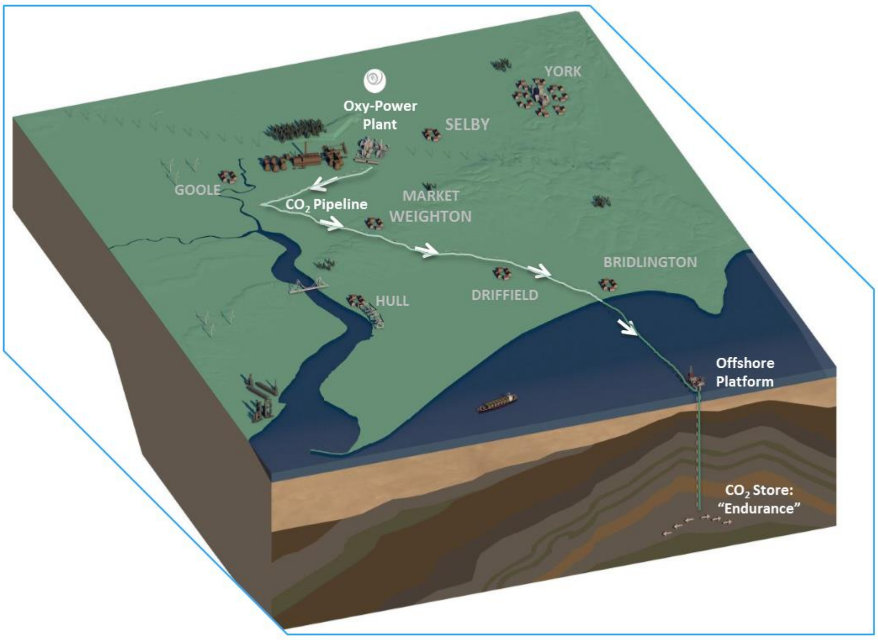
February 2016

K.05: Full Chain FEED Decision Report

Technical: Full Chain



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Contents

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Key Words

Key Word	Meaning or Explanation
Carbon Dioxide	A greenhouse gas produced during the combustion process
Carbon Capture and Storage	A technology which reduces carbon emissions from the combustion based power generation process and stores it in a suitable location
Coal	The fossil fuel used in the combustion process for White Rose
Development Consent Order	A statutory instrument granted by the Secretary of State to authorise the construction and operation of a Nationally Significant Infrastructure Project. The natures of these projects are defined by sections. 14-30 of the Planning Act 2008
Full Chain	A complete CCS system from power generation through CO_2 capture, compression, transport to injection and permanent storage
Key Knowledge	Information that may be useful if not vital to understanding how some enterprise may be successfully undertaken
Storage	Containment in suitable pervious rock formations located under impervious rock formations usually under the sea bed
Transport	Removing processed CO_2 by pipeline from the capture and process unit to storage
Oxy Boiler	The boiler within the OPP capable of producing full load in either the air or oxy-fired mode of operation
Oxy-firing	The use of oxygen (instead of air) in the combustion process
Oxyfuel	The technology where combustion of fuel takes place with 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
White Rose	The White Rose Carbon Capture and Storage project

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Executive Summary

The Full Chain Decision 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 document is one of a 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 Oxy Power Plant (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 (GE), BOC and Drax, and National Grid Carbon Limited (NGC), a wholly owned subsidiary of National Grid.

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 and CPL 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.

This report provides a summary description for 25 of the key decisions, specific to the application of CCS, taken during the FEED. The focus of the report is largely technical and techno-economic decisions as Key Decisions related to Commercial and Financial are covered in K.04 – Full chain FEED lessons learnt.

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1 Introduction

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.

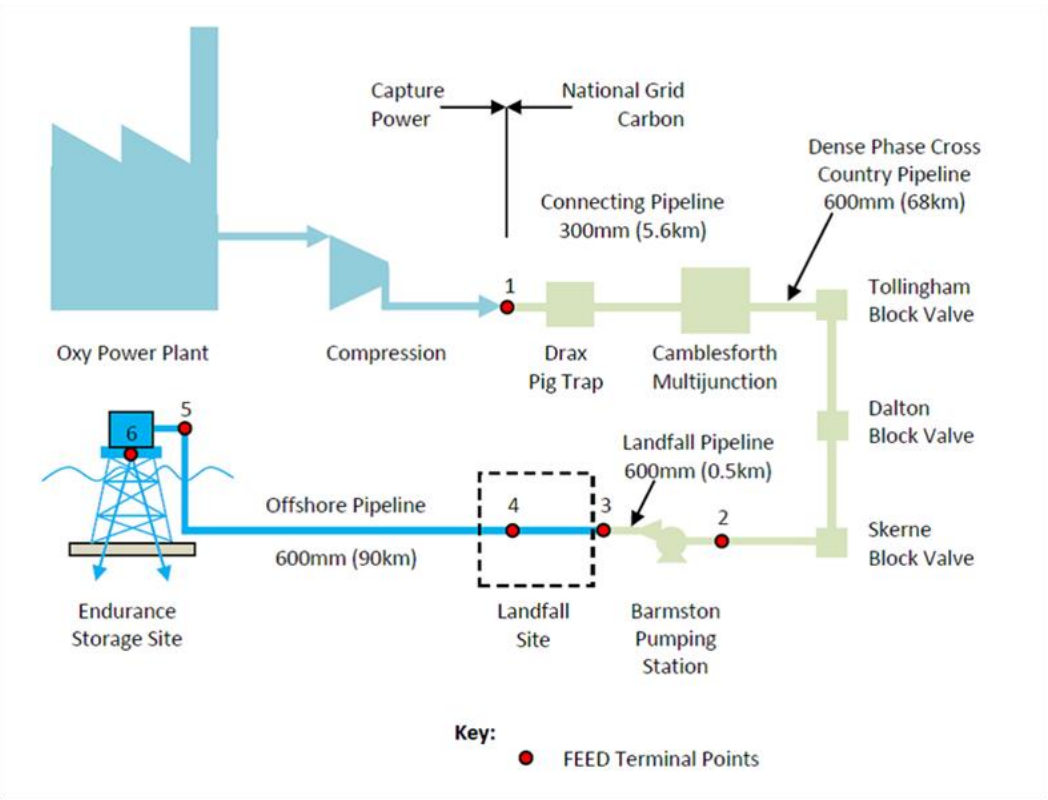
The OPP is a new ultra-supercritical power plant with oxyfuel technology of up to 448 MWe gross output that will capture around 90% of carbon dioxide emissions and also have the option to co-fire biomass.

One of the first large scale demonstration plants 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).

The Full Chain and its component parts (see Figure 1.1) are designed to be operated such that the target of two million tonnes of CO_2 per year can be safely stored.

Figure 1.1: Full Chain Schematic Diagram



Source: CPL

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2 Decision Making Governance

2.1 CPL

CPL implemented a decision making and change management process in FEED to ensure that a safe and operationally robust design for the OPP and Full Chain was achieved.

Decisions were assessed against a range of factors including reduction of risk (including those of environment, health and safety), impact on programme, capital cost and plant efficiency.

To allow an objective evaluation of options, value engineering factors were developed from the financial model to give a net present value (NPV) for changes in plant availability, CO_2 capture rate and efficiency.

All key decisions were assessed by CPL within this framework to ensure that they added value; following this the timing of implementation was assessed and a decision made on whether to implement.

While engineering changes associated with the T&S system were managed by NGC, those with the potential to impact the full-chain were subject to the same level of assessment and change control by CPL as for the OPP.

2.2 NGC

National Grid Carbon (NGC) introduced into the White Rose Project, the Decision making procedure established within National Grid. The procedure was designed to capture project design, commercial, programme and planning related decisions that could impact the FEED programme in terms of time and/or costs. The decision making and change management procedure was underpinned by European Business Development (EBD) Project Quality Management systems, process and procedures.

The project decision making procedure was designed during the FEED programme to ensure decisions were captured in a timely manner, evaluated to assess the impact on the FEED project and the wider CCS programme within NGC and subsequently recorded to ensure knowledge transfer within the project, the wider business and to the next phase of the project lifecycle.

The management of the decision making process was maintained by the CCS management team in the first instance and where necessary, decisions impacting the wider team or having significant programme implications were escalated to the EBD Management Team.

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3 Decisions

The decisions presented below represent the key decisions taken for the White Rose CCS Project during FEED.

3.1 Liquid Oxygen back-up Volume

3.1.1 Description of decision / change

The volume of liquid oxygen (LOX) storage dedicated to Air Separation Unit (ASU) back-up was reduced from four to one 300 m^3 LOX storage tank.

3.1.2 Reasons for decision / change

The initial FEED design included LOX storage associated with the two ASUs to achieve two functional requirements: first to allow the day/night flexibility option and secondly to provide a back-up oxygen supply, via vaporisation, to the boiler for a maximum of 8 hours on the trip of one of the ASUs. The latter requiring a little over 1000 tonnes of LOX to be stored in four 300 m^3 LOX storage tanks.

LOX back-up is a standard feature of ASU design and oxygen supply systems across all industries with the purpose of providing continuity of oxygen supply in cases of short term ASU trips (e.g. instrumentation failures). BOC's forecast, based on experience, was that each of the ASUs are likely to suffer a small number of short term trips every year. These could lead to outages of a few minutes through to the full 8 hours.

The resulting total LOX storage volume (combined with other hazardous substances on site) results in the site being classed as upper tier for the purposes of the Control of Major Accident Hazards (COMAH) 2015 Regulations.

A review of the economic impacts of installing and using LOX storage to allow for back-up in the case of an ASU trip, showed that it is not economically beneficial as, with a flat rate Contract for Difference (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 oxygen that would have allowed the boiler to operate at full gross load is diverted to liquid production and the production of the liquid increases the parasitic load thus further reducing the net output of the plant). The CfD regime, incentivising the operator to maximise output all the time, is different from typical oxygen supply schemes where LOX can be replenished during periods of low oxygen demand and/or low power prices.

This change 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, on such an ASU trip, to be smoothly run down from the full 100% load to 50% load which can be supported with just one of the two ASUs in operation.

The reduction of LOX storage reduces the quantity of hazardous substance stored on site which, as well as being an inherently positive result, would allow the site to achieve a lower tier COMAH status with the additional benefits to operations that this will bring.

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3.1.3 Overview of Impact

The decision to reduce the LOX storage volume has two main impacts:

a) A reduction in the capital cost through the removal of three 300 m3 LOX storage tanks from the scope of supply

b) Such a change of LOX storage will reduce the quantity of hazardous substance such that it should be possible to achieve a lower tier COMAH status for the OPP site. The change in tier status makes a noticeable difference to the upfront and on-going work required to demonstrate safe operation and also to the level of scrutiny that the project will receive from the Health & Safety Executive (HSE). The additional work an upper tier site has to undertake is:

- Production of a Safety Report (pre-construction, pre-commissioning and pre-operations)
- On-site Emergency Plan
- Off-site Emergency Plan
- Regular testing of Emergency Plans
- Provision of Information to the Public

This decision does not impact the LOX storage and associated equipment (liquefiers and vaporisers) that are included in the scheme to demonstrate the day/night flexible operation.

As there may be future market circumstances when additional LOX storage has commercial benefit it is intended that the original layout of the ASUs will be maintained and blanked connections to the necessary pipework will be specified to allow future installation of such LOX back-up storage.

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

3.2.1 Description of decision / change

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.

3.2.2 Reasons for decision / change

The CO_2 entry specification to the T&S system defines the acceptable level of non-CO_2 components entering the pipeline. While some of these are non-negotiable (e.g. H_2O, NO_x, SO_x, H_2S) for corrosion reasons, the oxygen content is set by the end use of the CO_2 and by the conditions at and materials to be used in the well. For White Rose an O_2 level of 10 ppm was specified in order to allow the use of less expensive materials for the well tubing where it is in contact with the highly saline water in the storage formation. This specification also made the CO_2 suitable for future re-use for Enhanced Oil Recovery

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(EOR). For the OPP this required a design for the Gas Processing Unit (GPU) with a higher capital and operating cost than the one originally envisaged to produce CO_2 at a specification suitable for storage in a saline formation.

The FEED well design used 25%Cr super duplex stainless steel (13Cr), based on an oxygen content of 10 ppmv, to avoid pitting corrosion. This selection is based on The IEA GHG report on corrosion and materials selection “Corrosion and Materials Selection in CCS Systems, Report 2010/03, IEA GHG, April 2010”, taking their recommendation for a low O_2 content stream into a highly saline environment.

The same report also makes material recommendations for higher oxygen contents, up to 0.785%.

Table 3.1: Well material selection recommendations

Salinity	Oxygen Content of Oxyfuel Emissions Stream	
	< 1 ppmv (essentially zero)	Up to 0.785%
< 50,000 ppmv	13 Cr	Alloy 625
> 50,000 ppmv	Super 13 Cr or 22 Cr	Alloy C276

With the high salinity of the brine solution in the storage formation, and a more easily achieved O_2 content of ~ 0.8%, the wells would have to be designed using Hastelloy (alloy C276).

Based on the current three well design, the total well tubing cost is ~ £6 million assuming an oxygen content of 10 ppmv allowing the use of 13Cr.

For three wells comprising of Hastelloy tubing the cost is expected to be around £19.5 million which corresponds to a cost increase of roughly £13.5 million to transport and store CO_2 with an oxygen content of 0.8%.

For the White Rose Project alone, not considering any advantage to future users of the T&S, the extra cost for the well tubing outweighed the capital and operating cost savings in the GPU, so the 10 ppmv O_2 specification was maintained.

3.2.3 Overview of Impact

Increased capital and operating costs in CO_2 purification process.

Reduced capital costs in wells.

Sets the standard for the future CCS industry joining the T&S system.

CO_2 specification allows for future EOR use.

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3.3 Flexibility Concept Adjustment

3.3.1 Description of decision / change

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 the traditional “two shifting” of conventional power plants. When power demand is low, the plant can move to a position that results in no net power export to the grid while still generating the clean power needed to operate the ASU and GPU and providing an uninterrupted flow of CO_2, at a reduced rate, to storage. During this period some energy is stored as liquid oxygen and this can be recovered within the process when demand returns giving an enhanced net output from the OPP.

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.

3.3.2 Reasons for decision / change

For White Rose, the payment mechanism will be through a CfD which favours baseload operation, and there is no mechanism within this for rewarding the flexible operation that the OPP Is designed for. However the Developers still viewed the demonstration of oxy-fuel as a flexible low carbon mid-merit plant as essential to the Project’s success.

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Through the value engineering review the original concept was adjusted to allow “demonstration of concept” rather than its original optimum configuration.

3.3.3 Overview of Impact

Capital savings were achieved through the reconfiguration of the coal mills from 5x25% to 4x33% and the simplification of the windbox design. This change reduced the turndown range without oil support of the OPP boiler, restricting it to a minimum output of 33% rather than 25%.

As a result the power output from the OPP steam cycle can no longer reduce in an efficient manner sufficiently to match the increased power demands from the ASUs and other auxiliaries in high LOX production/energy storage mode. While the energy storage and recovery within the OPP can still be demonstrated through the operation of the ASUs, the power production and demand do not balance to give no net export to the grid (virtual two-shifting). This can be demonstrated if further inefficient adjustments are made to the steam cycle to artificially reduce its output (and efficiency) in turndown, e.g. through steam bypass around the turbine.

3.4 Avoidance of underground installations and basements on the OPP

3.4.1 Description of decision / change

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.

3.4.2 Reasons for decision / change

A CCS plant naturally introduces the additional hazard of large quantities of concentrated CO_2 and also in the case of an OPP, large quantities of stored liquid oxygen. These are potential hazards not present on conventional power plants.

While the hazards associated with oxygen are well known and guidance is available from organisations such as European Industrial Gas Association (EIGA), for CO_2 there is less industry guidance available, with CO_2 not classified as a hazardous substance, although it is both toxic and an asphyxiant.

For the OPP it was decided to take an approach to minimise the potential hazards with a combination of designing to minimise leakage, monitoring for leaks through both fixed monitors and operators having to wear personnel gas detection equipment measuring for CO_2, oxygen enrichment and oxygen depletion, and to review and change standard power plant layouts and arrangements to eliminate, as far as possible, areas where CO_2 and cold oxygen, both being heavier than air, could concentrate.

3.4.3 Overview of Impact

The design of the OPP reflected the following approach:

- No cable trenches or machine basements

- Aerial cables instead of buried
- Installation level of steam turbine increased to allow installation of condensate extraction pumps at level 1

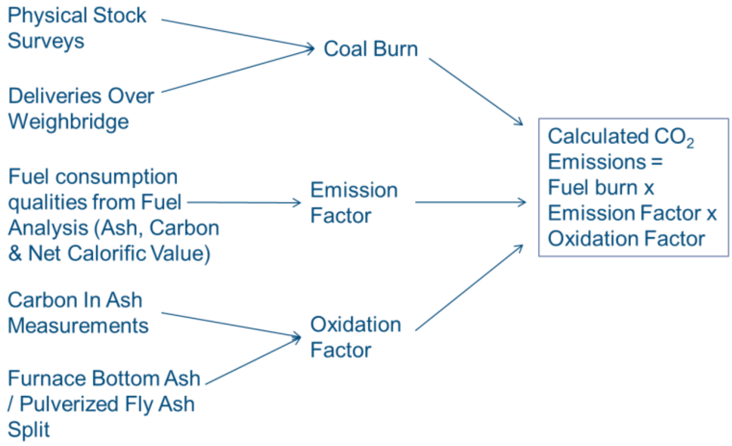
Capturing this requirement at the FEED stage minimises rework and unforeseen costs during execution.

3.5 CO_2 capture rate measurement approach

3.5.1 Description of decision / change

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 3.1: 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 would be combined with direct real time measurement of the CO_2 captured and sent to storage.

Figure 3.2: Original CO_2 Capture Rate Measurements

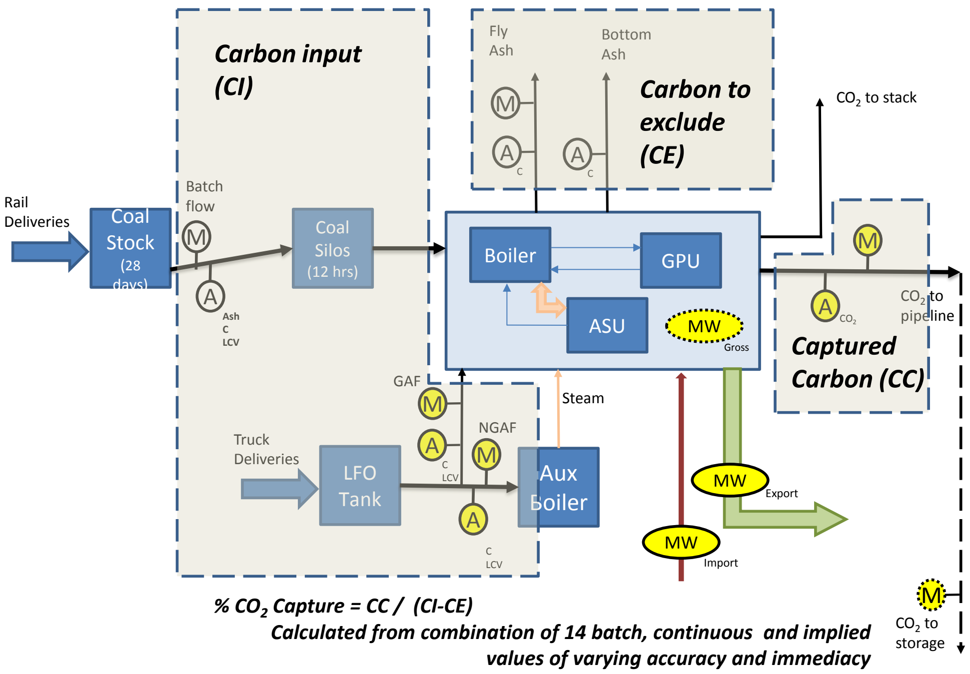
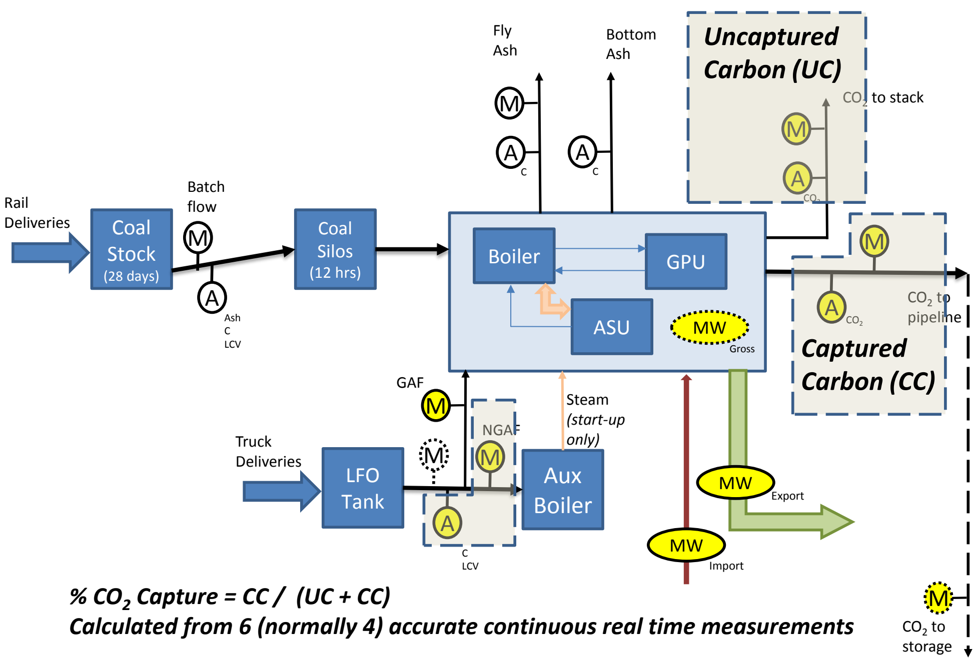


Figure 3.3: Revised CO_2 Capture Rate Measurements



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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 being 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 an “audit” for the revised approach.

3.5.2 Reasons for decision / change

The “cash register” for the project is dependent on both power export and capture rate, with the latter potentially much less accurate than the former which gives uncertainty on income in a way that would be very unusual for a power project. The need to match the requirements of the CfD and to maximise the accuracy of measurement leads to the decision to use output rather than input CO_2.

3.5.3 Overview of Impact

Measurement uncertainty for CO_2 capture rate improved form +/- 3.8% to +/- 0.4%.

Capture rate measurement available in real time to meet requirements of 30 minute payment periods of the CfD.

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3.6 Stack emissions specification approach

3.6.1 Description of decision / change

For White Rose it was proposed to use a different parameter for measuring the emissions to atmosphere of SOx, NOx and particulates as the parameter of mg/Nm^3 as used in the EU Industrial Emissions Directive (IED) is not appropriate.

An alternative measure of mg/MJ was proposed which can also be equated to the IED parameter.

3.6.2 Reasons for decision / change

Under the EU IED stack emissions are limited to maximum concentrations for key pollutants. The metric applied for emission in Europe for the main pollutants (NOx, SOx, CO and particulates) is mg/Nm^3 corrected to remove the water content (dry basis) and adjusted to an oxygen content in the flue gas of 6%.

Currently there are no agreed emission limits applicable to oxy-mode and the EU Directive values cannot be sensibly applied. When fuel is burned in oxygen, the same quantity of CO_2 and the same or lower quantities of pollutants are produced, however the total quantity of flue gas produced is significantly lower (~25% of air-firing). The oxy-mode flue gas also undergoes additional purification and separation to capture the majority of the CO_2. As a result a much smaller stream of inert gases (argon and nitrogen), unused oxygen, uncaptured CO_2 and any remaining pollutants will be emitted via the stack. The flowrate is about 2.5% of the quantity of flue gas emitted during air-firing.

Therefore for White Rose, while the assessed impacts are lower for oxy-mode, if the emissions are expressed on a volume basis (mg/Nm^3), as in the IED, they would appear higher. In addition the IED limit values are expressed in mg/Nm^3 dry corrected to 6% O_2 in the flue gas corrected using the formula below and taking NOx emission as an example:

$$c[NOx]reference = \frac{21 - c[O2]reference}{21 - c[O2]actual} . c[NOx]actual$$

where c[O2]reference = 6

This basis cannot be readily applied to an oxy power plant as the flue gas has a much higher O_2 content, typically varying between 16% & 21% (and even above 21% in part load operation) and the calculated corrected values become implausibly high, infinite, and then negative as the O_2 content moves to, through and beyond 21%.

In order to provide a meaningful metric, it is proposed that emission limits for the plant in oxy-mode should be expressed on an energy input basis, as milligrams per Mega-Joule (mg/MJ) of fuel burnt. This basis allows for an easy correlation and comparison with the air mode emissions.

Table 3.2: IED and Proposed Corresponding Limits

Stack emissions	EU Directive Value	Proposed Corresponding Limit
SOx	150 mg/Nm^3, 6 % O_2 dry	corresponds to 52 mg/MJ
NOx	150 mg/Nm^3, 6 % O_2 dry	corresponds to 52 mg/MJ

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Stack emissions	EU Directive Value	Proposed Corresponding Limit
Particulates	10 mg/Nm^3, 6 % O_2 dry	corresponds to 3.5 mg/MJ

3.6.3 Overview of Impact

The proposed change in parameter allows the emissions from an oxy-fuel plant to be regulated against a meaningful set of parameters which also provide direct comparison to the standards for conventional air fired plants.

The air quality modelling undertaken for the Environmental Impact Assessment (EIA) in support of the Development Consent Order (DCO) demonstrated that the OPP operating in oxy-mode has a lower impact compared to the same plant operating in air mode. In addition the actual mass emissions are lower in oxy-mode than in air mode. Therefore the expectation was that there would be no issue in the OPP meeting these equivalent limits.

Recognising the importance of an agreed interpretation of the IED appropriate for CCS, the proposed change was raised with the Environment Agency (EA) at a very early stage. At the time of FEED termination, discussions were on-going with the EA to agree how the plant should be regulated in terms of emissions through the Environmental Permit (EP) application process, including application of the proposed, oxy-combustion appropriate, IED equivalent limits.

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

3.7.1 Description of decision / change

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.

In a conventional wet limestone/gypsum FGD system the reaction tank is integrated in the FGD itself, below the absorber module, and the oxidation 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.

3.7.2 Reasons for decision / change

This approach was reviewed and it was deemed technically feasible and would increase the overall CO_2 capture rate and "clean electricity" production".

However there were some downsides:

- additional power consumption in ASUs (for extra O_2)
- additional power in GPU for removing unreacted O_2.
- additional technical risk on a First of a Kind (FOAK) unit.

Based on the above considerations it was decided not to change to O_2 as the oxidant for the FGD. It was considered more important to prove the core OPP technology.

Nevertheless this has been identified as an improvement that could be considered for follow on projects.

3.7.3 Overview of Impact

No change from original FEED Design.

CO_2 generated and released in the FGD must be considered in the overall CO_2 capture rate for the OPP and thence in to the clean energy calculation for the CfD.

3.8 Output in Air Mode

3.8.1 Description of decision / change

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.

This assumption was reviewed during FEED.

3.8.2 Reasons for decision / change

Oxy-mode is the main operating mode with air mode for start-up, shut down and as a backup mode in the event that the T&S system, ASUs or GPU are unavailable.

However air mode sets the design sizing points for some areas of the OPP and allowing the output in air mode to reduce, with oxy-mode alone setting the equipment sizes, would allow some capital savings.

Limiting the output in air mode to approximately the same as oxy-mode has the following benefits:

- Some reduction in fan sizing / optimisation of efficiency in oxy-mode
- Reduction in flue gas duct sizing
- Reduction in size of step up transformer for electricity export to the grid
- Easier compliance with grid code requirements in air mode

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3.8.3 Overview of Impact

While there were some capital and minor efficiency savings, the option was not pursued.

The potential benefit of higher output and revenue in air mode, provides some potential mitigation to the commercial risk during the early years of operation when there is a possibility of lower than expected availability for the full chain as the operational learnings associated with CCS are identified and implemented on a FOAK project. Operation in air mode, if required, would be in compliance with the permitted limits.

3.9 Coal Specification

3.9.1 Description of decision / change

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.

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.

3.9.2 Reasons for decision / change

The Basis of Design at the start of FEED considered a broad range of international coals reflecting those typically used at Drax. This included UK coals with a sulphur content of up to 2.7% by weight.

As the FEED progressed it became clear that the UK coals in the Basis of Design would not be available during operation due to mine closures and the opportunity was taken to review the coal basket and its impact on the plant design.

There is a benefit in managing coal spec for the plant particularly with regard to sulphur content. Sulphur is removed by a chemical reaction in the FGD unit but this reaction also results in the generation and release of CO_2 which is not captured in the OPP. The CO_2 release is proportional to the amount of sulphur in the coal and has to be considered in the overall CO_2 capture rate. More sulphur in the coal leads to a lower overall CO_2 capture rate and reduced payment for “clean electricity”.

The impact of moving to low sulphur coals is much more significant than for the UK’s existing coal plants where the CO_2 emissions from the FGD are covered by extra carbon credits required for EU Emissions Trading Scheme.

Consideration was also given to moving to coal spec of <1% S to allow removal of SO_3 mitigation system, but the final FEED specification reflected the need to retain an available UK coal as the basis of design and the sulphur range was revised to <2% S.

The coal specification also impacts the duty on the Selective Catalytic Reduction (SCR) unit, as well as O_2 consumption & ASU sizing. Managing the coal specification can limit the auxiliary load and capital cost of the ASU.

3.9.3 Overview of Impact

Dropped highest NO_X coal to reduce SCR duty and NH_3 usage.

Lower ash coal also reduced bottom ash and fly ash removal requirements.

Design coal changed to Ravenstruther.

Updated ASU O_2 demand.

3.10 Biomass Co-firing

3.10.1 Description of decision / change

During the FEED CPL undertook a value engineering & cost reduction exercise on the oxy-power plant. 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, the co-firing of biomass was removed from the FEED scope.

3.10.2 Reasons for decision / change

Since its inception the White Rose CCS project has looked at delivery of a power generation solution where all of the generated electricity is clean. The project has also targeted the goal of capturing and storing more carbon than the net non-renewable fuel consumed at the station. The underlying solution to achieve this is through deployment of biomass co-firing for the project. With the carbon capture facility designed for a 90% CO_2 capture rate, a use of 10% biomass in the fuel mix (by heat) enables 100% clean electricity generation. Increasing the co-firing ratio to 15% allows the facility to achieve negative carbon emissions.

Biomass co-firing was part of the original FEED design with the expectation that once the cost and performance implications had been detailed the Authority would make a final decision on whether or not co-firing would be supported, and if so, how. CPL developed the FEED design that allowed potential biomass co-firing but retained the ability to be a 100% coal firing station, with biomass co-firing not required.

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As there was no mechanism within the proposed CfD to realise the benefits of biomass co-firing and no clarity on a route to achieve this, the decision was made to remove biomass co-firing from the FEED scope but to retain it as a future potential option.

3.10.3 Overview of Impact

The decision to remove biomass co-firing from the scope reduced the capital cost of the OPP by removing the scope associated with biomass co-firing including the tie-in to the existing Drax biomass system, new biomass conveyors, biomass silo, hammer mills, discharge system and windbox height increase to accommodate a biomass injection level, as well as the additional civil work, electrical and C&I scope associated with biomass systems.

The removal of the proposed level of co-firing did not change the rest of the OPP design or any significant change in overall plant performance.

Biomass co-firing was considered in FEED, but is now a future potential option rather than part of base OPP design. Should it be implemented at a later stage, the capital outlay would be higher than had it been incorporated when the plant was built.

3.11 CO_2 Specification - Temperature

3.11.1 Description of decision / change

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 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.

3.11.2 Reasons for decision / change

The option of operating at 30ºC compared to 20ºC was briefly reviewed as part of the value engineering phase.

For the OPP the 30ºC specification retains the heat exchanger after the CO_2 pump but allows the removal of the chiller unit giving both capital and operating cost savings.

For the T&S the 30ºC specification gives increased capital and operating costs, such as increased pipeline material costs and potential additional cooling requirements at Barmston pumping facility. Further work is also required to understand the impacts and costs associated with transporting dense phase CO_2 at temperatures above the original basis of 20ºC. These include:

- Pipeline stresses due to heat expansion of the metal
- Impact on maximum flow rate in the pipeline.

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- Impact of cooling during prolonged shutdowns.

As the net benefit of moving to 30ºC for White Rose was not clear cut with further analysis and quantification of impacts required, it was decided not to change the FEED Basis of Design and to limit the CO_2 fluid temperature to 20ºC.

3.11.3 Overview of Impact

No change to FEED basis of design.

Sets entry specification, with concomitant capital and operating costs for future users.

3.12 Full Chain Control

3.12.1 Description of decision / change

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.

3.12.2 Reasons for decision / change

At an early stage in FEED the philosophy for controlling the full chain was assessed and developed between the eventual operating partners. An approach was chosen for control of the full chain that recognised the diverse operating environments, specialist skills required and asset ownership for each element of the chain.

Each element of the full CCS chain will be supervised and operated in an independent fashion from its own permanently-manned control rooms according to local operating procedures.

The proposed scheme is consistent with the control solutions deployed for similar applications – such as National Grid's existing natural gas pipeline networks. Integration of the chain control systems into one unified system was not considered suitable as it is not required and the approach would not support the system ownership and local operational requirements.

However in order to allow the chain to realise the overall CCS full chain functionality, a degree of system interfacing and operations coordination is required. This means that while each element's 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. In this way 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. While the philosophy of interfacing has been established during FEED, the detail of which signals would be exchanged was to be developed in the implementation phase.

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.

Dynamic modelling of the OPP and the T&S system confirmed this approach with their control systems giving safe, reliable and stable operation as they respond to operational changes within other elements of the chain.

3.12.3 Overview of Impact

The approach of interfacing rather than integrating provides the level of control required and also facilitates new CO_2 emitters entering the chain, recognising 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.

3.13 OPP layout Optimisation

3.13.1 Description of decision / change

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.

3.13.2 Reasons for decision / change

Safety review with key subcontractors led to identification of changes to site layout in order to improve safety for personnel.

3.13.3 Overview of Impact

This approach was identified early in FEED and so could be implemented with limited requirements for re-engineering.

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3.14 Minimisation of air in-leak

3.14.1 Description of decision / change

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 inert gases 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 Direct Contact Cooler (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 sootblowers
  - RFG instead of air as seal gas to pulverizers, water cannons

3.14.2 Reasons for decision / change

To achieve reduced air in-leakage into flue gas stream (for reduced need of separation duty by GPU).

3.14.3 Overview of Impact

Design changes incorporated.

3.15 NO_x removal in Selective Catalytic Reducer (SCR)

3.15.1 Description of decision / change

SCR and ammonia system redesigned to increase the NO_x reduction achieved in the SCR from 82% to 89%.

3.15.2 Reasons for decision / change

Detailed design based on pilot plant results showed that the most economical way of reducing NO_x in the CO_2 product stream to the low levels required by the T&S entry specification, is to reduce the NO_x present in the flue gas by increasing the removal rate in the SCR before exiting the boiler, rather than seeking to remove the NO_x in a process in the GPU.

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3.15.3 Overview of Impact

Additional catalyst surface required and increased ammonia usage in SCR.

Ability to effectively and economically achieve T&S CO_2 entry specification.

3.16 Additional flue gas duct in the main stack

3.16.1 Description of decision / change

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

3.16.2 Reasons for decision / change

Separate flue gas ducts are provided within the OPP to accommodate the very different flue gas flowrates in air and oxy-mode. These stacks have different diameters to ensure that the flue gas leaving the stack has sufficient velocity to allow it to disperse.

In oxy-mode operation, as well as the flue gas to the stack, there is also the occasional need to vent cold streams from the safety valves associated with the GPU's cryogenic CO_2 separation process. To avoid the risk of freezing out any moisture content in the flue gas and causing a blockage, a separate gas duct is provided within the main stack in order to route any cold streams released from the GPU safety valves to atmosphere.

3.16.3 Overview of Impact

Additional gas duct in main stack, increasing number of ducts from two to three.

Improved operability of the OPP.

3.17 White Rose Visitor Centre

3.17.1 Description of decision / change

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

The design of the combined administration building and visitor centre has been developed by Arup Associates in collaboration with CPL to be highly sustainable, constructionally 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 fund both constructing the centre and fitting internal 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.

3.17.2 Reasons for decision / change

CPL were keen to maximise the economic benefits from the Project to the Yorkshire and Humber region and were planning to develop a visitor centre as part of the proposals for the CCS Project.

The visitor centre is intended to accommodate up to 100 visitors at a time and will act as a focus for the demonstration and promotion of CCS technologies to a local, national and international audience including technologists, academics, governments and the public, facilitating knowledge transfer and acting as a showcase for advancements in clean energy. Below is an artist’s impression of the planned visitor centre produced by CPL’s architectural consultants Arup Associates.

Figure 3.4: The White Rose Visitor Centre

Source: Arup

The visitor centre is designed to both showcase CCS technologies and promote understanding of Science, Technology, Engineering and Maths (STEM) subjects through knowledge exchange.

3.17.3 Overview of Impact

In a study undertaken by Genecon for CPL, it has been estimated that the centre will attract 20,000 visitors per year. This estimate reflects the performance of comparable industrial infrastructure related visitor attractions in the UK, including the existing visitor centre at Drax, centres operated by EDF Energy and centres developed to promote the development of wind generation technologies.

The Genecon report also analysed the employment effects and economic benefits of the White Rose Visitor Centre to the Yorkshire & Humber (Y&H) region, and also to the more local Selby area. The table shows the net additional employment estimates for both the Yorkshire & Humber region and for Selby.

Table 3.3: Summary of employment effects

	Net additional – Y&H	Net additional - Selby
Construction	54 job years (5.4 FTE)	46 job years (4.6 FTE)
Operation	2.7 FTE jobs annually	2.3 FTE jobs annually
Visitor Spend	13 – 15 FTE jobs annually	8 – 10 FTE jobs annually

Most of the economic benefits of the White Rose Visitor Centre will occur in the Yorkshire and Humber region. The Economic Benefits Model estimates that the White Rose Visitor Centre will generate £12.3m in Gross Value Added (GVA) to the Yorkshire and Humber regional economy up to 2035. The net present value (NPV) of these benefits is estimated to be £9.0m.

This is the combination of the following:
- £3.2m in GVA generated through construction activities (£2.8m at present value)
- £1.2m in GVA generated through operational activities (£0.79m at present value)
- £7.9m in GVA generated through visitor spending effects (£5.5m at present value)

Whilst the economic benefits of the visitor centre will occur across the Yorkshire and Humber region, it is likely that the benefits will be concentrated in the Selby area. The estimated GVA to Selby's economy up to 2035 is £10.4m. The NPV of these benefits is estimated to be £7.6m.

This is the combination of the following:
- £2.7m in GVA generated through construction activities (£2.3m at present value)
- £1.0m in GVA generated through operational activities (£0.67m at present value)
- £6.7m in GVA generated through visitor spending effects (£4.6m at present value)

Beyond the quantifiable economic benefits in terms of employment and GVA impacts, there are a number of other non-quantifiable benefits associated with the delivery of the White Rose Visitor Centre. These include the value of knowledge transfer, the potential of the centre to help attract additional investment in the region and the local community benefits that could be achieved. These are important benefits that reflect the wider role of the centre as a technology showcase and a mechanism for promoting the UK and Yorkshire and Humber region as a centre for energy innovation and technological excellence:
- Providing the setting for showcasing CCS technologies
- Providing enhanced image value and acting as a catalyst for further development in the Selby and Goole area

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- Contributing to regional energy sector and visitor economy growth agendas
- Providing access to applied STEM
- Adding to the learning experience, particularly highlighting Climate Change concerns

3.18 Change to minimum temperature for flange design

3.18.1 Description of decision / change

Decision to:

- Implement -55ºC minimum design temperature for flange design, and
- Implement 'L7' flange bolting with a minimum design temperature -101ºC.

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 condition 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.

3.18.2 Reasons for decision / change

The following conclusions are arising from this CFD flange leak cold temperature study:

- Flange bolts & nuts minimum metal temperature is predicted to be -71.2ºC. Design should consider metallurgy for the bolts & nuts with a cold temperature limit of at least -74.0ºC (allowing margin) or colder.
- Flanges material minimum metal temperature is predicted to be -53.2ºC. Design should consider metallurgy for the flange material with a cold temperature limit of at least -55.0ºC (allowing margin) or colder.

3.18.3 Overview of Impact

The decision has been accommodated within FEED and has been implemented in the pipe specs / datasheets etc.

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3.19 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).

This would be achieved by increasing the design pressure of the onshore pipeline (that exiting the Barmston pumping station only), the offshore pipeline and the offshore platform reception facilities.

The design pressure would be increased from 182 barg to 235 barg.

3.19.1 Reasons for decision / change

As part of the early cost estimation work being carried out by Genesis, the costs of the future retrofit of offshore CO_2 booster pumps (as specified in the Basis of Design) have been investigated. The costs, especially those associated with the provision of an electrical power cable from a grid connection on land to the offshore injection facilities have proved to be very high.

The post-investment costs of the offshore booster pump module solution would have to be borne by the users of the system when the injection capacity at the Endurance site was exceeded - it was questioned whether this would represent an insuperable economic barrier to the development of the Humber Gateway T&S system beyond the Endurance storage site.

3.19.2 Overview of Impact

The decision has been accommodated within FEED.

The costs associated with this change for detailed design and construction are a saving of circa £2.5M Capital Expenditure (CAPEX) initially with a subsequent additional saving of circa £125M by not having to install future offshore booster pumps and onshore/offshore electrical supply cable.

(Note that the additional costs of increasing the offshore pipeline wall thickness are substantially offset by the reduction in concrete coating required for the pipeline).

3.20 CO_2 Storage Monitoring

3.20.1 Description of decision / change

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

3.20.2 Reasons for decision / change

EU and UK government legislation require NGC to assure 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 (but is not limited to) 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.

At this stage in FEED, the proof that these technologies could provide evidence of leaking or induced fracturing does not exist. It is the considered opinion of the wells FEED contractor that neither of the technologies will provide information which could be interpreted (by trending of data recorded from the instruments) to deliver the information for which it might be installed to detect.

At this stage in FEED, the cost of the DTS and DAS equipment is unknown, but would increase wells CAPEX, as these technologies are currently not included in wells CAPEX estimates. Similarly, the Reliability Availability and Maintainability (RAM) study did not consider this equipment, and since it is relatively new technology, reliability is relatively unknown. If the equipment failed, it would require a 'Heavy Workover', requiring a Drilling Rig to pull the completion tubing, at a significant OPEX.

Mainly on the basis that the suitability of these technologies to this application is unknown at this time, but is believed not to be able to detect leaks or faulting (which is the intent of the use of this technology) then at this time DTS and DAS are deemed not to be required in White Rose CO_2 injection wells. The appropriate use of the downhole temperature and pressure (DTP) gauge, in conjunction with pressure monitoring of the 'A' and 'B' annuli at the wellhead will perform the task of leak detection (both from the wellhead and within the well), and this is deemed adequate for MMV requirements at the well.

3.20.3 Overview of Impact

No impact on FEED.

DTS and DAS techniques could be considered further within the detailed design phase.

3.21 Final location of Offshore Platform

3.21.1 Description of decision / change

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 5/42 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.

3.21.2 Reasons for decision / change

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.

3.21.3 Overview of Impact

The decision has been accommodated within FEED.

The Storage Permit Application has been based on this location.

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

3.22.1 Description of decision / change

Decision to have EU ETS metering for the Storage element of the Transportation and Storage installations located 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).

3.22.2 Reasons for decision / change

NGC obtained a positive response from the EA to the following question it posed:

"In light of the requirements of the legislation establishing the scheme for greenhouse gas emission trading in the Community (the 'ETS'), and in particular Article 49 of Regulation 601/2012 with regard to the transfer of carbon dioxide between CCS Transport and Storage Installations, does the EA consider that a carbon dioxide flow measurement system situated at the Bramston Pumping Station (as indicated in Figure 1 of the attached Metering Proposal document) would satisfy the ETS metering requirements relating to the transfer of carbon dioxide between the Transport Installation and Storage Installation which form part of the CCS transportation and storage system proposed by NGC (i.e. will flow meter readings at a point mid-way through the Transportation Installation system adequately evidence, for the purposes of the ETS, the actual carbon dioxide flow at the inlet to the Storage Installation)?"

NGC wanted to avoid the additional OPEX costs associated with maintaining EU ETS metering for the Storage Installation if located on the offshore platform noting that the offshore platform has been designed to be normally unmanned.

3.22.3 Overview of Impact

The decision has been accommodated within FEED and will result in both reduced post FEED CAPEX and OPEX costs.

3.23 Well Sizing

3.23.1 Description of decision / change

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

3.23.2 Reasons for decision / change

Prior to the wells FEED, the guidance was that 3 wells would be expected to fulfil the injection capacity range of 0.58 to 2.68 MTPA. The 3 wells were notionally expected to be of 1 x 4-1/2" OD tubing and 2 x 5-1/2" OD tubing. 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. Given that the pre-FEED perceived benefit of the 4-1/2" well was proven to be of limited to no benefit, 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.

Wells RAM study looked at the use of 2, 3 and 4 well configuration to determine the availability of injection capacity. The study concluded that 2 wells would lead to an availability of 86%, 3 wells; 99.2% and 4 wells, 99.9%.

3.23.3 Overview of Impact

The decision has been accommodated within FEED.

The overall T&S system availability with the pumping station, pipeline and 3 Wells is estimated at 99%.

An additional Well (for a 4 well system) would cost £21m in CAPEX, which is deemed to be an unnecessary pre-investment.

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3.24 CO_2 Modelling Technique

3.24.1 Description of decision / change

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

3.24.2 Reasons for decision / change

It was decided to perform detailed ventilation and gas dispersion modelling, using CFD, for the Barmston Pumping Station, part of the White Rose CCS project.

The CFD model was subject to independent validation and based upon the observed level of correlation between the CFD modelling and the experimental results from the COOLTRANS Research and Development (R&D) programme it was considered that the CFD model used was suitable to model the CO_2 vent analysis and associated design work of a similar nature as part of the White Rose FEED Project.

There was a need to undertake safety-related modelling studies to assist the design and to provide input information to the Quantified Risk Assessment (QRA).

Due to the local topography and the 5m high retention walls surrounding Barmston Pumping Station, detailed CFD analysis was deemed necessary to understand interaction of the airflow with the local three-dimensional geometry and to its impact on dispersion behaviour.

3.24.3 Overview of Impact

The decision has been accommodated within FEED.

3.25 Use of Polarcus data

3.25.1 Description of decision / change

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

3.25.2 Reasons for decision / change

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 existing Ocean Bottom Cable (OBC) dataset that NGC had under licence from WesternGeco. AGR TRACS undertook the analysis of the potential benefits for NGC and recommended that no further work be undertaken on the basis 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 is required with the Polarcus dataset for the purposes of applying for a CO_2 Storage Permit.

The conclusion from AGR is that whilst the Polarcus data would allow for a more confident time-horizon network to be generated, this would have a minimal impact on the storage characterisation work already completed to date (as there is no change in the structure or internal characterisation).

It was decided that there was no benefit to proceed with this during FEED.

3.25.3 Overview of Impact

The decision has been accommodated within FEED.

Eliminated need for additional subsurface spend during FEED.

Enabled CO_2 Storage Permit application to be submitted to DECC without significant delay (potentially 6 months).

Subsequent interpretation of the Polarcus data would cost between £100,000 for basic fault interpretation across the structure to £500,000 for a full interpretation including the data within the geological models. In addition the timescales for these works ranges from 2 months to 6 months respectively.

4 Glossary

Abbreviations	Meaning or Explanation
ASU	Air Separation Unit
ºC	Degrees centigrade
C	Carbon
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CfD	Contract for Difference
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COMAH	Control of Major Accident Hazards
CPL	Capture Power Limited
Cr	Chromium
DAS	Distributed Acoustic Sensing
DCC	Direct Contact Cooler
DCO	Development Consent Order
DECC	The UK Government's Department of Energy and Climate Change
DTP	Downhole Temperature and Pressure
DTS	Distributed Temperature Sensing
EA	The Environment Agency
EBD	European Business Development
EDU	The Energy Development Unit (EDU) of the UK Department of Energy and Climate Change (DECC)
EIA	Environmental Impact Assessment
EIGA	European Industrial Gas Association
EOR	Enhanced Oil Recovery
EP	Environmental Permit
ESP	Electrostatic Precipitator
ETS	Emission Trading Scheme
EU	European Union
FEED	Front End Engineering Design
FGD	Flue Gas Desulphurisation
FOAK	First of a Kind
FTE	Full Time Equivalent
GE	General Electric
GPU	Gas Processing Unit – processes the flue gases to provide the dense phase carbon dioxide
GVA	Gross Value Added
H_2O	Water
H_2S	Hydrogen Sulphide
HMG	Her Majesty's Government
IED	Industrial Emissions Directive
kg	Kilogrammes
KKD	Key Knowledge Deliverable

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Abbreviations	Meaning or Explanation
LCV	Lower Calorific Value
LFO	Light Fuel oil
LOX	Liquid Oxygen
LP	Low Pressure
m	meter
mm	millimetre
m^3	Cubic meter
M	million
mg	milligram
MIS	Management Information Systems
MJ	Mega joule
MMV	Measurement, Monitoring & Verification
MTPA	Million Tonnes per Year
MW_e	Megawatts of electrical power
MW_{th}	Megawatts of heat
NGC	National Grid Carbon Limited
NH_3	Ammonia
nm^3	Normal meter cubed (measured at 0°C and 1 atmosphere)
NOx	Nitrogen oxides
NPV	Net Present Value
O_2	Oxygen
OBC	Ocean Bottom Cable
OD	Outer Diameter
OPEX	Operating Expenditure
OPP	Oxy Power Plant
ppmv	Parts per million by volume
QRA	Quantified Risk Assessment
RAM	Reliability Availability and Maintainability
R&D	Research and Development
S	Sulphur
SCR	Selective Catalytic Reduction
SO_3	Sulphur Trioxide
SO_x	Sulphur Oxides
ST	Steam Turbine
STEM	Science, Technology, Engineering and Maths
T&S	Transportation and Storage
Y&H	Yorkshire & Humber

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