC Contractors. The PMC will co-ordinate commissioning on behalf of CPL.

There are a number of key commissioning issues that will be resolved between the parties prior to finalisation of the supply chain contracts. These items include the 'hot' commissioning of Interconnections and commissioning of the OPP downstream of the Gas Processing Unit (GPU) once the onshore pipeline is available to receive CO_2.

The commissioning plan to be drawn up during the earlier stages of the Implementation Phase will address how EHS matters, and particularly the safety issues, related to commissioning will be handled.

10.7.4 Operations Readiness

Operation of the OPP will be the responsibility of CPL's Asset Manager through the services of a suitably experienced and qualified O&M Contractor. DPL will be responsible for operation of the Interconnections with the Drax Power Plant (DPP), and NGC will be responsible for operation of the T&S.

CPL will mobilise its Operations team during the Implementation Phase. The OPP EPC Contractor will provide classroom based and on-the-job training for CPL's Operations Team. As part of their training, CPL's Operations Team will participate in commissioning of the OPP under the direction of the OPP EPC Contractor.

The CPL Operations team will participate in design, safety and operations reviews undertaken by CPL or in those performed by the EPC Contractors in which CPL participates. The CPL Operations team will be responsible for defining the operational spares holding for the OPP.

The CPL Operations team and O&M Contractor will begin preparing for the hand-over of responsibility for operation of the OPP in the construction phase. Prior to take-over of the OPP, the CPL Operations team and O&M Contractor will support the CPL Delivery team during construction and commissioning. Transition to Operations for the O&M Contractor will commence during their mobilisation phase, while that for the CPL Delivery team will formally commence during the latter stages of commissioning. The PMC, on behalf of the CPL Delivery Director, will be responsible for ensuring that all systems are fully tested and operational prior to take-over of the OPP, working closely with the CPL Asset Manager.

10.7.5 Finance and Insurance

Finance

In the Implementation Phase, the Finance function will move from focusing primarily on reporting and compliance to serving as an integral part of the management team. The Finance function will support the Company during its construction phase as well as the operations phase by providing critical information and financial analysis for management to make operating decisions, whilst focusing on processes and risk minimisation. The role of the Finance function will also be key to providing the business insight required to prepare financial reporting and analytics to meet investors' and lenders' requirements.

The core finance activities of CPL cover accounting and finance, regulatory and tax compliance, financial control, and risk and funding management.

Insurance

The insurance programmes implemented by CPL and NGC are expected to perform an important role in the overall commercial framework of the White Rose CCS Project in seeking to transfer risk from their respective special project vehicles, being CPL, NGC, their respective shareholders and DECC, and into the commercial insurance markets. The programmes are designed to be complementary to provide suitably integrated insurance cover and associated efficient claims response for the full chain project.

The overall insurance programme and its procurement is based on delay and interruption liquidated damages being payable by NGC to CPL under the TSSA (and vice versa). NGC liquidated damages will be backed by appropriate NGC security in favour of CPL, such as a parent company guarantee.

CPL will procure insurance programmes for the construction phase of the OPP, and separately for the Commissioning, Commercial Proving and Operations phases of the project.

Similarly, NGC will procure a construction insurance programme for the T&S construction phase, and separately an operational insurance programme for the T&S Commercial Proving and Operations phases. Both NGC programmes will incorporate onshore and offshore assets.

NGC will also procure stand-alone cover for offshore Delay in Start-up (DSU) for the construction phase, and separately for offshore Business Interruption (BI) for the Commissioning, Commercial Proving and Operational phases of the project. It is anticipated that both programmes will cover CPL and NGC for their respective risks.

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11 Top 10 Project Risks

This section highlights the 10 most significant CCS related project risks, a fuller description of the risks, including a description and definition of the risk scoring system and processes can be found in K.06 – Full chain FEED risk report.

11.1 Full-chain engineering activities

Full-chain engineering activities to be executed during the construction phase were being scoped, assigned and dependencies established based upon work done in FEED. There was a risk that (considering a lack of precedents) gaps and misalignments are discovered during execution which might impact project delivery.

Risk title	Category	Score when identified	Current score	Mitigation effectiveness
Full-chain engineering activities	Project management	Probability: 3 - Possible Impact: 3 - High	Probability: 2 - Unlikely Impact: 3 - High	Effective

The mitigation strategy was based upon a detailed assessment and planning of execution work during the FEED phase. This included scoping, allocation, scheduling, interfaces and dependencies establishment, project management plan preparation etc. Work was also underway at the close of the technical FEED activities to identify and resolve any gaps and misalignments to ensure all necessary scope was contracted for the Implementation Phase.

11.2 Full-chain operating practices and procedures

The project would have included a first-time (in the UK) establishment of full-chain operating practices and procedures integrating generation facilities, CO_2 transport systems and CO_2 storage systems. This task would have also involved paying due consideration to a future expansion to a network tying in multiple emitters. There was a risk that this task was not appropriately scoped and gaps and/or issues are discovered which needed to be addressed and these would involve rework / outages.

Risk title	Category	Score when identified	Current score	Mitigation effectiveness
Full-chain operating practices and procedures	Project management	Probability: 4 - Probable Impact: 3 - High	Probability: 3 - Possible Impact: 3 - High	Partially effective; full assessment not possible at the point of FEED termination

The mitigation strategy that had been established (though not fully implemented at the point of FEED termination) included a detailed project management plan for the identified tasks with scoping, allocation, scheduling, interfaces and dependency establishment. The project was also planning employment of specialist consultants to support execution of these tasks as part of detailed engineering. Work was also underway to develop mechanisms that enable an early visibility as well as an efficient resolution of any gaps and misalignments.

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11.3 Electricity Market Reform (EMR) – Emissions Performance Standard (EPS) requirements

An emissions performance standard (EPS) which imposes an annual limit on CO_2 emissions from new-build thermal power plants is an integral part of the EMR for the GB market. EPS limits do not present any problems for CCS enabled plants and additionally, the regulation provides for a three year exemption period for initial operation of CCS commercialisation projects. There was however a risk that OPP commissioning which is pre-operation and involves commissioning the station in air mode before commencement of oxy mode commissioning might be restrained by EPS requirements, thereby delaying the project.

Risk title	Category	Score when identified	Current score	Mitigation effectiveness
EMR – EPS requirements	Environmental & Permitting	Probability: 3 - Possible Impact: 3 - High	Probability: 3 - Possible Impact: 3 - High	Assessment not possible at the point of FEED termination

As a first step, a detailed review of applicable requirements and regulations was launched. This was augmented by independent reviews of the requirements by technical and legal experts. This confirmed that the exemption period was not available until the full-chain was ready to commence commissioning. As a next step, potential plant operating profiles expected during commissioning were prepared and various scenarios investigated to assess the scale of challenge. As the applicable limit is an annual average, based on calendar years (or part years), the scenarios also included commissioning happening over different combinations of calendar months. Assessments and review were still ongoing at the point of termination of the FEED Contract.

11.4 CO_2 stream specification

The CO_2 pipeline materials, CO_2 wells and the storage formation are sensitive to certain impurities and for this reason, the full-chain was designed to an agreed CO_2 specification informed by extensive R&D work performed by NGC. There was however a risk that despite appropriate design out-of-specification CO_2 enters the pipeline causing damage or reducing the design life of the system and its storage capability. In the shorter term it would also cause reduced availability of the full-chain as the transport and storage system operator might have refused to accept out-of-specification CO_2 and costs might have been incurred for remediation or repair.

Risk title	**Category**	**Score when identified**	**Current score**	**Mitigation effectiveness**
CO_2 stream specification	Technical	Probability: 3 - Possible Impact: 5 - Critical	Probability: 2 - Unlikely Impact: 3 - High	Effective

A thorough review was carried out on the OPP design to obtain assurance with respect to the achievability, measurement and control of the CO_2 specification. In addition to the internal review by CPL and CPL's

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technical advisor, an additional independent review of the Gas Processing Unit design by a third-party specialist consultant was commissioned which also confirmed design suitability.

Further, in order to minimise the impact from any, however unlikely, out-of-specification event, it was being considered that independent CO_2 stream composition analysers be installed on both sides of the terminal point between the OPP and CO_2 transport infrastructure (with online exchange of signals) to ensure that both the OPP and the CO_2 transport infrastructure respond immediately and isolate the system at the first possible termination point to minimise the potential for impact to the onshore pipeline.

The specification for CO_2 composition had been agreed with NGC, and was based on research and study work they had carried out. NGC also planned to monitor for corrosion during routine pipeline inspection activities using in line inspection tools.

11.5 Overall metering concept

The Contract for Difference (CfD) proposed a clean electricity metering concept combining fuel, electricity, and captured CO_2 analysis and metering. The proposed formula, adapted from the standard EU ETS approach, combined both measured and calculated values along with continuous and batch measurements. While this approach is appropriate for EU ETS where the values are aggregated over a year’s operation, it leads to inaccuracy and retrospective adjustment when applied to the 30 minute CfD settlement periods. There was a risk that the suggested approach would lead to determined amount of clean electricity being less than actual clean electricity generated leading to the need for a higher nominal strike price. Lastly, the approach would have also unduly disadvantaged future CCS projects competing with other clean electricity technologies.

Risk title	Category	Score when identified	Current score	Mitigation effectiveness
Overall metering concept	Commercial	Probability: 4 – Probable Impact: 3 - High	Probability: 4 - Probable Impact: 3 - High	Assessment not possible at the point of FEED termination

An alternative simplified approach, using a smaller number of measurements, all available in real time, and offering a reduced measurement tolerance was developed and presented to the Authority for its consideration. Feedback on this proposal was still pending at the point of FEED termination.

11.6 Full-chain commissioning alignment

Though the construction of the OPP, CO_2 transport infrastructure and CO_2 storage infrastructure could largely proceed independently of each other, the full-chain required alignment for achievement of milestones such as start of full-chain commissioning, full-chain testing as well as start of the CfD. There was a risk that CPL is unable to achieve an aligned completion, commissioning and testing milestone regime that works for all scenarios leaving the project exposed to claims / liabilities which are not backed-off. Lack of alignment may also hinder the ability to perform tests and plant modification, if necessary.

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Risk title	Category	Score when identified	Current score	Mitigation effectiveness
Full-chain commissioning alignment	Commercial	Probability: 3 – Possible Impact: 3 - High	Probability: 2 – Unlikely Impact: 3 - High	Effective

As a primary mitigation measure the full-chain project execution plan was assessed for minimisation of dependencies between the OPP and CO_2 T&S infrastructure activities, e.g. completion of OPP commissioning largely independent of T&S infrastructure. Where dependencies could not be eliminated, concepts were developed to enhance certainty of a timely completion of full-chain activities. Attention was also paid to development of a clear completion definition and underlying planning for milestones that tie the full-chain together. Appropriate compensation and damages mechanisms were also being discussed between CPL and NGC. Lastly, as the risk was only inherent to anchor projects, appropriate use of Project Contract mechanisms was also proposed.

11.7 Mandatory access requirement causing delays

Regulations governing mandatory third-party access (TPA) to the T&S system were already in place and there was a risk that exercising of such an access request by a third-party might delay the T&S infrastructure construction or if exercised during the operational phase might lead to operational down time (associated with a potential need to take the T&S system offline to implement necessary modifications). Any such down-time would have had an economic impact and potentially also impact CPL's obligations under various contracts and agreements.

Risk title	Category	Score when identified	Current score	Mitigation effectiveness
Requirement of mandatory access to T&S system causing delays	Commercial	Probability: 3 - Possible Impact: 3 - High	Probability: 3 - Possible Impact: 2 - Medium	Partially effective; full assessment not possible at the point of FEED termination

A thorough review of the applicable regulations governing third-party access to T&S system was commissioned and key findings discussed within the project team and with relevant specialists. Based on the assessment, potential scenarios were simulated to review likely impacts. It was clear that the T&S system would have to manage access requests for the project's operational phase as the network grew and potentially multiple emitters might be impacted by any downtime. Accordingly, the intended mitigation for CPL was to primarily address the risk through the commercial provisions of the T&S services agreement (TSSA). For NGC, the intended mitigation of this risk was through the requirement for the TPA party to bear the implications arising from such access. In any case, the T&S system design included the use of multi-junctions etc. to minimise potential downtimes.

11.8 Location of offshore wind turbines impacts subsurface monitoring

The location of offshore wind turbines, for example near Hornsea, was recognised as potentially causing problems with subsurface monitoring.

Firstly, the background noise caused by the turbines could interfere with micro-seismic monitoring, a technique using highly sensitive instruments to detect mini-seismic events in the vicinity of the formation. Although it was not clear whether micro-seismic monitoring would be required given other monitoring techniques that could be used, if the data from this would have been required to satisfy regulatory bodies there was a risk that this may cause issues around the reliability of monitoring.

Secondly, it was identified that offshore wind turbines could also cause problems with seismic monitoring, making it difficult to update seismic surveys in the future. Although alternative monitoring techniques were possible, a lack of reliable seismic data might have caused issues with the regulator.

Risk title	Category	Score when identified	Current score	Mitigation effectiveness
Location of offshore wind turbines impacts subsurface monitoring	Commercial / CO_2 Offtake	Probability: 4 - Probable Impact: 4- Very High	Probability: 2 - Unlikely Impact: 3 - High	Partially effective; full assessment not possible at the point of FEED termination

To mitigate this risk, NGC engaged with relevant industry contractors to establish suitable monitoring techniques and determine the sensitivity of the micro-seismic monitoring technique to extraneous noise. A wind farm noise study to assess extent of impact on seismic signal quality and repeatability was also undertaken. Based upon the work performed, it was concluded that the noise spectrum will not cause a problem.

NGC were also engaged with the regulator as part of the Storage Permit Application (which included arrangements for monitoring of the store) at the point of FEED termination.

11.9 Permit for discharge of formation water

The formation where the CO_2 would have been stored contains saline water and it was foreseen that at a later stage some of this water might need to be discharged. A permit for formation water discharge was not yet in place and there was a risk it may not be granted due to water composition. This might have led to a revision to the project scope as produced water would have needed to be brought to the platform for discharge/ treatment which could have restricted further utilisation of system.

Risk title	Category	Score when identified	Current score	Mitigation effectiveness
Permit for discharge of formation water	Commercial / CO_2 Offtake	Probability: 3 – Possible Impact: 5 – Critical	Probability: 2 - Unlikely Impact: 4 - Very High	Partially effective; full assessment not possible at the point of FEED termination

Subsurface modelling work confirmed that the White Rose development did not require water discharge, and this would only be necessary in the future with additional users, at higher CO_2 injection rates. During FEED, analysis of the formation water was undertaken based on samples taken during the appraisal, and risk assessment and dispersion modelling carried out. There was also a consultation with the regulator, and at the point of FEED termination this issue was not envisaged to be a problem.

11.10 Insurance coverage

Considering the commercialisation nature of the project, availability of full insurance coverage as necessary for the construction and/or operation of the full-chain project could not have been assumed. Any lack of insurance products or gaps in insurance coverage might have made continued construction and/or operation unviable and/or impact project economics.

Risk title	Category	Score when identified	Current score	Mitigation effectiveness
Insurance coverage	Financial	Probability: 3 - Possible Impact: 5 - Critical	Probability: 3 - Possible Impact: 5 - Critical	Assessment not possible at the point of FEED termination

As a first step the project’s insurance advisors conducted a market engagement exercise to gauge market interest and availability of suitably worded insurances. Subsequently regular assessments were being conducted to assess positive or negative changes to initial assumptions. Discussions with the Authority were ongoing to assess potential impacts and develop mechanisms to address changes in insurance coverage in the construction and operational phases. These were not limited to changes originating from events tied to the project.

12 Key Findings from CCS Specific EHS Reviews

12.1 Introduction

During the FEED CPL and its Key Sub-Contractors undertook a wide range of specific Environmental, Health and Safety (EHS) related studies as would be expected on a project of this scale. These were in addition to the EHS considerations that were part of all aspects of project design and development. The specific studies undertaken related to the objectives of FEED, the relevant ones being:

- Achieving all the major consents and permits required to construct and operate the full chain CCS system; and
- Reduction of EHS related risks to an acceptable level, sufficient to achieve the cost certainty objective for the capital works as laid down in the FEED Contract.

The studies undertaken played their necessary parts in achieving these goals. Whilst this section of this KKD is focussing on the CCS related EHS studies as there are very few EHS studies which are purely concerned with CCS matters (CO_2 venting being possibly the only one) it provides a summary of all the major EHS studies undertaken in FEED. The full details of these studies and their outputs can be found in the specific KKDs as follows:

K.12 - Full Chain Health and Safety Report

K.13 - Full Chain Environmental Report

12.2 EHS Studies Undertaken During FEED

12.2.1 Health & Safety Studies

The following specific health and safety studies were undertaken during FEED. Further details of the outputs of these studies are provided in section 12.3 below:

- Oxy-Power Plant (OPP) Hazard Identification (HAZID) Study;
- Gas Processing Unit (GPU) Hazard and Operability (HAZOP) study;
- Control of Major Accident Hazards Regulations 2015 (COMAH) Tier Assessment;
- OPP Layout Risk Assessment;
- OPP Occupied Building Risk Assessment;
- OPP CO_2 Vent Dispersion Modelling;
- Interface HAZID between the OPP and the Transport and Storage (T&S) System;
- Four separate HAZIDs covering the Onshore Transport System;
- Offshore T&S HAZID;
- Onshore Pipeline HAZOP;
- Barmston Pumping Station HAZOP;
- Offshore T&S HAZOP; and
- T&S CO_2 Vent Dispersion Modelling.

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12.2.2 Environmental Studies

The following specific environmental studies were undertaken during FEED. Further details of the outputs of these studies are provided in section 4 below:

- OPP Environmental Impact Assessment (EIA) and Environmental Statement (ES) for the Development Consent Order (DCO) (and associated reports and assessments);
- Onshore Pipeline EIA and ES for the DCO (and associated reports and assessments);
- Offshore Environmental Statement; and
- Environmental studies supporting the Storage Permit Application.

12.3 Summary Outputs of Health and Safety Studies

12.3.1 OPP Hazard Identification (HAZID) Study

The key issues identified through the HAZID study were:

- Internal and external security threats shall be further analysed by owner (CPL discuss with Drax security);
- Domino effect with ammonia or O_2 storage shall be further analysed by CPL & Drax, Drax to provide safety report of Lytag plant;
- HAZOP study shall be conducted during project execution to ensure that the design is correctly done;
- Frost protection concept to be prepared during project execution;
- Fire hazards and firefighting shall be further studied during project execution;
- Explosion hazards & detection/protection and hazardous area classification (Atex/DSEAR) shall be studied during project execution, taking into account the high risk of oxygen enriched atmosphere (due to high oxygen quantity on site);
- CO_2 hazards & detection/protection and critical area identification shall be studied during project execution;
- Heating, Ventilation and Air Conditioning concept shall be defined during project execution, taking into account the high risk of oxygen-enriched atmosphere; and
- SIS for functional safety to be further analysed during project execution.

12.3.2 Gas Processing Unit (GPU) Hazard and Operability (HAZOP) study

The following summarises the key outputs from the GPU HAZOP that related to CCS:

- The GPU High Integrity Pressure Protection System (HIPPS) needs to protect the T&S pipework from over pressure and potential fracture. A surge analysis was recommended to cover both upstream and downstream effects of HIPPS operation;
- The CO_2 delivery temperature from the OPP GPU needs to be limited to avoid exceeding the design temperature (25 ^{o}C) of the T&S pipeline. Exceeding the temperature could lead to pipeline fracture. Therefore a temperature alarm and trip function for the GPU was recommended; and

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- It was also recommended that the OPP GPU CO_2 product analyser should be connected to the protection system to trip CO_2 export if the product is out of limits for the T&S system.

12.3.3 COMAH Tier Assessment

The calculations for the OPP, based on the currently assumed quantities of each hazardous substance, show the installation to be lower tier. This is principally driven by the quantities of two substances; anhydrous ammonia, used in the Selective Catalytic Reduction (SCR) process that removes NOx from the boiler flue gas, and the Liquid Oxygen (LOX) that is held within the Air Separation Plant, both within the plant itself and within the liquid storage system.

12.3.4 OPP Layout Risk Assessment

Building on work done Pre-FEED, the design team undertook an initial FEED Layout Risk Assessment early in the FEED process. This review created a number of actions that were subsequently closed out as part of FEED design. A further layout review was undertaken at the close of OPP technical FEED to ensure that none of the small changes that had occurred in FEED since the initial review resulted in any issues that need to be addressed.

12.3.5 OPP Occupied Building Risk Assessment (OBRA)

An OBRA study was undertaken by CPL's Technical Adviser, Mott MacDonald Ltd. This review showed there were no matters of significant concern although final consideration on the positioning of the anhydrous ammonia storage should be undertaken to ensure the risk is as low as reasonably possible (ALARP). This has been completed in FEED.

12.3.6 OPP CO_2 Vent Dispersion Modelling

The CO_2 Vent Dispersion Modelling on the OPP has shown that in all cases the CO_2 will disperse and that the concentration of CO_2 at ground level due to the venting will be low. This low concentration of CO_2 will not be a risk to personnel on site nor adversely affect the operation of the ASUs.

12.3.7 Interface HAZID between the OPP and the T&S System

The key outputs from the interface OPP/T&S HAZID were as listed below:

- The cathodic protection systems on each element of the plant must take into account the presence of the other;
- CPL to consider the need to include the Above Ground Installation (AGI, PIG launcher) area within the overall site security fence and ensure emergency egress design for OPP and NGC is aligned;
- Ensure the redundancy requirements for CO_2 monitoring is considered as part of the control strategy;
- Determine whether pipeline can be over pressured and provide adequate overpressure protection as required;
- Determine whether pipeline maximum design temperature can be exceeded and provide adequate protection as required;

- Ensure dispersion calculations are carried out to identify the extent of occupational hazards of ammonia leakage;
- Ensure the installation plan for the pipeline includes suitable protection against mechanical damage and adequate route marking;
- Clarity on response required from CPL and NGC to incident at PIG trap. (The AGI enclosure is normally unmanned, but will be manned during PIG operations); and
- Ensure that site alarms are audible and visible within AGI site.

12.3.8 Four separate HAZIDs covering the Onshore Transport System

The HAZID for the onshore transport system (pipeline, AGIs and pumping station) was undertaken in four discrete elements. The key findings were:

- Consider provision of closed-circuit television (CCTV) not only to detect intruders but also to detect visible leaks;
- Ensure that the emergency response plan includes other stakeholders and emergency services and includes local residents;
- Consider the need for the detection of CO_2 external to buildings;
- Ensure that the dispersion modelling from flange leaks or vents addresses the possibility of dense clouds of CO_2 flowing off site for example down any slope (and the actions to be taken should this occur and the effect on third parties);
- Define the philosophy for evacuation of the block valve sites in the event of a major CO_2 release and identify the optimum position for escape routes;
- Confirm that the dispersion of the CO_2 from the vent during depressurisation of the upstream or downstream pipeline does not adversely affect personnel or local residents;
- Review the pipeline design once the seismic activity has been defined;
- Normal operating procedures must highlight the importance of maintaining pipeline pressure at the high point;
- Depressurising calculations need to ensure that minimum temperature limits are not transgressed at the high points of the pipeline; and
- Consider the need for additional crossing points over the ditch at Barmston to improve evacuation routes.

12.3.9 Offshore T&S HAZID

The key outputs from the interface OPP/T&S HAZID were as listed below:

- Confirm that there are no mining activities in the area that would affect the design or routing of the offshore pipeline;
- Resolve whether additional facilities need to be incorporated into the current design for the future accommodation and transportation of construction workers to the platform;
- Provide back-up information on current best practice for access to normally unmanned installations;
- Review the capacity of the Totally Enclosed Motor Propelled Survival Craft (TEMPSC) (currently based on carrying 10 plus two helicopter crew);

- Consider the need to pre-invest (for example provide additional space) for unplanned future developments;
- Consider whether the crane is required to cover the helideck;
- Review the requirement to access infrequently operated isolation valves and equipment to determine whether permanent access is required, or whether temporary access will be acceptable;
- Consider the need to initiate a platform shut down after a time delay following loss of communications;
- Review how long wells can continue to operate without corrosion inhibitor injection;
- Ensure that an emergency air supply is available within TEMPSC since launching the TEMPSC may drop into a cloud of CO_2 at the sea surface;
- Review the consequences of leaks to determine areas where liquid CO_2 might impact structural steel and determine what additional safeguards might be required to prevent brittle fracture;
- Define the philosophy for protection of personnel and provision of escape sets, personal CO_2 monitors and so on.

12.3.10 Onshore Pipeline HAZOP

The key CCS related outputs from the Onshore Pipeline HAZOP were as listed below:

- Consider provision of a CO_2 detection system at all AGIs;
- Ensure that the findings of the Computational Fluid Dynamics (CFD) modelling of flange releases and the low temperatures that are generated, are taken into account in material selection;
- Review the consequences of exceeding the current design temperature of the pipeline (25°C). If necessary, consider adding safeguards at CPL to protect the pipeline against excessive temperature;
- Complete the venting depressurisation calculations to ensure that the minimum design temperature is not transgressed during venting;
- Develop the operating procedures to ensure there is timely communication between the CPL and NGC control centres to ensure smooth operation;
- Consider whether there should be an interchange of information and/or executive action between the CPL and NGC control and safety systems, particularly to safeguard against fast acting transients;
- Ensure that the maintenance procedures specify the venting arrangements to allow the safe discharge of the large inventory of $CO_{2;}$
- Ensure CPL provides continuous feed to NGC of the product analyser output and the upstream water analyser output;
- Complete flow assurance transient study;
- Develop specifications requiring rigorous attention to suitability for CO_2 duty; and
- Since third party emitters are not considered in this HAZOP then ensure that the potential overpressure from other CCS lines must be reviewed in a future HAZOP.

12.3.11 Barmston Pumping Station HAZOP

The key CCS related outputs from the Barmston Pumping Station HAZOP were as listed below:

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- Define the overall system control philosophy which should specify how control parameters should be adjusted in anticipation of changes in flow rate through the system;
- Define the philosophy for controlled access to buildings containing CO_2 equipment;
- Consider whether facilities are required to direct operators to emergency exits from buildings if visibility is reduced by $CO_{2;}$
- Consider installing CO_2 detection on building HVAC air intakes;
- Consider installing a CO_2 detection system for external areas of Barmston pump Station;
- Ensure that the findings of the CFD modelling of flange releases and the low temperatures that are generated, are taken into account in material selection;
- Confirm there are no trapped inventories that cannot be monitored or depressurised during extended shutdown;
- Review the pump design to ensure it can operate with the maximum density CO_2 that can be produced;
- Clarify limitations on venting, which are currently under review/discussion;
- Ensure that CPL provides continuous feed to NGC of the product analyser and the upstream water analyser output. If off specification material is detected by the Barmston analysers at the metering skid the onshore pipeline will already contain a significant inventory of off specification material;
- Confirm that there are no compatibility issues between seal oil and the $CO_{2;}$
- Complete the flow assurance transient study;
- Ensure that training programme takes account of the unusual hazards relating to the handling of $CO_{2;}$; and
- Develop specifications requiring rigorous attention to suitability for CO_2 duty.

12.3.12 Offshore T&S HAZOP

The key CCS related outputs from the Offshore T&S HAZOP were as listed below:

- Consider whether the vent line from the Pressure Relief Valve (PRV) on each fine filter should be removed to ensure that venting is from low points;
- Ensure that CPL provides a continuous feed to NGCL of the output from the CO_2 product analyser and the upstream water analyser;
- Complete Flow Assurance Transient study;
- Consider the need for a subsea isolation valve in the pipeline to minimise the release of CO_2 in the event of riser failure;
- Develop technical specifications that require rigorous attention to demonstrating the suitability of components for CO_2 duty;
- Ensure that the effect of phase separation in the well string is investigated during well FEED and that safeguards such as bull heading with Nitrogen are identified;
- Ensure that the well FEED reviews the simultaneous opening of all choke valves;
- Ensure that the well FEED reviews the requirement for limiting the maximum flow into any given well if necessary (for example soft stop on maximum choke valve opening);
- Ensure that the well FEED considers the effects of the reservoir fluid entering the well string during an extended shutdown;

- Ensure that the well FEED addresses the issue of water washing and the consequences of inadequate water wash time; and
- Ensure the well FEED takes account of the minimum temperature downstream of the choke valve during start-up.

12.3.13 T&S CO_2 Vent Dispersion Modelling

Detailed ventilation and gas dispersion modelling, using Computational Fluid Dynamics (CFD), were carried out for the onshore transport (Barmston Pumping Station) and the offshore T&S. The conclusions and recommendations that flowed from these studies were as follows:

Onshore:

- When conducting equipment manual venting operations, it is recommended that personnel entry into the process plant area is restricted; if personnel are required to enter the process plant area as part of the venting operations then personnel must be equipped with a full self-contained breathing apparatus set;
- When conducting equipment manual venting operations, it is recommended that the HVAC system dampers at the administration building are closed;
- Given the required duration of a pipeline venting operation and the potential for the plume to breach the security fence at concentrations up to the Long Term Exposure Limit (LTEL), it is recommended that offshore pipeline venting operations are not conducted onshore;
- As far as practicable, manual venting operations in low wind speed conditions should be avoided; and
- Any personnel entering the process plant area carry a CO_2 monitor with them.

Offshore:

- For all release scenarios (manual controlled and relief valves), the vented flow is never observed to impair the topsides facilities due to the orientation and location of the vent tips. The plumes are seen to disperse underneath the platform;
- The long duration pipeline depressurising scenarios (up to 14 days) give rise to large Short Term Exposure Limit (STEL) clouds accumulating on the sea surface and therefore significant dosage values. This would impact any activities at the sea surface, such as supply vessels located in the vicinity of the platform or standby vessel located within the 500m zone of the platform; and
- Manual venting procedures should be produced using the results contained within this study to ensure helicopter and supply vessel operations are not impacted/impaired.

12.4 Summary Outputs of Environmental Studies

12.4.1 OPP Environmental Impact Assessment (EIA) and Environmental Statement (ES) for the Development Consent Order

The EIA and ES encompassed a wide range of reports, studies and assessments including:

- Screening and scoping reports;

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- Habitat Risk Assessments (HRA);
- Surface Water Assessment;
- Flood Risk Assessment (FRA);
- Transport Assessment;
- Noise and Vibration Assessment;
- Air Quality Study;
- Geology Study;
- Archaeology Study;
- Socio-economic Impact Study;
- Landscape and Visual Impact Assessment; and
- Ecology Study.

These studies and assessments were used to support the Preliminary Environmental Information Report (PEIR) and the DCO ES itself.

Across these various study areas there were no issues that were CCS specific. The key findings were as follows:

- Habitat Risk Assessments (HRA);
    - Whilst a number of protected species had the possibility of being impacted by the development for all except badgers the only requirement was to undertake future checks that there had been no incursion of the species into the protected area;
    - With respect to badgers one sett would have to be moved and a number of old setts closed;
    - With respect to habitat areas further afield that might be impacted by atmospheric pollution it was concluded that any such impact was within allowable limits;
- Surface Water Assessment;
    - No significant findings;
- Flood Risk Assessment;
    - There is a need to raise the site to 5.13m AOD in order to ensure no flood risk to critical equipment;
- Transport Assessment;
    - Even during construction, with the adoption of an appropriate green travel plan for staff, the local road network was capable of handling the additional expected traffic without significant issue;.
- Noise and Vibration Assessment;
    - Given the low levels of ambient noise in the area, any development would have the potential for significant impact. Prior to close of DCO examination it had not been possible to reach full agreement with the local authority on the acceptable operational noise level. At the time of FEED termination this was with the Examining Authority to determine;
- Air Quality Study;
    - In oxy mode with the OPP abated the quantity of pollutants emitted with the flue gas is significantly reduced compared to air mode;.
- Geology Study;
    - No significant findings;

- Archaeology Study (including two site investigations – ground penetrating radar and physical excavation);
    - As anticipated there are a number of artefact locations associated with the Augustinian Drax Abbey Scheduled Monument that occupied land adjacent to the site;
    - Previously unknown Roman remains, although of a similar nature to remains known elsewhere in the area, were identified under one of the proposed laydown areas;
- Socio-economic Impact Study;
    - Significant economic benefit to the local area was identified;
- Landscape and Visual Impact Assessment;
    - Whilst there was much debate with the local authority the key issue is that the OPP, whilst a significant development, remained visually small compared to the existing Drax power station;
- Ecology Study;
    - No significant findings other than those noted under the HRA above.

12.4.2 Onshore Pipeline EIA and ES for the DCO (and associated reports and assessments)

With respect to the EIA and ES for the onshore pipeline DCO the key issues that arose were:

- Air Quality;
    - The key issue was dust generated during construction;
- Noise;
    - Construction noise was to be constrained to agreed limits;
    - Operational noise is negligible apart from at the pumping station and occasional venting for maintenance;
- Surface Water and Flood Risk;
    - The only significant issue is the management of run-off during construction;
- Geology;
    - No significant findings;
- Socio-economic Impact;
    - There is a risk of disruption to communities along the length of the pipeline which has to be managed through good practice and consultation with stakeholders;
- Traffic;
    - To be managed during construction but no significant impacts;
- Landscape;
    - The pipeline has been routed to minimise impact on the landscape and disruption;
    - The only significant permanent above ground structures are at the AGIs (not significant) and at the Barmston Pumping Station where the architectural design has been carefully chosen to integrate the structures into the landscape;
- Ecology;
    - The pipeline has been routed to minimise impact on areas of important ecology. Where it has not been possible to avoid them completely necessary actions will be taken in agreement with the appropriate authorities to minimise the impact;
- Archaeology;
    - The pipeline has been routed to minimise impact on areas of important archaeology. Where it has not been possible to avoid them completely necessary actions will be taken

in agreement with the appropriate authorities to undertake investigations prior to construction and agree schemes of work that minimise the impact.

12.4.3 Offshore Environmental Statement

With respect to the offshore Environmental Statement the key issues that arose were:

- Atmospheric Emissions;
    - No significant findings;
- Physical Disturbance;
    - No significant findings with respect to geology;
    - There would be temporary disturbance of existing sand waves although these are expected to re-establish in a relatively short time after pipeline construction;
    - Sea bed fauna will be disturbed during pipeline installation but it is expected to recover over a number of years;
    - Surveys indicate it unlikely that significant archaeology exists along the chosen route of the pipeline;
- Physical Presence impact on Fauna;
    - No significant findings;
- Noise;
    - No significant findings;
- Discharges to Sea;
    - Given the application of standard North Sea construction and operation practices, no significant impacts will result;
    - The potential impact of accidental CO_2 discharges has been investigated and found not to have significant impact;
- Socio-economic Impact;
    - No significant findings.

12.4.4 Environmental Studies Supporting the Storage Permit Application

The most significant studies in addition to those undertaken for the offshore Environmental Statement related to the potential for and the impact of water production to the ocean at the point on the seabed at which the formation outcrops. This was the subject of much discussion with the regulator as to the likely quantity and nature of any such water production and, therefore, the potential for adverse impact on the marine environment. Whilst FEED termination occurred prior to issue of the Storage Permit it was anticipated that agreement would be reached that impacts would be minor and that a monitoring regime should be implemented.

13 Key Decisions Specific to CCS

The following is a summary of the key decisions specific to CCS:

Further detail can be found in K.05 –Full Chain FEED decision report

13.1 Liquid Oxygen back-up Volume Reduced

Following a detailed review of the interactive operation of the OPP and the use of Liquid Oxygen (LOX) the volume of LOX storage dedicated to Air Separation Unit (ASU) back-up was reduced from four to one 300 m^3 LOX storage tank. This in turn allowed the site to be considered lower tier rather than upper tier under COMAH.

13.2 CO_2 specification to have low O_2 content (10ppmv)

During the FEED CPL undertook a “value engineering & cost reduction” exercise on the oxy-power plant. As part of the exercise some decisions that were made in pre-FEED were challenged to confirm whether the economic evaluation made at that time is still valid for the project as a whole.

The oxygen content specification of the CO_2 to the T&S system was reviewed.

13.3 Flexibility Concept Adjustment

The OPP was specified in order to demonstrate the flexible operation that will likely be required from CCS enabled fossil fuel power plants within the long term requirements of the UK electricity market (although not supported by the baseload CfD proposed for this project). This requirement was determined, before the start of FEED, by considering the future energy scenarios in Great Britain and the effect of the planned increases in wind deployment on thermal demand (for further discussion see K.03 Appendix A). To accommodate this requirement the Full Chain has been specified to have the capacity to allow flexible operation in each element of the system.

The OPP was specified to operate flexibly in a way that mimics traditional “two shifting” operation. “Two shifting” operation for a conventional power plant is where power is delivered to the grid (up to the maximum output) for typically 16 hours per day and then the plant is shut down (usually overnight) with no power delivered to the grid. For the OPP this regime entails the plant moving to an operating position that results in export of no power to the grid while still generating the clean power needed to operate the ASUs and the GPU, for a period of up to approximately 8 hours on a daily basis. During this period some energy is stored as liquid oxygen.

When demand returns the OPP is immediately available to move to full output and has the option to recover the energy stored as liquid oxygen to give an enhanced net output (above the OPP’s normal full output) for a sustained period.

By doing this, the plant can operate very flexibly without shutting down and CO_2 is provided continuously, at a reduced rate, to the T&S system,

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The benefits of this operating mode are enhanced by the savings realised due to the reduction in the number of start-ups and shut-downs as well as by the "electrical energy storage" in the form of liquid oxygen.

To achieve this some particular design features were included in the OPP.

- Coal handling and firing designed to give greater turndown range:
    - 5 x 25% coal mills and associated firing levels in the furnace windboxes.
- ASU cycle design optimised to include flexible operation rather than baseload operation:
    - Additional ASU equipment: standalone liquefier, power recovery turbines, cold compressors, LOX storage vessel.

During the FEED CPL undertook a "value engineering & cost reduction" exercise on the oxy-power plant. As part of the exercise some decisions that were made in pre-FEED were challenged to confirm whether the economic evaluation made at that time is still valid for the project as a whole. For flexible operation the decision was taken that it should be maintained but the additional costs mitigated to an extent by revising the coal handling and firing design to a more typical arrangement of 4 x 33% coal mills and the associated simpler windbox arrangements. The ASU design was not altered.

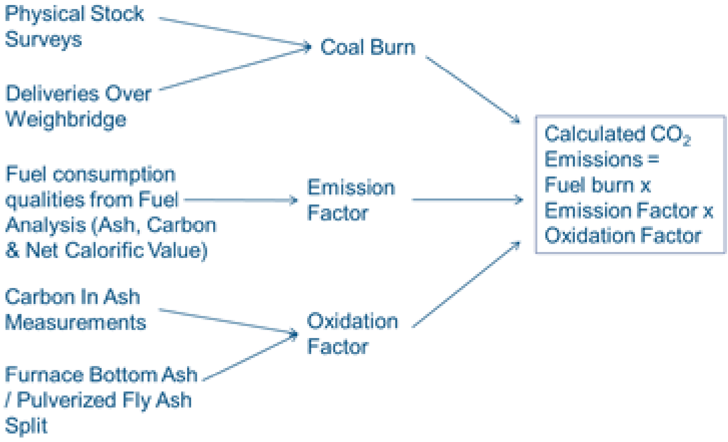
13.4 Avoidance of underground installations and basements on the OPP

A decision was taken to design the OPP to eliminate potential areas where CO_2 could accumulate, e.g. avoid basements in buildings and avoid buried cable ducts, in order to minimise the risks associated with a CO_2 leak.

13.5 CO_2 capture rate measurement approach

At the outset of FEED an approach to metering and determination of the CO_2 capture rate was defined. This approach originated from the current industry practice which reflects the requirements of European Union (EU) Emission Trading Scheme (ETS) reporting, the carbon input to the plant calculated on a quarterly or annual basis with no need for real time results and the long timeframes smoothing out anomalies and allowing good prediction of CO_2 emissions prior to EU ETS submission. Accurate direct measurement of CO_2 emissions are impractical from traditional coal plants and (as there is no capture) can be calculated indirectly from a number of discontinuous inputs to the required accuracy as shown below:

Figure 13.1: Typical EU ETS Measurement Methodology



For the White Rose CCS plant it was initially assumed that this approach of retrospective calculation of the carbon input be combined with direct real time measurement of the CO_2 captured and sent to storage.

Figure 13.2: Original CO_2 Capture Rate Measurements

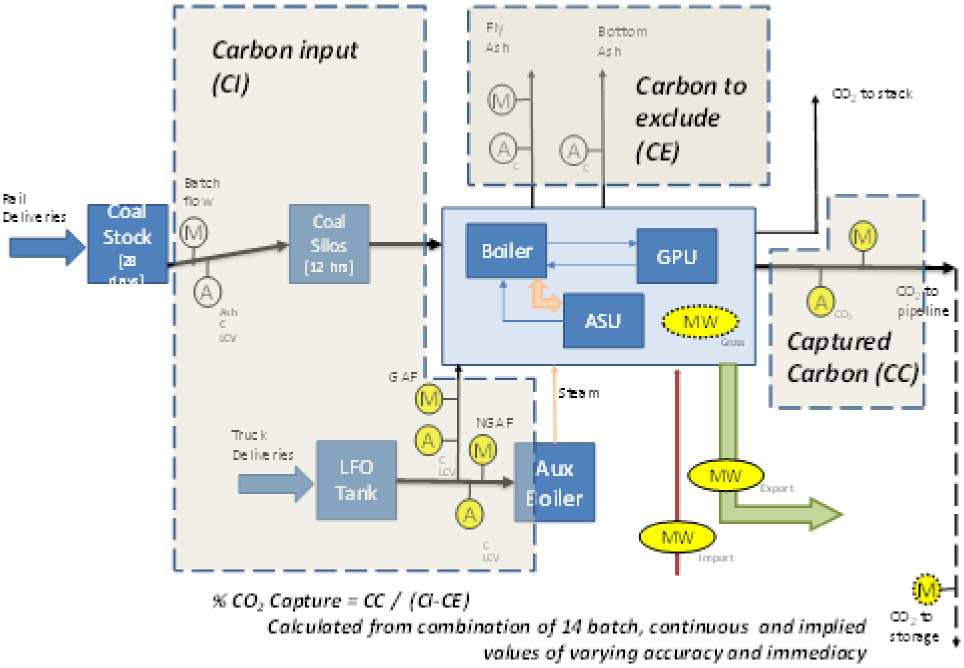
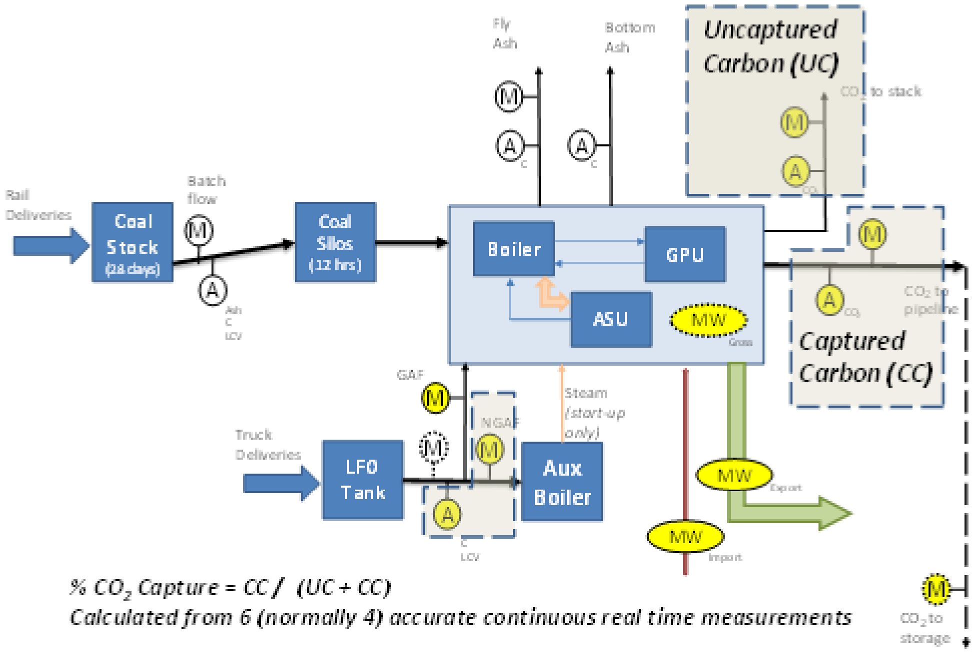


Figure 13.3: Revised CO_2 Capture Rate Measurements



However the CfD reporting requirements are very different to the EU ETS: there are 30 minute settlement periods and measurements must be clearly attributable to each period, this means real time results are required for both the carbon input and CO_2 sent to storage in order to determine the CO_2 capture rate for that period. Furthermore, the CO_2 capture rate has a high impact on profitability and so measurement uncertainty should be minimised, with simple and transparent methods employed that are not open to interpretation.

Due to the much lower flowrates (~5% of a conventional coal plant) and higher CO_2 concentration (~35%) CO_2 stack emissions from the OPP can be measured accurately, reliably and continuously using commercially available instrumentation.

This approach moves the calculation from relying on a combination of 14 batch, continuous and implied values of varying accuracy and immediacy to be calculated from four accurate continuous real time measurements. This approach also reduces the uncertainty in capture rate calculation by an order of magnitude.

Therefore for White Rose the approach was changed and rather than using a retrospective calculation of carbon into the plant, continuous measurements of CO_2 to the atmosphere via the stack and CO_2 into the T&S system will be used for determining the capture rate each half hour. This approach automatically excludes any unburned carbon from the calculation, so no retrospective adjustment for carbon in ash is required.

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The EU ETS related measurements and associated periodic calculations can provide an “audit” for the revised approach.

13.6 Stack emissions specification approach

Due to the reduced quantities of contaminants but a significantly greater reduction in flue gas volume when operating in oxy mode, for White Rose it was proposed to use a different parameter for measuring the emissions to atmosphere of SO_x, NO_x and particulates. The parameter of mg/Nm^3, as used in the EU Industrial Emissions Directive (IED), is not appropriate and an alternative measure of mg/MJ was proposed which can be equated to the IED parameter.

13.7 Review of Use of Oxygen Stream as the oxidant in the FGD

The configuration of and oxidant provision for the Flue Gas Desulphurisation (FGD) unit was reviewed to assess the benefit of an arrangement that would allow capture of its CO_2 emissions and thus improve the total capture rate of the OPP.

In a conventional wet limestone/gypsum FGD system the reaction tank is integrated in the FGD itself, below the absorber module, and the oxidisation process takes place in the FGD. The CO_2 from the oxidation process is released directly into the flue gas stream and exits via the stack.

For the OPP design an external reaction tank is used in order to avoid introducing the residual unreacted oxygen and inert gases from the oxidising air into the flue gas stream. The impact would be, while capturing additional CO_2, to reduce the overall CO_2 content of the stream and increase the duty on the GPU to remove the additional inert gases and oxygen.

An alternative configuration would use O_2 from the ASU as oxidant instead of air. This would avoid increasing the inert gas content of the flue gas and allow the reaction to take place within the FGD and the CO_2 released to be included with the flue gas to the GPU. This concept was not pursued as the economics of producing the additional oxygen – capital cost and parasitic power load – did not make it worthwhile.

13.8 Output in Air Mode

Pre-FEED design assumed that the OPP would be designed for full boiler output in both air (~390 MWe net) and Oxy (~300 MWe net) modes. Given that air mode operation is a temporary mode a review was undertaken during FEED to see if there was any advantage in equipment sizing or operational costs in reducing/limiting the air mode output even if that reduced efficiency in air mode.

Whilst it was identified that the sizing of some equipment items was governed by air mode operation there was no net benefit to be obtained in making any changes.

13.9 Coal Specification

A review of the basket of coals that the OPP should be designed to burn was undertaken as a result of the closure of a number of UK collieries (Kellingley, Maltby, Daw Mill) which had provided the designated performance coal as well as the design limits for some components.

The review resulted in a change to the coal basket and a reduction in the specified range for sulphur and ash content. This review showed that being an oxy-fuel power plant led to additional considerations, over and above those for an unabated coal-fired plant, when making such a decision. These included understanding the oxygen demand of the coal and the impact on GPU operation of the basket of contaminants in the flue gas.

While the plant is designed to burn a range of UK and imported coals, an alternative UK coal specification, SC Ravenstruther SC01, was specified as the performance coal.

13.10 Biomass Co-firing

During the FEED CPL undertook a “value engineering & cost reduction” exercise on the OPP. As part of the exercise some decisions that set the basis of FEED were challenged to confirm whether they provided economic benefit for the project as a whole.

As part of this process, it was decided that although the OPP was designed and enabled for co-firing, CPL would not install the required equipment during implementation post FEED as the proposed clean energy formula under the CfD would not give the necessary additional credit for the use of biomass to justify the investment. If however, the economic circumstances changed for biomass then the specific equipment for co-firing could still be installed at a later date.

13.11 CO_2 Specification - Temperature

CPL undertook a “value engineering & cost reduction” exercise on the OPP. As part of the exercise some decisions that were made in pre-FEED were challenged to confirm whether the economic evaluation made at that time is still valid for the project as a whole.

The FEED Basis of Design specified a maximum CO_2 temperature to the T&S of 20ºC. The benefit to the OPP of relaxing this to either 40ºC or 30ºC was assessed against its impact on the T&S system. Whilst there would be cost savings (capital and operational) for the OPP there would be additional capital cost savings for the transport system and, on balance, making the change on White Rose would not be economic.

13.12 Full Chain Control

System modelling of full chain CCS systems has often sought to develop control strategies for the full chain with a master controller over-seeing its operation.

For White Rose, through the FEED work, a different approach has been developed and a decision taken to interface rather than integrate the control system for each element of the chain. This has the advantage of allowing separate asset ownership and control which will be essential as cluster networks of emitters are established.

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13.13 OPP layout Optimisation

The layout of the OPP was reviewed and adjusted in view of the additional CCS related risks, for an oxyfuel plant this is in particular associated with CO_2 and oxygen production and storage.

The additional hazards to personnel from a CO_2 or O_2 release led to extra site safety exits added to the general layout.

The Administration building was relocated to the west of the site (upwind of the prevailing wind direction) following a site layout assessment to minimise risk to personnel in event of a leakage of CO_2 or O_2.

13.14 Minimisation air in-leak

Minimisation of air leakage into the syngas path for the OPP reduces the energy requirement of the CO_2 separation in the GPU by minimising the level of O_2 and inerts to be removed.

Various design changes were identified and assessed to meet this objective including:

- Electrostatic Precipitator (ESP);
  - Purging with air changed to purging with recirculated flue gas;
  - Thick flanged bolted design for inspection door (change from normal flap type design);
- Change from tri-sector to quad sector Air Pre-Heater;
  - pressurized sealing system & rotor purging system to minimize ASU oxygen losses and to maximize CO_2 content into GPU;
- Type of dampers and sealing for dampers from FGD to Stack and from FGD to the GPU’s DCC;
  - tandem or multi-louver damper sealed with hot air for the damper from FGD to Stack;
  - guillotine damper for the one between FGD and DCC;
- Boiler;
  - Special seals with knife gates for retractable soot-blowers;
  - RFG instead of air as seal gas to pulverisers, water cannons.

13.15 NOx removal in Selective Catalytic Reducer (SCR)

SCR and ammonia system redesigned to increase the NOx reduction achieved in the SCR from 82% to 89%, This was not done for emissions reasons but in order to reduce the separation load on the GPU.

13.16 Additional flue gas duct in the main stack

Additional flue gas duct was added to the main stack to route vent cold streams from GPU safety valves to the atmosphere.

13.17 White Rose Visitor Centre

The OPP administration building was resized / redesigned to accommodate a visitor’s centre.

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The design of the combined administration building and visitor centre has been developed by Arup Associates in collaboration with CPL to be highly sustainable, structurally robust and cost efficient whilst at the same time providing a high quality visitor experience and working environment.

The design is for a three-floored building with a footprint of 45m x 16.5m. This would provide adequate space for a range of functions. Internally, around half of the building will be reserved for office and laboratory space, to provide an administration and ongoing testing function for the CCS plant.

The remaining half of the building will be reserved for visitor use. Current plans for the visitor centre element include 450m^2 of exhibition space, a 100m^2 auditorium, a 100m^2 café area and a meeting / reception area. The remaining space will be a mix of utility, storage and access areas. A roof terrace would also provide visitors with views across the CCS plant, Drax and wider Selby surrounds.

Under current plans, the visitor centre aspects of the development are anticipated to require an investment of £5.5m. The investment will be sufficient for building and fitting out the centre including installation of various educational displays. There will be ongoing revenue costs for maintaining and staffing the centre, and CPL currently estimate that running the visitor centre will require around 3 full time equivalent (FTE) staff.

13.18 Change to minimum temperature for flange design

Decision to:

- Implement -55^{o}C minimum design temperature for flange design, and
- Implement 'L7' flange bolting with a minimum design temperature -101^{o}C.

A Computational Fluid Dynamics (CFD) analysis was performed to predict the minimum possible metal temperature for an uncontrolled leak at a typical flange used in the White Rose CCS Project. The general concern on cold temperatures is that if a temperature falls below the corresponding material minimum design temperature, the flange will be exposed to increasing risks of brittle fracture and crack propagation. Therefore, the results of this study can be used for material selection of the flange components in order to manage these risks.

Two locations of leak were examined which assumed a bolt failure yielding a thin gap allowing CO_2 liquid to leak through to the ambient medium. The worst case constant process conditions, at each leak location, were considered in this analysis (i.e. high pressure and low temperature). It was preliminarily identified that the impact of cold temperature would be most significant at smaller flanges because of a high leak area to affected metal mass ratio (unit: mm^2/kg), indicating that smaller flanges contain less thermal inertia. It has been found that 6” flanges will always experience colder metal temperatures in case of leak than 8” or greater flanges. So, all cold metal temperature CFD results predicted in this study for the 6” or 8” flanges are conservatively applicable for larger flanges.

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13.19 Offshore CO_2 Booster Pumps / Offshore Pipeline Pressure Uprating

Decision: to modify the transportation design to remove the requirement for offshore located booster pumps (needed for flowrates above 10MTPA) which would have entailed the need for significant power at the platform.

This would be achieved by increasing the design pressure of the onshore pipeline exiting the Barmston pumping station, the offshore pipeline and the offshore platform reception facilities. The design pressure would be increased from 182 barg to 235 barg.

13.20 CO_2 Storage Monitoring

Decision: not to incorporate DTS (Distributed Temperature Sensing) and DAS (Distributed Acoustic Sensing) techniques for Injection Well monitoring during FEED.

EU and UK government legislation require adequate Measurement, Monitoring & Verification (MMV) is undertaken to monitor the White Rose CO_2 store. For MMV located in the wells, the base case is to install pressure and temperature monitoring downhole and surface pressure monitoring of 'A' and 'B' annulus pressure. This monitoring is standard oilfield practice with well proven equipment and will enable monitoring of the store and also checking for potential leaks from the well during injection service.

Additional monitoring technology has been identified as potentially applicable to monitoring the well for leaks. This technology includes DTS and DAS. DTS potentially has an application to identify leaks from the store (up the sides of the well) and from the well pressure containment envelope (e.g. a leak from the packer or tubing and into the ‘A’ or ‘B’ annuli) by detection of temperature changes due to CO_2 leakage. DAS potentially has an application to detect ‘growth’ of CO_2 injection related induced fracturing which might result in compromising the store containment cap.

However, as proof that these technologies could provide evidence of leaking or induced fracturing does not exist, the reliability and the cost are unknown there was no certain or quantifiable benefit in adding them to the proven techniques being implemented.

13.21 Final location of Offshore Platform

- The platform location has been chosen following a review of alternatives. This review took account of potential constraints such as: keeping outside the SMartWind licence area;
- maintaining a safety zone between the platform and potential future wind turbines due to possible safe helicopter access requirements;
- staying away from the 2013 appraisal well location;
- avoiding faults in the overburden;
- maintaining a suitable offset from the Endurance structural spill point to further ensure CO_2 plume containment; and
- complying with the geo-technical and facilities engineering preferences to locate the platform in an area where large scale sea-bed sand waves are absent.

The chosen platform location was preferred since it satisfied the key fault and seabed sand wave ripple constraints. It lies outside the soft sediment Quaternary channel.

13.22 T&S metering location for European Union Emissions Trading Scheme (EU ETS)

Decision: following discussion with the regulator and for ease of maintenance, it was decided to locate the EU ETS metering for the Storage element of the Transportation and Storage installations at the Barmston onshore pumping station as opposed to being located on the offshore platform (i.e. at the interface of the Transportation and Storage installations).

13.23 Well Sizing

Decision: to have 3 Wells all at 5½” Outer Diameter (OD) tubing completion size.

Initially it was expected that 3 wells, 1 x 4-1/2" OD tubing and 2 x 5-1/2" OD tubing, would be required for the White Rose injection capacity range. The 4-1/2" OD tubing well was originally thought necessary to reduce or eliminate 2 phase behaviour of CO_2 in wells at low injection rates and the 5-1/2" wells would handle flow at high injection rates. Early in FEED it was realised that a 4-1/2" well would not eliminate 2 phase behaviour within the well, as this behaviour would always occur during the start-up of injection into wells. Consideration was therefore given to downhole choking, to keep CO_2 in dense phase within the well envelope, but all methods of accomplishing this had shortcomings and significant reliability risks. As a result the decision was made to have all wells configured for injection with 5-1/2" OD tubing and without down hole choking, and thereby accept 2 phase behaviour in the wells.

The wells RAM study confirmed that the required availability could be achieved with three wells..

13.24 CO_2 Modelling Technique

Decision: to use CFD techniques for the modelling of CO_2 dispersion and to carry out CFD model validation.

It was decided to perform detailed ventilation and gas dispersion modelling, using CFD, for the Barmston Pumping Station, as the local topography and the 5m high retention walls surrounding the Pumping Station, made detailed CFD analysis necessary to properly understand the interaction of the airflow with the local three-dimensional geometry and to its impact on dispersion behaviour.

13.25 Use of Polarcus data

Decision: not to carry out any further analysis during FEED using geophysical data for the storage area available from Polarcus.

During discussions with the regulator, The Energy Development Unit (EDU) of DECC, the possibility of incorporating the Polarcus dataset was raised. NGC subsequently acquired a sample subset of the seismic dataset and compared this to the Ocean Bottom Cable (OBC) dataset that were using. An analysis of the two datasets identified that the Polarcus data has no material differences from the OBC data set. This analysis and recommendation was presented to DECC EDU who subsequently agreed that no further work was required with the Polarcus dataset for the purposes of applying for a CO_2 Storage Permit.

14 Top 10 FEED Lessons Learnt Specific to CCS

Further information on lessons learnt can be found in K.04 – Full Chain FEED Lessons Learnt.

14.1 Cross-chain Liabilities and Default Risk

The dominant commercial risk facing the Project pertained to the liabilities faced by either CPL or NGC respectively through the potential default of the other. This risk is inherent in the commercial design of the full-chain Project, primarily through the contractual linkage of CPL and NGC through the Transport and Storage Services Agreement (TSSA).

Lessons Learnt

Although the mitigation measures embedded into the project's structuring helped make the risk of cross chain default (or so-called “project on project” risk) remote, evidence gathered by the Consortium showed that third party debt providers nonetheless remained uncomfortable taking the balance of such risks on a FOAK CCS project, bearing the potential impact of such events in mind as well as the likelihood of full recovery in a default scenario. In the absence of a single developer for the full-chain, it is the view of CPL and its financial and legal advisors as well as the appointed lenders legal advisors that given the experience with the White Rose project, part chain industrial developers are unlikely to bear cross-chain default risk and the potential financial consequences of such.

In considering lessons learnt from the Project, there remains a wider question as to whether there may be alternative ways of structuring future CCS projects, which would further minimise or remove project-on-project risk and potentially reduce costs (albeit possibly with transfer of risk to the public sector).

14.2 Storage Operation

A key requirement of the Project during the RRP to make it a financeable proposition was to obtain a Storage Permit consent for the chosen offshore carbon store from the relevant UK regulator, the Oil and Gas Authority (OGA), an executive agency sponsored by DECC. To secure this Storage Permit, it was necessary to provide sufficient evidence that the ‘Endurance’ geological carbon storage site in the North Sea would contain White Rose's captured carbon quantities safely and permanently, and that the Project had the necessary competencies to operate the offshore storage asset safely. As such, the attainment of the Storage Permit encompassed a number of commercial, technical and consenting activities, including fulfilling NGC's strategic intent for entering the offshore carbon storage business, the lessons learnt from which are outlined in this Section 14.2.

National Grid established its own storage company, Carbon Sentinel Limited (CSL), to undertake its storage development activities and to be the registered assignee of the Storage Permit, amongst other granted legislative rights. CSL had to consider the key technical and commercial risks associated with offshore geological carbon storage and develop solutions accordingly, including the establishment of agreed levels of financial securities it had to put in place as a requirement of the European Commission CCS Directive, as transposed into UK legislation. NGC decided that it was prudent to seek third party investors to take the lead role in delivering the offshore carbon store and subsequently promote the creation of a storage industry that could progress to deliver further storage sites as necessary to grow CCS at scale.

Lessons Learnt

Whilst the technical and commercial development of the carbon transportation and storage asset was able to progress during the RRP, with risk mitigations as described above, it was not possible to secure the entry of an equity investor in CSL. The principal reasons given for this lack of entry were:

- Lack of fit with corporate strategic intent;
- Lack of confidence in government CCS policy commitment; and
- Time and cost involved in completing a government procurement process.

Additional themes also emerged:

- Return on investment for the storage business of CSL deemed insufficient to justify taking reservoir / well performance risks that might be accepted by hydrocarbon project investors;
- Natural gas utilities are only interested in storage so as to further their transportation business;
- Financial investors are unable to bring the necessary offshore operator skills; and
- Hydrocarbon services companies are not interested in taking equity positions in the CO_2 storage sector.

There was found to be some interest in R&D co-operation, but potential investors believed that this learning could be satisfied elsewhere without the need for equity investment in a storage company.

The lessons learnt should inform those changes required to attract new investors to carbon storage and thereby help deliver the CCS industry. Principally, potential new entrants require a business model suited to the specifics of carbon storage as a low return, high risk activity, confidence in the government's long-term decarbonisation policy, and a less onerous programme to Financial Close.

Whilst the offshore activities of carbon storage are comparable to those of hydrocarbon exploration and production, the commercial model of the former, ostensibly a waste disposal business, is viewed as providing insufficient reward for the potential risk impact involved. The physical risks related to carbon storage are of low probability, whereas their potential financial impact remains high, including cross chain liabilities for service interruption and the purchase of emissions certificates at an unpredictable price in case of leakage to atmosphere. Furthermore, whilst the probability of a carbon storage risk incident occurring is low in comparison to the risks facing producers of hydrocarbons offshore, oil and gas businesses are able to balance such risks against the relatively high value of their product, compared with the storage of captured carbon, particularly since there is a track record of sufficient reward for taking such risks. There is no such track record of reward for investment in carbon storage; this will therefore only occur with the relevant assistance from government in delivering the commercialisation of the CCS industry.

In future, private investors in CCS commercialisation projects need to see clear, consistent and enduring government policy in order to provide the necessary commercial confidence to invest in storage operations. This in turn would lead to shorter negotiation timeframes for investment deals to be made.

If a store fails during operation for geological reasons, the store may need to be abandoned and a search for a replacement can be prolonged. Geological risk is site specific and may only manifest itself during operation whereas understanding of capture and transportation risks can be transferred from analogues or pilot schemes. Government support to establishing a commercial scale carbon store is essential so that these risks can be better understood and mitigated. The duration required for storage identification, access and characterisation can be several years requiring considerable financial commitment and involving geological (exploration) risk. Store characterisation is critical before other participants in the full-chain are willing to consider joining any development activities. In the case of the White Rose carbon store, Endurance, work would not have progressed without EEPR support ahead of the present Competition.

14.3 CCS Risk Definition and Sharing

The role of the HMG in the implementation of the White Rose CCS Project would involve not only financial support for its construction and operation but also a share in the financial impact of those incidents deemed a manifestation of a defined CCS risk. Essentially, the CCS market is widely considered to be ‘broken’ in that despite CCS technology being widely recognised as a potentially cost-effective approach to reducing carbon emissions from the power generation sector and from industry, CCS project construction and operation involves certain risks that private companies are unwilling to take alone, thereby creating a need for government-level intervention to mitigate such risks to a level at which Projects become financeable.

Establishing the point of market failure along a number of negotiating fronts between CPL and DECC, and in turn between CPL and its supply chain, insurers and debt providers, was in principle a core outcome of the RRP, against which the Baseline Risk Allocation Matrix (BRAM) defined DECC’s preferred outturn position. Without reaching a successful conclusion on CCS risk allocation, amongst other development challenges, the Project would not be able to achieve Financial Close, and if the development of contractual mechanisms for CCS risk allocation was not sufficiently thorough, it would leave both equity and debt investors at risk during the construction and operation of the Project.

Lessons Learnt

The CCS risk list was determined after several iterations between CPL and its commercial counter-parties, including the government. It was found that all stakeholders could be made comfortable with a list of CCS specific risks. This was achieved by striking a balance between clear definitions of such risks so that they could be understood and recognised, but were not overly prescriptive in the contractual documentation allowing a degree of interpretation and judgement should a CCS risk event actually occur.

14.4 Consenting

A full-chain consenting regime for the White Rose CCS Project did not exist prior to the start of the RRP. Instead, CPL and NGC pursued separately the necessary consents for the OPP and for the T&S System respectively. Since the key consenting challenge for the T&S System was the attainment of its Storage Permit, the lessons learnt from which are contained as part of Section 14.2, this section deals with the challenges relating to consenting the full-chain from the perspective of the CPL OPP.

Whilst there was no special consenting regime for the OPP, it still required existing consenting regimes to be fitted to the specifics of White Rose as a FOAK power plant project. This inevitably raised new issues with the regulators which needed timely resolution.

CCS is a new industry and as such provides extra challenges to regulating authorities as they attempt to understand the planning and development impacts of individual projects. The time required to obtain permits for such FOAK projects may therefore be less predictable (potentially longer) than for standard technologies; as such, the Project risked delays to its programme to Financial Close.

Lessons Learnt

The experience of progressing the consents application process provided important lessons for future CCS projects in the UK.

The level of input to the DCO from the engineering contractors in the supply chain was high and involved the development of information not associated with FEED studies, but which would set the basis of the DCO requirements and possibly constrain their execution strategy for the project. Engineering contractors need to be prepared to apply realistic experience based predictions concerning construction activities.

CPL discovered that the current approach adopted by the EA has the potential on a FOAK project to cause delay if not properly factored into the planning of the consenting process and overall schedule to RRP completion. A developer should allow for significant levels of questioning ahead of the EA beginning its formal evaluation of an EP application, rather than simply dealing with them during the normal examination process. In addition, the question of how BAT should be established and applied to a FOAK project needs to be tackled by all parties, well in advance of permit application, so that the application documents can fully address the matter. This approach needs upfront agreement with the EA and requires additional time to be allowed in the consenting programme. Furthermore, establishing BAT should be based on industry experience rather than on literature searches, particularly in the case of projects such as White Rose that introduce FOAK technology.

CPL learnt that whilst both its DCO and EP applications entered their respective examination and evaluation phases concurrently, the present consenting regimes do not permit their consideration in a manner which allows common issues to be dealt with unitarily, and thus enable the EA to engage fully in the DCO examination. Engaging the EA earlier in the White Rose consenting process on specific issues and items through the Consents Services Unit of PINS would, in retrospect, have provided beneficial support to the EA and CPL throughout the EP application process.

The following key learning points should be considered by a FOAK project developer, particularly with respect to allowing sufficient programme time to ensure that the challenges of agreeing an EP with the EA do not cause a delay to development completion.

- In instances such as the employment of new technology, the developer should work in parallel with a dedicated EA team that includes a case officer so as to identify potential issues and likely questions at an early stage;
- Whilst the EA has autonomy over the EP consenting process, the developer and the EA should aim to agree an engagement protocol from the beginning. Such a protocol should address, inter alia:
    - how the EA and PINS will interact in the DCO process, both during the preparation of the Preliminary Environmental Information Report (PEIR) and its subsequent examination; and
    - The agreement of, and issue by, the EA of appropriate BAT guidance (if it is to be applied) sufficiently early in the process to inform the applicant accordingly.

For specific health, safety and environment lessons, when the OPP is in commissioning and then operation, all operators need to wear three-way personnel gas detection equipment measuring for carbon dioxide, oxygen enrichment and oxygen depletion. CPL approached the design of the OPP to minimise the potential hazards through a combination of designing to minimise leakage, eliminating as far as possible areas where carbon dioxide could concentrate, and monitoring accordingly for leaks. Consideration also needs to be given to venting of concentrated carbon dioxide during periods when the T&S System is unavailable, in particular to ensure that ground level concentrations do not cause a hazard to life, or that the levels at the air intake to the air separation units do not exceed the safe limits for their operation. For White Rose, these were modelled and found to be satisfactory. Note that the T&S System design was conducted using the precautionary approach of assuming carbon dioxide is a hazardous substance. This has the advantage of future-proofing its design against changes in legislation.

For environmental impacts, CPL showed that in addition to reducing carbon dioxide emissions across the range of pollutants from conventional coal-fired power plant such as SOx, NOx, CO and heavy metals, the emissions mass flow rate is significantly lower in oxy mode, with impacts at ground level receptors significantly reduced.

The EPS places an annual limit on CO_2 emissions from a fossil fuel power station. The EA have published guidance on its application to CCS plants, in particular an exemption period of three years to cover the period during which commissioning of the full CCS system will take place. Liaison is required with the EA to ensure there is a clear understanding of the required commissioning sequence for the full CCS chain and that the exemption period can be most effectively applied to support its timely realisation. Early discussion on the detailed application of the 3-year exemption from EPS for CCS projects is therefore advised.

14.5 Fixed-Price Procurement

To facilitate a successful Financial Close at the conclusion of the RRP, the Project was required to demonstrate in advance that it met the minimum requirements of those stakeholders holding a financial interest. This demonstration would be achieved largely through the use of a detailed financial model that reflected accurately the expected economic performance of the Project, in conjunction with due diligence performed by HMG, in parallel with potential debt and equity investors, on the various finalised agreements that made up the commercial framework.

To minimise the risk of material change to a project's economic performance subsequent to a successful financial close, it is commonplace for the developer to seek, wherever possible, fixed-price contractual arrangements with its supply-chain, along with other determinations such as defined delivery dates and minimum technical performance standards of the delivered product. This in turn transfers risk from the employer to the contractor and normally results in the contractor adding a risk premium to the offered contract price.

Without a fixed price procurement approach, equity and debt investors are exposed to a material risk to the outturn economic performance of a project, either at completion of construction, where equipment and labour cost variations may impact, or later through imbalanced economic movements in the operational supply chain. The greater the duration between a project's Financial Close and the execution of the elements of a particular contract that is not fixed-price, the greater the economic risk to the project and its investors.

Lessons Learnt

Despite the inherent challenges to delivering fixed-price procurement arrangements that faced the Project over its full-chain, suitable commercial mechanisms were available to provide adequate mitigation so that in this regard, the Project could be considered a financeable proposition. This was only made possible in the context of delivering a commercial-scale coal-fired CCS project through the use of the risk-sharing mechanisms available within the Authority Funding agreements.

14.6 Full-Chain Commercial Integration

The full-chain White Rose CCS Project consists of a number of organisations across its full-chain commercial model. In order for the Project to operate as a full-chain system that is both financeable and maintains the long-term objectives of its various stakeholders, careful consideration is required as to the overall integration of the elements of its commercial model.

The key building blocks of the White Rose full-chain technical proposal are procured from different industries that each have their own commercial norms and typical approaches for contracting and risk allocation. The power generation block was procured from the power industry, the ASU from the chemical process equipment industry and the T&S System largely from the suppliers to the hydrocarbon industry, in particular for the offshore elements. In addition, and as outlined in earlier sections of this document, HMG was involved in providing capital and operating support to the Project, together with sharing in the various construction and operating risks in order to make the Project financeable.

As such, the development of an integrated full-chain commercial proposition that delivered long-term economic and strategic value to its equity investors, debt payment surety to its debt providers, and value for money to UK taxpayers and electricity consumers was challenging. The risks inherent in the Base Case commercial model therefore had to be considered carefully across the economic life of the Project so that they could be mitigated appropriately. This was achieved namely through the transfer of risk as far as possible from CPL (as the central contracting body) to those parties that were more suited to managing the risk. The allocation of such risks would be reflected accordingly in the Project's commercial pricing structure.

Lessons Learnt

Bringing together a combination of the power industry, chemical industry and offshore hydrocarbon industry under a governmental procurement framework that ultimately should satisfy allowable state aid funding criteria was challenging. The use of suitably experienced development team members supported by high-quality professional advisors is critical to making timely RRP progress.

As the project development progressed, it became apparent that although progress was being made, reaching a comprehensive agreement on risk allocation between DECC and the developers of the White Rose project was challenging. The associated iterative process involved in cascading the risk allocation to all counterparties to CPL including the supply and services chain (including NGC) and the debt providers presented challenges in terms of HMG's desired Competition process timescales.

For future programmes aimed at the commercialisation of CCS it may be worth considering alternative ways of approaching the allocation of risk and project implementation that provide HMG with the controls it needs for the deployment of government capital funding, as envisaged in the PPP/PFI approach, whilst being compatible with non-recourse debt financing structures potentially through a hybrid control process and common sign off. This is discussed further in Section 14.7.

14.7 Attraction of OPP Financing

The financing of CPL's OPP was composed of both debt funding from commercial institutions together with equity financing from its sponsors under the typical approach of non or limited-recourse financing principles commonly referred to as "project finance". Project finance is commonly adopted for the funding of independent power projects (IPPs) for which there is considerable market precedence, both in the UK since privatisation of the electricity industry in 1990, and many other countries such as the Middle East where the state backs or underpins certain risks. As a result, the major finance institutions, including commercial banks, export credit agencies and multilaterals, are highly familiar with the concepts and application of project finance, together with its accepted principles of risk allocation between the project company, its equity sponsors and debt providers.

Typically for IPP projects, candidate commercial debt providers and their appointed professional legal, technical and insurance advisors, are engaged latterly in the development programme once the commercial structure is largely complete and draft agreements are well developed. Furthermore, these IPPs are normally based on technology that has a consistent track record of deliverability and reliability.

In order to maximise both the pool of commercial debt providers familiar with the White Rose CCS Project and, ultimately, the level of competition between them when CPL would later procure debt finance, the CPL development team together with its financial advisor engaged over 20 such institutions early during the RRP. Several were even engaged prior to CPL being awarded its FEED Contract as it was recognised at an early stage that consensus needed to be developed with this community and that gaining their confidence and trust would take time given the lack of precedent for commercially funding a project of this type. With the relative complexity of the White Rose commercial, technical and financing structure when compared with the majority of recent project finance deals such as offshore wind farms, CPL deployed as an integral part of the RRP an ongoing campaign of both educating the commercial debt providers with respect to full-chain CCS and updating them as its negotiations with various counter-parties progressed towards its Financial Close objective.

Furthermore, bringing new equity investors to a project during its development phase can help bolster its appeal to debt providers and other stakeholders by demonstrating early the strategic and economic appeal of the project ahead of Financial Close. It can also mitigate sponsor risk and enable the continuation of the project when earlier financing assumptions change.

Lessons Learnt

A number of critical lessons were learnt in relation to engaging the commercial debt providers for the Project. Principally, there is wide variance in the degree of CCS literacy amongst these institutions and so early engagement to communicate the specifics of the Project is vital so as not to risk delays to the project financing negotiation programme. Furthermore, selection of a relatively few ‘pathfinder’ banks is advisable to provide the CCS project developers and DECC with a confidential and interactive sounding board for iterating optimal and bankable commercial structuring solutions.

Building on the early engagement with commercial debt providers, it nevertheless is prudent to develop a power generation-based CCS project to match as best as possible the commercial structure and risk allocation to that of a typical IPP. Overlaying this template onto the specific CCS project enables the developer to address any material differences with the lending community. Enabling the commercial debt providers to become comfortable with the chosen CCS technology, quality of Project sponsors, quality of supply chain organisation and their respective balance sheet strengths, together with risk insulation to the degree developed in White Rose goes towards getting banks interested in the first place. This in turn enables the developer to negotiate reasonable terms for example for debt-to-equity ratios, debt margins, required DSCR etc. The pathfinder banks and their professional advisors played a critical part in CPL’s efforts to evidence and then develop solutions to mitigate cross-chain liabilities and default risk described in detail in Section 14.1. The banks were comforted that the operation of key elements of the T&S System were familiar to them from their oil and gas activities and that a hierarchy of risk allocation and contractual protections could be provided in this FOAK project ahead of CCS transitioning to a more liquid, demonstrable and commercially financeable CO_2 transport and storage market.

HMG’s support for CCS specific risks was in general well received by the commercial debt providers in addition to its commitment to creating a wider CCS market as witnessed recently in regards to the creation of the offshore wind sector. Furthermore, the commercial debt providers viewed as positive certain other commercial features of the Project such as the tenor of the CfD, the inclusion of an indexation basket for the CfD Strike Price and the option to rebase the CfD Strike Price at two specific milestones in CPL’s economic lifecycle: at completion of the Construction Phase and at completion of the Commercial Proving Phase.

Material evidence of strong interest from high-quality potential third party equity investors in CPL was obtained during the RRP. This included Chinese investors attracted to White Rose due to their positive perception of the support package offered by HMG through capital grant funding, CfD and sharing in CCS risks. The opportunity to form a strong partnership with the world-renowned incumbent sponsors through third party equity participation was also viewed as attractive.

In addition, CPL discovered evidence of interest both from UK development funds and the EFSI, a significant European infrastructure development fund, the latter as a ‘de-risking’ tool giving further recognition to the fact that the CCS market is ‘broken’ and therefore requires national and/or multi-national government funding to initiate its delivery. The learning obtained from White Rose’s third party equity search process should prove useful to future CCS projects if similar governmental support packages and regulatory frameworks materialise together in the future.

14.8 Full-Chain Technical Design and Integration

As a FOAK project, the White Rose development team faced a number of design issues and some unprecedented project management challenges. Since the proper design and delivery of the Project as a technical endeavour is closely linked to achieving Financial Close and ultimately satisfying its target economic performance, such issues and challenges represent a key risk. The mitigation of these design and delivery risks provide important lessons for future CCS projects.

Lessons Learnt

Full-Chain Economic Proposition

Undertaking a multi-disciplinary effort to iterate the commercial design of the Project with its technical design, since the two are heavily linked, is a critical factor to progressing the RRP. The use of a comprehensive, detailed financial model containing an accurate coding of the Project’s technical characteristics, together with scenario analysis flexibility, enabled both the commercial teams and the technical teams to collaborate over a common tool in making various decisions jointly and transparently. Until successful Financial Close and subsequent delivery into full-chain completion is achieved, the financial model is all that is available in terms of a tangible full-chain representation of the Project. Outturn parameters can be used to replace values in the financial model that were decided upon at Financial Close to update the model as the project progresses through the delivery phases towards full commercial operation.

In the case of White Rose, the use of the CPL financial model was particularly important for value engineering analysis, discussing start-up times with candidate power purchasers, and deciding the LOX backup strategy.

CO_2 Entry Specifications

The developer of a CO_2 T&S System should consider how the CO_2 entry specification will impact on the ability of and attractiveness to emitters from a range of industries to provide CO_2 into the system. When CO_2 is supplied to the T&S System, a clear protocol needs to be established on how the measurements are made and verified so that there is clear traceability on the source of any contamination with robust controls to minimise the same. For the CPL OPP, this led to the move from a single to duplicate analysis stations with a procedure on how to address any divergence in their readings. This approach allowed greater assurance on limiting any liability for damage to the pipeline from off spec CO_2.

The T&S System needs to be as close as possible to “plug and play” for new entrants from a diverse range of industries, with clearly defined entry requirements that can be met easily. T&S System users should be able to concentrate on their core business and not be expected to become expert in other areas. Having to work outside their core competencies will make such connection projects much longer to develop and more expensive.

Cross-Industry Project

As a cross-industry endeavour, the design requirements of a full-chain CCS project manifest largely at the back end of FEED. This should be recognised when specifying the required outputs at the start of FEED so that the expectations and requirements of all stakeholders needed to make a final investment decision can be satisfied.

Particularly, as with White Rose, where elements of the chain are single-sourced, sufficient detail must be available so that the Employer’s Requirements can be fully defined in the respective EPC contracts and that the resultant pricing can demonstrate value to the employer and third party stakeholders.

Bringing together different industries in a full-chain project can also lead to confusion through the use of industry-specific terminology or short-hands. For instance:

i) The use of the relative positional terms “upstream” and “downstream” on the full-chain CCS project that is placing fluid into the store rather than extracting it from the store as would be typical when using hydrocarbon production terminology;
ii) Active commissioning of a plant with the process fluid would be known as “hot commissioning” on a power plant and “cold commissioning” on a cryogenic plant such as the ASU or GPU; and
iii) Definitions of reliability and availability may differ across different industries.

Full-Chain Control and T&S System Flexibility

Dynamic modelling of the OPP and the T&S System confirmed the approach in which their control systems give safe, reliable and stable operation as they respond to operational changes within other elements of the chain. The approach also facilitates new CO_2 emitters entering the chain, and recognises that for them the capture and storage of CO_2 is a necessity rather than their core business and should not be the primary driver controlling the operation of their assets.

Analysis also showed that the compressibility of the CO_2 in the dense phase is significantly less than for natural gas traversing traditional gas pipelines. However, it is possible that 'line-packing', the ability to compress the fluid, in the pipeline by a small additional margin, could be used to a very limited extent to manage abnormal conditions and small transients due to time lags between balancing supply and demand.

In order to allow the chain to realise the overall CCS function, a degree of system interfacing and operations coordination is required. This means that while each elements' control system will be entirely independent of each other, they will include the signal exchange required to provide reliable coordination of the overall process and appropriate responses to emergency or out of limits measurements. These signals will be transmitted directly between the control systems for each element of the CCS chain. Key operational monitoring and records data will also be transmitted from each control system to the Management Information Systems (MIS) databases. Key data from the MIS will be available to operators across the chain. The Full-Chain elements are interconnected such that a start, controlled stop or trip of any component within the chain can provide information and alarms to both the upstream and downstream process systems. Interfacing signals between the chain elements are therefore required to ensure the process is managed safely and efficiently.

A regime for the co-ordination of maintenance outage periods between the OPP and the elements of the T&S System was devised and drafted in to the TSSA. Whilst this co-ordination may not be possible with third party users of the T&S System, it was deemed as critical to CPL for the maximisation of green electricity generation and the subsequent payment of the T&S System tariff.

The project facilities design includes water facilities that allow the injection of a quantity of brine (seawater), envisaged to be approximately 1,000 m^3 in volume, to re-dissolve any precipitated halite and displace it out into the saline formation away from the near well bore area, reducing any skin factor that has been created. The benefits of pre-injecting seawater prior to first CO_2 injection would be considered later during the detailed design phase post Financial Close. The injection facilities will allow for the worst case scenario that formation water flows back to the injection well perforations whenever injection is interrupted and allows re-precipitation of halite in the near wellbore area when CO_2 injection recommences.

Liquid Oxygen Backup

A review of the impacts of installing and using LOX storage to allow for back-up in the case of an ASU trip showed that overall it is not economically beneficial. With a fixed CfD Strike Price, the cost of the lost power production during the period when the LOX storage is being replenished outweighs the benefit of continuing full boiler load running during such an outage.

During the replenishing phase a double hit to output occurs. Gaseous O_2 that would have allowed the oxy-fuel boiler to operate at full gross load is diverted to liquid production causing an increase in parasitic load, thus further reducing the net output of the OPP. The CfD regime, incentivising the operator to maximise output all the time, is different from typical O_2 supply schemes where LOX can be replenished during periods of low O_2 demand and/or low power prices. This allows volume of LOX back-up storage to be greatly reduced, although not eliminated as there has to be sufficient volume to allow the boiler, for example under an ASU trip, to be run down smoothly from 100% to 50% load.

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The reduction of LOX storage reduces the quantity of hazardous substance stored on site. This allows the site to achieve a lower tier COMAH status, bringing additional operational benefits**.**

14.9 Limitations of Insurability

The design and development of an integrated insurance programme played a key part in the development efforts to bring White Rose towards DECC's opening risk allocation position on full-chain commercial integration as expressed in the Baseline Risk Allocation Matrix, as described earlier in Section 14.1. However, the insurance market, and in turn the insurability of the Project, was found to have its limitations as described in this Section 14.9. Insurance alone therefore could not offer a standalone solution to the cross-chain liability and default risk development challenge, but nevertheless played an important role in the hierarchy of mitigations that made the likelihood of cross-chain default leading to termination remote.

Lessons Learnt

During the development of the Project insurance programme, the variability and limitations of the commercial insurance markets became understood more clearly. Whilst it may play an important role in large technical endeavours such as White Rose, and indeed the purchase of adequate insurance is a requirement of project financing, insurance is not a panacea for all risks, especially those relating to FOAK commercial-scale CCS projects.

14.10 Limitations of Alternate Uses

To cater for the possibility that the T&S system would fail to perform, or that the CfD be terminated under scenarios in which debt & equity were not fully recompensed, the White Rose development team sought alternative uses for its physical components, predominantly the OPP as a potentially valuable power generation asset. During the course of the RRP, no alternate uses of the T&S System were considered.

Following discussions between CPL and the US Department of Energy (US DoE) in 2014 it was apparent there was a joint interest in both oxy-combustion in general and potential application of the OPP technology with carbon capture in combination with co-firing of biomass with coal. One particular area of common interest related to the potential for fuel conversion and in 2014 CPL agreed to provide relevant White Rose data into a fuel conversion study planned by the US DoE. The output of the study would allow CPL to investigate means to mitigate the financial impact of a failure of CCS technology in the Project through a potential and subsequent fuel conversion of the power generation assets. To disaggregate the aims and objectives of the study, and thereby de-risk the study itself, three distinct phases/scopes were clearly defined:

- Phase 1 - investigation of the technical feasibility of future conversion using alternative fuels;
- Phase 2 - deeper investigation into the preferred alternative fuel option; and
- Phase 3 - a study on the application of BECCS.

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Phase 3 was of particular interest given the Project's proximity to Drax Power Limited, Europe's largest biomass conversion scheme. Following a competitive tender process, the engineering consultant AECOM was mandated by the US DoE to undertake the work.

Lessons Learnt

The initial findings of Phase 1 of the study were that there are no overriding technical barriers that could prevent the conversion of the OPP to fire biomass pellets. Additional or upgraded facilities to accommodate import of biomass to the OPP site are likely to include:

- Increased off-load and storage capacity at Hull / Immingham ports;
- Additional rolling stock to increase rail transport capacity from the ports to Drax;
- Additional biomass storage capacity at the OPP site; and
- Replacement of the proposed conveying and mill delivery systems (with potential re-use of the coal conveyor route and transfer towers).

Similarly, the Phase 1 study found no overriding technical barriers preventing the OPP being converted to fire natural gas, assuming that the OPP has a natural gas fuel demand of 2,000 m^3/h. Additional or upgraded facilities to accommodate the conversion to fuelling the CPL OPP on natural gas are likely to include:

- A new 12 inch fuel gas supply pipeline to the OPP site, comprising of a:
  - New NTS system exit point from National Grid feeder pipeline;
  - New pipeline route from NTS exit point to the OPP site;
  - New gas receiving / pressure reduction station on the OPP site; and
- NTS feeder pipes in the Drax area.

Given the significant difference in capital expenditure between the biomass and natural gas conversion options, and the fact that the current subsidy regime for biomass generation in the UK ceases as from 2027, should Phase 2 of the study have progressed, it would have delved deeper into the natural gas option so that CPL could have had more visibility to include in its risk mitigation activities.

The Phase 3 (BECCS) report was agreed as a follow-on report, given the potentially significant benefits that would accrue in North America if this technology was adopted. Following the cessation of the Competition, discussions are ongoing between the US DoE and GE regarding completion of both the Phase 2 and Phase 3 reports.

14.11 Sale of Carbon Transportation and Storage Capacity

The White Rose CCS Project was the anchor project underpinning delivery of the multi-user Humber Cluster. The Humber Cluster itself was conceived as the foundation of the UK CCS industry and represented a principal objective for the Project. Central to the White Rose scope of works was therefore the delivery of a T&S System with sufficient long-term capacity to satisfy multiple carbon capture sites in the Humber area, with CPL's OPP being the first connected user.

The Humber Cluster T&S System was designed to accept a peak flow of up to 17 million tonnes per annum of carbon dioxide captured from a number of network points. The offshore carbon store ‘Endurance’ to which the Humber Cluster T&S System was to be connected, is situated in a subsea geological Bunter sandstone formation in the North Sea. Endurance was selected for the White Rose CCS Project due to confidence in its ability to hold potentially 300 million tonnes of carbon dioxide injected at a rate of around 10 million tonnes per annum for a period of 30 years. This total capacity and injection rate was therefore more than sufficient for the carbon transportation and storage needs of the CPL OPP, capturing on average 2 million tonnes per annum over 20 years.

The long-term objective for NGC as the developer and operator of the Humber Cluster was to expand the Humber Cluster pipeline network to attract further users beyond those reachable from its initial layout under the scope of the White Rose CCS Project. It would also connect to other offshore carbon stores subsequently as the UK CCS industry’s storage needs expanded beyond that offered by Endurance. Additionally, the offshore portion of the T&S System could be expanded to facilitate the sale of captured carbon to oil producers using EOR techniques (injection of carbon dioxide into oil wells) to improve their production yields.

Considering the commercial objectives of the above, White Rose had to establish a fair and economically attractive methodology for the sale of T&S System services to not only CPL as the anchor customer, but also to follow-on users. The risk in not achieving such a capacity sales methodology meant that the Humber Cluster may not expand beyond having CPL as its only user, therefore reducing the ‘value for money’ legacy of the White Rose design scope.

Lessons Learnt

The consideration of both the anchor project and the long-term objective for a new multi-user CCS network is critical to its overall ‘value for money’ objective, both to the initial investors and governmental sponsor, but also to those individual follow-on users taking their own commercial decisions to install CCS equipment. Comparing the two methodologies, the incremental cost capacity fee approach gave the lowest economic barriers to entry for follow-on users and therefore had the greater chance of creating the long-term objectives of the Humber Cluster.

However, under the incremental cost methodology as described above, there were two distinct disadvantages to CPL as the anchor project. Firstly, the resultant CfD Strike Price was greater than under the average cost methodology, since as the anchor user, CPL is responsible for repaying the total capital cost for the initial scope of the T&S System. This impact created a challenge for CPL when the economic attractiveness of the White Rose proposal as a whole was being considered purely on the magnitude of the CPL CfD Strike Price alone. Secondly, the greater capacity fee charges created an increase in the cross-chain liability considerations between CPL and NGC as covered in more detail in Section 14.1. There were proposed revenue and upside sharing arrangements in the agreements between CPL and the Authority, which allowed the option for the CfD Strike Price to be abated in order to share the benefit of increased use of the shared infrastructure across all users. The detailed arrangements of such an approach, in particular the consequences of costs relating to a third party being dependent upon the performance of an independent counterparty, had not been settled before the closure of the competition.

14.12 Interconnections Design

The CPL OPP is designed to be constructed and operated entirely on land owned by the site host, Drax Power Limited. To reduce the capital spend required for the new-build OPP, the CPL development team, in conjunction with Drax, designed the OPP to make use of existing infrastructure at the Drax site. Such existing infrastructure included the raw water extraction, processing and discharge system, the fuel stockpiling area and rail delivery facilities, the 400 kV sub-station and the fly ash storage mound. CPL would require the construction of a new coal conveyor, ash removal conveyor, an underground cable to the sub-station and various connection infrastructure, mainly various water media, to the existing Drax systems so that the OPP could function as necessary.

Use of such existing Drax infrastructure, and any consumables therein, would be charged to CPL under a long-term Site Services Agreement. In addition, long-term land rights would be granted to CPL by Drax for placement of new interconnection infrastructure. Since Drax is a live operating plant of significant electrical generating capacity, it was decided that Drax alone would be responsible, and therefore take the risk, for constructing the new interconnection infrastructure under an EPC contract with CPL.

The reliance of CPL on Drax for interconnection construction and operation was deemed a risk to CPL. This risk was required to be properly mitigated, predominantly through careful technical design, insurance provisions and robust land rights in order for CPL to be a financeable entity. Similarly, the construction and operation of the CPL oxy power plant represented a risk to Drax's own existing operations.

Lessons Learnt

The risk of default or insolvency of the host site organisation is a significant risk in any independent tenant development project, particularly where the tenant makes use of existing infrastructure owned, operated and relied upon by the host. However, through pragmatic technical, contractual and commercial discussions between host and tenant, these risks can be suitably mitigated. In this regard, the success of the interconnection discussions between CPL and Drax mean that White Rose remained a financeable project.

14.13 Metering and Measurement Regime

Critical to the effective and reliable operation of any multi-entity commercial model in the energy sector is a robust and reliable measurement and metering regime. In the case of the White Rose CCS Project, with its full-chain commercial model consisting of several inter-linked organisations, the development of the measurement and metering regime was a key part of the technical design process.

An important operating parameter for White Rose as a coal-fired low carbon commercial demonstration project is the effectiveness by which it captures carbon from the combustion of its coal fuel, transports it offshore and delivers it securely to its geological formation store. The measurement and metering of carbon volumes passing along the full-chain is therefore a critical element of the Project's commercial model, particularly since CPL earns CfD revenue only from its 'clean electricity' output, and pays both capacity reservation fees and variable charges to NGC for the transportation and storage of captured carbon.

In addition, CPL monitors its carbon capture rate as a key performance indicator for the OPP, and upon which the success of its construction is determined at completion and subsequent commissioning. Damages may be levied to the construction contractor if this carbon capture rate is below a given target (90%) since CPL would in this event suffer financial loss over its operating lifetime.

Both CPL and NGC are required to purchase the necessary EU ETS carbon emissions certificates for any ejection of carbon to atmosphere, either through the normal operation of the OPP or as the result of emergency venting or leakage. The risk of an inadequate metering and measurement system therefore is that the economics and lawful operation of the CCS full-chain becomes difficult to ascertain.

Lessons Learnt

For the OPP it was initially assumed that this approach of retrospective calculation of the carbon input be combined with direct real time measurement of the CO_2 captured and sent to storage. However, the CfD reporting requirements are very different to that of the EU ETS. The CfD operates under 30-minute settlement periods and so emissions measurements must be clearly attributable to each period. This means real time results are required for both the carbon input and CO_2 sent to storage in order to determine the CO_2 capture rate for that period. Furthermore, the CO_2 capture rate has a high impact on profitability and so measurement uncertainty should be minimised, with simple and transparent methods employed that are not open to interpretation.

Due to the much lower flowrates (around 5%) and higher CO_2 concentration (around 35%) when compared with a similar-sized conventional coal plant, CO_2 stack emissions from the OPP can be measured accurately, reliably and continuously using commercially available instrumentation.

The White Rose approach moves the calculation from relying on a combination of 14 batch, continuous and implied values of varying accuracy and immediacy to be calculated from four accurate continuous real time measurements. This approach also reduces the uncertainty in capture rate calculation by an order of magnitude. Therefore for White Rose, the approach was changed and rather than using a retrospective calculation of carbon into the plant, continuous measurements of CO_2 to the atmosphere via the stack and CO_2 into the T&S System will be used for determining the capture rate each half hour. This approach automatically excludes any unburned carbon from the calculation, so no retrospective adjustment for carbon in ash is required. The EU ETS related measurements and associated periodic calculations can provide subsequently an “audit” for the revised approach.

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15 Summary of Commercial Arrangements

Figure 15.1 below summarises the commercial structure of the White Rose CCS Project, as developed during the FEED.

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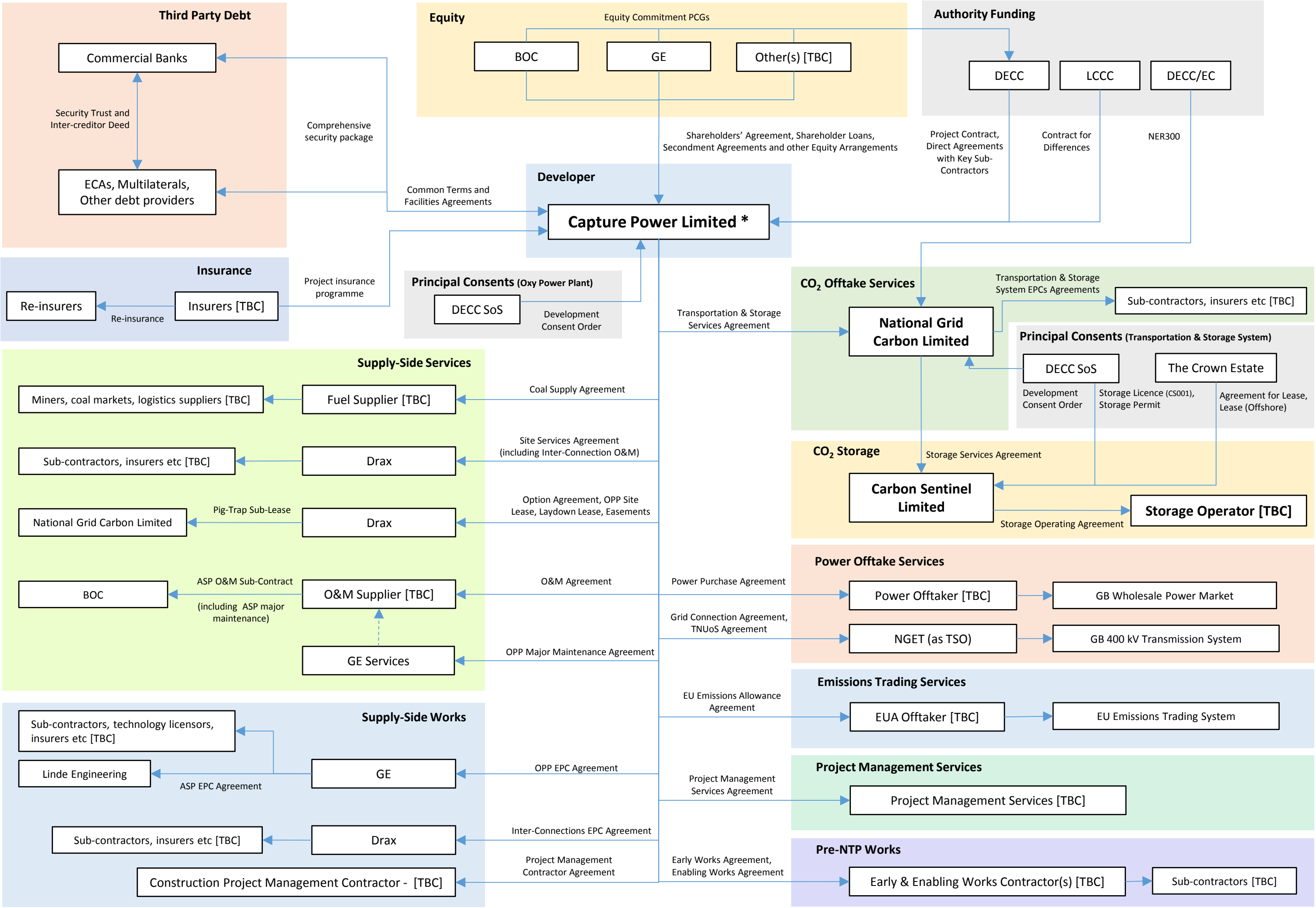
Figure 15.1: White Rose CCS Project Summary Commercial Structure



Source: CPL

The key commercial objective of the contract groups shown above in Figure 15.1 are outlined below:

15.1 Authority Funding

This group of contracts identified in figure 15.1 above provide amongst other things both capital and operation funding to the Project, together with financial support for the impact of CCS risk event occurrences.

15.2 Principal Consents

These consents permit the lawful construction and operation of the OPP and T&S system, subject to certain restrictions and requirements. The permits are obtained following a fixed duration democratic procedure involving the developer submitting proposals for planning consultation that involves a number of governmental departments and the general public. In addition, the offshore carbon storage field is placed under long-term lease to the carbon storage company sub-contracted by NGCL from the body responsible for awarding the rights for carbon storage in the UK's Gas Importation and Storage Zone.

15.3 Supply-Side Works

These contracts deliver the OPP, including infrastructure connections to fuel supply, electrical export systems and local utilities through fixed price, fixed duration EPC construction contracts. A Project Management Contractor (PMC) acts on behalf of CPL to manage the delivery of the works including the interface primarily between the OPP constructor (GE), the site host (Drax) and NGC as the responsible counter-party for the delivery of the T&S system. NGC opted to sub-contract the construction activities; this level of detail is not shown in Figure 15.1.

15.4 Supply-Side Services

These contracts provide long-term coal supply and associated delivery logistics to the OPP, along with the long-term site lease and associated easements for connections to utility infrastructure. Various utility supply services relevant to a coal-fired plant are provided under contract with Drax and the operations and maintenance of the OPP is contracted to a suitably experienced operator, supported by a specialist equipment maintenance contract with GE.

15.5 Power Offtake Services

These contracts enable the long-term purchase of the electrical output of the OPP at a pre-determined price by a commercial counter-party trader, with the relevant export capacity reserved accordingly on the Great Britain 400 kV network operated by National Grid Electricity Transmission.

15.6 Carbon Offtake Services

This contract provides the commercial link between the OPP and the T&S system, providing also the operating standards for the full-chain Project. CPL reserves capacity on the NGC T&S system through this contract.

15.7 Carbon Storage Services

NGC's duties towards CPL for the long-term storage of its captured carbon is sub-contracted to a separate storage services company that holds the legal responsibility for the safe operation and maintenance of the offshore carbon store. The storage services company may in turn sub-contract the day-to-day operation and maintenance of the carbon store to a suitably qualified offshore operator.

15.8 Insurance

CPL transfers a number of power plant construction and operation related risks to commercial insurers through a comprehensive framework of insurance policies. NGC has a similar framework of insurance policies related to pipeline and offshore platform construction and operation, although this is not shown in Figure 15.1.

15.9 Equity

This group of contracts provide the required level of injection of equity funding into CPL as a project financed special purpose company; this equity is provided as a loan to CPL. A shareholders' agreement governs the multi-shareholder ownership of CPL. The contractual commitments of the shareholders to CPL are supported by Parent Company Guarantees towards DECC.

15.10 Third Party Debt

These contracts provide the terms and conditions under which a collective of commercial banks, multi-laterals, export credit agencies and other organisations provide non-recourse debt finance to CPL, including the subsequent timescale and margins for repayment.

15.11 Project Management Services

This contract would provide a wide range of commercial, technical and financial services personnel on a flexible basis as required acting for and as an extension of the CPL core team in the implementation of its business, in particular its supply chain, during the Construction Phase. This service provision would be tapered off as CPL progressed beyond the Construction Phase, through the Commercial Proving Phase and in to the long-term Operating Phase when permanent CPL staff would be hired.

15.12 Pre-NTP Works

These contracts enable certain construction works to be undertaken that both shorten and de-risk the main Construction Phase for the OPP. Such works included the relocation of existing utility infrastructure and public rights of way over the OPP site, together with site raising and levelling works to meet various permitting and construction requirements respectively.

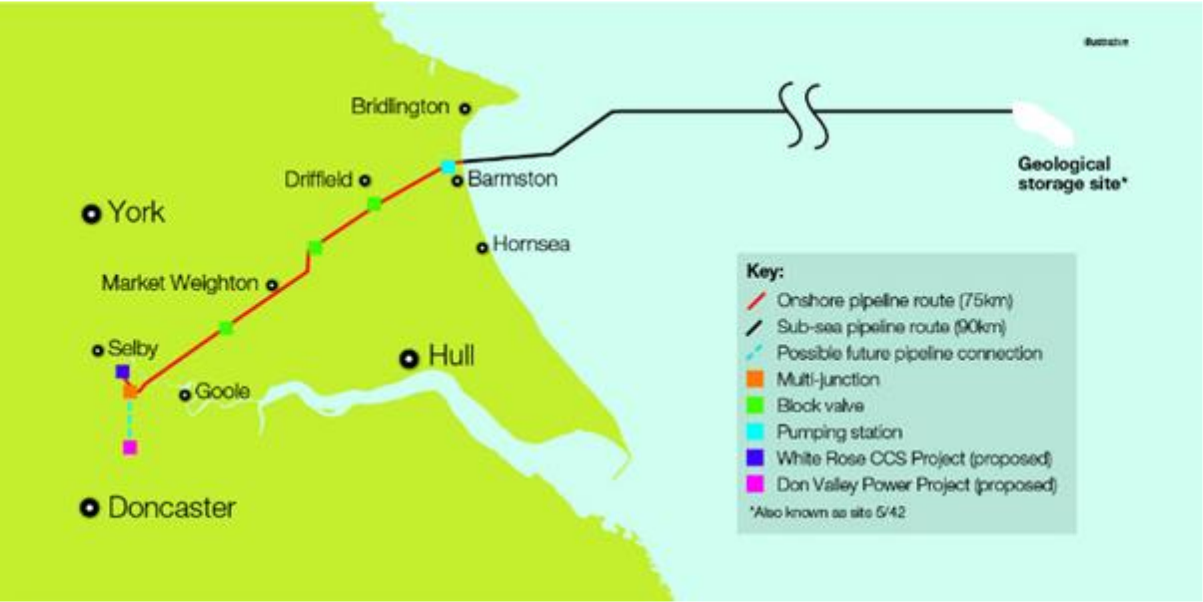
16 Transport and Storage

16.1 Overview

The White Rose CCS Project is to provide an example of a clean coal-fired power station of up to 448 MWe (gross), built and operated as a commercial enterprise.

The project comprises a state-of-the-art coal-fired power plant that is equipped with full CCS technology. The plant would also have the potential to co-fire biomass. The project is intended to prove CCS technology at a commercial scale and demonstrate it as a competitive form of low-carbon power generation and as an important technology in tackling climate change. It would also play an important role in establishing a CO_2 transportation and storage network in the Yorkshire and Humber area. Figure 16.1 below gives a geographical overview of the proposed CO_2 transportation system.

Figure 16.1: Geographical overview of the transportation facility



The standalone power plant would be located at the existing Drax Power Station site near Selby, North Yorkshire, generating electricity for export to the Electricity Transmission Network (the “Grid”) as well as capturing approximately 2 million tonnes of CO_2 per year, some 90% of all CO_2 emissions produced by the plant. The by-product CO_2 from the Oxy Power Plant (OPP) would be compressed and transported via an export pipeline for injection into an offshore saline formation (the reservoir) for permanent storage. Figure 16.2 below shows a schematic of the full chain.

The power plant technology, which is known as Oxyfuel combustion, burns fuel in a modified combustion environment with the resulting combustion gases being high in CO_2 concentration. This allows the CO_2 produced to be captured without the need for additional chemical separation, before being compressed into dense phase and transported for storage.

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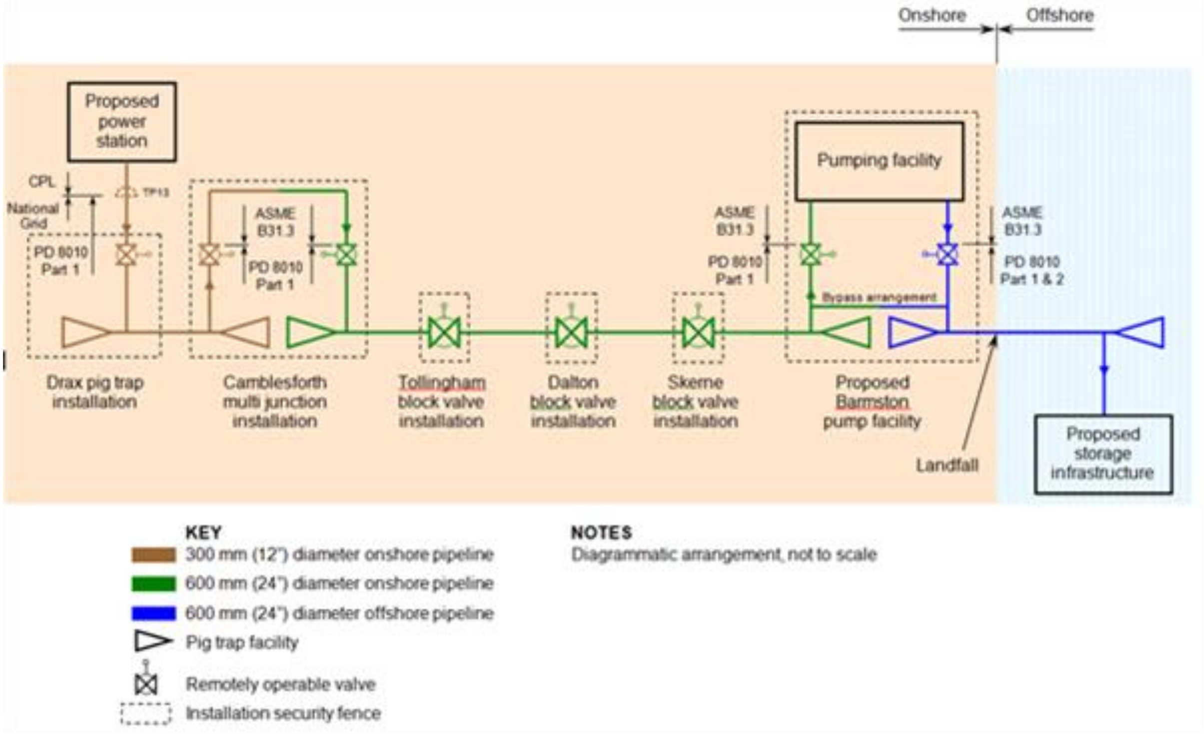
Figure 16.2: End to End Chain Schematic Diagram



16.2 Pipeline Description

16.2.1 Design Life

The minimum design life of the proposed onshore pipelines would be 40 years and this would be incorporated into the applicable design criteria for the pipelines. The Pipeline AGIs and the process and utility systems at the pumping station would also be designed for a 40 year life.

Some facilities/equipment, which may be subject to obsolescence such as control systems, , or fatigue such as wells, would have a shorter design life and would require upgrade or replacement.

16.2.2 Length and Diameter

The proposed dense phase transportation system would transport the CO_2 to the offshore storage facilities.

Between the Drax OPP and the proposed multi-junction near Camblesforth the pipeline would be 300mm in nominal diameter and approximately 6km in length. Provision for three future connections would be made at the multi-junction. The pipeline from Camblesforth multi-junction to Barmston pumping facility would be 600mm nominal diameter, approximately 69km in length with block valve installations located near Tollingham, Dalton and Skerne. The block valve installations and the multi-junction would be unmanned. The route and installation layouts have been pre-selected as per the description in the DCO application.

PIG trap/launcher arrangements and associated equipment would be located at Drax OPP, Camblesforth multi-junction installation and Barmston pumping facility to enable the internal inspection of the 300mm and 600mm pipelines.

The CO_2 would be transported from the Barmston Pumping Facility to the offshore storage facility through an 88km offshore (mostly subsea) pipeline of 600mm ND (24in). The offshore pipeline includes a short section between the pumping facility and the landfall. It would have a design pressure of 235 barg.

16.2.3 Materials

The onshore and offshore pipelines would be constructed from carbon steel.

16.2.4 Metering and Monitoring

The range of process conditions and quality of the dense phase CO_2 stream flowing from the Drax OPP would be limited to specific design parameters through the use of suitably SIL rated protection systems within the OPP GPU, which would respond to the input from the instrumentation monitoring the pressure, temperature and the oxygen content of the CO_2 stream, to protect the onshore transportation system from any operational upsets. The flow is further metered and monitored at the Barmston pumping facility.

The offshore platform would also be equipped with an integrated control and safety system (ICSS) for facility control monitoring and safeguarding. It also would include the following system functional elements:

- Process Control System;
- Emergency Shutdown System (ESD); and
- Fire and Gas element (F&G).

The ICSS would include a local HMI consisting of personal computer based operator workstations, to allow local control of the facility as and when required. The HMI would be located in a local equipment room (LER) that would house the control and safety system equipment cabinets and system marshalling. The LER would be located adjacent to the platform Emergency Overnight accommodation.

The platform would be designed for unmanned operation under remote supervisory control; systems would operate and control autonomously from the land based system at the control centre. Communications between the platform and the NGCL control centre would be by means of dual redundant VSAT satellite links.

From the manifold, CO_2 would flow to the First Load platform injection wells. Following future expansion, the CO_2 would also flow to additional platform injection wells or the future subsea wells. Each platform injection well inlet arrangement would be provided with an orifice plate for metering (outputs from the meters are corrected using pressure and temperature measurement), relief valves to protect piping from overpressure in the event of thermal expansion (closed in conditions) and a motor operated choke with downstream pressure and temperature measurement. A metering uncertainty of ±2.5% would be selected. The corrected value would be recorded within the ICSS and in the future would be used to control the flowrate to the wellheads.

The manifold pressure may be controlled by varying the variable speed drives of the future CO_2 booster pumps, which may be transporting surplus CO_2 to future storage sites away from the Endurance location.

16.2.4.1 Consenting Boundaries

The jurisdictional boundary is at the Mean Low Water Mark (MLWM) approximately 170m east of the cliff tops, north of Barmston. This location is driven by the Petroleum Act and therefore represents the terminal point for onshore Nationally Significant Infrastructure Projects. For consenting purposes, the onshore submission to the Planning Inspectorate shall include all required information up to this location.

Either Marker 3 or Marker 5 in Figure 17.3 could be the point of custody transfer of the dense phase CO_2 from the Onshore Transport system operator (say NGC) to the Offshore Storage operator (say Carbon Sentinel Limited). This would be important if these two operators were to be separately legal entities.

The quantity of the CO_2 would be measured for fiscal purposes only at Marker 1 (TP-13/OPP output). This quantity would be deemed to be the quantity entering the reservoir. It could be measured once more at Marker 3 (as it leaves the Pumping Facility site) or Marker 5 (as it enters the Offshore Platform Facility).

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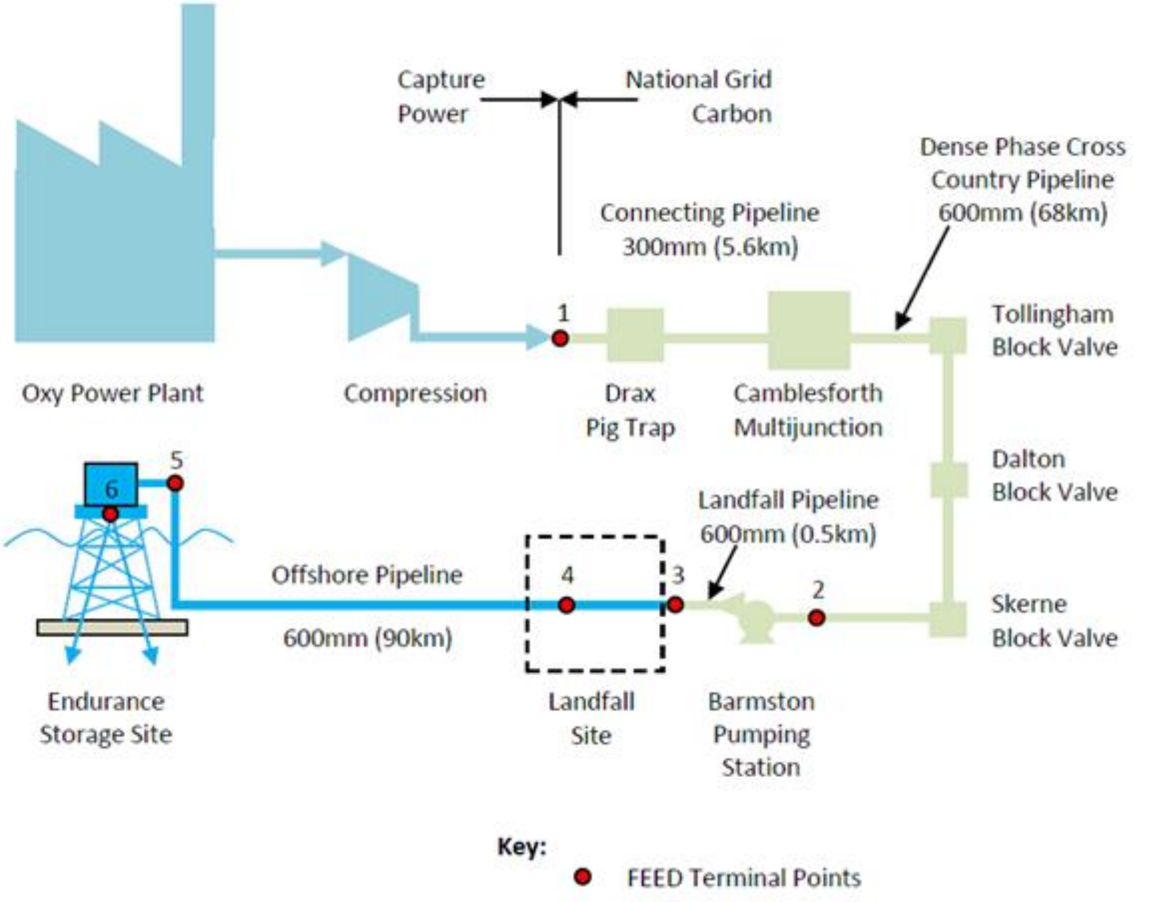
Figure 16.3: Full Chain Schematic Diagram



16.3 Booster Pump Station

Barmston pumping facility is located approximately 1km north of Barmston. It would be aligned with the onshore and offshore constraints and to minimise visual impact through the use of Hamilton Hill as a backdrop, and would be sited approximately 500m landward of the proposed landfall location.

The primary purpose of the pumping facility would be to ensure that sufficient pressure is available to overcome losses in the offshore pipeline and enable injection of the dense phase CO_2 into the storage site. It would also provide the filtration, metering, and PIG handling facilities and afford adequate overdrive protection as required for the downstream offshore pipeline.

A pump bypass arrangement would be provided to ensure the continued onward flow of CO_2 from the 600mm ND onshore pipeline to the offshore normally unmanned Endurance platform in the event of a shutdown or failure of the pump package. For the initial low flowrates, the expected pressure required at the discharge of Drax OPP would not need to be much greater than 90barg (say approximately 103barg) in

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order to overcome the frictional line losses and storage reservoir pressure, at least for the first five years of operation. In this instance the pumps at Barmston could be bypassed and the flow to the injection wells achieved using the OPP GPU pump only. The bypassed dense phase CO_2 would be filtered to meet the requirements of the offshore facilities and the flowrate measured for monitoring purposes. The bypass would be fitted with a non-return valve to prevent recirculation of the CO_2 stream when the CO_2 Booster Pumps are operating.

The operating discharge pressure for the Barmston pumps would initially be 132barg for year 5 flowrates with an injection pressure of 113barg at the offshore platform. Over time the injection pressure would need to be increased which would require a greater discharge pressure from the pumps.

The pumping facility would be designed to provide the highest level of efficiency that is practicable over the range of process conditions. To increase spares interchangeability and thus reduce the amount of spare required, a decision was made to use the same specification for all the booster pumps to be located at the Barmston pumping facility.

The pumping facility would be designed for unmanned operation under remote supervisory control by the remote control centre.

Dual buried 66kV high voltage connections from Northern Powergrid would be required to service the pumps and ancillary equipment.

16.4 Oversizing of Infrastructure and Clustering Potential

The proposed CO_2 transportation system of NGC would have the capacity to transport up to 17MTPA. The long-term aspiration is for the transportation system to form the foundation of a regional CCS network, potentially capturing tens of millions of tonnes of carbon dioxide every year in the Humber & Yorkshire area. The strategic decision was taken to design the transportation and storage system to reduce incremental costs for future entrants into the pipeline system. The Humber & Yorkshire area brings together a large concentration of emitters (power stations and industrial sources including the White Rose project) and currently accounts for around 20% of the UK's CO_2 emissions. The maximum feasible injection load for the Endurance formation is expected to be in the region of 10MTPA with an initial maximum injection load from Drax (White Rose project) of 2.68MTPA. To utilise fully the proposed CO_2 transportation pipeline it is expected that a further storage formation in proximity of the Endurance formation needs to be operated. The platform would be designed to allow for future expansion of the CO_2 injection systems.

16.5 Criteria Relating to Offshore Facilities Including

16.5.1 Location, type, capacity and site conditions (K.02)

Additional information on the location, type, capacity and site conditions relating to the offshore facilities can be found in KKD K.02 - Full chain basis of design

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16.5.1.1 *Platform type*

The offshore storage facility of the overall White Rose Carbon Capture and Storage network would be a Normally Unmanned Installation (NUI) wellhead injection platform. The platform comprises of the following:

- PIG handling facilities;
- cartridge type filters;
- injection manifold;
- CO_2 injection wells (a minimum of 3) which dispose of the CO_2 into the Endurance saline formationstorage site located in the North Sea block 5/42. In the future, the numbers of injection wells can be increased; each well would be individually metered;
- monoethylene glycol (MEG) storage and pumps to prevent CO_2 hydrate formation during well start-up operations and water wash activities;
- water wash treatment facilities to avoid halite build up in the well heads (seawater lift pumps and caisson, filters and chemical treatment). Additional temporary water wash facilities would be provided by a skid package (injection pumps, filters, power generation and chemicals);
- other utilities (drains system, diesel storage system, nitrogen (quads), fresh water system, power generation system, CO_2 vent, wellhead hydraulic power unit);
- support systems (crane, temporary safe refuge, local equipment room, marine navigation aids, telecoms and helideck); and
- safety systems (fire and CO_2 gas detection systems, helideck foam and DIFFS package, life-rafts and Totally Enclosed Motor Propelled Survival Craft (TEMPSC)).

The platform substructure would be a steel jacket. Additional allowance would be built into the jacket with a module support frame to allow for future installation of CO_2 booster pumps (and a recycle cooler for pump commissioning/proving purposes) to transport CO_2 further afield.

16.5.1.2 *Platform location*

The co-ordinates of the preferred injection platform (P5) and hence drill centre in UTM Zone 31 on the ED50 Datum are Easting's 366882 m and Northing's 6012790 m. The proposed storage site (referred to as “Endurance” and previously known as “5/42”) lies 60km to 70km east of Flamborough Head on the east coast of England in water depths ranging from 50m to 60m.

Figure 16.4, below, shows a geographical location of the offshore storage site, with existing gas fields shown in pink:

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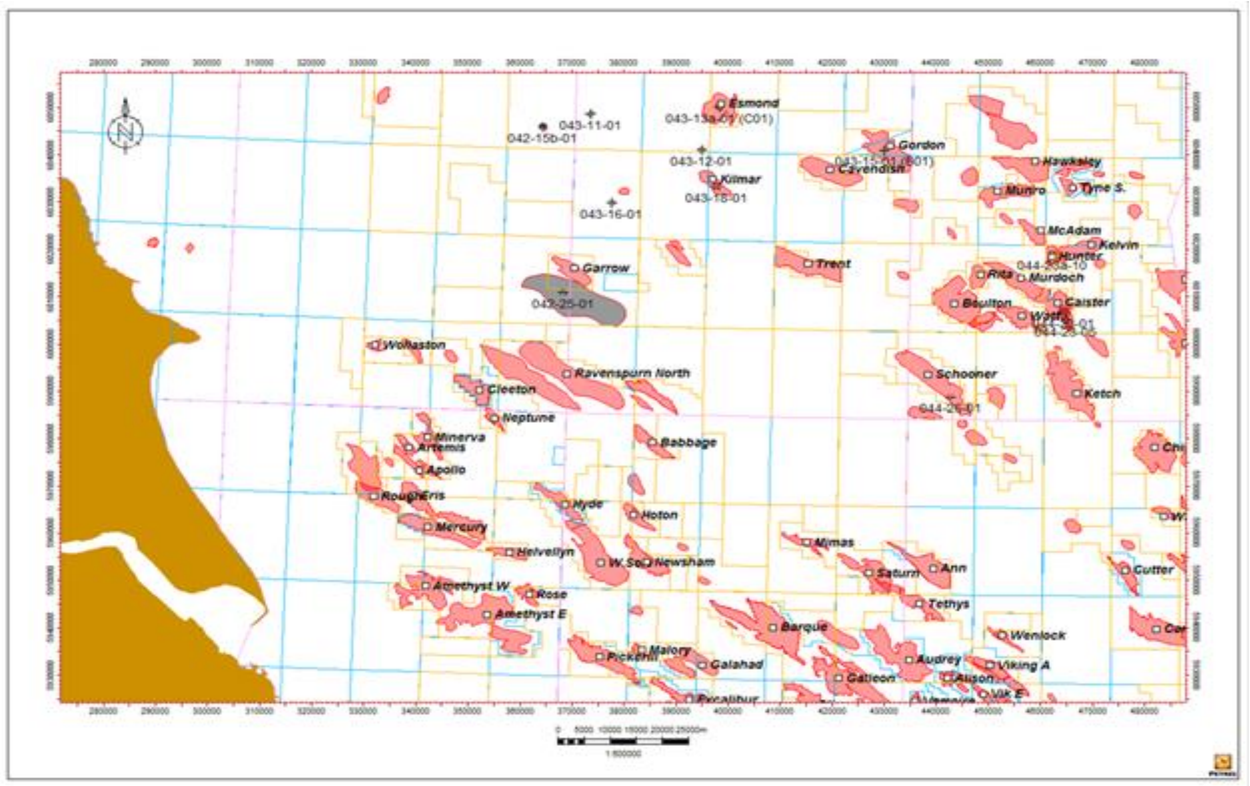
Figure 16.4: Geographical Location of the Endurance Offshore Transportation Site



16.5.1.3 Site Conditions

The maximum air temperature at the platform is 24°C and the minimum temperature is -7°C.

Wave data for the platform is presented in Table 16.1 and Table 16.2. Directional data specifies the direction where waves appear to originate. Wave data for other offshore locations can be found in KKD K02 -Full Chain Basis of Design.

Table 16.1: Maximum Wave Data

Site	Parameter	1 Year Maximum Wave Data	10 Year Maximum Wave Data	100 Year Maximum Wave Data
1	Hmax (m)	12.1	15.1	17.9
	Tass (s)	10.9	12.2	13.2

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Table 16.2: Site 1 Wave Data

Direction (From)	1 Year Wave Data		10 Year Wave Data		100 Year Wave Data	
	Hs (m)	Tp (s)	Hs (m)	Tp (s)	Hs (m)	Tp (s)
Omni - directional	6.3	11.2	8.0	12.6	9.5	13.7
North	6.3	11.2	8.0	12.6	9.5	13.7
North – East	5.6	10.6	7.1	11.9	8.5	12.9
East	4.8	9.8	6.1	11.0	7.2	12.0
South – East	5.0	10.1	6.4	11.3	7.6	12.3
South	4.9	10.0	6.3	11.2	7.5	12.2
South – West	5.1	10.2	6.5	11.4	7.7	12.4
West	5.4	10.4	6.8	11.6	8.1	12.7
North - West	5.9	10.9	7.5	12.2	8.9	13.3

16.5.1.4 Capacity

A number of other decisions in regards to the offshore NUI follow on from the decision to provide a 600mm ND pipeline, which would have a capacity of 17MTPA and is well in excess of the First Load supply of 2.68MTPA and expected maximum injection capacity of Endurance of 10MTPA:

- the platform would be designed to allow for future expansion of the CO_2 injection systems. This includes:
    - three spare well slots to allow for additional CO_2 injection wells within the Endurance storage site;
    - a spare export riser would allow for future onward transportation to further CO_2 storage sites;
    - a weight allowance would be provided in the platform jacket structure to allow installation of a module support frame and the future electric driven CO_2 booster pumps and their associated recycle cooler;
    - spare J-tube(s) would be provided for future import power cable(s);
    - spare risers and J-tubes would be included in the jacket to allow for future CO_2 and water production well tiebacks to maximise Endurance storage capacity;
    - space for future PIG launchers/receivers would be allowed for in the design;
    - space for an additional filtration vessel would be allowed for in the design; and
    - spare capacity would be included in the control systems for future CO_2 injection wells, water production wells and CO_2 booster pumps (a connection upstream of the manifold may be provided).

At First Load (Year 1), the manifold would have three connections to the injection wells. Additional space is allowed for the following future connections:

- three connections to platform injection wells; and
- two connections for future sub-sea tie-backs.

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16.5.1.5 Reservoir

The structure of interest is a saline aquifer, approximately 22km long, 7km wide and over 200m thick. This, the Endurance structure, is a four-way dip-closure straddling blocks 42/25 and 43/21 in the UK sector of the North Sea, some 60km to 70km east of Flamborough Head. The crest of the reservoir is located at a depth of approximately 1020 m below the sea bed. A layer of mudstone called the Röt Clay provides the primary seal. This in turn is overlain by more than 90m of a salt layer known as the Röt Halite at the base of the 900 m thick Haisborough Group which provide the secondary sealing capability. Reservoir datum pressure and temperature (at 1300mTVDSS) were estimated at 140.0bar and 55.9°C, respectively. The Storage Site is estimated to have a net pore volume of over 4.6Bm^3 and the 53.6MT of CO_2 planned for production by the White Rose power plant over 20 years will occupy approximately 2% of this volume under reservoir conditions.

The formation is considered to be fair to good to very good in terms of reservoir quality. The dynamic modelling confirms that Endurance is an extremely strong candidate for a CO_2 store. The modest Phase 1 loading into such a large structure, with what is thought to be a large and strong connected reservoir volume, can allow the operator to gain invaluable experience of CO_2 storage operations that could be shared with operators of similar projects in the future.

16.5.1.6 Platform Injection wells

The objective of the first phase CO_2 injection wells is to facilitate safe, reliable and efficient construction and subsequent use for the injection of CO_2 into the storage reservoir over a period of 20 years.

At First Load (Year 1), the manifold would have three connections to the injection wells that dispose of the CO_2 into the Endurance saline formation storage site. The proposed injection well tubing size of 5.5in for the wells allows for injection capacities of up to 2.8MTPA. In the future, the number of injection wells could be increased.

The wells must be designed with due consideration with respect to well operation, well abandonment, post abandonment long term CO_2 well/store integrity, and the need to monitor and verify the well integrity and mitigate risk.

The reliability of the system from power station to reservoir as a whole is expected to be 85%, with a requirement for the wells to operate at a target rate of 99%.

Originally consideration was given to including a 4.5in well as this was thought to help reduce the tendency for two phase flow at start-up and shut-down. However, it was concluded that:

- two phase flow would not be eliminated;
- if there was argument for a 4.5in well then on the basis of reliability there should be at least two; and
- using wells that could only handle a maximum flowrate of 1.8 MTPA, which is only about two thirds of the First Load design flowrate, reduced flexibility.

A decision was taken to use 5.5in wells only.

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Up to eight water production wells may be installed in phases over the design life. Water production from the formation is not required for the first load CO_2 injection rates.

Additional space will be provided on the platform to allow future expansion of the hydraulic power unit to accommodate six platform wells, which is the maximum.

16.5.2 Storage Licence Summary

Permission is required for the rights to lay, maintain and operate the proposed CO_2 pipeline on land, in coastal regions and on the seabed. Additionally carbon storage rights are needed for the rights over the 3D spatial extent in which CO_2 is proposed to be stored. The carbon storage rights within the lease area include entry into the area, drilling and use of wells, installation maintenance and decommissioning of facilities. As the CO_2 pipeline would be crossing several offshore blocks, crossing agreements would need to be negotiated with the Crown Estate for such activities within the 12 nautical mile territorial limit around the UK and with several third parties block operators such as E.On and Perenco (not an exhaustive list; further information on these can be found on the DECC website: https://itportal.decc.gov.uk/information/licence_reports/offshorebyblock.html.).

16.5.3 Interpretation of Geochemical, Geophysical and Hydrographical Data and Modelling

The evaluation of petrophysical data from well 42/25d-3 has demonstrated that the Endurance structure has excellent reservoir quality and good storage potential.

Sedimentological, log and core analyses show that the Storage Site is predominantly very-fine to fine-grained sandstone which is interspersed with thin mudstones that are interpreted to be laterally impersistent. Overall, the Storage Site is a homogeneous body of sand of excellent porosity and permeability.

A simple material balance model suggests the pressure increase in Endurance from injecting the first load of 53.6MT of CO_2 over a twenty year period may be in excess of 194bar; which is probably enough to fracture the reservoir and cap rock. However, it is believed Endurance is connected to a much larger volume which could be in excess of $1000x10^9$ m^3 , that is 200 times that of Endurance itself. This would help to limit the pressure increase associated with White Rose CO_2 injection and ensure that the sealing integrity of the cap rock is preserved. Depending on the size of the connected Greater Bunter aquifer and whether the outcrop is closed or open, the pressure increase at the crest of the structure from injecting White Rose CO_2 is between 38bar and 65bar, with a most likely value of 40bar.

The seabed outcrop of the Bunter sandstone formation to the East of Endurance is seen to be more of an opportunity than a threat. Geological arguments favour the outcrop both in hydrodynamic communication with Endurance and open to flow to the seabed.

The injection of the Phase 1 maximum mass of 53.6MT is expected to pool at the crest of the structure and no scenario can be envisaged where the CO_2 can get beyond the spill of the Endurance structure.

The basic conclusion is that with the White Rose CO_2 load of 2.68MTPA (as a maximum over 20 years), the Endurance structure when modelled with reasonable properties shows only minor uplift of 9cm at the

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crest. In reality, cumulative injection of the first load over 20 years will be less than the maximum possible aggregate of 53.6MTPA.

Cooling of the reservoir by the cold CO_2 is thought to be highly localised to the near wellbore region although the work done here has not been able to consider conductive cooling of the cap rock as the CO_2 flows down through the well. The geomechanical modelling done in parallel to this study suggests the biggest risk to the failure of the seal is more likely due to cooling than pressurising-up from the Phase 1 loading.

There should be more than enough permeability in the Lower Bunter to allow well perforations to be set deep thereby maximising the opportunity for residual trapping although the relative permeability data indicate the amount of residual trapping might be quite low. It had been thought this strategy would also keep the cold injectant away from the cap rock where it could lead to thermal fracturing.

The geomechanical simulations considered a number of ‘limit’ cases where the fault locations, fault strength and degree of cooling were pushed up to or possibly beyond realistic ranges to get some failure. Even in these cases the increased strain or failure appears to be minor and localised and is not likely to create a significant leak pathway.

For the White Rose CO_2 storage formation the main conclusion is that there is little risk of significant strain and/or failure of the Röt Clay and Röt Halite seals as a consequence of the Endurance structure being subject to the predicted pressure and temperature changes.

More detailed information may be found in KKDs K39 and K40.

16.5.4 Interpretation of Storage Studies:

More detailed information may be found in KKDs K39 and K40.

16.5.4.1 Injectivity

The three proposed wells with a tubing diameter of 5.5in are expected to cater for a range of injection rates from a minimum equivalent to 0.58MTPA to a maximum equivalent to 2.68MTPA. This corresponds to the agreed CO_2 delivery range of the Drax OPP power plant. The maximum expected injection rate is expected to be approximately 10MTPA when utilising additional wells are commissioned.

The speed at which the CO_2 would flow from the perforations of the injectors, assumed to be in the Lower Bunter, in the North-West of Endurance to the crest depends on: pressure levels, horizontal and vertical permeabilities, maximum gas (CO_2) relative permeability, drainage critical gas saturation, and the presence or not of horizontal baffles or barriers.

16.5.4.2 Leakage and Integrity

The Bunter sandstone formation in Endurance is considered to be fair to good to very good in terms of reservoir quality. The dynamic modelling confirms that Endurance is an extremely strong candidate for a CO_2 store.

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The injection of the Phase 1 maximum mass of 53.6MT is expected to pool at the crest of the structure and no scenario can be envisaged where the CO_2 can get beyond the spill of the Endurance structure. In fact there is no known mechanism by which the CO_2 can get out of the upper peak and into the eastern lower peak of Endurance.

The simulations considered a number of 'limit' cases where the fault locations, fault strength and degree of cooling were pushed up to or possibly beyond realistic ranges to get some failure. Even in these cases the increased strain or failure appears to be minor and localised and is not likely to create a significant leak pathway.

16.5.5 Subsurface Wells Selection and Proposal

The methodology of design of the CO_2 injection wells is the same as applies to the design of hydrocarbon wells. Typically therefore the starting point for the well design is to review offset analogue wells in the nearby area and most useful of these offset wells are wells which penetrate the same or very similar formations in the subsurface. This methodology has been applied to the design of the White Rose CO_2 injection wells. The offset reviews typically look for particular drilling problems and the formation or lithology in which the problems occurred. The following therefore discusses this information which applies to the White Rose wells.

16.5.5.1 Well Fluids

During the drilling of a well, holes of various sizes, starting large and becoming smaller, are drilled into the formations with the use of a bit on the bottom of a drilling 'string'. The drilling string consists of lengths of pipe connected together with threaded connections. In order for the drilling string to progress deeper, the cuttings of rock, produced by the bits drilling action must be removed from the bottom of the hole and back to the surface, where the cuttings are removed. The method by which the cuttings are removed is by the use of a "thickened" liquid, referred to as a drilling fluid or mud, which is pumped down the well on the inside of the drillstring and returns up the well in the gap between the drillstring and the sides of the new hole that has been drilled; note: the gap between the drillstring and the hole is referred to as the annulus. The velocity of the drilling fluid in the annulus (determined by the pump rate) and the rheological properties of the mud are the method by which the cuttings are removed from the well. The section below describes the well fluids or drilling fluids that have been used previously on offset wells and how this information is used in the selection of drilling fluids to be used for drilling the proposed new CO_2 injection wells.

16.5.5.2 Casing Concept Selection

A well consists of an initial large hole drilled into the formations. At a certain depth, the hole requires support, otherwise it may collapse. The support is provided in the first hole size by what is called a conductor. A conductor is the first pipe lowered into the well (or driven using a large hammer) and forms the support for this hole section. Once in place, with the lower part of the conductor at what is referred to as the casing point, cement is pumped down the conductor with the objective of placing it (whilst still in a liquid form) in the annulus around the conductor, where the cement will set. The conductor then forms a structural foundation for the rest of the well. When the second and subsequent hole sizes are drilled deeper, the same process of lowering a pipe into the hole and cementing it is used to construct the well. These pipes are referred to as casing. The casing points (at which the lowest part of the casing is positioned) are selected not only to avoid collapse of the hole, but also to ensure that the drilling is performed safely and that there is no uncontrolled release of formation fluids from the well. There are many other factors which determine when a casing should be run, but a primary reason is in order that the formation fluid pressures (in porous rock, which can contain hydrocarbons at high pressure) are contained in the well by the hydrostatic pressure imposed by the drilling fluid, due to the drilling fluids density. In order that the formation fluids are contained in the well, the casing has to be specified and designed in order that it has the material strength to hold back the formation pressure if there is unplanned flow from the well (referred to as a kick) and the casing scheme discussed below addresses this and other issues. Note also that the casing comes in standard lengths that require connecting together. These connections are also referred to below (e.g. DINO VAM and VAM TOP HT which are proprietary connection designs from particular manufacturers).

The casing scheme selected during the FEED stage is outlined below:

- 30in x 20in Conductor;
- 13-3/8in Surface Casing;
- 9-5/8in Intermediate/Injection Casing; and
- 7in Injection Casing.

16.5.5.3 Conductor Concept Selection

The conductor scheme selected during the FEED stage would be adequate for the design; it is detailed in the Well design rational.

30in x 1in API 5L X52/X56 conductor pipe has been used in many of the deep water platforms with more highly preloaded connectors such as GE/Vetco SR-20 and Oilstates Merlin. These are metal to metal sealing connectors and are more suited to long term fatigue applications.

In common with other suppliers, Oilstates offer a range with various ODs and IDs to be compatible with API pipe, plus versions designed to be driven. These would have an even higher rating in compression.

Since these wells would be slim hole, it may be possible to use 26inOD x 1.25inw.t. X52/X56 pipe with suitable fatigue resistant connections. The 26in conductor can be configured at the cellar deck to allow use of the same diverter and wellhead running sequence as the 30in pipe. At the bottom end, the conductor shoe joint would be swaged to 20ft of 20in casing with a 20in float shoe to allow clean drill out at the start of the 17½in diameter section of the hole.

For long term use, it would be advisable to have the joints from just below the seabed to the cellar deck coated in either thermal sprayed aluminium (TSA) or epoxy coated. The joints below seabed need not be coated. Heat shrink sleeves are available to mould around made up connectors, but these tend not to be used. This is mainly due to the probability that they would get damaged running through the conductor guides and also due to the problems removing the sleeves should the conductor need to be pulled and re-run.

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It would be beneficial to incorporate a small funnel on the bottom side of the conductor guides as well as a larger funnel on the upper side. This would allow cleaner passage of any drift or drilling assemblies and, if necessary, the recovery of conductor through the guides.

Although the wells are fairly shallow, the downward load on the conductor due to casing strings, the upper completion, wellhead and Christmas tree may cause the conductor to elastically buckle into the guides.

Any fatigue study of the conductor and connections would be likely to recommend that the pipe is well centralized in the conductor guides. However, if close fit centralizers are fitted to the pipe during running then there may be enough built-in interference between the centralizers and the platform guides to prevent the conductor being run to depth. Should excessive vibration occur after the conductor is installed, it may be that centralizers are required to be fitted in the guides. These would be split centralizers which could be fitted by an engineering contractor in any accessible guides above the water line. Retrofitting centralizers below water line may be more problematic. Provided the guide IDs were made to a fairly tight drift tolerance, then the running clearance between the conductor and the guides may be small enough to negate the need for retrofit centralizers. If this is the case then an under reamer would need to be used to open out the top hole for running conductor. Any buckling due to top weight could close any clearance at the guides and be beneficial to fatigue life.

It would also be sensible to try and avoid placing a connector at the splash zone and to ensure that any long term annulus fluid within the conductor are dosed with inhibitor to limit the risk of corrosion at the connectors from the inside.

Risks:

- platform guide drift diameters and alignment would be well defined in order to allow trouble free top hole drilling and conductor installation whilst minimizing clearances;
- long term fatigue life and long term corrosion, although existing standard equipment would be deemed adequate;
- impact damage at guides due to wave action and large clearances; and
- increased hydrodynamic drag over time due to marine growth.

16.5.5.4 Cement Concept Selection and Cement Verification

As previously mentioned, cement is used to bond the casing to the formation. Cement performs various tasks, such as zonal isolation, supporting the casing mechanically and other functions. The cement is mixed at surface and pumped down the well, but with the objective that the cement ends up in the annulus between the casing and the previously drilled open hole. The mixed cement is referred to as slurry, which has various properties (such as thickening time and compressive strength) which are reported in the following discussion. Typically the cement is pumped into the casing with a wiper bottom plug ahead of the slurry and a wiper top plug behind the slurry, after which displacement fluid is pumped to place the cement where it is required. The wiper plugs literally wipe the inside of the casing but also separate the displacement fluid from the cement in order that contamination of the cement is avoided.

16.5.6 Proposed Annual CO_2 Injection Rate, Duration and Total to Be Stored (K.30)

16.5.6.1 Design Flow Cases

Throughout the design life of the CO_2 transportation system, the anticipated flow rates will increase, as the number of power plants that capture carbon, using various technologies, become operational and start producing carbon dioxide for storage offshore.

The CO_2 transportation network is expected to develop in production over time and the predicted flowrates are shown in Table 16.3.

Table 16.3: Predicted Development of CO_2 Transportation System

	Year 1 (First Load)	Year 5	Year 10
Flow Case	MTPA	MTPA	MTPA
Design	2.68	10.0	17.0
Normal	2.31	10.0	17.0
Minimum	0.58	0.58	0.90

16.5.6.2 Feed Composition

The operational objective of the onshore transport system is to maintain the CO_2 stream in the dense phase from the tie-in point with the Drax OPP through to the injection wells at the offshore platform.

As detailed in the Basis of Design (K.02) the CO_2 captured, transported and stored across the End-to-End chain would comply with composition limits defined by the technical requirements of the transportation system and offshore storage facilities. The first load composition is expected to contain >99.7% CO_2 and up to 10ppmv of oxygen (O_2) and 50ppmv of water (H_2O) with the remaining balance of composition comprised of nitrogen (N_2) and argon (Ar). The first load CO_2 composition in year 1 is given in Table 16.4.

Table 16.4: Year 1/First Load Expected CO_2 Composition

Component	Volume %
CO_2	99.700
Ar	0.068
N_2	0.226
O_2	0.001
H_2O	0.005

Since small levels of impurities significantly impact the properties and phase envelope of pure CO_2 making it difficult to predict its behaviour over an anticipated operating envelope, a CO_2 transportation pipeline composition specification has been developed.

The entry specification applies to the offshore storage system and provides the permitted limits for each component relative to the following criteria:

- safety design;

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- Integrity design; and
- hydraulic efficiency.

The safe operating limit of the composition has also been investigated and comprises:

- a saturation pressure for the CO_2 rich mixture of no more than 80barg: and
- the individual maximum allowable component levels defined in the specification for CO_2 quality requirements.

A summary of the composition specification is shown in Table 16.5 below.

Table 16.5: Export System Entry Requirements

Component	**Limiting Criteria (Volume %)**		
	Safety Max	Integrity Max	Hydraulic Efficiency
CO_2	100	100	96
H_2S	0	0.002 (Note 1)	0
CO	0.2	0	0
NO_x	0.01	0	0
SO_x	0.01	0	0
N_2	0	0	(Note 4)
O_2	0	0.001 (Note 2)	(Note 4)
H_2	0	0	(Note 4)
Ar	0	0	(Note 4)
CH_4	0	0	(Note 4)
H_2O	0	0.005 (Note 3)	0

Notes:

1. National Association of Corrosion Engineers (NACE) limit for dense phase CO_2 at a total pressure of 150barg. Specified to avoid requirement for sour service materials.
2. Maximum oxygen content (10 ppmv).Specified to avoid material selection issues in the well tubing, where the dry CO_2 contacts saline aquifer water.
3. Maximum water content (50 ppmv). Specified to ensure no free water occurs during normal or transient operations.
4. The allowable mixture of non-condensable components in the CO_2 stream must be:
   Gaseous Phase: $N_2 + O_2 + H_2 + CH_4 + Ar \leq 9.0$ vol%
   Dense Phase: $N_2 + O_2 + H_2 + CH_4 + Ar \leq 4.0$ vol%, with H_2 no greater than 2.0%

The composition of the CO_2 is expected to change beyond the first year of operation of Drax and the CO_2 transportation network, even if the only source of captured CO_2 is from an oxyfuel technology power plant. Two compositions are proposed; see Table 16.6, to cover the possible range for the future operation of the CO_2 transportation system. Note that HYSYS is an oil and gas process simulation software that enables the optimisation of conceptual design and operations.

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Table 16.6: Anticipated Year 5 and Year 10 Future CO_2 Compositions

Component	Year 5 and 10 / Future – Generic Composition	Year 5 and 10 / Future – Sensitivity Composition HYSYS (Note 1)	Year 5 and 10 / Future – Sensitivity Composition non-HYSYS (Note 2)
	Volume %	Volume %	Volume %
CO_2	97.400	96.000	96.000
Ar	0.599	0.411	0.407
N_2	1.995	1.371	1.355
O_2	0.001	0.001	0.001
H_2O	0.005	0.005	0.005
H_2	0.000	2.000	2.000
H_2S	0.000	0.002	0.002
CO	0.000	0.200	0.200
NO_x	0.000	0.010	0.010
SO_x	0.000	0.010	0.010
CH_4	0.000	0.010	0.010

Notes:

1. The maximum specification for NO_x and SO_x is 100ppmv each (0.01vol%). However, these two components are not available for use in the GERG2008 fluid package specified for the HYSYS simulation work (the GERG2008 is an equation of state used for modelling CO_2 with impurities flow assurance studies). These have therefore been omitted from the HYSYS composition for the purposes of steady state modelling.
2. The non-HYSYS composition specified should be used for any other simulation work required for the FEED, for example, Flow Assurance, and where the software permits the use of NO_x and SO_x.

16.5.6.3 Impact on CO_2 Properties Due to Impurities

The impacts of various components on pure CO_2 properties are summarised in Table 16.7.

Table 16.7: Contaminant Components and Their Effect on Pure CO_2 PropertiesComponent	Effect
H_2S	Minimal effect on the phase behaviour of CO_2, but it does lead to sour corrosion within the pipeline
CO	Decreases density and viscosity
NO_x	Increases density and viscosity
SO_2	Increases density and viscosity
N_2	Decreases density and viscosity, more so than O_2. Expansion of the phase envelope, may increase the size of the two phase region and affects hydraulic efficiency
O_2	Decreases density and viscosity, affects hydraulic efficiency, may increase the size of the two phase region and may cause corrosion problems within the well tubing when contacting saline water
H_2	Decreases density and viscosity, more so than N_2 and raises saturation pressure and affects hydraulic efficiency
Ar	Decreases density and viscosity, similar to N_2. Hydraulic efficiency is affected and may increase the size of the two phase region

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Table 16.7: Contaminant Components and Their Effect on Pure CO_2 PropertiesComponent	**Effect**
CH_4	Decreases density and viscosity, similar to N_2. Hydraulic efficiency is affected and may increase the size of the two phase region
H_2O	In high enough concentrations H_2O can cause corrosion and, under certain conditions, form solid hydrates in the system.

Various carbon capture technology CO_2 product stream compositions were also studied:

- pre-combustion CO_2 product streams demonstrated the greatest divergence from the phase envelope of pure CO_2 when compared to other technologies, due to the high levels of H_2 in the composition;
- the addition of impurities within the CO_2 stream will affect the hydraulic efficiency of the offshore transportation system; and
- for a given flow rate, the pressure drop within the pipeline increased, meaning that a greater upstream pressure was required.

At the storage site, the mass flow injected to the wells will be reduced, for a given differential pressure between the offshore pipeline and reservoir, when the CO_2 stream contains additional impurities. Storage capacity may be impacted by non-condensable components occupying space.

The increase of impurities expands the phase envelope. In particular non-condensable components such as hydrogen, increases the possibility of moving to two-phase conditions; a region with gas and liquid coexisting; reducing the operational area for the pipeline, restricting pipeline operations, which in turn can reduce the operating range for emitters in order to keep out of the two-phase region. Operating within the two-phase region is to be avoided due to the high likelihood of operational instability.

16.5.7 Storage Development Concept

The storage development concept, the operation, control and management of the Endurance storage site and storage complex follows the DIRECTIVE 2009/31/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 and its related Guidance for Implementation.

The Guidance Document 1 (GD1) addresses the overall framework for geological storage in the CCS Directive for the entire life cycle of geological CO_2 storage activities including its phases, main activities and major regulatory milestones. The most important issues dealt with is the high-level approach to risk assessment and management which is intended to ensure the safety and effectiveness of geological storage, and the processes by which the Competent Authority or Authorities (CA or CAs) in each Member State can interact with the operators at key project stages. This is termed the ‘CO_2 Storage Life Cycle Risk Management Framework‘.

With the initial characterisation of the storage complex complete, the independent storage quantitative risk assessment (Storage risk Assessment) thereby underpins development of the day-by-day operation plan and the preparation and execution of the associated plans for the Measurement, Monitoring and Verification (MMV) Plan and the Corrective Measures Plan.

16.5.7.1 Storage Risk Assessment (K.42)

The purpose of the risk assessment is to analyse the risks associated with underground aspects of CO_2 storage throughout the lifecycle of the project and demonstrate that the risks are low and/or can be adequately managed by NGC's subsurface CO_2 storage activities at the Endurance site.

The risk assessment has been undertaken using a 'top down' approach accompanied by development of a robust audit trail, with the aim of facilitating the communication of outcomes and transparency of rationale to the benefit of all parties.

The risk assessment used a system description prepared from the full storage complex appraisal and characterisation analysis and studies commissioned by NGC including but not limited to:

- data acquisition, including seismic data and information from new and legacy boreholes;
- geological interpretations;
- reservoir simulations;
- geochemical investigations; and
- geomechanical investigations.

The assessed risks were divided into two categories:

- risks to the protection of human health and the environment; and
- risks to the permanent containment of CO_2 within the defined storage complex.

It addressed the subsurface aspects of the project, in particular:

- the storage site; the defined volume within Endurance used for CO_2 storage and associated wells and pumps;
- the storage complex; which includes the storage site, the associated infrastructure; injection wells, appraisal wells, legacy wells and the surrounding domains that may be impacted by leaking CO_2, displaced natural formation fluid and physical disturbances to the solid geosphere (these domains are between the Top Rotliegend c. 2900 to 3650m to the top of the Lias formation c. 50 to 60m);
- the pre-existing formation fluid, which will be displaced by the injected CO_2 and which will interact with the CO_2 by:
    - Dissolving in the dense CO_2 stream, leading to desiccation and possibly salt precipitation from the residual brine (likely to be close to the injection wells); and
    - Dissolving the CO_2;
- injection boreholes and associated infrastructure;
- legacy boreholes that might be contacted by any migrating or leaking CO_2;
- actual and potential economic assets adjacent to the storage complex that might be impacted by any CO_2 that unexpectedly leaks; and

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- the ecosystems in the region surrounding the storage complex that might be affected by any CO_2 that unexpectedly leaks or pre-existing formation fluids, that are caused to flow as a consequence of CO_2 injection.

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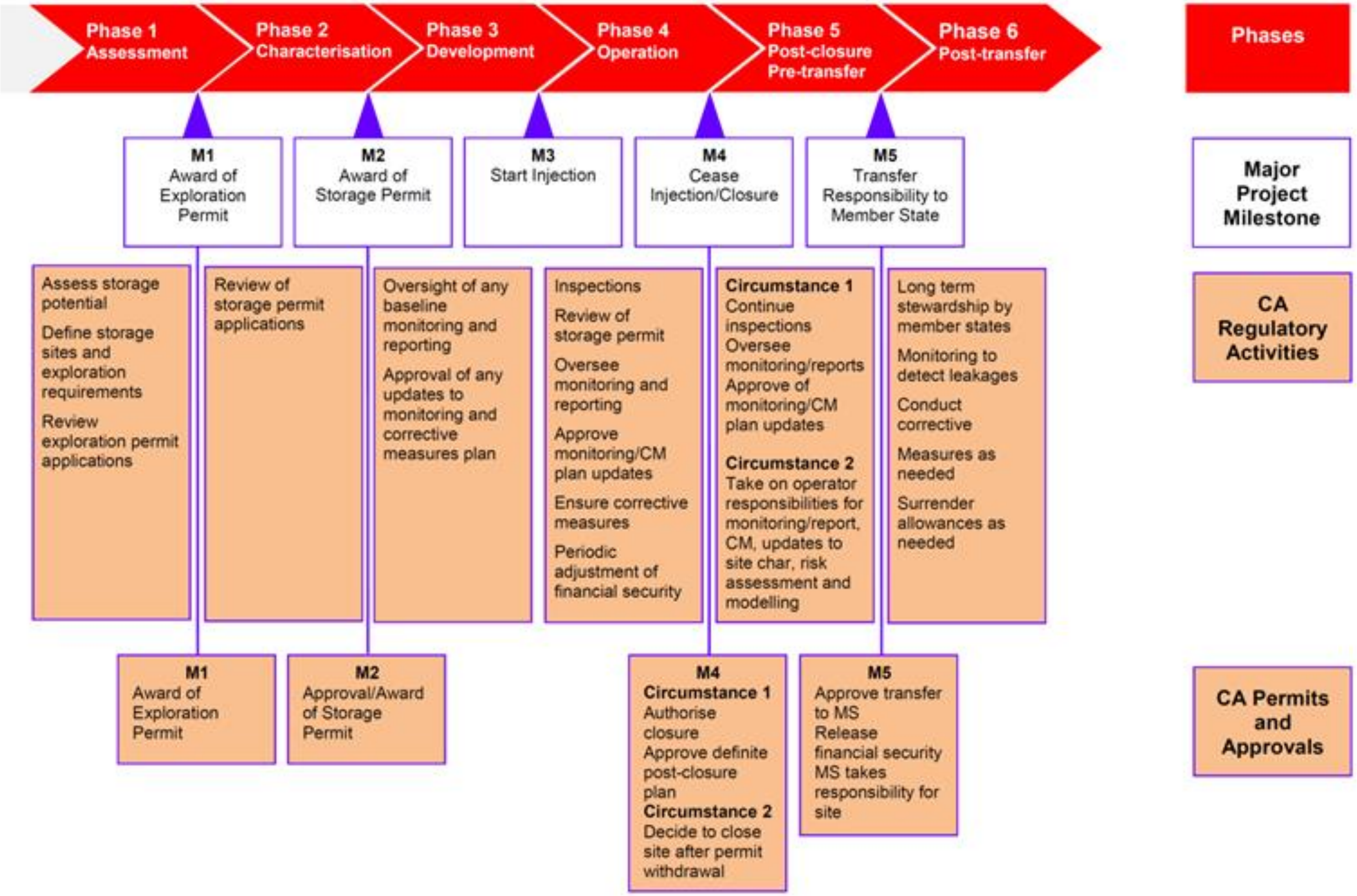
Figure 16.5: Summary of CO_2 Storage Lifecycle Phases and Key Milestones (after EC, 2011)



The following timeframes were considered (as illustrated in Figure 16.5):

- between two and three years from phase 2, covering activities during storage system characterisation and development operations (phases 2 and 3 in Figure 16.5) that are likely to affect the risks following the start of CO_2 injection;
- from c. 20 years after the start of injection, until the end of CO_2 injection operations (phase 4 in figure 16.5);
- an unspecified period between the end of CO_2 injection and responsibility for the CO_2 store being transferred from NGC to DECC (the competent national authority under the terms of 2009/31/EC CCS Directive);
- a few thousand years following the transfer of responsibility for the CO_2 store to DECC;
- the period for timeframe 3 is not well-defined but, in accordance with 2009/31/EC CCS Directive, sufficient for it to be shown that the stored CO_2 will be completely and permanently contained; and
- the period for timeframe 4 is open-ended but, in accordance with the 2009/31/EC CCS Directive which requires the CO_2 to be permanently contained it will be long enough that the storage system has become stable and its risk profile will not change. Such a timescale is likely to be many 1000s of years; Lindeberg (2002) calculated that to prevent climate change CO_2 should be retained in underground reservoirs for at least 10,000 years.

The end-point of the assessment was to present an assessed level of confidence that the storage system will perform as expected and that risks and impacts are low and therefore acceptable. Specifically the assessment addresses Article 18, Point 1 of the 2009/31/EC CCS Directive by:

- providing evidence that the projected volumes of CO_2 to be injected will be stored safely and completely and permanently contained; and
- stating risks to complete and permanent containment (as a basis for developing monitoring and mitigation plans), including risks of exceeding any pressure limits and thereby threatening the maintenance of site integrity.

The assessment also contributed to addressing Article 19, Point 2 of the 2009/31/EC CCS Directive by providing evidence that the storage site will evolve towards a situation of long-term stability following the completion of CO_2 injection.

16.5.7.2 Storage monitoring and Reporting (K.42)

Monitoring and reporting of the storage site and storage complex is effected by the MMV Plan. The MMV Plan is provided to ensure that the parameters of the Endurance Storage Site and Storage Complex are adequately recorded in order to ensure conformance to predicted behaviour and to verify containment of stored CO_2. The monitoring and measurement is designed to provide for the early detection and recognition of irregularities and thereby initiate contingent actions to be taken on their occurrence according to the Corrective Measures Plan.

The MMV Plan has been developed based on the characterisation of the Storage Site and Storage Complex and on the independent Storage Complex Risk Assessment, and in accordance with National Grid's Environmental Policy to protect and enhance the environment. In addition, the proposed MMV Plan has been designed to adhere to Environmental Legislation - specifically, the requirements of The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010 (2010 No. 2221), for monitoring, reporting and notification.

The MMV Plan will be subject to annual reporting but will also require updates which will be presented at least annually during the operational phase. The purpose of the updates to the Plan is to ensure that the most recent developments in methodology, data interpretation and technology are used whenever appropriate to ensure conformance and containment. The review and update process requires the Plan to be continuously challenged and amended whenever necessary. Updates will be provided not only during the period of active injection but also during the post-injection and post closure periods. The MMV Plan will be reviewed, revised and issued for the start of the operational phase once the pre-injection baseline surveys have been recorded and the three injection wells drilled and evaluated. After site closure and the permanent removal of the injection facilities, the ownership of the storage site will pass to the Competent Authority in the UK. In line with current regulations, this transfer of ownership is accompanied by a financial contribution from the storage operator to the Competent Authority to fund the monitoring activities for at least 30 years. The monitoring activities after transfer will reflect the monitoring technologies used and the data obtained up to this time and the monitoring activities of the Competent Authority will proportionately decrease throughout these 30 years.

Containment

The Endurance Storage Complex is designed for the permanent secure containment of CO_2. The risks to containment are a major consideration for the MMV Plan to ensure that any Significant Irregularity can be detected as early as possible and the associated Corrective Measure determined. To ensure that all the threats to containment have been identified, the risk assessment details the various databases of features, events and processes have been interrogated and both expected and alternative evolution scenarios that arise have been audited against these carbon capture and sequestration databases.

The overall conclusion of the risk assessment process is that it provides a high level of confidence that permanent containment of the CO_2 planned to be stored will be achieved, and the system will evolve to long-term stability. Risks to human health or environmental receptors associated with loss of containment (in the unlikely event it occurs), displacement of brine and deformation, are either low or very low.

Containment focuses on the fact that the injected CO_2 should remain in the Bunter Sandstone Formation and within the Storage Complex for long term storage. Containment is a safety critical risk and therefore as a key part of the Risk Assessment, a containment ‘bowtie’ has been developed and is fully reported therein. With it, the potential risks to CO_2 containment (lack of containment of the volumes planned to be stored) are identified and these, along with their escalating factors, are:

- leakage through existing boreholes (legacy wells) and new wells (injectors). Escalation factors are:
    - Induced seismicity damages/bypasses plugs and seals; and
    - sabotage to wellheads;
- Leakage through caprocks/seals with escalation factor:
    - Induced seismicity created new faults/fractures;
- Leakage due to unintentional human intrusion;

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- Lateral leakage of free or dissolved CO_2;
- Accidental overfilling;
- Pressure changes due to nearby resource exploitation; and
- Required injectivity (planned volumes) cannot be injected due to physical or geochemical changes.

And the potential consequences are:

- observable/significant loss of containment;
- observable/significant impact on environmental receptors in the seabed and/or the seawater column;
- observable/significant impact on hydrocarbon resources; and
- required capacity cannot be accessed.

Conformance

During the operations phase, under normal operation conditions, containment is assured and the focus of the MMV programme is to prove conformance. Conformance means that the Storage Complex is behaving in a predictable manner and is fully consistent with the subsurface model.

In case of any inconsistencies, or if any significant discrepancy exists between the model based assumptions, the response of the Storage Complex or the observed migration of the CO_2 plume, these inconsistencies will require explanation and possible revision, including history matching, of the subsurface models.

The potential consequences associated with the loss of conformance are:

- the containment risk changes;
- changes to the duration of post injection and post closure phases;
- changes to conditions for transfer of the Storage Complex to the Competent Authority; and
- changes to the storage efficiency and capacity of the Storage Complex.

In each case, the consequences may be positive or negative with regard to the operation of the Storage Complex and hence the importance of the frequent and regular review and updates to the MMV Plan. The potential threats towards demonstrating conformance are either because the original modelling is not correctly predicting the performance of the Storage Complex or that there are errors from the monitoring. These monitoring errors can arise due to bias in the acquisition or systematic processing or interpretation errors.

Therefore, conformance is to verify storage performance by confirming that the Storage Site is responding to the injection and migration of CO_2 in a predictable manner and to calibrate and revise performance predictions provided by subsurface modelling on the basis of measured parameters.

MMV Plan Design Framework

The framework for the preparation of the MMV Plan is the relevant UK legislation and the Storage of Carbon Dioxide (Licensing etc.) Regulations 2010 (2010 No. 2221). It also considers the EU Directive and associated Guidance (Ref. 2) and further reference is made to international recommendations including:

- Greenhouse Gas Inventory Guidelines (IPCC 2006);
- IEA Greenhouse Gas Research and Development program;
- Risk Assessment - Quintessa 2004;
- Monitoring Tool selection – IEA 2006;
- Site Selection, Characterisation and Qualification (DNV 2010); and
- World Resource Institute (WRI 2008).

The monitoring and measurement programme will be adapted via the annual update and review process according to the performance of the Storage Complex, revised forecasts and the possible introduction of new technologies, data acquisition and interpretation.

The design principles for the MMV Plan adhere to the following order of precedence:

- protection of human health and safety;
- protection of ecosystems and the environment;
- protection of physical assets;
- reputation and confidence in greenhouse gas sequestration; and
- facilitation of cost effective and cost beneficial systems.

They also will apply the following principles:

- comply with the latest regulatory standards and prevailing industry best practise;
- establish thresholds, trigger points and actions for the detection of and the response to irregularities;
- select monitoring and measurement components that will mitigate risk to as low as reasonably practicable (ALARP); and
- select monitoring and measurement components intended to manage aspects that are not critical to health, safety and the environment on the basis of technical feasibility and the economic value of data acquisition.

The equipment, technologies and the methodologies of the plan address the risks of the project through its four phases. Various technologies are proposed for inclusion within the MMV Plan but, the most important aspect of the plan is its annual update, where new technologies might be introduced if they provide an improved definition of conformance or containment.

The conformance of the Storage Complex is based on the dynamic and geomechanical modelling. Not only do these models have to be calibrated with data as it is received through the life of the project but the drilling and evaluation of the three injection wells will also provide substantial additional data that will drive a revision of the models and a review and possible update to the Risk Assessment.

16.5.7.3 *Corrective Measures Plan (K.42)*

Corrective measures are intended to ensure the safety and effectiveness of geological storage. Therefore, the corrective measures plan is part of the overall risk management process that is intended to ensure the safety of geological storage and to manage the risks from leakage during the project life cycle. The plan is activated by the recognition of significant irregularities under the monitoring regimes of the MMV Plan.

The plan is site and complex specific; it is risk based and linked to risks, which were identified from site characterisation, to risk assessment and to the MMV plan and subject to the limitations of available measurement and monitoring technologies.

The priorities for the corrective measures plan are ranked in the following order:

1. prevention of risks to human health;
2. prevention of risks to the environment; and
3. prevention of leakage from the storage complex.

The definitions relevant to the corrective measures plan are:

- significant irregularity: any irregularity in the injection or storage operations or in the condition of the storage complex itself, which implies the risk of a leakage or risk to the environment or to human health;
- leakage: any release of CO_2 from the storage complex; and
- storage complex: the storage site and surrounding geological domains that can affect overall storage integrity and security.

The risk assessment has identified a total of 18 risks to the operation of the injection and storage. These are listed below and complete descriptions, along with expected and alternative evolution scenarios, are fully documented in the risk assessment:

- physical uplift of the seabed*;
- lateral migration of dissolved CO_2 out of storage complex;
- induced seismicity*;
- natural seismicity*;
- reduced injectivity due to chemical changes/reactivity*;
- resource exploitation elsewhere disturbs CO_2*;
- interaction of CO_2 storage with other resources*;
- sabotage of wellheads;
- leakage through caprock/seals;
- lateral migration of free CO_2 out of storage complex;
- displacement of higher salinity waters and interaction with benthic or pelagic biota*;
- physical/chemical conditions prevent required capacity being accessed*;
- overfilling (attempted storage of substantially higher volumes than authorised);
- reservoir pressurisation/compartmentalisation*;
- failure of historical (legacy) well seals;

- failure of injection well seals;
- inadvertent human intrusion leads to leakage; and
- tectonic processes disturb CO_2.

*Note: risks identified, do not have the potential to cause leakage of CO_2 and therefore are not considered to contribute to or constitute a significant irregularity.

Risks that do not have the potential to cause leakage of CO_2 from the Endurance storage complex are not considered further and the remainder are classified below both according to their probability of occurrence and according to whether or not their consequence would be detrimental to one or more receptors and would not call into question the effectiveness of the Endurance CO_2 storage as a contributor to mitigating climate change:

Risks sub-divided according to probability and consequence:

- Almost certain not to occur but with observable detrimental consequence:
    - Failure of historical (legacy) well seals;
    - Failure of injection well seals; and
    - Inadvertent human intrusion;
- almost certain not to occur but with detrimental consequence that would not be observed:
    - overfilling;
- almost certain not to occur but with no detrimental consequence:
    - sabotage;
    - leakage through caprock/seals;
    - CO_2 disturbed by tectonic processes; and
    - lateral migration of free CO_2 out of the storage complex; and
- almost certain to occur but with no detrimental consequence:
    - lateral migration of dissolved CO_2 out of the storage complex.

In order to be included as significant irregularities, the consequence of the risk events need to be detected by MMV plan technologies. The latter two categories have consequences that are generally below the detection threshold of the MMV plan and therefore, even if they were to occur, with the exception of the special case of sabotage, their consequences would not be detected. The consequence of sabotage, which in any event can only occur during the operational phase, would not cause leakage due to the reaction of the system to close the subsurface safety valves which are specified to be installed in all the injection wells.

Overfilling, which would be immediately detected by the MMV plan's inventory measurement, would have to take place on a massive scale in order to cause any detrimental effect and become a significant irregularity as a result neither needs to be considered with respect to the corrective measures plan.

The corrective measures plan therefore addresses three significant irregularities:

- failure of historical (legacy) well seals;
- failure of injection well seals; and
- inadvertent human intrusion.

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Failure of Historical (Legacy) Well Seals

The mechanisms and processes that would cause a failure of historical well seals are extensively discussed and modelled in the QRA. Of primary importance is the consideration that in order for a leakage to occur, multiple barriers have to fail and it is the presence of these multiple barriers that control the flux of a leakage to very low levels.

Corrective Measure: should there be a leakage via the multiple seals that are associated with these wells that results in the detection of CO_2 at the seabed, the flux of the leak firstly needs to be quantified. Depending on this quantification; appropriate corrective measures will be proposed in consultation with the competent authority.

Failure of Injector Well Seals

The failure of injector well seals fall into three time frames:

1. during the operational phase;
2. during well abandonment; and
3. after closure.

During the Operational Phase: in order for leakage to occur during the operational phase when injection is ongoing, multiple barriers need to be breached. The wells are designed with a minimum of two barriers both of which need to be breached before any leakage can occur. Once the first of two barriers are breached, the instrumentation deployed under the auspices of the MMV plan will detect the anomaly and the necessary remedial actions can be taken before the second barrier is compromised. Each of the barriers will be designed to be capable of containing the worst case leak and no possibility exists of an uncontrolled leakage. Affected wells will be shut in for investigation and determination of appropriate remedial actions.

No further corrective measure is required for injection wells during the operational phase.

During Well Abandonment: in order for a leakage to occur during well abandonment operations, a major breach of standard operating procedures must take place. At all times, a minimum of two barriers must be in place and the systems are designed so that any failure of a barrier is immediately detectable. Once a failure is detected, standard operating procedures will be implemented to remedy the failure.

No further corrective measure is required.

After Closure: free CO_2 is only present for a limited time after closure as the injection wells are down a dip and the CO_2 cap will migrate to the crest of the structure. The injection wells will be constructed of CO_2 corrosion resistant materials and, as in the case of the crestal legacy wells, multiple seals must be breached in order for a leak to occur.

The corrective measure will require that a mudline suspension or similar device will allow the re-establishment of a pressure connection to the intermediate and production casing so that the well can be re-entered and any leak paths present can be sealed.

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Inadvertent Human Intrusion

In order that inadvertent human intrusion occurs it is necessary to postulate that at some time in the future, all records of the Endurance store have been lost and that there is also an attempt to drill an exploration type well. It is further necessary to assume that the well intercepts the free CO_2 trapped at the top of the anticline which could result in release of CO_2 gas to the atmosphere if preventative drilling practices are not adopted, or if there is some failure in equipment or operational procedures designed to prevent gas leakage. It is reasonable to assume that if the 'explorers' have the technology to drill into the storage complex, they would likely have the technology to successfully seal the well.

No corrective measure for this potential significant irregularity is planned.

The corrective measures plan is not a static document. During detailed design, implementation and during annual updates that address the risk assessment and MMV plan, it will be challenged and amended as necessary.

16.5.7.4 Decommissioning / Abandonment Plan

Overview

Shut down and decommissioning of the CO_2 transport and storage system will not be a routine operation. When carrying out this type of operation involving hazardous plant, processes and substances, which will typically not have been conducted before or be covered by existing site procedures, there will be a detailed safe system of work .

The Need to Monitor

Monitoring is essential to identify and quantify potential risks to humans and the environment and to provide verification that the CO_2 injection profile is being maintained as expected. The aim would be to prove that the containment and conformance during the injection phase of the project meets expectation and subsequently that the CO_2 would be permanently contained post-injection and post-closure.

Observing the migration of the CO_2 plume to ensure that it does not leak would be essential. Data collected at the beginning of the project would help improve the project model to predict long term behaviour and performance. Beginning with site characterisation prior to CO_2 injection, baseline measurements would be obtained and evaluated again once injection commences. Monitoring would continue through the entirety of the injection phase focusing on reservoir properties and ensuring total containment of the CO_2. The data collected whilst monitoring injection would be able to provide measurements of injection rates and various pressures surrounding the wellbore. Seismic events may occur after injection activities cease, therefore, it is important to continue monitoring into the post-closure phase.

Subsurface monitoring would be crucial in identifying the CO_2 plume location, any changes in seal integrity and reservoir differences once injection commenced. Deep focused monitoring methods would be used to identify and characterise changes occurring within the storage reservoir including the movement of the CO_2

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plume and migration. Shallow monitoring systems would be used to detect and measure any CO_2 that has migrated up to the seabed or into shallower formations.

Selecting the right monitoring equipment based on the characteristics of both the reservoir and storage site would be critical in order for a successful programme.

Monitoring Techniques Overview

From near surface monitoring to gathering data deep into the subsurface, reputable and well proven technology is available. Geophysical, geochemical, in-well and near-surface monitoring are all types and categories that exist. Geophysical monitoring uses tools that provide images for assessing physical changes throughout the subsurface, whilst geochemical monitors the actual chemical changes in the subsurface by means of collecting fluid samples from the well and analysing them onshore.

Various established and reliable monitoring methods and tools are offered in today’s market. Tools can be advantageous for many reasons including sensitivity, reliability, continual monitoring, and narrowly focused vs. more wide spread measurements. A leak could initially be very small and in order to identify it quickly, tools that can pinpoint small changes in behaviour from a wellbore are needed. Comprehensive monitoring inclusive of not only intermittent techniques, but continuous is beneficial as a leak may vary with time and might be missed by a one off measurement or assessment. A combination of monitoring systems would be used in order to obtain the benefits of each depending on the area of focus, spatial coverage, resolution and overall costs.

Well Design

The well design has been kept simple so as to facilitate secure permanent abandonment. Dry trees (well head at or above the sea surface) will be used and well inclination will be limited to 60°, which will allow sufficient bottom hole well spacing to prevent significant injection interactions, whilst still allowing wireline entry. The deepest that injection will occur is approximately 30m above the containment spill point, whilst the shallowest injection depth has not been fixed.

A 9⅝in, 53.5lb/ft, L80, VAM TOP production casing string will be run and set +/- 20m above the Rot Clay cap rock in the Rot Halite formation at ±1173mTVDSS (±1646m MDBRT). The 9 ⅝in will cover most of the potential mobile salt sections allowing the Rot Halite, Rot Clay and Bunter Sandstone to be cored. It will also provide a production conduit with sufficient burst, collapse and tensional strength to withstand the pressure experienced during the CO_2 injection phase. The casing setting depth can be moved higher up the well, in the Rot Halite, if future abandonment requirements (for improved store integrity to CO_2 leakage) dictate the need for a larger cement plug above the Rot Clay cap rock.

Well abandonment is being optimised for CO_2 storage. This includes both the choice of cement that will be used to plug the wells, but may also involve casing removal. The casing may be removed by milling to allow the plugs to be placed in direct contact with the rock. This removes the risk of an open annulus between the casing and plug. If the plug is in direct contact with the Röt halite, creep of the halite against the plug will act to maintain a good seal. The casing might also be removed in a section of the Röt halite without plugging, thereby allowing the halite to fully creep and close the hole.

Responsibility Transfer

The immediate post-closure/pre-transfer phase is defined in 2009/31/EC CCS Directive, during which the storage system will be monitored. The time is imprecisely defined, but will last until the competent authority, DECC, is satisfied that the stored CO_2 is evolving in line with expectations and moving towards a state of greater stability (risks, initially very low anyway, are continuing to decrease).

Injection will cease at the start of the short term post closure phase, but the wells may not be plugged and abandoned until the end of this phase so they can be used for monitoring. The abandonment process will include installation of plugs designed to fulfil the long-term sealing requirements. CO_2 will rapidly migrate away from the injection wells, but some will have dissolved in the pore water close to the injection well. Therefore any plugs within the reservoir may encounter acidic conditions, but it is assumed that the materials chosen can withstand acidic conditions.

If no significant deviations are experienced during the post injection period, it is unlikely that any will be detected during the post abandonment period as the pressure will continue to drop and the integrity of the storage site and storage complex will increase, not only from the decaying pressure but also from the permanent abandonment of the injection wells removing the possibility of well failure from the alternative evolution scenarios.

For the longer term, the post-transfer of responsibility phase is defined in 2009/31/EC CCS Directive. The time period is imprecisely defined, but will be several thousands of years.

The fully history matched simulation will be used to predict the rate of decay of the average reservoir pressure after injection ceases. If the pressure decay trajectory does not match the prediction it may be necessary to increase the post-injection duration before the decision is made to abandon the injection infrastructure.

16.5.7.5 Development Concept and Wells

The storage site is in the Triassic Bunter sandstones in the Endurance structure which is a four-way dip-closure approximately 22km long, 7km wide and over 200m thick located some 60 miles east of Flamborough Head. The Bunter sandstones in this area are saline aquifers. The crest of the storage site is located at a depth of 1020 m below the sea bed in a water depth of between 50 m and 60 m. Reservoir datum pressure and temperature (at 1300m TVDSS) are 140.0bar and 55.9°C, respectively. The primary seal is provided by a layer of mudstone called the Röt Clay. This in turn is overlain by a salt layer, known as the Röt Halite which is consistently more than 90 m thick and at the base of the 900 m thick Haisborough Group which provides additional multiple secondary sealing capability.

The Bunter sandstone within the structural closure (the “Storage Site”) is estimated to have a net pore volume of over 4.6 Bm^3 and the total of up to 53.6MT of CO_2, planned to be captured from the OPP over 20 years, will occupy approximately 2% of this volume.

The characterisation of the Storage Site and Storage Complex relies on regional seismic and well data. There have been three wells drilled on the structure, two are abandoned hydrocarbon exploration wells, the third was a dedicated CCS appraisal well drilled by CSL in 2013 which undertook a comprehensive data acquisition and evaluation programme designed to quantify and characterise various aspects of the structure for its use for permanent secure CO_2 storage.

For the performance of the Storage Site and Storage Complex under operating conditions, extensive use of simulation and modelling is required in order to reliably predict the outcomes of the complicated and inter-related effects. The modelling uses separate platforms for the different sections and each subsequent platform uses the output of preceding stages. The order of precedence of the models used for the characterisation of the Endurance Storage Site and Storage Complex is as follows:

- Static Geological Modelling of the storage site and storage complex: this model uses as its inputs the seismic interpretation of the structure, the under and overburden. It uses the logs from local and regional wells in order to specify the stratigraphy. For the Storage Site, it uses the log and core analyses to specify the facies for each subdivision and to interpolate and extrapolate the primary rock properties across the structure. The key outputs from this stage of modelling are the structural framework model and the permeability and porosity fields within the reservoir intervals;
- Reservoir Simulation is the dynamic modelling of the reservoir. Taking the static modelling results and adding permeabilities, relative permeabilities, fluid characteristics and wells, the movement of CO_2 from the injection wells to its final static location are predicted. Additional data comes from the analysis of core and well testing and is significantly upscaled from the limited local results right across the reservoir structure. For these tasks, the information gained from the appraisal well namely; routine and special core analysis results, advanced vertical interference tests and conventional production and injection test interpretation results have been most important. The outputs of the reservoir simulation provided both the expected CO_2 plume migration plus the pressures and temperatures across the structure – key inputs to the geomechanical modelling;
- Geochemical Modelling: the geochemical modelling assesses the reactions of the Mineral Trapping mechanism over a 10,000 year time-frame. The most significant outputs to be carried over to the geomechanical modelling below are any predicted changes to the mechanical properties of the reservoir and the cap rock and consequently any long-term changes to the trapping and seal integrity of the Storage Complex; and
- Geomechanical Modelling: this model takes in the full RSFM from the static geological modelling and then populates it with mechanical properties across the structure to predict movement and stress changes based on the pressure and temperature responses from the dynamic simulation of CO_2 injection. The modelling process uses confining blocks to establish boundary constraints both laterally and below the underburden. Specific inputs are derived from logs and from mechanical properties testing of core samples. Also included in the model are the North-West striking overburden faults interpreted from seismic data.

The injection wells will be hosted on an NUI platform. The platform is designed with six well slots and will be equipped with filters for the CO_2, meters for well allocation measurement and will have provision for temporary equipment for well maintenance as well as providing control and measurement interfaces.

Three CO_2 injection wells are to be drilled by jack-up rig through the platform. The design of the wells specifically addresses the requirement for safe and efficient injection of CO_2 during the 20 years of injection and for their closure and abandonment for permanent containment of the stored CO_2.

The wells will be moderately deviated to optimise the separation of their bottom hole locations within the Storage Site. The CO_2 will be injected into the Bunter Sandstone reservoir through perforation in the lower (deeper) half of the reservoir thickness in order to maximise the residual trapping of CO_2. The CO_2 plume will develop and migrate, initially vertically towards the top of the reservoir, and then laterally towards the crest of the structure in an east-south-easterly direction. Over 90 % of injected CO_2 is predicted to form an approximately 25m thick CO_2 cap trapped below the cap rock.

The Storage Complex comprises the Storage Site, its Triassic underburden down to the base of the Zechstein Halite and the overburden up to the top Jurassic Lias. Conformance of the observed and predicted response of the Storage Site to CO_2 injection will be monitored during the injection period under a comprehensive MMV Plan. If the operation of the Storage Site behaves as forecast and the dynamic capacity is confirmed, consideration may be given to increasing the quantity of CO_2 to be stored in the Endurance structure. After injection ceases, the Storage Site and Storage Complex will be monitored for a number of years after which the platform and wells will be decommissioned before responsibility for the Storage Complex will be transferred to the designated Competent Authority.

In the longer term, over thousands of years, the structurally trapped dense phase CO_2 cap will diffuse and dissolve into the underlying brine creating a CO_2-rich brine phase which, due to its increased density, will initiate a convection process that gradually depletes the CO_2 cap and thereby enhances dissolution trapping. Simulation indicates that it will take of the order of 10,000 years for the CO_2-rich brine to reach the base of the structure (assuming no temperature anomalies and no reactivity of the dissolved CO_2 with the formation) by which time approximately 25 % of White Rose CO_2 is predicted to be dissolved.

17 Glossary

Abbreviation	Meaning or Explanation
AACE	Association for the Advancement of Cost Engineering
AES	Alternative Evolution Scenario
AGI	Above Ground Installation
Am^3/h	Actual Cubic Metres per Hour
AONB	Area of Outstanding Natural Beauty
API 2	Argus Price Index 2 (benchmark price reference for coal imported into northwest Europe, calculated as an average of the Argus CIF ARA assessment and the IHS McCloskey NW Europe Steam Coal marker)
Ar	Argon
ASU	Air Separation Unit
bara	Bar Absolute
barg	Bar Gauge
BAT	Best Available Technology
BI	Business Interruption (insurance)
BIS	Department of Business, Innovation & Skills
BoP	Balance of Plant
BV	Block valve
c.	circa
°C	Degrees Celsius
CA	Competent Authority
CAR	Contractors All Risks (insurance)
CBI	Confederation of British Industry
CBS	Cost Breakdown Structure
CCB	Current Control Budget
CCP	Carbon Capture Plant
CCS	Carbon Capture and Storage
CCSA	Carbon Capture and Storage Association
CCTV	Closed Circuit Television
CDM	Construction (Design and Management) Regulations 2015
CEO	Chief Executive Officer
CfD	Contract for Difference
CFD	Computational Fluid Dynamics
CH_4	Methane
CIF	Cost, Insurance and Freight
CLIMA	Climate Action (European Commission department)
CO_2	Carbon Dioxide
COD	Commercial Operations Date
COMAH	Control of Major Accident Hazards Regulations 2015
CP	Cathodic protection (a technique used to control the corrosion of a metal surface by making it the cathode of an electrochemical cell)
CPL	Capture Power Limited
CPP	Commercial Proving Period
CPRE	Campaign for the Protection of Rural England

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Abbreviation	Meaning or Explanation
CSA	Coal Supply Agreement
CSF	Critical Success Factor
CSI	Commercially Sensitive Information
dBA	Decibel
DCO	Development Consent Order
DECC	Department of Energy and Climate Change
Dense Phase	Fluid state that has a viscosity close to a gas while having a density closer to a liquid. Achieved by maintaining the temperature of a gas within a particular range and compressing it above a critical pressure.
Disconnector	Isolation of power equipment from the network (usually where no significant change in voltage occurs across the terminals)
DoA	Delegation of Authority
DoW	Division of Work
DPA	Data Protection Act
DPL	Drax Power Limited
DPP	Drax Power Plant
DSU	Delay in Start-Up (insurance)
E3G	Independent Body for Climate Diplomacy and Energy Policy
EAR	Erection All Risks (insurance)
ECA	Export Credit Agencies
EDMS	Electronic Data Management System
EEPR	European Energy Programme for Recovery
EES	Expected Evolution Scenario
EFEP	External Features Events and Processes
EHS	Environment, Health and Safety
EHSQ	Environment, Health, Safety and Quality
EIA	Environmental Impact Assessment
ENER	Energy (European Commission Department)
EPC	Engineering, Procurement and Construction
ERP	Enterprise Resource Planning
ESD	Emergency Shutdown
ESDV	Emergency Shutdown Valve
EU	European Union
EUEAA	EU Emissions Allowances Agreement
EUETS	European Emissions Trading System
F&G	Fire and gas
FC	Financial Close
FEP	Features Events and Processes
FEED	Front End Engineering Design
FID	Final Investment Decision
FIDIC	International Federation of Consulting Engineers
FRA	Flood Risk Assessment
GAAP	General Accepted Accounting Principles

Abbreviation	Meaning or Explanation
GCCSI	Global CCS Institute
GIP	Good Industry Practice
GPU	Gas Processing Unit
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen Sulphide
H&S	Health and Safety
Halite	An isometrically crystalline form of salt (Sodium Chloride, NaCl)
HAZID	Hazard Identification
HAZOP	Hazard and Operability
HIPPS	High Integrity Pressure Protection System
HRA	Habitat Risk Assessments
HMI	Human Machine Interface
HSE	Health and Safety Executive
HoT	Heads of Terms
Hydrates	Crystalline materials made up of water and one or more hydrate forming substances such as CO_2, nitrogen and methane.
ICSS	Integrated Control and Shutdown System
IEACCC	International Energy Agency Clean Coal Centre
IEAGHG	International Energy Agency Greenhouse Gas (Research and Development Programme)
IFRS	International Financial Reporting Standards
IR	Industrial Relations
ISO	International Organisation for Standardisation
ITP	Inspection and Test Plan
ITT	Invitation To Tender
JCB	Joint Commissioning Board
kg/h	Kilograms per Hour
kg/m^3	Kilograms per Cubic Metre
KKD	Key Knowledge Deliverable
KKS	Key Knowledge Services
km	Kilometre
KPI	Key Performance Indicator
KSC	Key Sub-Contract
KT	Knowledge Transfer
LCCC	Low Carbon Contract Company
LCR	Local control room
LEP	Local Enterprise Partnership
LER	Local equipment room
Line-packing (1)	Allowing fluctuation of the density (and pressure) of the fluid in a pipeline as a flow control mechanism.
Line-packing (2)	Holding a fluid in a pipeline within the operating pressure range to allow resumption of its transportation on an immediate basis.

Abbreviation	Meaning or Explanation
LOX	Liquid Oxygen
LPA	Local Planning Authority
LTEL	Long Term Exposure Limit
MAOP	Maximum Allowable Operating Pressure
MAPP	Major Accident Prevention Policy
MCM	Machine Conditioning Monitoring
MCP	Master Control Programme
MD	Measured depth (actual length along the path of the well bore)
MEG	Monoethylene glycol
MEP	Member of the European Parliament
MIP	Maximum Incidental Pressure
MMV	Measurement, Monitoring and Verification
MOC	Management of Change
MP	Member of Parliament
MTPA	Million Tonnes Per Annum
MTU	Master Terminal Unit
MWe	Megawatt electric
N_2	Nitrogen
NACE	National Association of Corrosion Engineers
NAECI	National Agreement for the Engineering Construction Industry
NETS	National Electricity Transmission System
NGC	National Grid Carbon Limited
NGET	National Grid Electricity Transmission Limited
NGO	Non-Governmental Organisation
NSBTF	North Sea Basin Task Force
NSOAF	North Sea Offshore Authorities Forum
NTP	Notice to Proceed
NUI	Normally Unmanned Installation. A term usually applied to an offshore installation.
O&M	Operations and Maintenance
O_2	Oxygen
OAR	Operations All Risk (insurance)
OCB	Original Control Budget
OCIP	Owner Controlled Insurance Programme
OEM	Original Equipment Manufacturer
OPP	Oxy Power Plant
P&ID	Piping and Instrument Diagram
PC	Principal Contractor
PCI	Pre-Construction Information
PCS	Process Control System
PD	Principal Designer
PEP	Project Execution Plan

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Abbreviation	Meaning or Explanation
PIG	Pipeline Inspection Gauge: a unit, which is inserted into the pipeline at the Launcher and recovered at the Trap, to clean inner bore surface and/or monitor the integrity of the pipe.
PIG Launcher	A facility to allow PIGs to be inserted into a section of pipeline while transport operations continue.
PIG Trap	A facility to allow PIGs to be recovered from the pipeline.
ppmv	Parts per million by volume
PMC	Project Management Contractor
PPA	Power Purchase Agreement
PST	Partial stroke test
PMF	Process Mass Flow
QA	Quality Assurance
QMS	Quality Management System
QRA	Quantitative Risk Assessment
ROV	Remote operated valve
RAM	Reliability, Availability and Maintainability
R&D	Research and Development
RACI	Responsible, Accountable, Consulted, Informed
RL	Reserved List
RSPB	Royal Society for the Protection of Birds
RTD	Resistance temperature detectors
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SCR	Selective Catalytic Reduction
SDV	Shutdown valve
SIL	Safety Integrity Level
SMP	Standard maintenance procedures
SOL	Safe Operating Limit
SOx	Sulphur Oxide (various)
SO_2	Sulphur Dioxide
SPV	Single Purpose Vehicle
SSSV	Sub surface safety valves
T&S	Transport and Storage
TA	Target Audience
TEMPSC	Totally Enclosed Motor Propelled Survival Craft
TP	Terminal Point
TPL	Third Party Liability (insurance)
T/R	transformer/rectifier
TUC	Trades Unions Congress
TSSA	Transport and Storage Services Agreement
TVD	True Vertical Depth
UMV	Upper master valves
UPS	uninterruptible power supply
US Exim.	Export-Import Bank of the United States

Abbreviation	Meaning or Explanation
VSAT	Very small aperture terminal, an earthbound station used in satellite communications of data, voice and video signals, excluding broadcast television
VSD	Variable speed drive
VW	Valve Wings
VOWD	Value of Work Done
WBS	Work Breakdown Structure
WWF	World Wildlife Fund
ZEP	Zero Emissions Platform