Coal-Fired Advanced Supercritical Retrofit with CO_2 Capture

Contract No.: C/08/00393/00/00
URN 09D/739

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Contractor

Doosan Babcock Energy Limited

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EXECUTIVE SUMMARY

Objectives

The overall aim of the project (DTI Project 407) is to evaluate the technical and economic feasibility of retrofitting UK coal-fired power plants with advanced supercritical boiler/turbine technology (ASC BT) and carbon dioxide capture.

Specific objectives were:

(i) To establish optimum ASC BT retrofit solutions for the reference power plant site selected for study (Ratcliffe) judged to be typical of the majority of the UK coal fleet (500 MWe and larger).

(ii) To determine the relative benefits of alternative approaches to the possible staging of retrofits for the short-term (capture-ready ASC BT retrofit) or the long-term (ASC BT retrofit with CO_2 capture).

(iii) To review the applicability of the optimum retrofit solutions for a range of UK coal fired power plant sites (including Drax and West Burton) and to provide an indication on the variances arising due to site conditions.

Introduction

In order to achieve the global target reduction in CO_2 emissions of some 60% by 2050, carbon dioxide capture and permanent underground storage (CCS) is likely to be necessary. Carbon abated clean coal technologies (CATs) which are suitable for progressive retrofit will be needed.

The retrofit of carbon abatement technology to existing coal-fired pulverised fuel (PF) power plant minimises capital expenditure and maximises the use of the existing infrastructure, leading to environmental benefits being realised faster and more widely than the replacement of existing plant with new build plant. Two complementary approaches, providing both short-term and longer-term benefits are possible. In the short-term, power plant efficiency improvements and biomass co-firing (a CO_2 neutral fuel) can deliver substantial reductions in CO_2 emissions. These plants can be designed to be capture-ready, ie suitable for the later retrofit of capture plant. Longer term, as regulations and infrastructure permit, CCS will deliver essentially zero CO_2 emissions.

Based on the two approaches above, the project aims to evaluate and optimise how retrofit of carbon abatement technologies can be accomplished on the UK fleet of subcritical coal-fired power plants.

The project brings together Doosan Babcock's innovative, first-of-class, POSIFLOW^{TM} wall-fired advanced supercritical boiler technology with Alstom's latest technology for turbine and balance-of-plant modifications based on state-of-the-art European steam conditions (nominally 290bara, 600°C final steam temperature, 620°C reheat steam temperature). These together with innovative state-of-the-art concepts in post combustion (based on Fluor's proprietary process, Econamine FG Plus^{SM}) and Oxyfuel combustion technologies (based on Air Products air separation, CO_2 purification and compression technologies) for CO_2 capture are evaluated.

Work Completed

The project was based on state-of-the-art supercritical steam conditions (nominally 290bara final steam pressure, 600°C final steam temperature, 620°C reheat steam temperature) providing the short-term efficiency improvement and innovative concepts in Post Combustion (amine based flue gas cleaning) and Oxyfuel Combustion for the longer term carbon dioxide capture aspects.

Three PF Advanced SuperCritical Boiler/Turbine Retrofit (ASC BTR) designs were selected to represent the range of carbon abatement technology options for the study Reference Power Plant Site (four x 500 MWe boiler / turbine units at Ratcliffe Power Station):-

(i) **ASC BTR** : Retrofit within existing power station infrastructure.

(ii) **ASC BTR Amine CO_2 Capture Plant**; and
ASC BTR Amine Capture-Ready Plant operated without Amine CO_2 Capture.

(iii) **ASC BTR Oxyfuel CO_2 Capture Plant**; and
ASC BTR Oxyfuel Capture-Ready Plant operated without Oxyfuel CO_2 Capture.

The applicability of the retrofit solutions chosen for the reference power plant site to other coal fired power plant sites around the UK has also been considered. This aims to demonstrate whether or not the optimum solutions determined for the reference plant are applicable to the other plant sites and whether or not the economic feasibility is dependent on the plant site.

Key work activities successfully completed under the project cover:-

- Definition of the project design basis and assumptions for the techno-economic evaluation of the CO_2 abatement retrofit cases with consideration against the CO_2 purity requirements.

- Generation of Technical Guidelines following a series of R&D paper studies on key technical aspects and risk areas. The aim of the technical guidelines was to provide an initial set of rules for the retrofit supercritical plant with CO_2 capture activities within the project. Key guidelines developed under the project covered: integration of CO_2 capture technologies with power plant steam cycle, amine and Oxyfuel CO_2 capture technologies, operating flexibility, chemistry and corrosion aspects, health and safety, gaseous emissions and CO_2 purity requirements.

- Overall power plant steam cycle optimisation for advanced supercritical boiler/turbine technology and carbon dioxide capture retrofit including capture-ready plant performance, both pre- and post- capture plant retrofit.

- Conceptual design of the advanced supercritical retrofit boiler / turbine plant including consideration for retained balance of power plant for target design life extension of 25 years post retrofit. The scope of supply for the retrofit plant was established for costing purposes.

- Conceptual design of the advanced supercritical boiler/turbine retrofit with amine-based post combustion as a CO_2 capture plant and as a capture-ready plant including considerations for safety and operability. The scope of supply for the retrofit plant was established.

- Conceptual design of the advanced supercritical boiler/turbine retrofit with Oxyfuel combustion as a CO_2 capture plant and as a capture-ready plant. Consideration was given to operating the retained balance of power plant under Oxyfuel derived flue gas conditions and implications for safety and operability. The retrofit plant scope of supply was established.

- Overall site plans with capture equipment footprint added.

- Reliability, availability and maintainability (RAM) assessment, as used to provide suitable quantitative input for the economic assessment of the retrofit options.

- Initial investigations to potential changes to plant flexibility as a result of adding carbon capture technologies.

- Economic assessment of the three retrofit cases; considering capital, operational, maintenance and CO_2 avoidance costs.

- Programme / schedule requirements for the retrofit cases based on consideration of site specific constraints and planning consents.

<u>Results</u>

The work undertaken under the project has:-

- Demonstrated the technical feasibility of Advanced Supercritical Retrofit capture-ready plant to UK power plant fleet with compliance to LCPD new plant emissions standards.

- Demonstrated it is technically feasible to retrofit carbon capture technologies of Post Combustion or Oxyfuel Combustion to an existing coal-fired power plant. However, in most UK power plants there is insufficient space (and insufficient cooling capacity) available for the application of carbon capture equipment to all units of the power plant.

- Demonstrated that Advanced Supercritical Retrofits and Advanced Supercritical retrofits with Carbon Capture (subject to carbon tax / future CO_2 prices) are economically viable in terms of the Cost of Electricity generated.

Overall, based on a 25 year plant design life extension, advanced supercritical retrofit at the UK power plants considered are estimated to deliver overall plant thermal efficiencies of 44 - 45% net, LHV at a cost of electricity of 2.4 to 2.5p/kWh (see **Figures 1 & 2**). The ASC BT retrofit plant can reduce carbon dioxide emissions by around 16% compared to the average UK power plant. The plants can be designed for enhanced biomass cofiring – up to 20% (based on thermal input), giving a further 20% reduction in carbon dioxide emissions and can be made capture ready. However, the overall performance depends on various technical and economic factors, including fuel price.

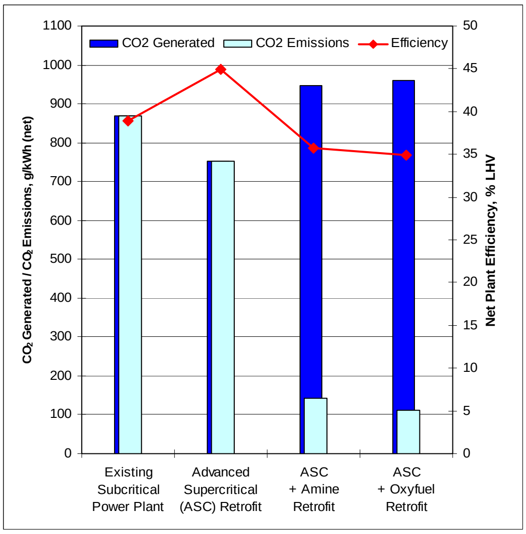


Figure 1: Retrofit Plant Performance

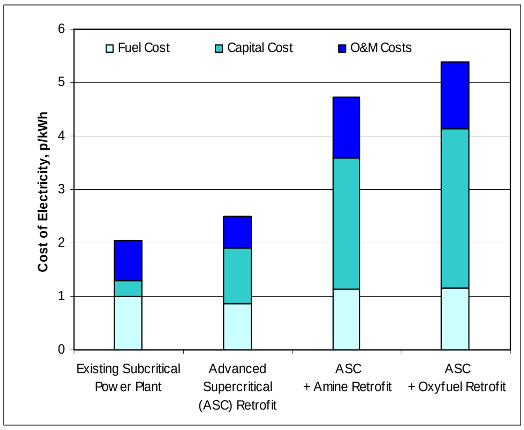


Figure 2: Cost of Electricity

Adding CO_2 capture technologies to achieve large reductions in CO_2 emissions of >85% reduces the plant efficiency by some nine to ten percentage points, **Figure 1**, and increases the cost of electricity by some 2.0 to 3.0p/kWh, **Figure 2**. The estimated cost of CO_2 capture and compression (excluding CO_2 transport and storage) is 36 - 45£/tonne of CO_2 emissions avoided (relative to the existing subcritical plant) or 35 - 47£/tonne of CO_2 emissions avoided (relative to ASC boiler / turbine retrofit) for the UK power plants considered.

The specific investment (Year 2005-2006 cost basis) of the ASC BTR plant optimised based on maximum plant electrical output by retaining the same fuel heat input rate as per the existing plant is estimated at 625£/kWe net. For ASC BTR with CO_2 capture, the specific investment required based on Post Combustion (amine based flue gas cleaning) technology is estimated at 1195-1280£/kWe net compared to Oxyfuel Combustion of 1440-1530£/kWe net. The Oxyfuel concept developed retains full air-firing capability thereby minimising both operational and commercial risk of the early adoption of the technology.

For both carbon capture technologies, the opportunity for further improvements in power plant performance and reductions in costs are envisaged as the technologies advance. Post Combustion Capture will continue to focus on developing new generations of technology which minimise steam consumption, by ensuring that a high degree of thermal integration is achieved in the process and/or by using amines with lower stripping steam requirements, either with improved formulations or improved amines (which have a much lower specific stripping heat requirement than MEA). For Oxyfuel Combustion, an alternative to the cryogenic ASU is the Ionic Transport Membrane (ITM) which is currently being developed and envisaged as being commercially available in the medium term. The cost of producing oxygen by this method is potentially 30% lower than the present oxygen production costs.

Reliability, Availability and Maintainability assessments of Post Combustion and Oxyfuel Combustion carbon capture technologies show similar availabilities when mature – availability is expected to be some 80% – 85% (capture mode operation) or 86% - 89% (capture plant by-passed) in comparison with 86% – 90% for ASC retrofit plant without CO_2 capture.

This study has identified a number of areas where adding CO_2 capture technologies may have a bearing on plant operating flexibility. Although further work is required to improve understanding of the potential positive and negative impacts on plant flexibility associated with CO_2 capture, the study has not identified any technical show-stoppers.

The overall programme duration required to complete an advanced supercritical boiler/turbine retrofit is estimated at approximately 56 months (from contract award to unit return to commercial operation). The overall programme duration for the retrofit plant with CO_2 capture is estimated at 56 to 58 months. The programme duration to complete the intrusive site works is estimated to be 25 months (from unit off-line to unit return to service).

Consideration must be given to the various planning consents required for retrofit. In particular Section 36 application will be required for expansion of the power plant sites for CO_2 capture plant retrofit.

For capture plant retrofit, greater health and safety considerations are necessary to meet the requirements of the UK Control of Major Accident Hazards (COMAH) regulations based on the threshold of quantities of certain substances for both on-site storage and process use. Adoption of a top-tier status under COMAH will require extra safety measures on behalf on the operator; including the publication of a safety report, an on-site and off-site emergency plan. The site must also provide certain information to the public concerning these activities. The safety or health risks associated with power generation plant incorporating CO_2 capture are not considered to be fundamentally any different from the requirements that are not already established in industry.

There are a number of practical aspects to consider with retrofitting carbon abated clean coal technologies to an existing power generation unit; these are associated mainly with the operational status of the surrounding station. Key considerations are access and egress, materials lay-down, Construction

Design & Management (CDM) regulations and the increased on-site workforce. These aspects will require careful pre-planning prior to demolition and construction of the retrofit plant.

The execution of the study has coincided with a global market upturn in demand for coal fired power plant, with the market competing for relatively limited raw material supply, manufacturing facilities and engineering resources. This is expected to result in an extension of lead times for high temperature materials and an increase in prices from those developed during the term of this project.

Conclusions

Retrofit of carbon abated clean coal technologies (CATs) is a practical solution with no technical or physical show stoppers being identified in the course of the study.

Advanced supercritical boiler/turbine (ASC BTR) technology is available now with the appropriate guarantees for retrofitting to coal-fired power plant to improve efficiency, reduce fuel costs and reduce carbon dioxide emissions.

When CO_2 capture and storage becomes economic or mandatory the retrofit routes studied are likely to be amongst the best and most economic options for existing pulverised fuel power generation plant. The project consortium members (Doosan Babcock, Alstom, E.ON UK, Air Products, Imperial College London and Fluor Ltd) are well positioned to exploit the opportunities worldwide.

Project objectives were successfully achieved and concluded:-

- Subcritical to supercritical retrofit to an existing coal-fired power plant is technically feasible with substantial use of existing balance of power plant components and layout.
- Advanced supercritical conversion will deliver significant reductions in CO_2 emissions as net plant efficiency is increased – more than 16% reduction in CO_2 emissions (compared with existing subcritical power plant) to some 730 – 750g/kWh corresponding to approximately 44% - 45% net plant efficiency, LHV basis, is achievable for ASC retrofit technology. Additional flue gas clean up plant, in form of DeNOx (Selective Catalytic Reactor - SCR) and low cost upgrade to existing DeSOx (WLG FGD) plant are included in the scope to ensure compliance with Large Combustion Plant Directive new plant emission standards.
- It is technically feasible to fit carbon capture technologies based on Post Combustion or Oxyfuel Combustion to an existing coal-fired power plant. Carbon dioxide abatement technology concepts developed aimed at targeting near-term exploitation based on minimum risk technology. However, it is concluded that in most UK power plants, currently there is insufficient space to fit carbon capture equipment to all units and

insufficient cooling capacity. Further considerations are required to address these key issues, particularly in securing the appropriate space required beyond the power station fence.

- Retrofit capture plant performance achievable with CO_2 emissions capture level of >85% through optimisation of process integration, practical plant flexibility and reliability, availability and maintainability (RAM).

- Key specific issues have been identified and addressed relating to:-
  - Condition of existing / retained balance of power plant for 25 year design life extension post retrofit
  - Essential requirements and considerations for Capture-Ready Plant
  - CO_2 capture plant energy penalty and steam cycle optimisation
  - % CO_2 removal
  - Waste streams / emissions performance
  - Capture Plant utilities and cooling water requirements
  - Capture Plant footprint / layout requirements
  - Reliability, availability and maintainability (RAM) including operability and plant flexibility.
  - Dismantle / erection / overall project schedule
  - Planning consents
  - Health and safety requirements including UK Control of Major Accident Hazards (COMAH) as applied to CO_2 capture plant

Recommendations

Over the next five to six years, investment in capture-ready carbon abated clean coal power plants (retrofits and new-build) can make a major contribution to filling UK's generation gap, which is expected to be at least 20 GWe by 2015, due to the closure of opted-out coal fired power stations and nuclear plant retirement. Against concerns for security of supplies, the level of investment in coal fired plant is recognised in the recent UK Government 2007 Energy White Paper (EWP).

Clean coal power plants and clean coal conversions of existing power plants, both available today with guarantees, will reduce dependence on imported expensive natural gas that would imbalance the generation portfolio. Clean coal technology brings reductions in specific CO_2 emissions compared to the plants replaced at a cost of electricity less than that from new-build gas-fired power stations and can be fitted later with carbon capture and storage (CCS) when this becomes available and commercially viable.

In parallel, the UK Government's commitment to support a full-scale (at least 300 MWe) first-of-class CCS project (to be selected by competition as launched in November 2007) is an important step to early demonstration of the technology over the period 2008 – 2014. The benefits of demonstration include potential reductions in the cost of the technology as a result of experienced gained through implementation.

Beyond 2015, capture-ready coal-fired power plants are to be retrofitted with CCS and any further coal power plants constructed with CCS incorporated. As accepted by EWP, development and deployment of CCS has been recognised as a component of European energy policy by the Council of the European Union which supports European Commission proposals to encourage a CCS demonstration plan involving up to 12 demonstration plants operating in Europe by 2015, with the aim that all new coal-fired power plants are to be fitted with CO_2 capture from 2020 onwards.

Together, these actions will demonstrate a practical commitment by the UK to CO_2 emission reductions from fossil fuel power plant using technologies suitable for both developing and developed countries. This will position the UK at the forefront of these technologies taking a leading role in their commercialisation and roll-out world-wide.

CONTENTS

ABBREVIATIONS

AH	Air Heater
ASC	Advanced SuperCritical
ASC BT	Advanced SuperCritical Boiler/Turbine
ASC BTR	Advanced SuperCritical Boiler/Turbine Retrofit
ASU	Air Separation Unit
AVT	All Volatile Treatment
BOFA	Boosted OverFire Air
BFP	Boiler Feed Pump
BFPT	Boiler Feed Pump Turbine
BoP	Balance of Plant
BTR	Boiler & Turbine Retrofit
BUF	Boost Up Fan (for FGD)
C&I	Control & Instrumentation
CAT	Carbon Abatement Technology
CCS	Carbon Capture and Storage
CDM	Construction, Design and Management
CF	Corner Fired
CFD	Computational Fluid Dynamics
COMAH	UK Control of Major Accident Hazards (COMAH) Regulations
CO_2	Carbon Dioxide
CPP	Condensate Polishing Plant
CW	Cooling Water
D/A	Deaerator
DBA	Di-Basic Acids
DCS	Distributed Control System
DeHg	Mercury Removal
DeNOx	NOx Removal
DeSOx	SOx Removal
DTI	UK Department of Trade & Industry
EFG+	Fluor's Econamine FG^{SM} Plus
EOR	Enhanced Oil Recovery
ESP	Electro Static Precipitator
EWP	Energy White Paper
FD	Forced Draught
FWF	Front Wall Fired
FGD	Flue Gas Desulphurisation
FGR	Flue Gas Recycle
GAH	Gas Air Heater
GGH	Gas Gas Heater

H&MB	Heat & Mass Balance
HARP	Heater Above Reheater Point
HAZOP	Hazard and Operability
HGI	Hard Grove Index
HP	High Pressure
ID	Induced Draught
IP	Intermediate Pressure
IPPC	Integrated Pollution Prevention Control
LCPD	Large Combustion Plant Directive
LHV	Lower Heating Value
LOX	Liquid Oxygen
LNB	Low NOx Burner
LNCFS	Low NOx Concentric Firing System
LP	Low Pressure
MBFW	Main Boiler Feed Water
MCC	Motor Control Centre
MCR	Maximum Continuous Rating
MEA	Mono-Ethanol Amine
MWe	Megawatt Electrical
MWt	Megawatt Thermal
NCV	Net Calorific Value
NOx	Nitrogen Oxide (NO) and Nitrogen Dioxide (NO_2)
NGET	UK National Grid Electricity Transmission
NPSH	Net Positive Suction Head
OWF	Opposed Wall Fired
O&M	Operating & Maintenance
OT	Oxygenated Treatment
PA	Primary Air
PF	Pulverised Fuel
PFD	Process Flow Diagram
PFGR	Primary Flue Gas Recycle
PPM	Parts Per Million
PS	Power Station
RAM	Reliability, Availability, Maintainability
R&D	Research and Development
SA	Secondary Air
SCC	Stress Corrosion Cracking
SCR	Selective Catalytic Reduction
SFGR	Secondary Flue Gas Recycle
SOFA	Separated Over Fire Air
SO_2	Sulphur Dioxide
SOx	Sulphur Oxides (SO_2, SO_3, sulphurous and sulphuric acid vapour)

TMCR	Turbine Maximum Continuous Rating
TPD	Tonnes Per Day
TSV	(HP) Turbine Stop Valve
v/v	by volume
w/w	by weight
WLG	Wet Limestone Gypsum

1. INTRODUCTION

1.1 Background

To achieve the global target reduction in CO_2 emissions of some 60% by 2050 [1], carbon dioxide capture and permanent underground storage (CCS) will be necessary. Carbon abated clean coal technologies (CATs) which are suitable for progressive retrofit will be needed; the reasons for the focus on retrofit being:-

(i) If global targets for CO_2 reduction are to be met in addition to global needs for energy demand and security of supply, CATs will be needed now on existing coal-fired plants, plants under construction (in the period 2006 - 2015), as well as future plants (from 2015 to 2030 and beyond). Many new plants will be built or committed before CCS is commercial.

(ii) In developed countries, including the UK, opposition is strong to greenfield plant at the planning stage. Re-use of existing sites is therefore preferred, allowing continuity of employment and maximizing use of existing infrastructure (grid connections, coal handling, road / rail links).

(iii) Retrofits allow CATs to be introduced more quickly and at lower cost than new-build plant.

(iv) Retrofits allow innovative technologies to be proven in shorter timescales and at less risk and cost than on complete new plants, making commercial demonstrations more affordable and more valuable within a national CAT development strategy.

(v) Carbon capture is likely to evaluate more favourably if the underlying cycle can be improved since with an improved cycle there is less carbon dioxide per exported kW to capture.

Two approaches to carbon abatement for coal-fired power plant are widely recognized, referred to in the UK DTI's Carbon Abatement Technologies Strategy [1] as Track 1 and Track 2 respectively - see **Figure 1.1-1**.

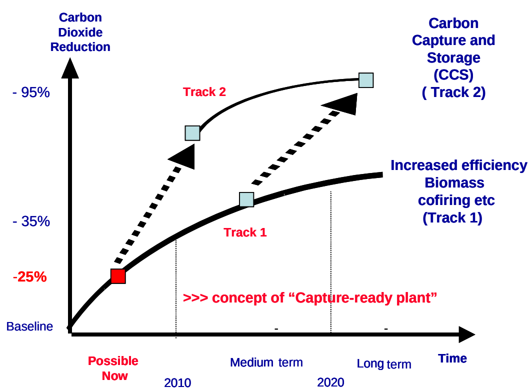


Figure 1.1-1: Twin-track approach to Carbon Abatement

The Track 1 approaches are available now. These bring reduced CO_2 emissions per unit of electricity generated. Track 1 approaches include improved cycle efficiency by introduction of Advanced SuperCritical (ASC) boiler/turbine technology and biomass co-firing (a CO_2 neutral fuel). These plants can be designed to be capture-ready, ie suitable for the later retrofit of capture plant.

The Track 2 approach, carbon dioxide capture and permanent underground storage, is necessary to achieve much larger reductions up to 95% (and in fact capture of CO_2 from carbon neutral fuels achieves a net credit in CO_2 emissions released with the application of biomass co-firing and CCS together). Track 2 CCS technologies are sufficiently understood to allow the design of the rest of the plant to be made capture-ready. Efficiency improvement is an important precursor to CCS. The efficiency improvement offsets the energy penalty of the capture equipment and both approaches are necessary to achieve a near-zero emissions power plant economically.

1.2 DTI Project Overview

The project aims to evaluate and optimise how such retrofits (Tracks 1 and 2) can be accomplished on the UK fleet of coal-fired power plants.

The project is based on state-of-the-art steam conditions for Europe (nominally 290bara final steam pressure, 600°C final steam temperature, 620°C reheat steam temperature) and innovative concepts in Post Combustion and Oxyfuel Combustion for carbon dioxide capture. More detail on this advanced supercritical boiler/turbine technology is given in DTI Best Practice Brochure BPB010 [2].

Based on three pulverised fuel Advanced SuperCritical Boiler/Turbine Retrofit (ASC BTR) designs, the range of staged carbon management retrofit options selected for the study Reference Power Plant Site (Ratcliffe, UK) are:-

(i) ASC BTR : Retrofit within existing power station infrastructure.

(ii) ASC BTR Amine CO_2 Capture Plant; and
ASC BTR Amine Capture-Ready Plant operated without Amine CO_2 Capture.

(iii) ASC BTR Oxyfuel CO_2 Capture Plant; and
ASC BTR Oxyfuel Capture-Ready Plant operated without Oxyfuel CO_2 Capture.

The applicability of the optimum retrofit solutions to other power plant sites around the UK has also been considered. This aims to demonstrate whether or not the optimum solutions determined for the reference plant are applicable to the other plant sites and whether or not the economic feasibility is dependent on the plant site.

Initial technical results of the project have been presented at the GHGT8 [3] international conference.

2. TECHNICAL DESCRIPTION OF RESULTS

2.1 Project Power Plant Sites

Reference Power Plant Site : Ratcliffe Power Station

Figure 2.1-1: Ratcliffe Power Station

Ratcliffe Power Station has an installed capacity of 2000 MWe (four x 500 MWe net) and comprises four subcritical boiler units each generating 422kg/s of superheat steam at 160bara and 566^{o}C and reheat steam at 38bara and 566^{o}C and is typical of most of the 500 to 600 MWe units in the UK, ie the boilers are of the natural circulation, balanced draught, two pass type and are fired with either domestic or internationally traded bituminous coals. Each boiler unit is equipped with Low NO_X Burners arranged on the front furnace wall. The units have operational Wet Limestone Gypsum FGD plant and therefore have opt-in status under the LCPD [4].

Like the majority of the UK 500 MW_e unit class of power plants, the steam turbine sets are of the tandem-compound design comprising five cylinders (one High Pressure; one Intermediate Pressure; three Low Pressure) with single reheat. Steam extraction points from the cold reheat line, boiler feed pump turbine, intermediate pressure turbine and low pressure turbines provide regenerative heating of condensate and feedwater. The feed system comprises of seven feedwater heater stages (two LP Heaters, Deaerator, four HP Heaters).

Ratcliffe Unit 4 has been selected as the basis of the study. Overall unit thermal net efficiency is estimated at 38.9%, LHV basis with specific CO_2 emissions of 868g/kWh (net).

Alternative Power Plant Site #1: Drax Power Station

Figure 2.1-2: Drax Power Station

Drax Power Station has an installed capacity of 3960 MWe (six x 660 MWe gross) and comprises six subcritical boiler units each generating 554kg/s of superheat steam at 160bara and 565^{o}C and reheat steam at 40bara and 565^{o}C. The boilers are of the natural circulation, balanced draught, and two pass type and are fired with either domestic or internationally traded bituminous coals. Each boiler unit is equipped with Low NO_X PF Burners arranged on the front and rear furnace walls (opposed wall firing). The units have operational Wet Limestone Gypsum FGD plant and therefore have opt-in status under LCPD.

The steam turbine sets are of the tandem-compound design comprising five cylinders (one High Pressure; one Intermediate Pressure; three Low Pressure) with single reheat. Steam extraction points from the cold reheat line, boiler feed pump turbine and low pressure turbines provide regenerative heating of condensate and feedwater. The feed system comprises of eight feedwater heater stages (five LP Heaters, Deaerator, two HP Heaters).

Drax Unit 1 was selected as the basis of the Alternative Site #1 study. Overall unit thermal net efficiency is estimated at 39.1%, LHV basis with specific CO_2 emissions of 825g/kWh (net).

Alternative Power Plant Site #2: West Burton Power Station

Figure 2.1-3: West Burton Power Station

West Burton Power Station has an installed capacity of 2000 MWe (four x 500 MWe gross) and comprises four subcritical boiler units each generating 434kg/s of superheat steam at 159bara and 565^{o}C and reheat steam at 38bara and 565^{o}C. The assisted circulation boilers are of the two pass type and are fired with either domestic or internationally traded bituminous coals. Each boiler unit is equipped with a Low NO_X Concentric Firing System comprising of eight corner assemblies (each assembly consisting of six PF burners) with Separated Over Fire Air in a twin furnace arrangement. The units have operational Wet Limestone Gypsum FGD plant and therefore have opt-in status under LCPD.

The steam turbine sets are of the tandem-compound design comprising five cylinders (one High Pressure; one Intermediate Pressure; three Low Pressure) with single reheat. Steam extraction points from the cold reheat line, intermediate pressure turbine exhaust and low pressure turbines provide regenerative heating of condensate and feedwater. The feed system comprises of seven feedwater heater stages (three LP Heaters, Deaerator, three HP Heaters).

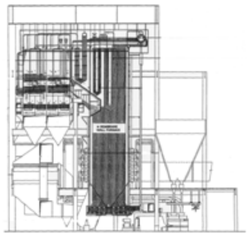
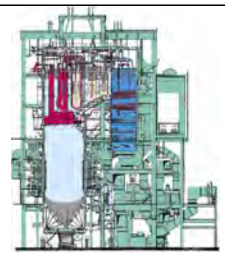
West Burton Unit 1 has been selected as the basis of the Alternative Site #2 study. Overall unit thermal net efficiency is estimated at 37.4%, LHV basis with specific CO_2 emissions of 895g/kWh (net).

General Plant Information

Table 2.1-1 below presents the general plant information and current emission control equipment for the project power plants selected for evaluation:-

- Reference Power Plant Site : Ratcliffe-on-Soar PS (four x 500MWe)

- Alternative Power Plant Site #1: Drax PS (six x 660 MWe)
- Alternative Power Plant Site #2 : West Burton PS (four x 500 MWe)

			
Project Site Power Station Owner Power Station Name	**Reference** **E.ON UK** **Ratcliffe PS**	**Alternative #1** **Drax Power Ltd** **Drax PS**	**Alternative #2** **EDF Energy** **West Burton PS**
No. of Sets x Gross Capacity	4 x 500 MWe	6 x 660 MWe	4 x 500 MWe
Year 1st Set Commissioned	1968	1974	1967
Unit Net Efficiency	38.9% LHV (Unit 4)	39.1% LHV (Unit 1)	37.4% LHV (Unit 1)
Boiler Supplier	Doosan Babcock	Doosan Babcock	International Combustion Ltd
Boiler Type	Natural Circulation Two-Pass	Natural Circulation Two-Pass	Assisted Circulation Two-Pass
Boiler Firing Arrangement	FWF	OWF	CF
Main Steam @ TSV	158.6bar/565°C	159.6bar/565°C	158.6bar/565°C
Reheat Steam @ TSV	39.0bar/565°C	40.2bar/565°C	37.9bar/565°C
Approx. IP/LP Cross-Over	3.6bara	6.4bara	3.5bara
Steam Turbine Supplier	NEI Parsons & Co Ltd	NEI Parsons & Co Ltd	English Electric
Steam Turbine	1HP / 1IP / 3LPs	1HP / 1IP / 3LPs	1HP / 1IP / 3LPs
MBFW Pumps	2 x 50% Turbine	2 x 50% Turbine	2 x 50% Turbine
FW Heaters	2 x LPs + D/A + 4 x 2-HPs	5 x LPs + D/A + 2 x 2-HPs	3 x LPs + D/A + 3 x 2-HPs
Final FWT	254°C	256°C	250°C
Condensing	Cooling Tower 55mbara	Cooling Tower 52mbara	Cooling Tower 50mbara
Environmental	LNBs ESP FGD	LNBs ESP FGD	LNCFS ESP FGD
Unit Draught Plant Layout	2 x FDs 2 x IDs 8 x Hot PA Fan System 3 x Bi-Sector AHs	2 x FDs 2 x IDs 10 x Hot PA Fan System 2 x Bi-Sector AHs	2 x FDs 2 x IDs 2 x Cold PA Fan System 2 x SA Bi-Sector AHs 2 x PA Bi-Sector AHs

Key

LHV	Low Heating Value	LNBs	Low NOx Burners
FWF	Front Wall Fired	LNCFS	Low NOx Concentric Firing System
OWF	Opposed Wall Fired	FGD	Flue Gas Desulphurisation
CF	Corner Fired	FD	Forced Draught
TSV	Turbine Stop Valve	ID	Induced Draught
MBFW	Main Boiler Feed Water	PA	Primary Air
D/A	Deaerator	SA	Secondary Air
		AHs	Airheaters

Table 2.1-1: Project 407 Power Plants : General Plant Information

Age Profile

The UK fleet of coal-fired power stations were constructed in the period 1960 to mid-1980's. The selected project sites cover the age profile 0-20 years old (Drax), 21-35 years old (Drax, Ratcliffe) and 36+ years old (Ratcliffe, West Burton).

Boiler Types

The three main types of two-pass boiler designs employed in the UK bituminous PF coal-fired power plants are shown in **Table 2.1-1**. The two-pass boiler burner firing configurations of the power plants sites selected for the project are as follows:-

- Reference Power Plant Site: Ratcliffe (four x 500 MWe) like most of the 500 - 600 MWe natural circulation units in the UK is a two-pass front wall-fired boiler.
- Alternative Site #1: Drax (six x 660 MWe) is the largest plant in UK and has opposed wall-fired two-pass natural circulation boilers with parallel back-end which are similar to most of the boilers exported from the UK in the 80s and 90s.
- Alternative Site #2: The two-pass assisted circulation boiler units at West Burton (four x 500 MWe) are corner / tangential fired. In this configuration, the burners are arranged at each corner of a twin furnace and discharge onto an imaginary firing circle in each combustion chamber to produce a vortex.

The project power plants selected are representative of the UK boiler unit size (500 MWe and 600 MWe class) and cover the three types of boiler burner firing configurations of front-wall fired units, opposed-wall fired units and corner fired units.

Steam Turbine Set and Feedwater System

The arrangement of the LP and HP feedwater heaters differ between the project sites as summarised below:

Project Site Power Station Owner Power Station Name	**Reference E.ON UK Ratcliffe**	**Alternative #1 Drax Power Ltd Drax**	**Alternative #2 EDF Energy West Burton**
Total No. of Feedwater Heater Stages	7	8	7
LP Heaters	4	5	3
	FW Tank & Deaerator	FW Tank & Deaerator	FW Tank & Deaerator
HP Heaters	2 (double train)	2 (double train)	3 (double train)

Table 2.1-2: Project 407 Power Plants : Existing Feedwater Heater System Arrangement

The project power plants selected all differ in the arrangement of the feedwater heating train and therefore demonstrate the extent of the application of the retrofit options, particularly with respect to the integration of the waste heat into the steam cycle for the CO_2 capture retrofit solutions.

Emissions Control Equipment

The project selected power plants have operational FGD plant and therefore have declared opt-in status under LCPD [4].

FGD plant is an important consideration for the ASC BT Retrofit (under LCPD the retrofit plant would be required to meet a SO_X limit of 200mg/Nm^3 at 6% O_2 dry) and the ASC BT Retrofit with CO_2 Capture (particularly with respect to the performance enhancements/polishing options necessary for post combustion CO_2 capture). The FGD plant is also an important consideration in the Oxyfuel CO_2 capture option.

<u>Pulveriser System Layout</u>

The pressurised pulveriser systems of the UK coal-fired power plants operate as direct-fired systems ie coal leaving each pulveriser is fed directly to the combustion process. The components forming the direct-fired system can be arranged in several ways based primarily on project economics at the time of construction. The two basic direct-fired system arrangements employed in the UK coal-fired power plants are:-

- Direct-fired hot fan fuel-air system
- Direct-fired cold fan fuel-air system

The direct-fired hot fan fuel-air system utilises hot primary air fans with a dedicated fan for each pulveriser.

In the direct-fired cold fan fuel-air system, the primary air fans operate cold and are located ahead of a dedicated airheater and a hot air supply system with lateral ductwork to the individual pulverisers.

The power plants sites selected under the project cover both direct-fired system arrangements:-

- Project sites Ratcliffe and Drax operate with a hot fan fuel-air system, and
- Project site West Burton operates with a cold fan fuel-air system.

The above plant system arrangements were retained for ASC BT Retrofit and for the case of ASC BT with CO_2 Capture Retrofit.

For the design basis of minimum capital investment through maximum use of existing installed plant, the retained fan fuel-air system will result in different process flow sheet configurations (flue gas recycle system) for the Oxyfuel CO_2 capture route. On this basis, the selection of project sites ensured that at least two basic process flow sheet options for application of Oxyfuel were evaluated under the study.

<u>General Site Layout</u>

The general arrangement layout of the project selected sites is an inland site with natural draught cooling water and delivery of the coal by rail.

One of the key constraints for the retrofit of ASC BT with CO_2 capture is the footprint requirements of the CO_2 capture plant. Each site presents different technical challenges, but in terms of the available space and hence ease of retrofit of the CO_2 capture plant, the selected sites offer key differences for the assessment of site constraints:-

- Reference Power Plant Site Ratcliffe: moderate space available for CO_2 capture plant footprint requirements
- Alternative Site #1 Drax: smallest space available for CO_2 capture plant footprint requirements
- Alternative Site #2 West Burton: largest space available for CO_2 capture plant footprint requirements

2.2 Project Design Basis and Assumptions

2.2.1 Basic Design Data

The basic design data for the technical evaluation of the CO_2 abatement retrofit cases is defined in **Table 2.2-1**.

Location	Inland UK
Site Conditions	Site Elevation • Ratcliffe: 38.0m • Drax: 6.1m • West Burton: 7.0m Ambient temperature: • Ratcliffe: 10.9°C • Drax: 11.5°C • West Burton: 10.0°C
Design Coal Specification	UK domestic bituminous coal – see Table 2.2-2.
Cooling Water	Natural draught cooling towers CW source / temperature : • Ratcliffe: River Trent / 17.6°C • Drax: River Ouse / 18.2°C • West Burton: River Trent / 19.1°C
ASC Water Steam Cycle	Feedwater temperature: 310°C Main steam : 290bara / 600°C Reheat steam : 60bara / 620°C
Design Codes & Standards	European
Construction Period	ASC BTR: 25 Months ASC BTR with CO_2: 25 Months
Target Plant Life	25 years design life extension post ASC BTR
Plant Load Factor	ASC BTR: Plant Utilisation (85%) x Availability ASC BTR with CO_2: Plant Utilisation (85%) x Availability
Environmental Limits	Directive 2001/80/EC : 2001
Gaseous Emissions	NOx: ≤ 200mg/Nm^3 @ 6% O_2 v/v, dry (stack)
	SO_2 : ≤ 200mg/Nm^3 @ 6% O_2 v/v, dry (stack)
	CO: ≤ 50mg/Nm^3 @ 6% O_2 v/v, dry (stack)
	NH_3: ≤ 10mg/Nm^3 @ 6% O_2 v/v, dry in flue gas
Solid Emissions	Dust: ≤ 30mg/Nm^3 @ 6% O_2 v/v, dry (ESP Outlet)
	Ash: ≤ 5% Carbon in fly ash (A/H outlet) Ash: ≤ 50mg/kg NH_3 in total ash due to DeNOx
Liquid Effluent	Retrofit plant waste water to comply with current EU concentration limits.
Noise	Retrofit plant to maintain plant boundary decibel levels below current site maximum allowable.
Target CO_2 Capture Level	> 85%
CO_2 Quality Requirements	See Table 2.2-3 for CO_2 quality requirements.
CO_2 Delivery Conditions	CO_2 delivery pressure: 110bara CO_2 delivery temperature: 45°C max

Table 2.2-1: Project Basic Design Data

2.2.2 Design Coal Specification

The ‘as-received’ bituminous design coal specification is listed in **Table 2.2-2**:-

Project Site Power Station Owner Power Station Name		**Reference** **E.ON UK** **Ratcliffe**	**Alternative #1** **Drax Power Ltd** **Drax**	**Alternative #2** **EDF Energy** **West Burton**
COAL SOURCE **COAL NAME**		**UK Domestic** **Daw Mill**	**UK Domestic** **Kellingley**	**UK Domestic** **Thoresby**
GCV (as received)	MJ/kg	27.301	24.030	24.643
NCV (as received)	MJ/kg	26.114	23.000	23.500
HGI	-	51	56	56
ULTIMATE ANALYSIS				
CARBON C	% w/w	66.80	56.20	59.71
HYDROGEN H	% w/w	3.94	3.64	3.80
OXYGEN O	% w/w	7.73	6.88	5.49
NITROGEN N	% w/w	1.10	1.20	1.00
SULPHUR S	% w/w	1.71	1.86	1.75
CHLORINE Cl	% w/w	0.27	0.42	0.55
MOISTURE H_2O	% w/w	10.00	12.30	12.00
ASH	% w/w	8.40	17.50	15.70

Table 2.2-2: Design Coal Specification

2.2.3 CO_2 Quality

Table 2.2-3 presents two CO_2 quality requirement scenarios considered under the project. These are defined as:-

Basic Design Case: *Pipeline transport and geological storage.* The project ASC BTR with CO_2 power plant sites are designed to fulfil this requirement scenario considering only removal of major impurities. This requirement scenario is based on CO_2 transport via pipelines and CO_2 storage in geological formations.

EOR Case**:** *Pipeline transport and EOR*. The need for and costs for additional cleaning regarding mainly water and oxygen content and sulphur compounds to meet stricter requirements for EOR (Enhanced Oil Recovery) was assessed / estimated for CO_2 capture cases. This requirement scenario is based on CO_2 transport via pipelines and storing CO_2 combined with EOR.

The technical evaluation of the CO_2 abatement retrofit cases has been undertaken for the agreed Basic Design Case CO_2 quality requirements. Sensitivity of performance to meet the more stringent requirements for EOR has also been investigated.

	Project Requirement Scenarios (Approximate Values)	
Component	**Basic Design Case**	**EOR Case**
H_2O	< 500 ppm[1]	< 50 ppm[1]
CO_2	> 90% mol	> 90% mol
SO_2	From H&MB[2]	< 50 ppm[3]
NO	From H&MB[2]	From H&MB[2]
H_2S	< 1.5% mol	< 50 ppm[3]
O_2	< 4% mol[4]	100 ppm
CO	< 4% mol[4]	< 4% mol[4]
Ar	< 4% mol[4]	< 4% mol[4]
N_2	< 4% mol[4]	< 4% mol[4]
Hydrocarbons	From H&MB[2]	From H&MB[2]
Hg	From H&MB[2]	From H&MB[2]
Particulates	From H&MB[2]	From H&MB[2]

Notes
1. Design case <500ppm H_2O based on North American specifications for pipeline transport of CO_2. EOR <50ppm H_2O conservative requirement to avoid hydrate formation in pipeline transport.
2. According to mass balance for the respective ASC BTR CO_2 Capture plants ie no specific requirements.
3. Total content of all sulphur compounds <50ppm in order not to increase sulphur content in recovered oil and for safety concerns.
4. Total content of all non- condensable gases <4%mol.

Table 2.2-3: Project CO_2 Quality and Requirement Scenarios

2.3 Technical Guidelines

Technical guidelines were generated following a series of R&D paper studies on key technical aspects and risk areas. The aim of these guidelines was to provide an initial set of rules for the retrofit supercritical plant with CO_2 capture activities within the project and enable these to be further developed and incorporated into subsequent and future design/demonstration retrofit projects.

The technical guidelines developed under this project cover:-

- Integrating Capture with ASC BTR Steam Cycles: Basic principles for integrating post combustion CO_2 capture with overall power plant steam cycle to minimise cost and energy penalty and notes on steam cycle / capture with Oxyfuel Combustion CO_2 capture.
- Post Combustion CO_2 Removal: Types of amines, solvent degradation issues, solvent consumption and DeSOx (WLG FGD) plant considerations.
- High Level Philosophy of Conceptual Oxyfuel Process Flow Diagram (PFD): Outline design philosophy for ASC BTR Oxyfuel with CO_2 capture in the form of a conceptual PFD for maximum plant performance including consideration for retained ESP plant and FGD plant.

- Operating Flexibility: Basic operating flexibility for post combustion capture and Oxyfuel combustion capture technologies.

- Chemistry and Corrosion: High temperature fire-side corrosion, carburisation, furnace wall fire-side corrosion, Oxyfuel combustion flue gas corrosivity, dew point corrosion, chemical corrosion.

- Health & Safety (Carbon Dioxide, Amine and Oxygen): Safety requirements and handling of gaseous CO_2 and liquid CO_2. Bulk storage and handling of amine solvents for post combustion CO_2 capture. Safety issues and handling of oxygen for Oxyfuel combustion CO_2 capture technology covering ASU safety aspects, oxygen distribution, oxygen preheating, oxygen injection into boiler's combustion system, and oxygen cleanliness.

- Gaseous Emissions: Preliminary assessment of the technological and economic traits of commercially available NOx reduction technologies as applied to the carbon abatement technologies. Flue gas desulphurisation requirements associated with ASC BT retrofit with and without CO_2 capture.

- CO_2 Purity Requirements: Legality of CO_2 disposal in geological formations, requirements for CO_2 and purity expectation from CO_2 capture technologies.

2.4 Technology Level

Present European state-of-the-art advanced supercritical boiler/turbine technology level with steam turbine inlet conditions of **290bar / 600^{o}C / 620^{o}C** for ASC BTR plant and ASC BTR plant with CO_2 capture:-

Boiler Island:	Advanced supercritical boiler retrofit based on state-of-the-art Doosan Babcock Two-Pass single reheat BENSON [5] boiler with POSIFLOW^{TM} Technology, Balance Draught. Appropriate Oxyfuel combustion equipment design based as far as possible on existing knowledge, experience and expertise in the design of air-fired PF boiler technology for ASC BTR Oxyfuel CO_2 Capture.
Turbine Island:	Alstom's state-of-the-art advanced supercritical turbine retrofit technology, including advanced 3-D blading, and turbine island balance-of-plant modifications.
DeNOx:	Current market SCR technology. Note: DeNOx plant is considered not to be a requirement within the Oxyfuel boiler island. However, DeNOx plant will need to be retained in the Oxyfuel boiler island if full load air-firing capability is to be maintained.

ESP:	As per current installed plant.
DeSOx:	Upgraded current installed plant to meet emissions regulations / requirements of the carbon dioxide abatement technologies.
ASU:	Current state-of-art oxygen production based on cryogenic separation technology for ASC BTR Oxyfuel CO_2 Capture.
CO_2 Capture:	Current state-of-art amine based stack-gas CO_2 absorber / desorber system for ASC BTR Amine CO_2 Capture.
CO_2 Compression:	Current state-of-art CO_2 purification and CO_2 compression technology (differs for CO_2 capture cases).

Note : Retrofit of DeHg plant is not specifically addressed under the project.

2.5 Outline Basis of Design

The outline 'basis of design' for the CO_2 abatement retrofit plant considered under this project is summarised below:-

- Carbon dioxide abatement technology concepts targeted at near-term exploitation based, where possible, on conventional well-proven / proven technology for minimum risk.

- Reference Ratcliffe and Alternative Site#2 West Burton: Maximum plant electrical output (ie retaining the same fuel heat input rate as the existing subcritical plant within the installed capacity of the existing mills / combustion equipment);

  Alternative Site#1 Drax: Same gross electrical output as per the existing subcritical plant.

- ASC BT Retrofit as the base for ASC BTR Amine and ASC BTR Oxyfuel CO_2 capture retrofit cases.

- PF Boiler Plant: Retrofit state-of-art ASC PF Doosan Babcock Two-Pass POSIFLOW^{TM} boiler.

- Retain existing burner arrangement for the retrofit furnace design to minimise costs.

- Steam Turbine Plant: Maximum efficiency ASC turbine retrofit based on following outline plant scope:

  - New advanced supercritical HP & IP Cylinders.
  - Retrofit LP innerblocks to maximise plant performance.

– Condensate and LP feedwater heating system upgrades as appropriate to meet water chemistry requirements of ASC plant.

– Upgraded feedwater pumping and HP feedwater heating system to achieve uprated pressure.

– New condensate polishing plant.

– Auxiliary system upgrades, as appropriate.

- 100% HP steam bypass station and pressure safety relief system

- Emissions: Upgrade and retrofit of appropriate emissions control plant to new plant standards including additional requirements of CO_2 capture plant.

- CO_2 Plant: Electrically driven rotating plant.

- Retained Plant: Maximise use and installed capacity of the existing subcritical power plant equipment and layout where practical and economic.

- Maximise plant performance through process integration including low grade heat integration with steam cycle.

- Maintain plant total cooling water mass flow rate as per the existing subcritical plant. For CO_2 capture (Oxyfuel), this cooling water restriction results in an increase in surface condenser pressure due to the increase in condenser heat rejection combined with the additional capture plant cooling water requirements. Supplementing the main cooling water system pumps would lead to an increase in the overall plant efficiency of the Oxyfuel CO_2 Capture system.

2.6 ASC BT Retrofit

2.6.1 Thermodynamic Imperative & Steam Cycle Optimisation

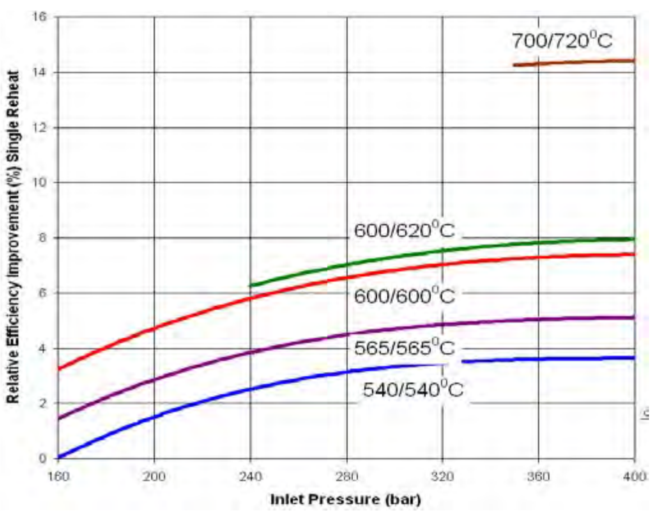


Figure 2.6-1: Effect of Steam Conditions on Cycle Efficiency (single reheat units)

The thermodynamic efficiency of the conventional (subcritical) single reheat cycle can be improved significantly if the average temperature at which heat is added to the cycle is increased. The most obvious method of increasing the average temperature at which heat is added to the cycle is by increasing main and reheat steam temperatures.

Figure 2.6-1 shows that the

overall improvement in relative cycle efficiency obtained purely from increasing steam conditions at turbine inlet from 160bar/565°C/565°C to 290bar/600°C/620°C will be in the order of six percentage points with corresponding reductions in both fuel burned and boiler emissions.

The average temperature of heat addition can be increased still further by increasing the temperature of the boiler feedwater. The turbine cycle (steam turbine island feed heating train) must be arranged to provide boiler feedwater at the correct pressure and temperature for optimum overall efficiency and will normally incorporate a feedwater heater above the reheat point using steam extracted from the HP turbine.

2.6.2 Overall Process Description

Overall System Components: Retrofit Capture-Ready ASC Boiler/Turbine, New DeNOx Plant (SCR), Existing ESP, Upgraded DeSOx (WLG FGD).

As the basic building block for capture-ready, the existing plant is retrofitted to operate at ASC steam conditions 290bara/600°C/620°C. This is achieved by replacing the existing subcritical boiler with a Doosan Babcock POSIFLOW™ low mass flux BENSON two-pass advanced supercritical boiler re-using the existing steel support structure, coal and ash handling plant, coal mills, draught plant and retrofitting the high temperature main and reheat steam valves / pipework and as a minimum the HP and IP turbine sections. The most advanced commercially available materials are employed for the boiler/turbine high-temperature components.

For the agreed design basis, the retrofit supercritical plant has been optimised based on either maintaining the same fuel firing rate (Ratcliffe and West Burton) or maintaining the same gross output (Drax) as the existing subcritical plant.

The retrofit turbine cycle is arranged to provide boiler feedwater at the correct pressure and temperature for optimum boiler thermal efficiency and incorporates a feedwater heater above the reheat point (HARP) using steam extracted from the HP turbine. The optimized feedwater train comprises nine feedwater heater stages (four LP Heaters, Deaerator, three HP Heaters + Topping Desuperheater). The existing condenser is re-tubed to meet the water chemistry requirements of the advanced supercritical plant and to regain design vacuum. Full flow condensate polishing is provided.

The ASC BTR plant is designed to meet the future emissions requirements of LCPD (see **Table 2.2-1**) with retrofit of DeNOx plant (in the form of SCR plant), existing electrostatic precipitators and low cost upgrade to the existing conventional DeSOx plant - Wet Limestone Gypsum FGD plant, viz:-

- NOx 200mg/Nm^3 at 6% oxygen dry
- Particulates 30mg/Nm^3 at 6% oxygen dry
- SO_2 200mg/Nm^3 at 6% oxygen dry

Layout feasibility of SCR retrofit has been confirmed for the reference plant (see **Figure 2.6-6**). Although no detailed design work has been undertaken to prepare possible conceptual SCR retrofit plant layouts for the alternative sites, it is not envisaged that there will be any undue difficulties in locating the SCR reactors given the possibility of several location options. However, this will need to be confirmed through further feasibility studies. The additional flue gas cleaning plant requirements represent a significantly larger gas-side pressure drop duty for the boiler draught plant, necessitating upgrade or replacement of boiler fans. A further consideration is the requirement to enamel the regenerative airheater cold-end elements due to introduction of the SCR unit upstream.

Figure 2.6-2 presents the basic process flow block diagram of the existing subcritical plant and the power plant process flow block diagram proposed for ASC BT Retrofit plant based on the above outline retrofit philosophy.

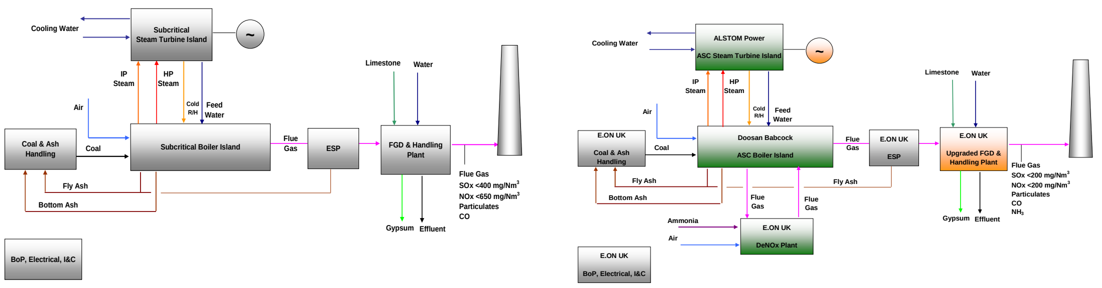


Figure 2.6-2: Process Flow Block Diagram – Subcritical Plant and ASC BT Retrofit Plant

The conceptual Process Flow Diagram (PFD) as proposed for the project reference power plant (Ratcliffe) ASC BT retrofit is presented in **Figure 2.6-3.** The conceptual PFDs for the project alternative sites (Drax and West Burton) are presented in **Figure 2.6-4** and **Figure 2.6-5** respectively. The overall boiler island PFD is based on retaining the existing air / flue gas system arrangement (including existing in-furnace measures of BOFA / SOFA for control of NOx emissions).

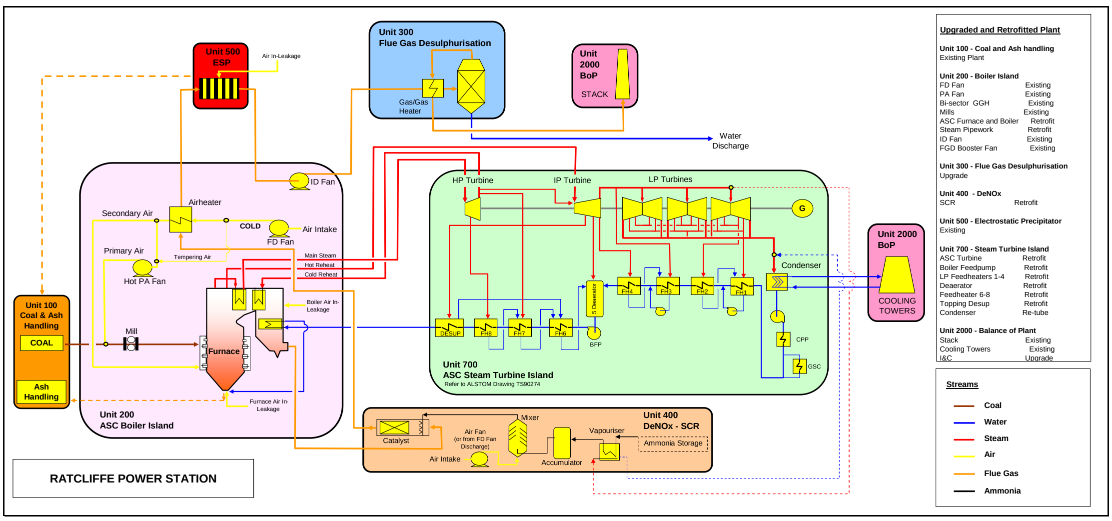


Figure 2.6-3: Conceptual PFD – Reference Site : Ratcliffe ASC BT Retrofit

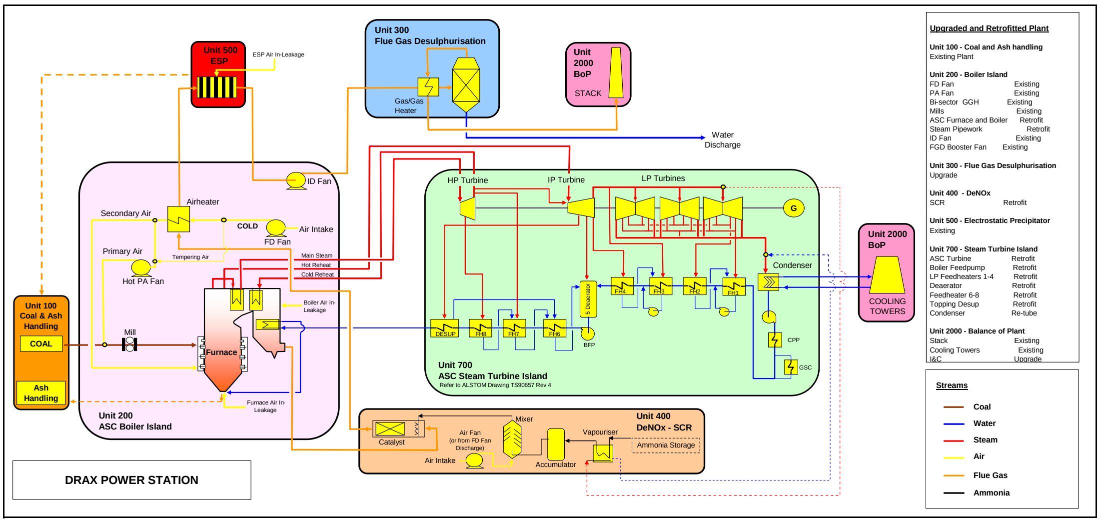


Figure 2.6-4: Conceptual PFD – Alternative Site #1 : Drax ASC BT Retrofit

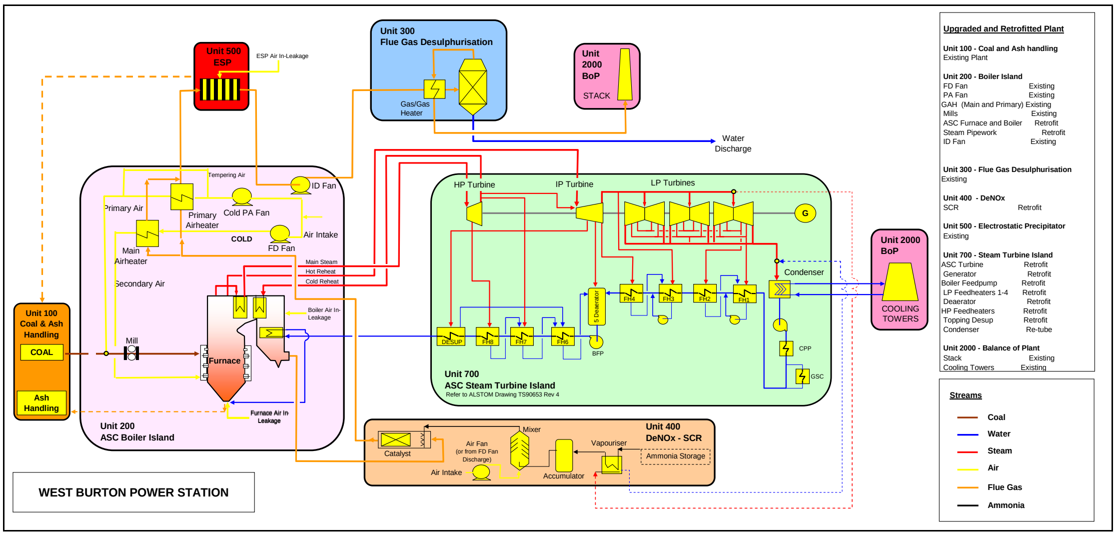


Figure 2.6-5: Conceptual PFD – Alternative Site #2 West Burton ASC BT Retrofit

2.6.3 <u>ASC Boiler Island</u>

<u>ASC Retrofit : Boiler Design</u>

The proposed state-of-the-art boiler design for retrofit, Figure 2.6-6, is based on the established two-pass layout once through supercritical design utilising the BENSON principle with the incorporation of low risk novel cost reduction features. The use of furnace arrangement with POSIFLOW^{TM} vertical internally ribbed low mass flux tubing in place of the traditional spiral wound tubing offers several cost advantages.

The boiler design has been based on the BS EN 12952 design code. In addition to this, consideration was given to design margins required for the pressure part scantlings based on upsets to gas and steam-side imbalance, heat flux profiles and heat imbalance.

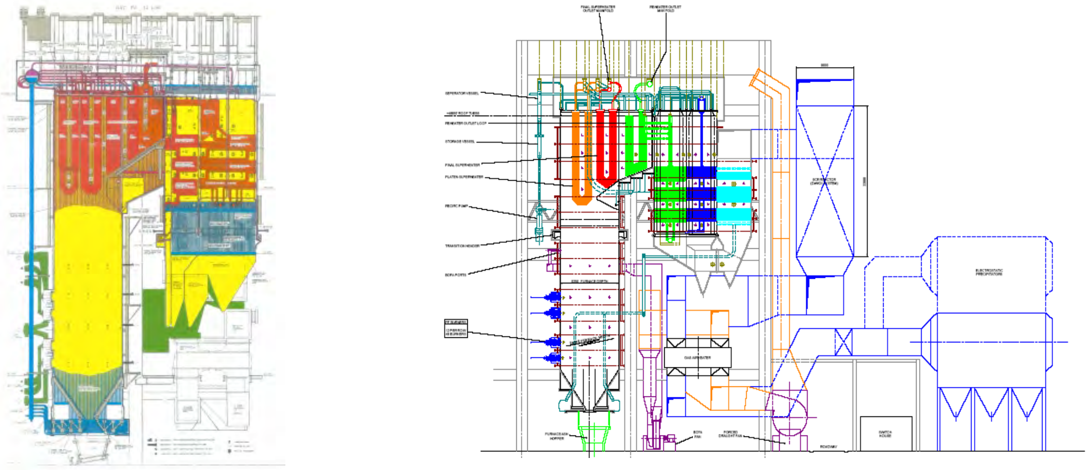


Figure 2.6-6: Boiler Arrangement : Ratcliffe Subcritical vs ASC Retrofit with SCR Plant

Water/Steam Circuit

Figure 2.6-7 presents a typical once through boiler water/steam circuit flow diagram with POSIFLOW^{TM} furnace for advanced supercritical retrofit.

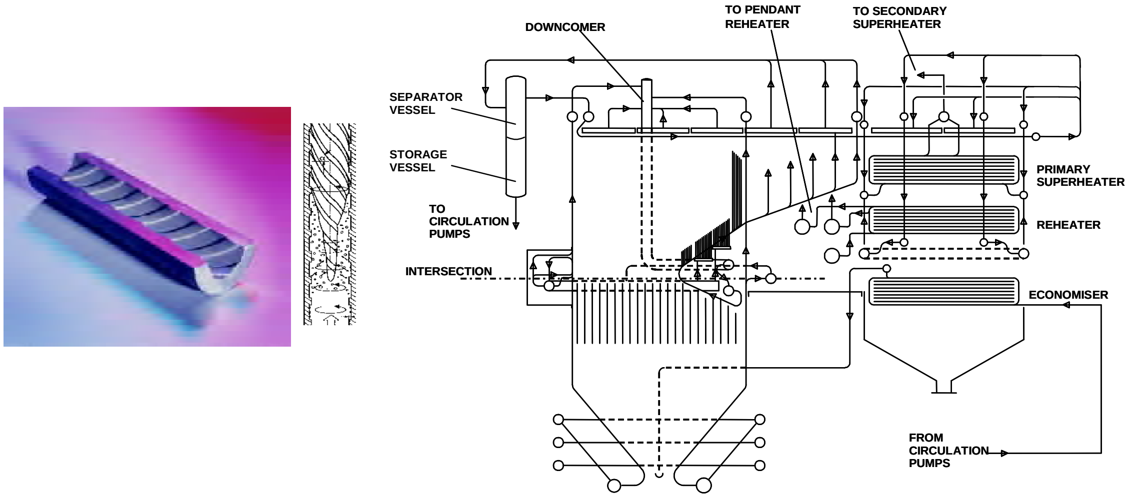


Figure 2.6-7: Typical Once Through Boiler Water/Steam Circuit with POSIFLOW^{TM} Furnace

ASC Furnace Design

The use of internally ribbed vertical tubes for furnace design allows the water/steam mass flux to be reduced whilst ensuring the required cooling of the tubes. The vertical tube furnace is a development that enables once through supercritical boilers to operate with lower absorbed power due to reductions in furnace water/steam side pressure drops as well as lower BENSON loads to improve operational flexibility.

The retrofit furnace design retains the existing burner arrangement so as to minimise costs. The final superheat and reheat heating surfaces are of the proven pendent design, which resist slag build-up. The second pass comprises typical convective surface; primary reheat and primary superheat.

Superheater, Reheater & Economiser

The superheater and reheater with advanced steam conditions are similar in arrangement to those for conventional subcritical plant. The superheater tubes are designed to operate up to 50K above the final steam temperature. The higher steam temperatures imposes additional stresses on the superheater material and increase the rates of both fire-side and steam-side corrosion/oxidation. To offer good service lifetimes, austenitic materials with the higher chromium content are necessary.

For the reheaters, the operating pressure is almost one fifth of that of the superheater and this allows either less advanced materials or, more commonly, higher steam temperatures of some +20K to be employed.

A continuous multi-loop economiser is included so as to reduce the flue gas temperature to the required level for the existing regenerative airheaters. The economiser also acts as a buffer between the feedwater supply system and the furnace circuits and hence reduces the potential for fatigue damage caused by thermal stress variations.

High Temperature Pressure Parts Material

Based on current state-of-art, the preliminary material selection for the high temperature pressure parts are summarised in **Table 2.6-1**.

	High Temperature Pressure Parts Material
Pipes & Manifolds	
Final Superheater Outlet Manifold	EN 10216-2 – X10CrWMoVNb9-2 (P92)
Main Steam Pipe	
Hot Reheat PIpe	
Final Reheater Outlet Manifold	EN 10216-2 – X10CrMoVNb9-1 (P91)
Headers	
Primary Superheater Outlet Headers	EN 10216-2 – X10CrMoVNb9-1 (P91)
Platen Superheater Outlet Stub Headers	
Final Reheater Outlet Stub Headers	
Final Superheater Outlet Stub Headers	SA 335 P92 (NF616)
Heating Surface	
Platen Superheater Outlet Leg	TP310HNbN
Final Superheater Outlet Leg	
Final Reheater Outlet Leg	
Primary Superheater	EN 10216-2 – X10CrMoVNb9-1 (T91)
Primary Reheater	EN 10216-2 - 10CrMo9-10
Furnace	
Internally Ribbed Tubes	EN 10216-2 – 13CrMo4-5
Roof Tubes	EN 10216-2 – 10CrMo9-10

Table 2.6-1: ASC Boiler Retrofit: Summary High Temperature Pressure Part Materials List

2.6.4 ASC Turbine Island

ASC Retrofit : Turbine Design

The existing turbines in UK power plants use 1960s and 1970s steam path technology which will give, at best, cylinder internal efficiencies corresponding to that era. The application of Alstom advanced steam path technology to the HP, IP and LP turbines will provide a significant improvement in internal turbine cylinder efficiencies.

Alstom has developed advanced fixed and rotating blade technology in recent years, which is capable of providing the highest levels of turbine efficiency in steam turbine plant.

The proposed turbine configuration for the advanced supercritical retrofit consists of the following:

- One complete single flow high pressure (HP) turbine with welded drum type rotor, vertically split inner casing fitted with shrink rings, horizontally split outer casing with bolted flange connection.

- One complete intermediate pressure (IP) turbine of single flow disc and diaphragm construction and monoblock type rotor, horizontally split inner and outer casings, all with bolted flange connections.

- Three double flow low pressure (LP) reaction turbine inner block retrofits with welded drum type rotor, horizontally split inner casings with bolted flange connections.

The increase in admission pressure and temperature renders the HP / IP turbine inner casings, HP/IP rotors, HP/IP steam chest and inlet loop pipework unsuitable for operation at advanced supercritical conditions. Retaining the HP turbine outer casing is possible with a consequent ceiling on the overall cycle performance. Also in a small minority of cases, the IP turbine outer casing can be retained, if the extraction points are compatible with the upgraded cycle and if an arrangement can be provided to prevent excessive casing inlet temperatures.

In general, it is expected that a complete new HP module, new IP module and steam chests will be required for conversion to supercritical conditions and to achieve maximum cycle efficiency. Replacement of complete HP and IP turbine modules, HP and IP steam chests are envisaged for Ratcliffe, Drax and West Burton Power Plants.

Figure 2.6-8 presents the advanced supercritical retrofit conceptual Turbine Island PFD proposed for the project reference power plant site (Ratcliffe).

Conceptual Turbine Island PFDs for the alternative sites (Drax and West Burton) are presented in **Figure 2.6-9** and **Figure 2.6-10** respectively.

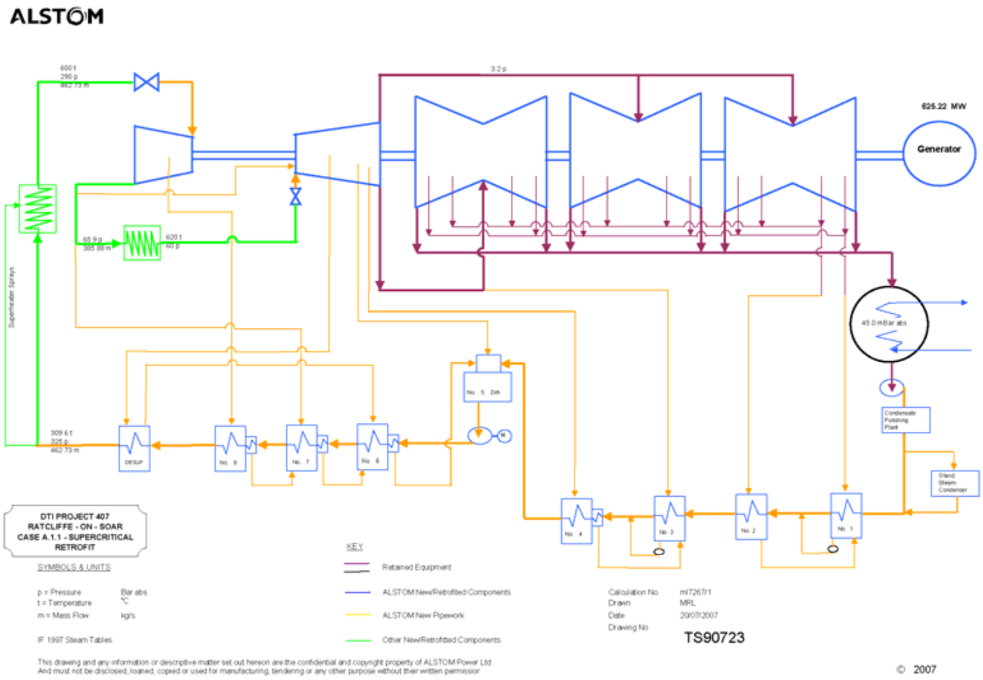


Figure 2.6-8: ASC BT Retrofit : Steam Turbine Island PFD – Ratcliffe

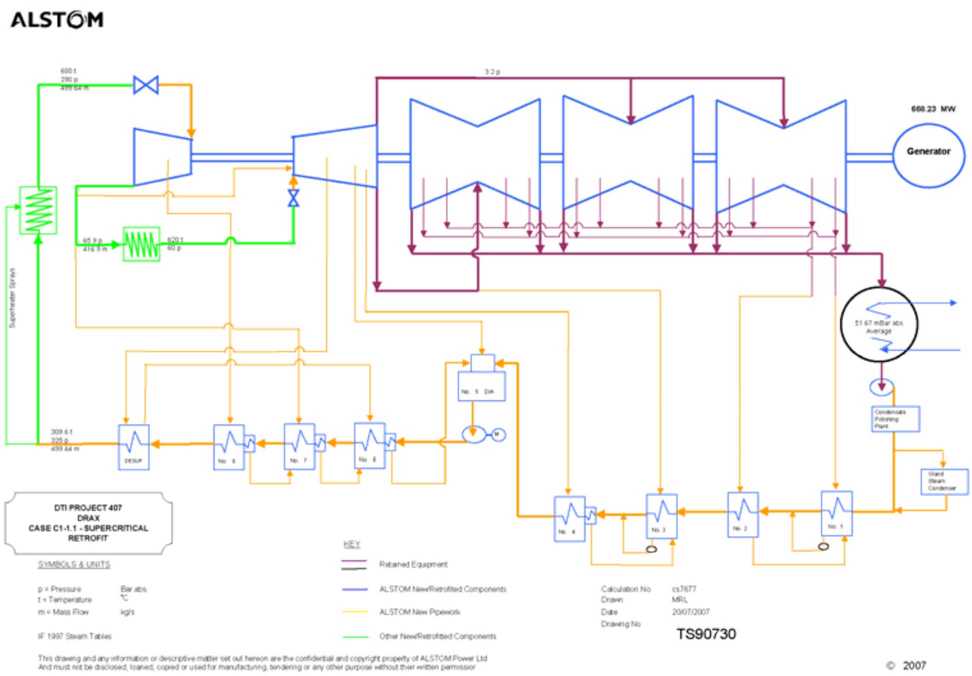


Figure 2.6-9: ASC BT Retrofit : Steam Turbine Island PFD – Drax

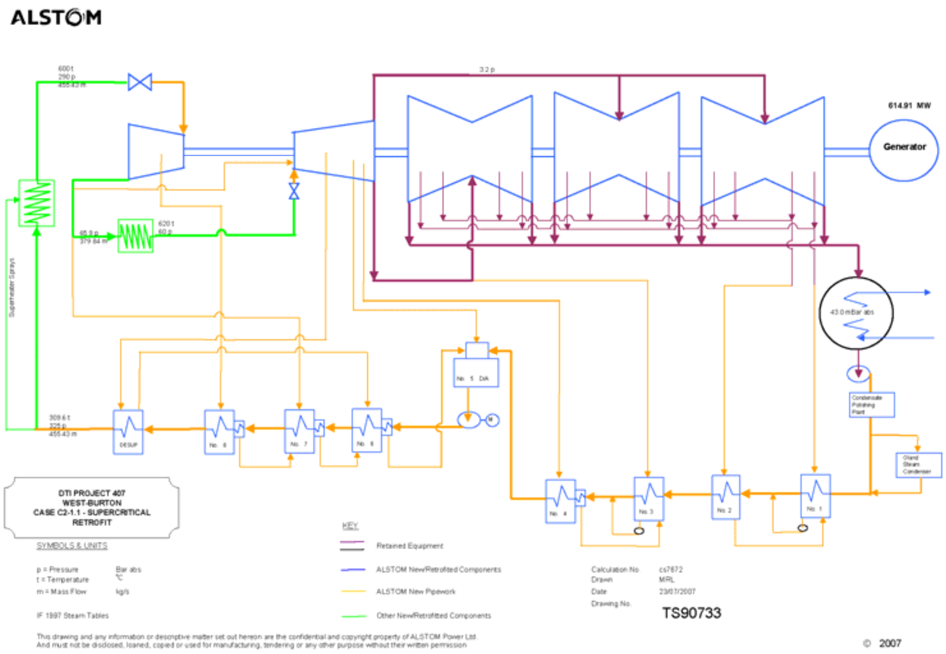


Figure 2.6-10: ASC BT Retrofit : Steam Turbine Island PFD – West Burton

HP Turbine

In order to accommodate the increase in steam conditions both at the inlet and exhaust, a complete new HP module is required for advanced supercritical retrofit.

Alstom propose an HP cylinder similar to the standard HP modules for new build 600°C applications. It is of single flow reaction construction and employs shrink ring sealing technology to minimise casing distortion and wall thickness. The standard module design, **Figure 2.6-11**, would be modified to accommodate the existing HP outer casing foundation interface locations.

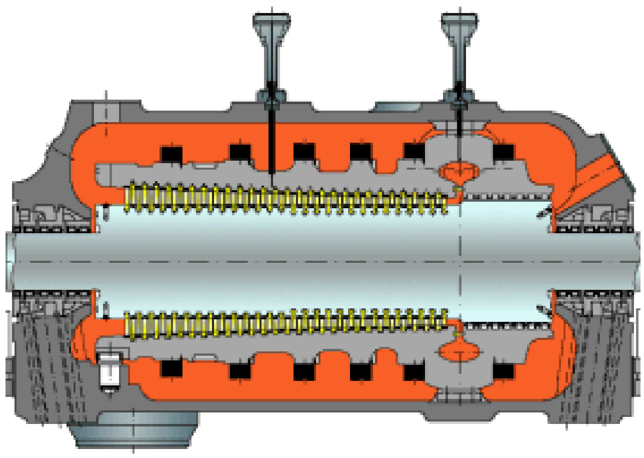


Figure 2.6-11: Advanced Supercritical HP Turbine

The Alstom welded rotor design provides excellent operational behaviour, improved thermal flexibility, fast start-up times and high loading rates. The new HP rotor is of the welded drum type. To minimize start-up times it is important to have a rotor design, which ensures thermal stresses remain at a low level. Extensive research undertaken demonstrates that the welded rotor design employed by Alstom will ensure low thermal stresses at transient conditions, as verified by operational experience gained over several decades.

Alstom anticipate the following materials for the retrofit ASC HP turbine:

	EN Identification
Rotor Forgings	25CrMoV3-8 X12CrMoVNbN10-1-1
Casing	GXCrMoVNbN9-1
Blading	X12CrNiWTi17-14 X22CrMoV12-1
Shrink Rings	21CrMoV5-7 X22CrMoV12-1
Bolts	21CrMoV5-7 X22CrMoV12-1

Table 2.6-2: Materials for Advanced Supercritical HP Turbine Module

IP Turbine

In order to accommodate the increase in steam conditions both at the inlet and exhaust, a complete new IP module, **Figure 2.6-12**, is required for advanced supercritical retrofit.

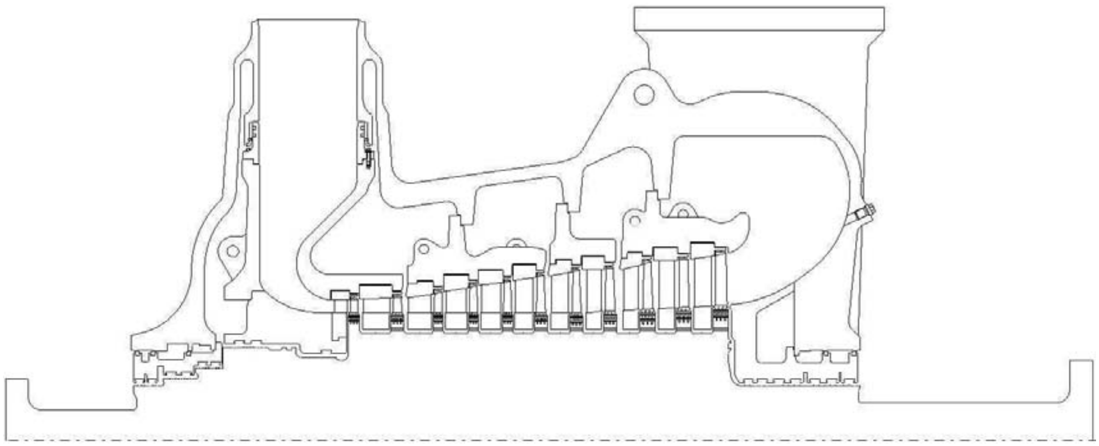


Figure 2.6-12: Proposed Advanced Supercritical IP

Alstom propose an IP cylinder based on disc and diaphragm construction using low reaction (impulse) blading, whereby the majority of the stage pressure drop occurs across the fixed blade diaphragm. The low moving blade pressure drop results in low axial thrust thus permitting rotor thrust balance with modest balance piston diameter.

Alstom anticipate the following materials for advanced supercritical IP turbine, subject to a final design assessment.

	EN Identification
Rotor forging	X14CrMoVNbN10-1 with cladded bearing areas
Casings	G15CrMo9-10, G17CrMoV5-10, GX12CrMoVNbN9-1
Rotating Blading	X17CrMoVNbB9-1, X19CrMoVNbN11-1

Table 2.6-3: Proposed Materials for Advanced Supercritical IP Turbine Module

LP Turbine

For the agreed design basis, the advanced supercritical retrofit plant has been optimised for maximum cycle efficiency; therefore LP innerblock retrofits have been selected.

LP turbines designed in the 1960s were based on 1D and quasi 2D flow codes. With these codes, only the flow characteristics at the midspan of the blades could be predicted with any accuracy. In recent years, computational fluid dynamics (CFD) has become an essential tool for turbomachinery design. With CFD, three-dimensional and quasi three-dimensional programs calculate the flow characteristics with a very high resolution and are able to resolve flow phenomena. By combining this data with the results from test turbines, significant efficiency improvements can be obtained over earlier designs.

Figure 2.6-13 presents the proposed LP turbine retrofit.

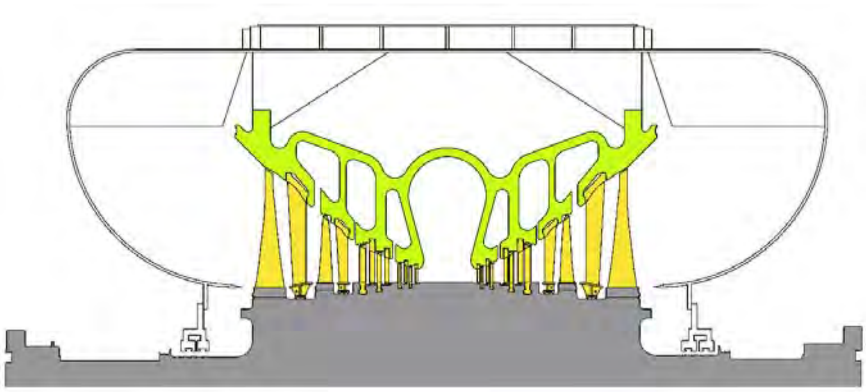


Figure 2.6-13: Proposed LP Turbine Retrofit

The original LP inner casings will be removed and replaced by new LP inner casings made out of nodular cast iron. The Alstom LP rotor of the welded drum type is proposed; **Figure 2.6-14**. All parts of the rotor consist of solid forgings.

Figure 2.6-14: Forgings for a Typical Welded LP Rotor

Turbine Drains System

To accommodate increased temperature operation, a completely new drains system with drains receiver is required for the retrofit HP and IP steam chests, loop pipes and cylinders. Other existing drains are retained together with existing HP and IP drains.

Generator Upgrade

Ratcliffe and West Burton: In order to accommodate the increase in output achievable through advanced supercritical boiler and turbine retrofitting, a new generator will be required to meet the anticipated increase in output at the generator terminals. Likewise, the excitation system will also have to be upgraded.

With any generator replacement, a civil engineer must be consulted to check the suitability of the existing foundation to be able to withstand the forces exerted by the new generator in both normal running and fault conditions.

Drax: The existing generator is retained for ASC BT retrofit.

Condensate System

For advanced supercritical retrofit, the once through boiler water chemistry requirements dictate that a number of the existing plant components in the condensate system will be required to be upgraded due to the need to replace copper and copper based alloy components. In the main, these include:-

- Condenser Upgrade: The existing condenser tubenests replacement with copper free materials, ie titanium or 316 stainless steel, whilst retaining the existing shell, turbine connections, flashboxes and cooling water pipes. The use of thinner wall titanium and modern tube patterns mitigate to some extent the poorer overall heat transfer rates of the titanium tubes.

- Condensate Extraction Pumps: Replacement vertical, multistage, can-type condensate pumps (in addition to meet the requirements of the proposed replacement Deaerating System, as discussed below).

- LP Feedwater Heater Retrofit: All of the existing LP heaters are replaced with horizontal shell and tube units, space permitting, based on providing an economic feed heating arrangement.

Feedwater Storage & Deaerating System: With the exception of some copper alloys in the deaerating section, the existing subcritical plant Feedwater Storage & Deaerating Systems are considered suitable for re-use from a cycle chemistry perspective. However, the proposed design of the retrofit LP and HP feed-heating system has been optimised around a replacement deaerator to minimise the number of feedheaters exposed to the feedwater pressure. A study will need to be performed during a Front End Engineering Design stage to verify feed pump NPSH provision during transient operations such as full load rejection.

Boiler Feedwater Pumps

All of the existing power plants considered under this project employ steam driven feed pump drives, fed from cold reheat, exhausting preferentially to the deaerator, with the balance of flow either extracting from or returning to the IP-LP cross-over.

For the retrofit plant in order to raise the final feedwater to the required pressure, either a new boiler feed pump and drive or a booster pump is required. The choice of feed pump drive method is the critical starting point in determining the feed train arrangement. A techno-economic evaluation was undertaken based on consideration of the following retrofit options to deliver final feedwater at the required pressure of 325bara:-

- Maximum plant retention: Use of existing boiler feed pump turbine (BFPT) and boiler feed pump (BFP) with consideration of supplying the existing BFPT with steam at correct conditions and new motor-driven booster feedwater pumps.

- New BFPT and BFP.

- Retrofit electrically driven feed boiler feed water pumps.

Based on the above considerations and the configurations available to suit the selected power plant sites, the evaluation concluded that electrically driven feed pumping is expected to offer the best performance, particularly considering subsequent capture plant integration, for the retrofit plants considered.

HP Feed Heaters and Topping Desuperheater

The existing HP feedwater heaters are replaced entirely because of the higher operating conditions for advanced supercritical retrofit and to meet the optimised heater arrangement including a topping desuperheater. The topping heater acts as the final heating stage and uses the high level of superheat in the IP turbine extraction to increase final feedwater temperature.

HP and LP Bypass System

A HP steam bypass system including 100% HP bypass station and reheater pressure safety reliefs is included as part of the retrofit scope.

It was found that it was not practical to fit an LP bypass at the reference site, however, this may not be a constraint at other sites. It was found to be technically feasible to start the plant without an LP bypass system, however, the water inventory loss is considerable.

2.6.5 Balance of Power Plant

Cooling Water Systems

With the design basis of maintaining the same cooling water mass flow rate as per the existing subcritical plant, no major modifications are required to the existing cooling water system for advanced supercritical retrofit. Minor modifications will be required to distribute auxiliary cooling water to the new consumers (eg electrically driven boiler pump, circulation pump).

Water Treatment Plant

In general, the quality requirements for once-through boiler plant are more stringent than those for drum type boilers, as there is no possibility of blowdown to reduce the level of impurities in the boiler water. Power station high pressure drum type boilers can operate with feedwater containing up to 500 μg/kg total solids, whereas for a once-through boiler a total solids level of 50 μg/kg would cause very rapid internal deposition, corrosion and deterioration in steam purity and necessitate boiler shutdown.

To meet the water quality requirements following ASC BT retrofit, full flow condensate polishing and oxygen dosing system is proposed. The condensate polishing plant (CPP) is intended to provide the retrofit boiler plant with a continuous source of purified feedwater and to provide emergency protection in the event of a condenser leak.

Although it is intended to operate the ASC BT retrofit plant with Oxygenated Treatment (OT), it is important to note that this can only occur once the chemical conditions are correct. There are very strict limits set on impurities in the water and steam circuit before oxygenated chemistry can be initiated. This means that at start-up and for the period after start-up the plant will operate on low oxygen all volatile treatment (AVT), thus a deaerator is required. As a result the dosing system must have the ability to dose all of the chemicals associated with AVT as well as oxygenated chemistry. Hence ammonia dosing and hydrazine dosing are proposed to allow operation with low Oxygen AVT.

For two-shifting operating regime, further consideration of cycle chemistry is required.

The use of OT has an influence on the selection of materials of construction for ASC BT retrofit. It is recommended that there is no copper bearing alloys throughout the steam cycle, for example, preferred condenser materials are titanium, although type 304 / 316 stainless steel may be acceptable in some instances. It is known that condensate polishers are effective at removing copper and thus, a compromise on a retrofit plant, would be to allow some copper material upstream of the CPP – downstream of the CPP would not be acceptable.

There is concern that OT can cause Stress Corrosion Cracking (SCC) of hard facing materials such as Stellite. There are acceptable alternatives such as martensitic chromium steels. It is generally considered that austenitic materials in boiler's superheaters are acceptable and do not present a significant risk of SCC.

Internationally recognised standards and guidelines for once through boiler water treatment are referenced below:-

- BS EN 12952-12:2003
- VGB-R 450 Le Second Edition 2004
- EPRI TR-102285 1994

Electrical Systems

The plant electrical system will require an upgrade to cater for the ASC BT retrofit. Increase in generator output (in case of Ratcliffe and West Burton) and introduction of electrically driven boiler feed pump will call for upgrades/replacement as appropriate.

The electrically driven boiler feed pump envisaged for ASC BT retrofit would be driven at 11kV. It could either replace one of the existing start-up / standby feed pumps on the station board, or take a new connection on the unit board.

If the boiler feed pump is to connect to the station board, the board load will increase. It is probable that two new station transformers will be required. If the boiler feed pump is to connect to the unit board, new unit transformers will be required.

Switch gear upgrades will also be required to cater to the ASC BT retrofit requirements.

Control and Instrumentation

The boiler and turbine field instruments in the HP and IP systems will require replacement due to increase in pressure and temperature. Furthermore, replacement of other boiler island and turbine island field instruments may also be required to cater for the requirements of the current state of the art control systems.

Three basic options for controlling the retrofit advanced supercritical boiler / turbine plant were given consideration:-

- To continue with the existing equipment.
- Upgrade of the existing equipment.
- Replace with completely new DCS system.

2.7 ASC BTR Amine CO_2 Capture Plant

Overall System Components: Retrofit ASC Boiler/Turbine, New DeNOx Plant (SCR), Existing ESP, Upgraded DeSOx (WLG FGD), Econamine FG Plus^{SM} CO_2 Capture Plant, CO_2 Compression Plant.

The existing plant is modified to operate at ASC steam conditions with integrated Amine CO_2 capture plant (approximate capacity of 9000tpd), installed downstream of the upgraded FGD plant to recover CO_2 from the power plant flue gas (containing about 14% mol CO_2). The CO_2 capture plant is based on Fluor's Econamine FG Plus^{SM} (EFG+) technology that uses a formulated Mono-Ethanol Amine (MEA) solvent that has an inhibitor which protects equipment against corrosion.

Figure 2.7-1 presents the process flow diagram of a Fluor's proprietary EFG$^+$ amine CO_2 capture plant including the proposed flue gas path integration with boiler plant flue gas.

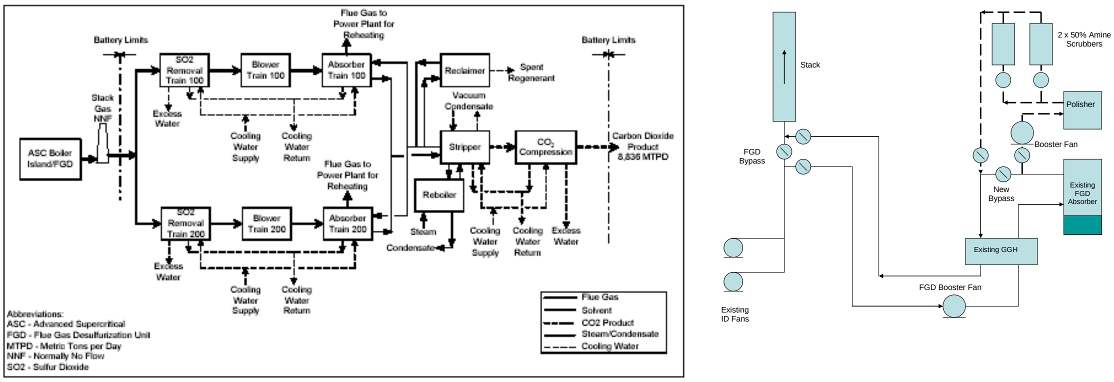


Figure 2.7-1: Fluor EFG$^+$ Amine CO_2 Capture Plant Schematic & Boiler Flue Gas Integration

The retrofit ASC boiler/turbine plant incorporates SCR plant with a NOx emission target of 200mg/Nm^3 @ 6% O_2 to meet the limit required by LCPD. For a maximum NO_2 concentration of 5% of total NOx, no special or further NOx abatement is necessary to meet the amine capture plant requirement (on economic grounds) of NO_2 typically less than 20vppm (41mg/Nm^3 @ 6% O_2).

The existing FGD plant is modified with an additional limestone based polishing plant to reduce SOx content in the flue gas to 30 mg/Nm^3 @ 6% O_2 v/v, dry as required by the amine system. Downstream of the FGD, the flue gases are cooled with a direct contact cooler and fed to the amine system where some 85% of the CO_2 is captured, compressed and liquefied. The remaining flue gases leaving the amine system are reheated using the existing FGD gas/gas heater and discharged to atmosphere via the existing flue stack.

To allow the boiler and FGD plant to operate without CO_2 capture, if required, separate flue gas by-passes are included for the FGD plant and for CO_2 capture plant. This arrangement of equipment is described schematically in **Figure 2.7-1**.

Given the similarity in boiler thermal performance requirements, the retrofit ASC boiler design for post-combustion CO_2 capture follows that of the capture-ready ASC boiler retrofit plant. No essential modifications to the boiler proper are foreseen.

The capture energy penalty is minimised through integration of the capture plant in the thermal cycle by extracting process steam (approximately 50% of IP exhaust steam flow for amine regeneration), **Figure 2.7-2**.

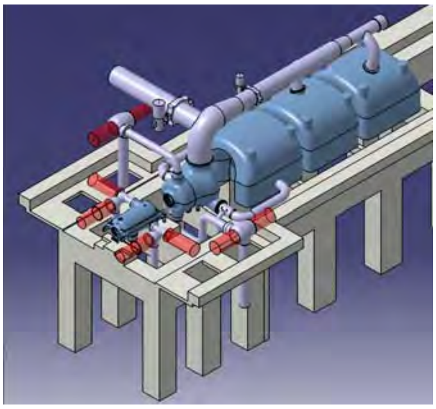


Figure 2.7-2: Steam Turbine Arrangement Isometric including Steam Extraction & Control Valves for Post Combustion CO_2 Capture

In this arrangement, consideration has been given to the LP turbines to take full benefit of the higher steam mass flow rate in the capture-ready configuration. Low grade heat recovered from the EFG+ Plant is usefully directed into the turbine cycle for condensate heating. CO_2 compression is intercooled using cooling water, which allows lower intercooled temperatures than by using steam cycle condensate, thereby minimising the compression system power consumption.

The effect on plant efficiency of the pressure of the steam extracted for amine regeneration has been assessed and found to be extremely sensitive to this parameter (a one bar increase in extraction pressure, with a fixed transfer of heat to the amine reboiler, results in approximately a half percentage point reduction in plant net efficiency). Hence, matching the extraction supply pressure to the minimum pressure required by the amine reboiler as closely as economically practical is recommended. Also consideration should be given to the effect on cycle performance due to pressure drop across the steam supply pipework and valves whilst sizing of the pipework.

Heat integration options for amine processes were investigated both in terms of overall plant performance, plant operability and reliability, including fault tolerance, water chemistry compatibility and the ability of the systems to operate satisfactorily at part load, although part load performance was not fully assessed.

Figure 2.7-3 presents the conceptual PFD proposed for the project reference power plant site (Ratcliffe) ASC BT Amine CO_2 Capture retrofit. Conceptual PFDs for the alternative sites, Drax and West Burton, are presented in **Figure 2.7-4** and **Figure 2.7-5** respectively.

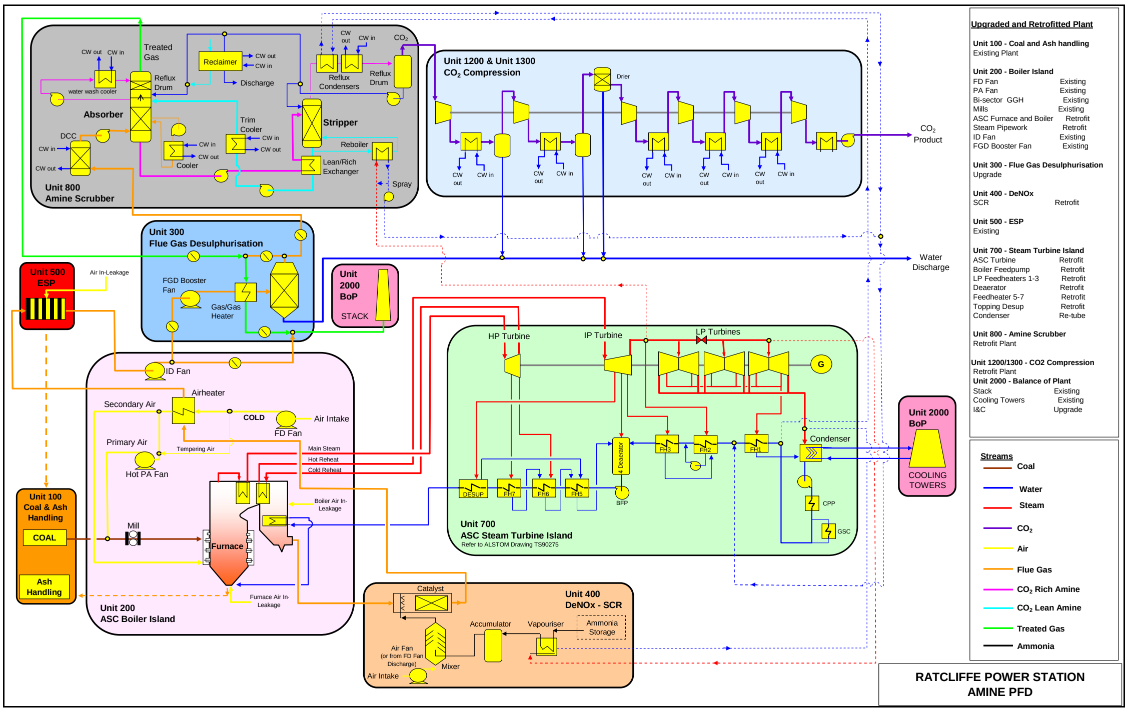


Figure 2.7-3: Conceptual PFD – Reference Site : Ratcliffe ASC BTR Amine CO_2 Capture

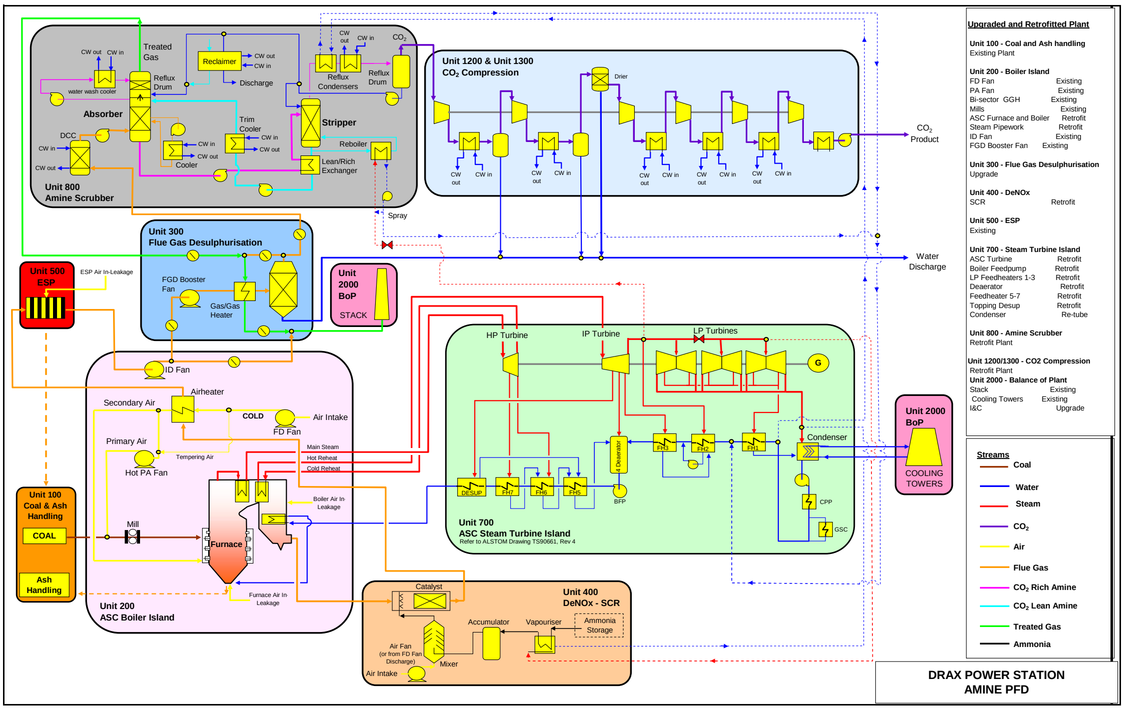


Figure 2.7-4: Conceptual PFD – Alternative Site #1 : Drax ASC BTR Amine CO_2 Capture

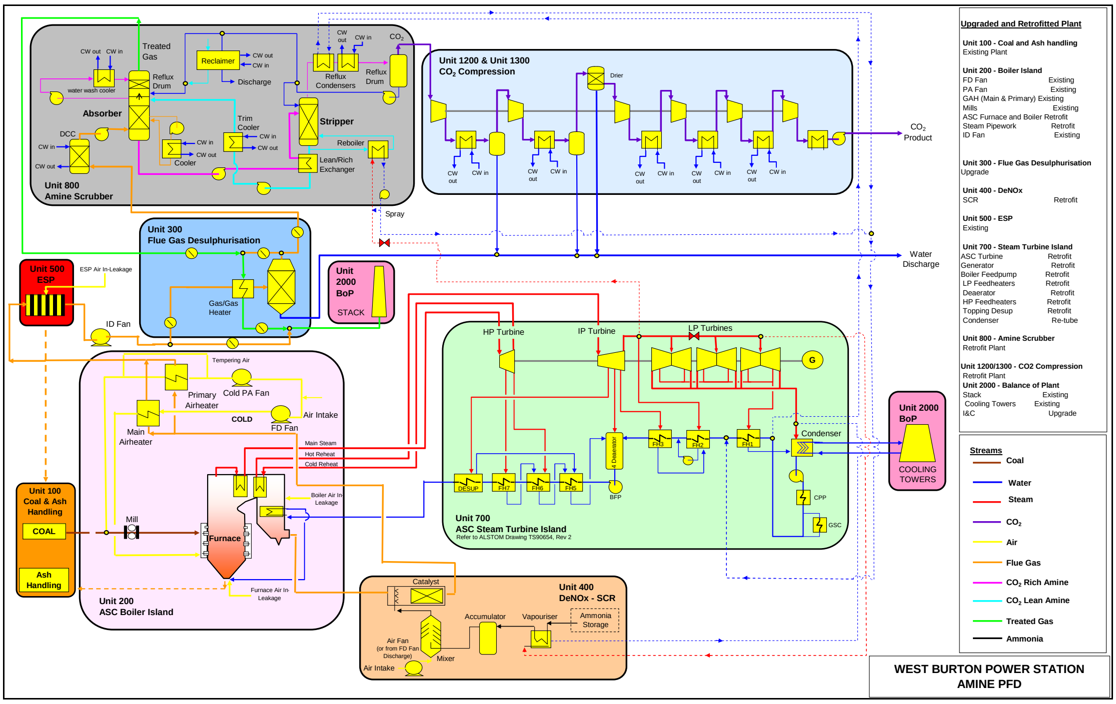


Figure 2.7-5: Conceptual PFD – Alternative Site #2 : West Burton ASC BTR Amine CO_2 Capture

The corresponding conceptual Turbine Island PFD proposed for the project sites, Ratcliffe, Drax and West Burton for ASC BT Amine CO_2 Capture retrofit are presented in **Figures 2.7-6** to **2.7-8** respectively.

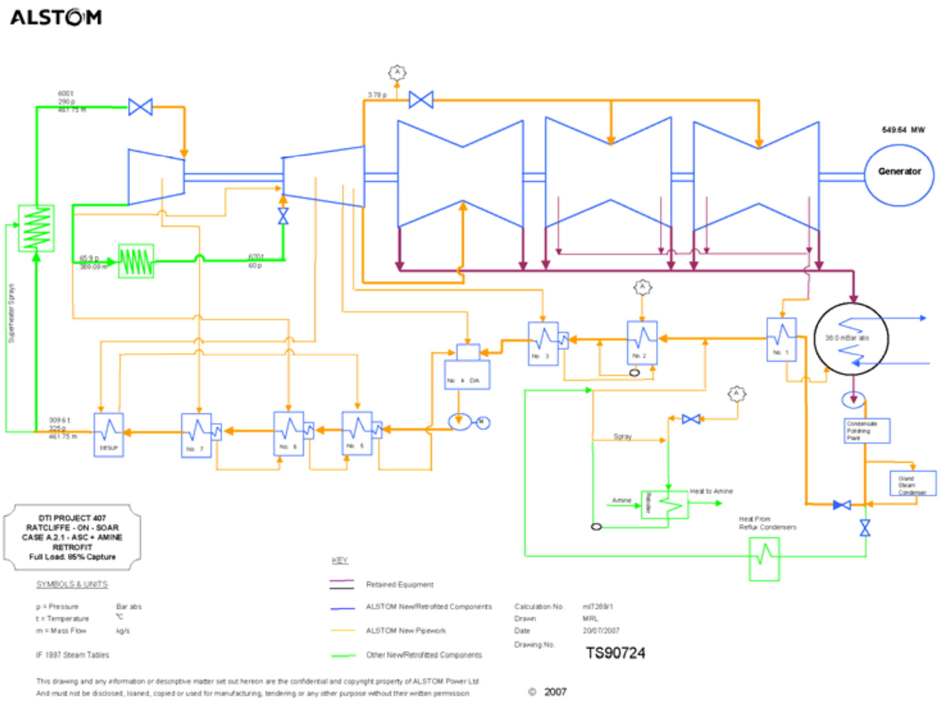


Figure 2.7-6: ASC BTR Amine CO_2 Capture : Steam Turbine Island PFD – Ratcliffe

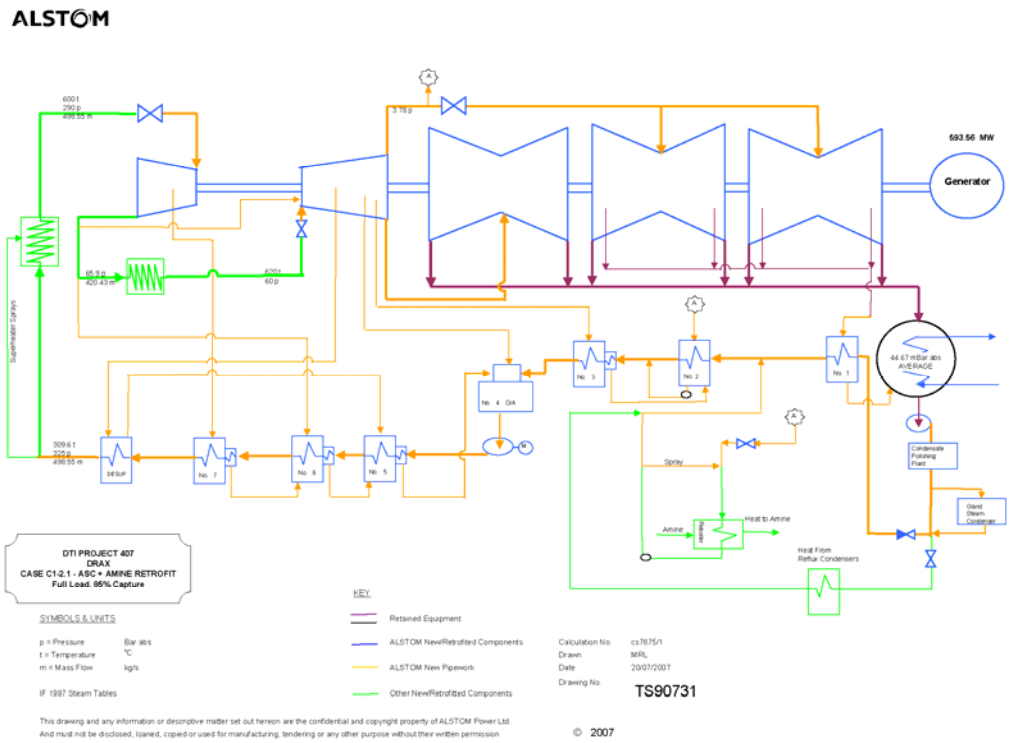


Figure 2.7-7: ASC BTR Amine CO_2 Capture : Steam Turbine Island PFD – Drax

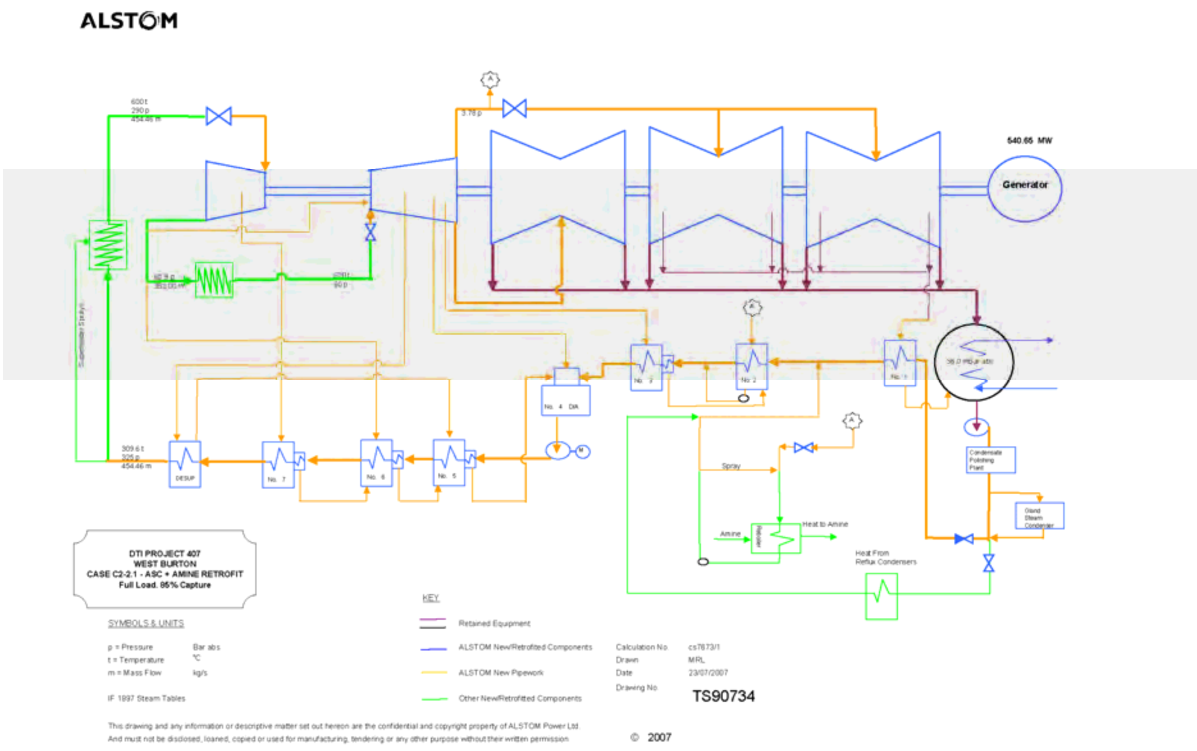


Figure 2.7-8: ASC BTR Amine CO_2 Capture : Steam Turbine Island PFD – West Burton

2.8 ASC BTR Oxyfuel CO_2 Capture Plant

Overall System Components: Retrofit ASC boiler/turbine, Air Separation Units with Oxygen Preheat, Modified ESP, Flue Gas Heat Recovery Units, Existing DeSOx (WLG FGD), CO_2 Purification and CO_2 Compression Plant. Note: DeNOx Plant (SCR) is retained to meet emission limits during air-firing operations. SCR is by-passed during Oxyfuel operation as appropriate.

The existing plant is modified to operate at ASC steam conditions with integrated Oxyfuel CO_2 capture plant. For the selected project power plants, commercially available Cryogenic ASUs with a total oxygen production capacity of some 9500tpd are envisaged.

The cryogenic ASU cycle can be designed to produce either low purity oxygen (95% purity) or high purity oxygen (99.5%) at a higher capital cost and power consumption. The cryogenic ASU low purity cycle is expected to be the choice technology employed in the first generation Oxyfuel PF Power Plants. Given that the main power plant efficiency reduction for Oxyfuel CO_2 capture is due to the electric power consumption of the cryogenic ASU (approximately 12% of plant gross output), efficient heat integration between the cryogenic ASU (eg recovery of low grade heat from ASU compressors) and the power plant will be a necessity. ASU back-up in the form of liquid oxygen (LOX) storage provides flexibility to power plant operation should the changing demand in flow exceed the ASU ramp rate limit of two to three percentage of full flow per minute. ASU plant flexibility including turndown considerations is further briefly discussed in **Section 2.16**.

To improve the overall plant efficiency, oxygen preheating with LP steam is proposed for the Oxyfuel concepts developed.

Figure 2.8-1 presents the arrangement of two x 50% cryogenic ASUs as proposed for Oxyfuel CO_2 capture retrofit.

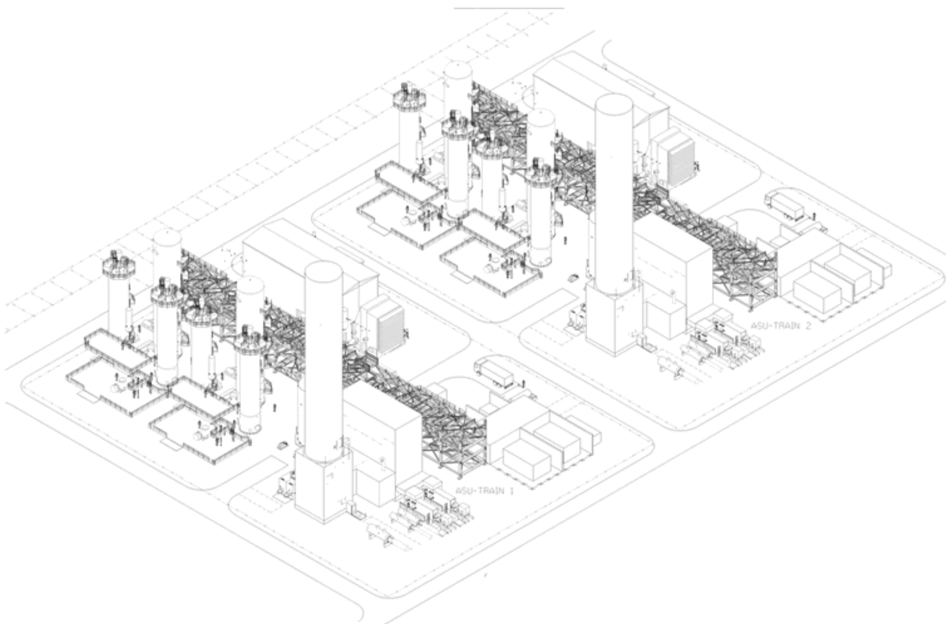
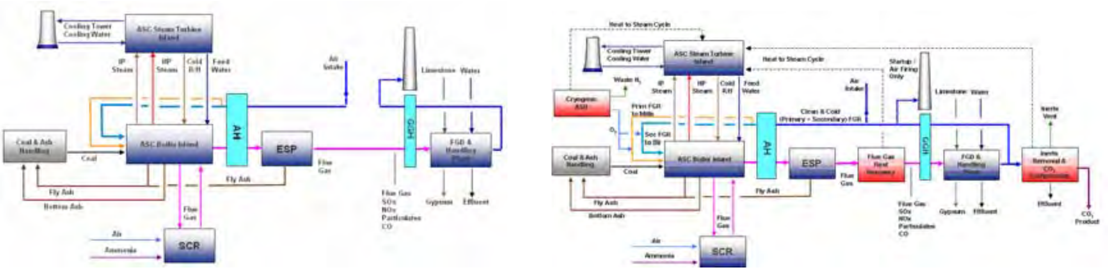


Figure 2.8-1: ASC BTR Oxyfuel CO2 Capture – Cryogenic ASUs Arrangement

The basic concept of the overall system is to replace air with near pure oxygen (95% mol) for combustion of coal. A stream of recirculated flue gas to the boiler is required to provide (i) transport medium for pulverized fuel and (ii) maintain conventional combustion equipment design and retrofit furnace/boiler design. The net high CO_2 content flue gas (72%mol, dry basis) leaving the boiler system is further processed to provide high pressure CO_2 (97%mol). The CO_2 capture level is some 88%.

The proposed retrofit Oxyfuel CO_2 Capture Plant concept is aimed at targeting near-term opportunity and is based on conventional well proven / proven technology, where possible, to minimise risk to generation. Further details of the Doosan Babcock approach to the conceptual design of the Oxyfuel Boiler Island as an integral part of the overall Oxyfuel CO_2 Capture Power Plant retaining full air-firing capability and hence minimising both the commercial and technical risk to power generators is further described in a recent technical paper [6].

Conceptual process flow diagrams presented in **Figure 2.8-2** show the proposed Oxyfuel PF boiler island operating in air-firing mode and Oxyfuel firing mode.



Air-Firing Operation **Oxyfuel Firing Operation**

Figure 2.8-2: ASC Oxyfuel Boiler Island – Operating in Air-Firing Mode & Oxyfuel Firing Mode

Plant performance is optimised through process integration of the Boiler Island (including achievable minimum air infiltration), Turbine Island, Balance of Power Plant and CO_2 Compression Plant to a level compatible with high reliability and availability. Essentially all of the SOx and some 90% of the NOx is converted to sulphuric acid and nitric acid respectively during the CO_2 purification and compression stage [7] – these acid streams are treated by the existing FGD Waste Water Treatment Plant without the need for plant upgrade.

Heat integration options for Oxyfuel technology were investigated both in terms of plant performance and plant operability & reliability, including fault tolerance, water chemistry compatibility and the ability of the systems to operate satisfactorily at part load, although part load performance was not fully assessed.

Oxyfuel technology has minimal effect on the conventional steam turbine island plant. With the inclusion of heat recovery by process integration, steam turbine bleed flows to the feedheater train can be reduced, allowing increased power generation from the turbine / generator set. The resultant additional power achieved partially offsets the power requirements of the air separation system and the CO_2 compression plant.

An imperative of the conceptual design is the need for the Oxyfuel boiler plant to cover the same range of fuels as is covered by the existing conventional air-fired technology particularly with respect to sulphur content and chlorine content of the coal. In order to ensure that the retrofit Oxyfuel plant is no more susceptible to high temperature corrosion due to increased concentrations of SO_2 (and SO_3) and HCl, the Oxyfuel flue gas needs to be cleaned before being recycled to the Milling Plant and Boiler Plant. The existing installed conventional Wet Limestone Gypsum FGD Plant is employed to provide clean Oxyfuel Flue Gas Recycle (FGR), which ensures the corrosive gaseous components in the Oxyfuel FGR result in concentrations no worse than that experienced with air-firing. The level of flue gas cleaning for boiler plant will vary with different fuel properties from having no requirement for FGD with low sulphur fuels to full FGD plant with higher sulphur fuels.

The Oxyfuel FGR recycle stream is split into primary and secondary streams. The primary stream quantity is set according to the requirements of the milling plant. The secondary stream quantity is set to give the optimum balance between the combustion equipment and furnace requirements.

Within current knowledge of the characteristics of Oxyfuel combustion the application of proven air burner systems in combination with the appropriate level of flue gas recirculation is expected to enable stable, efficient combustion to be achieved. The project gave consideration to adaptation of pulverised fuel burner designs as proven on conventional utility air-fired systems.

The ASC BTR Oxyfuel boiler proper follows conventional air-fired ASC PF boiler technology without any Oxyfuel CO_2 capture-ready features. For coal firing, the furnace thermal radiation is dominated by coal quality, soot, char and fly ash particles in the flue gas countering any enhancement of heat transfer capability of Oxyfuel flue gas as a result of increased proportion of radiating gaseous components; namely H_2O and CO_2. The similarities of flame and flue gas emissivities for Oxyfuel PF combustion and air-firing along with similarity of boiler temperature profiles (based on the appropriate selection of FGR rate) led to the conclusion that modifications to the boiler's heat transfer surfaces may not be required post Oxyfuel retrofit. As discussed above, concerns relating to any high temperature corrosion related metal wastage rates are expected to be no worse than that of conventional air-fired plant with the use of clean Oxyfuel FGR to limit the SO_2 and SO_3 to levels similar to air-firing experience with high sulphur coals.

Excessive air in-leakage will lead to operating the plant with low CO_2 capture rate and low CO_2 quality. Minimum achievable and maintainable air-ingress levels are considered in the design of the Oxyfuel retrofit boiler island and the downstream CO_2 purification and compression plant to achieve the project target CO_2 purity levels.

The majority of the boiler island modifications required for Oxyfuel CO_2 capture will be with respect to the air and flue gas ductwork and draught plant equipment, to enable combustion of fuel with CO_2 rich flue gas recycle and near pure O_2 mixture instead of air. The remaining changes (relative to air-fired plant) are largely external to the boundary of the boiler island, and relate to the utilisation of well-proven air separation plant and the CO_2 processing facilities.

Figure 2.8-2 presents the conceptual PFD proposed for the project reference power plant (Ratcliffe) ASC BT Oxyfuel CO_2 Capture retrofit. The conceptual PFD with respect to the alternative sites, Drax and West Burton, are presented in **Figure 2.8-3** and **Figure 2.8-4** respectively.

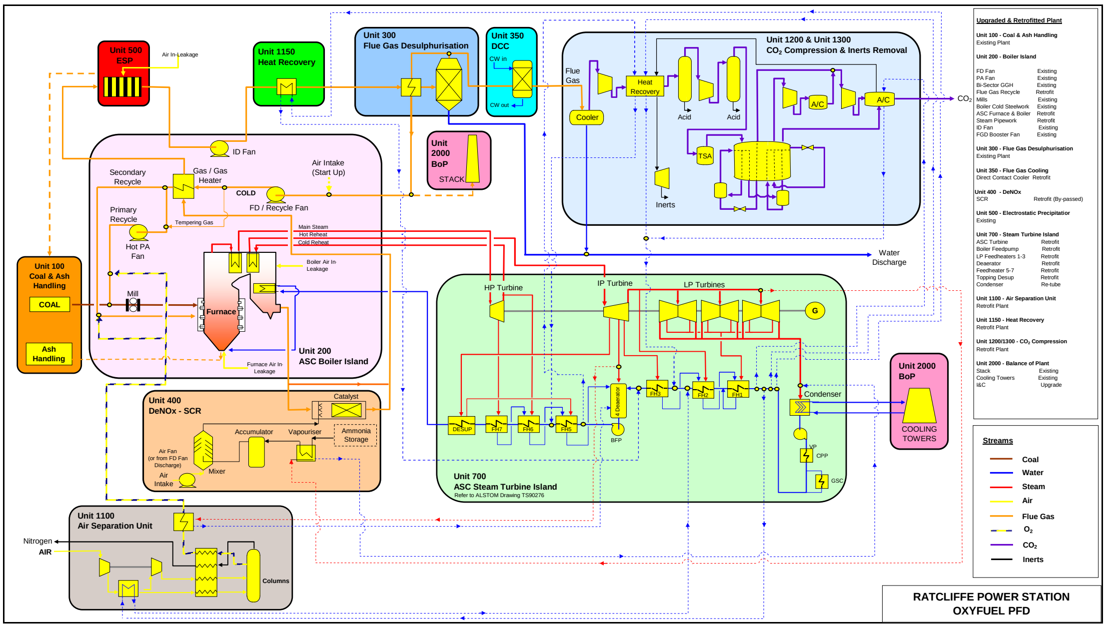


Figure 2.8-2: Conceptual PFD – Reference Site : Ratcliffe ASC BTR Oxyfuel CO_2 Capture

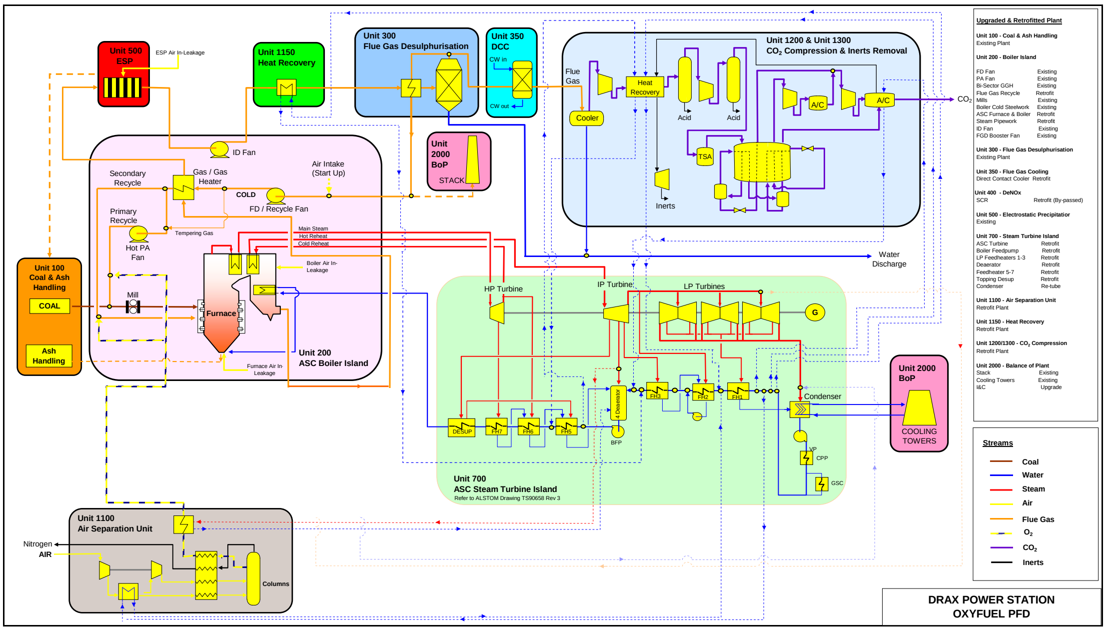


Figure 2.8-3: Conceptual PFD – Alternative Site #1 : Drax ASC BTR Oxyfuel CO_2 Capture

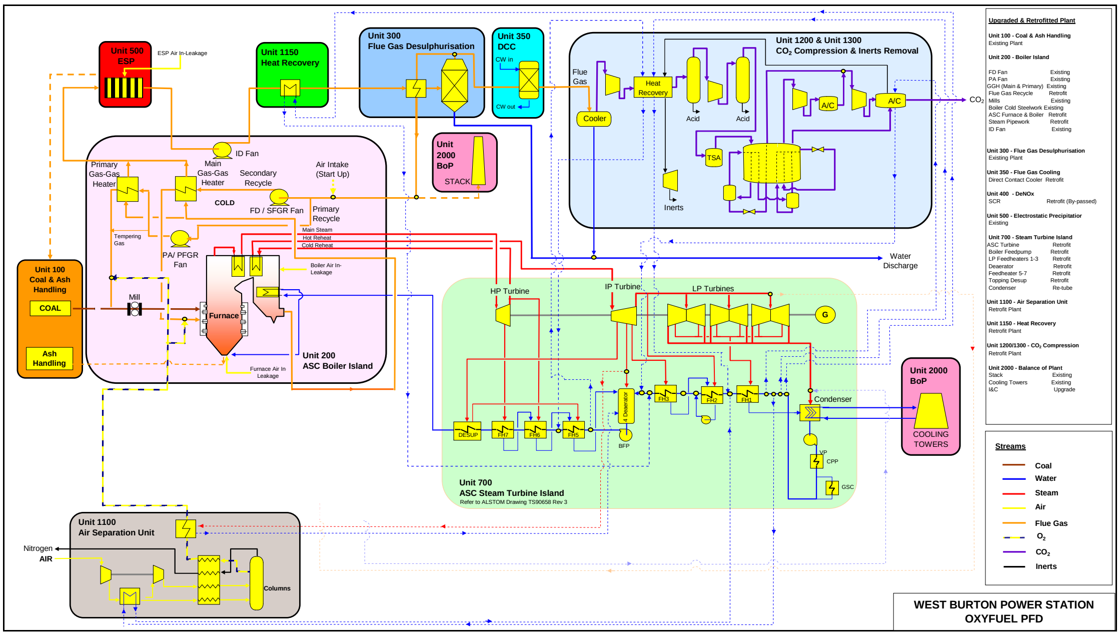


Figure 2.8-4: Conceptual PFD – Alternative Site #2 : West Burton ASC BTR Oxyfuel CO_2 Capture

The corresponding conceptual Turbine Island PFDs for ASC BT Oxyfuel CO_2 Capture retrofit as proposed for the project power plant sites, Ratcliffe, Drax and West Burton are presented in **Figures 2.8-5, 2.8-6** and **2.8-7** respectively.

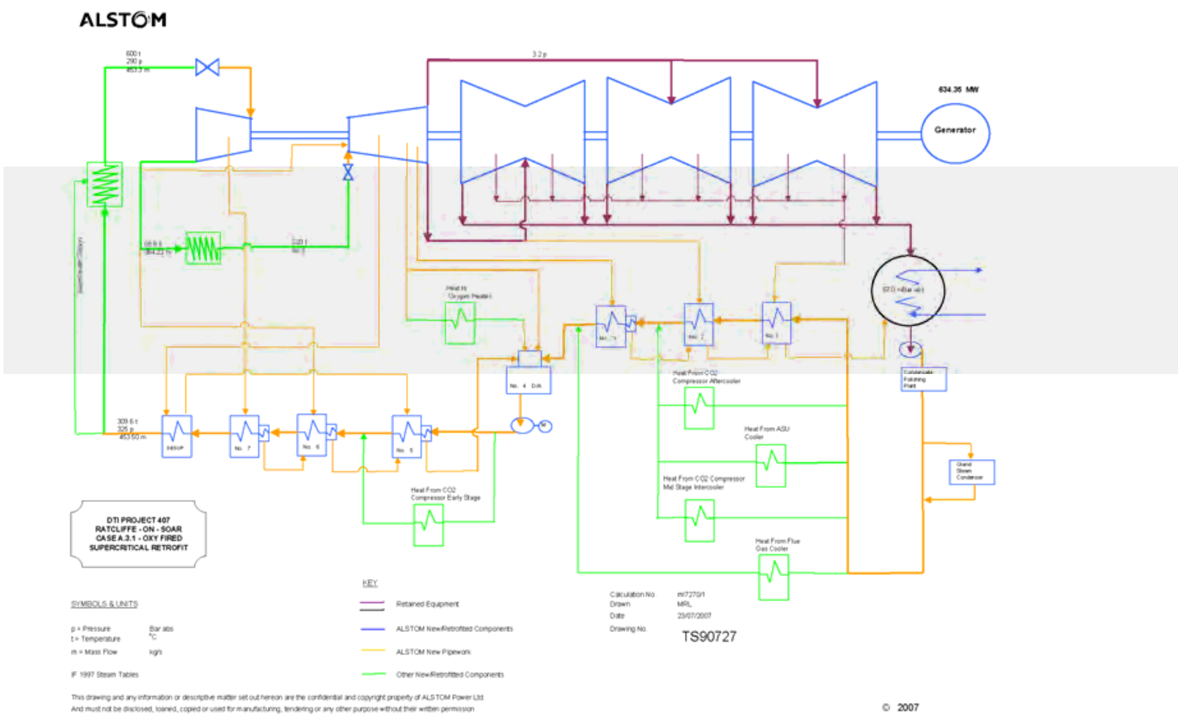


Figure 2.8-5: ASC BTR Oxyfuel CO_2 Capture : Steam Turbine Island PFD – Ratcliffe

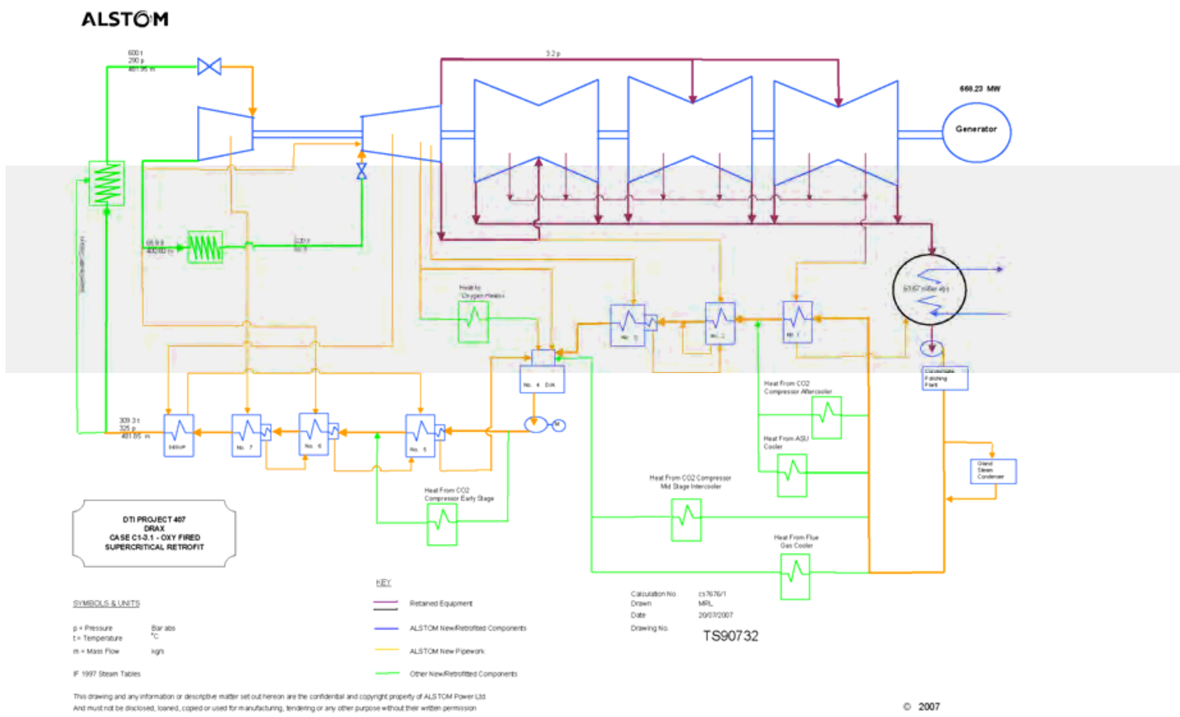


Figure 2.8-6: ASC BTR Oxyfuel CO_2 Capture : Steam Turbine Island PFD – Drax

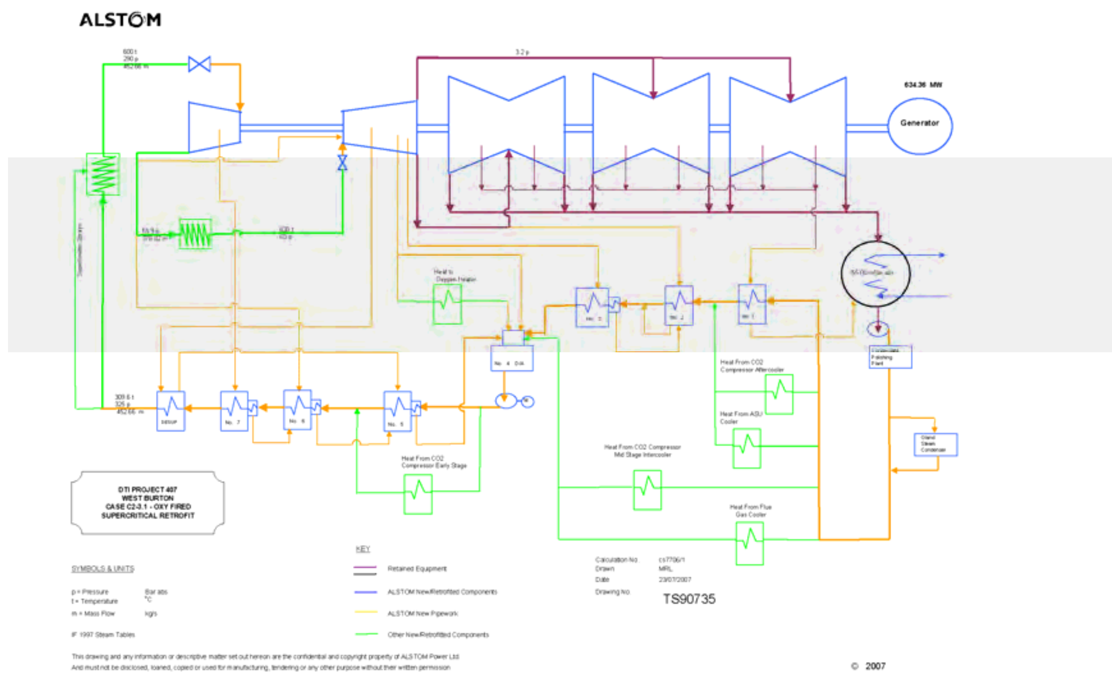


Figure 2.8-7: ASC BTR Oxyfuel CO_2 Capture : Steam Turbine Island PFD – West Burton

2.9 Retrofit Plant Performance

The plant thermal efficiencies, on a lower heating value (LHV) basis, and the auxiliary power consumptions of the retrofit plant with and without CO_2 Capture for Ratcliff, Drax and West Burton are shown in **Table 2.9-1.**

ASC BT retrofit offers a net efficiency of 44% to 45% LHV, compared to the current plant performance of 37 - 39%, LHV. The performance penalty for both ASC BTR CO_2 capture technologies considered, both installed at the outset or retrofitted at a later date, are similar at approx. nine to ten percentage points. For Post Combustion CO_2 capture, the majority of the efficiency reduction is due to the use of low-pressure steam for CO_2 capture solvent regeneration. The main efficiency reduction for Oxyfuel CO_2 capture is due to the electric power consumption of the cryogenic ASU plant. The power consumption for CO_2 compression for Oxyfuel is higher than required by Post Combustion due to the presence of impurities in the feed gas and hence the requirement for an additional purification step.

The performance presented in **Table 2.9-1** above is based on the plant restriction of constraining the cooling water system to its current mass flow rate. For Oxyfuel CO_2 Capture, it is estimated that the increase in condenser heat rejection combined with the additional cooling water requirements elsewhere would increase the condenser pressure by some 12mbar at average ambient conditions with this cooling water restriction. Supplementing the main cooling water system pumps and using less adiabatic compression (capture plant) would lead to an increase in the plant efficiency of the Oxyfuel CO_2 Capture system of some one percentage point.

	Coal Flow	Gross Output	Net Output	Conventional Aux. Power	Capture Plant Aux. Power	Compress. Aux. Power	Surface Condenser Pressure	Net Plant Effcy
	kg/s	MWe	MWe	% Gen	% Gen	% Gen	mbara	%, LHV
Project Reference Site : Ratcliffe ASC BT Retrofit & CO_2 Capture : Plant Performance								
Existing PF Plant	49.2	521	500	4.1%	-	-	55.0	38.9%
ASC BTR	49.2	625	577	7.7%	-	-	45.0	44.9%
ASC BTR Amine								
Amine CO_2 Capture	49.2	550	459	8.7%	2.5%	5.3%	38.0	35.7%
Amine Capture Ready	49.2	624	575	7.8%	-	-	45.0	44.7%
Amine Post Retrofit	49.3	550	459	8.7%	2.5%	5.3%	38.0	35.7%
ASC BTR Oxyfuel								
Oxyfuel CO_2 Capture	49.2	634	448	7.2%	12.2%	9.9%	57.0	34.9%
Oxyfuel Capture Ready	49.2	625	577	7.7%	-	-	45.0	44.9%
Oxyfuel Post Retrofit	50.3	647	460	7.2%	12.2%	9.9%	57.0	34.8%
Alternative Site #1 : Drax ASC BT Retrofit & CO_2 Capture : Plant Performance								
Existing PF Plant	70.0	668	634	5.1%	-	-	51.7	39.1%
ASC BTR	60.2	668	613	8.3%	-	-	51.7	44.0%
ASC BTR Amine CO_2 Capture	60.2	594	493	9.2%	2.4%	5.2%	44.7	35.4%
ASC BTR Oxyfuel CO_2 Capture	58.7	668	476	7.7%	11.6%	9.6%	63.7	34.1%
Alternative Site #2 : West Burton ASC BT Retrofit & CO_2 Capture : Plant Performance								
Existing PF Plant	54	500	479	4.2%	-	-	43.0	37.4%
ASC BTR	54	615	568	7.6%	-	-	43.0	44.5%
ASC BTR Amine CO_2 Capture	54	541	451	8.6%	2.6%	5.5%	36.0	35.3%
ASC BTR Oxyfuel CO_2 Capture	54	634	452	7.1%	12.0%	9.7%	55.0	34.4%

Table 2.9-1: ASC BT Retrofit & CO_2 Capture : Summary of Power Plant Performance

2.10 Retrofit Plant Emissions Performance

Table 2.10-1 present the quantities of CO_2 emitted, captured and abated for the selected project sites.

	Coal Flow kg/s	Net Output MWe	CO_2 Emissions g/kWh (net)	CO_2 Captured g/kWh (net)	CO_2 Captured %	CO_2 Abated Relative to Existing Plant %
Project Reference Site : Ratcliffe ASC BT Retrofit & CO_2 Capture : CO_2 Emissions						
Existing PF Plant	49.2	500	868	-	-	-
ASC BTR	49.2	577	753	-	-	13%
ASC BTR Amine						
Amine CO_2 Capture	49.2	459	142	805	85%	84%
Amine Capture Ready	49.2	575	756	0	0%	13%
Amine Post Retrofit	49.3	459	142	805	85%	84%
ASC BTR Oxyfuel						
Oxyfuel CO_2 Capture	49.2	448	115	854	88%	87%
Oxyfuel Capture Ready	49.2	577	753	0	0%	13%
Oxyfuel Post Retrofit	50.3	460	116	856	88%	87%
Alternative Site #1 : Drax ASC BT Retrofit & CO_2 Capture : CO_2 Emissions						
Existing PF Plant	70.0	634	825	-	-	-
ASC BTR	60.2	613	733	-	-	11%
ASC BTR Amine CO_2 Capture	60.2	493	137	774	85%	83%
ASC BTR Oxyfuel CO_2 Capture	58.7	476	109	805	88%	87%
Alternative Site #2 : West Burton ASC BT Retrofit & CO_2 Capture : CO_2 Emissions						
Existing PF Plant	54	479	895	-	-	-
ASC BTR	54	568	754	-	-	16%
ASC BTR Amine CO_2 Capture	54	451	143	807	85%	84%
ASC BTR Oxyfuel CO_2 Capture	54	452	112	829	88%	88%

Table 2.10-1: ASC BT Retrofit & CO_2 Capture: CO_2 Emissions

The quantities of CO_2 abated are relative to the emissions of the existing subcritical PF plant. The percentages of CO_2 captured are based on the agreed project design basis target of >85% CO_2 Capture. It is noted that this design basis is not necessarily the technical limit or economic optimum for the retrofit technologies considered. Post combustion inherently produces high-purity CO_2, whereas Oxyfuel produces lower purity CO_2 which can be further refined if a higher (EOR-grade) purity is required, with a minor increase in power consumption.

The key waste and by-products together with emissions to atmosphere per unit of net electricity output for selected power plants are shown in **Table 2.10-2.**

(g/kWh on Net Output Basis)	Coal Flow g/kWh	Net Output MWe	Waste and By-Products: Ash g/kWh	Waste and By-Products: Gypsum g/kWh	Waste and By-Products: Waste Water g/kWh	Emissions to Atmosphere: CO_2 g/kWh	Emissions to Atmosphere: SOx g/kWh	Emissions to Atmosphere: NOx g/kWh
Project Reference Site Ratcliffe ASC BT Retrofit & CO_2 Capture : Waste / By-Products and Emissions								
Existing Plant	354	500	29	32	32	868	1.31	1.64
ASC BTR	307	577	25	29	28	753	0.57	0.57
ASC BTR Amine CO_2 Capture	386	459	32	39	135	142	0.13	<0.01
ASC BTR Oxyfuel CO_2 Capture	395	448	33	40	270	115	0	0.02
Alternative Site #1 : Drax ASC BT Retrofit & CO_2 Capture : Waste / By-Products and Emissions								
Existing Plant	398	634	69	40	38	825	1.25	2.03
ASC BTR	354	613	62	37	35	733	0.56	0.55
ASC BTR Amine CO_2 Capture	439	493	77	47	153	137	0.16	0.01
ASC BTR Oxyfuel CO_2 Capture	443	476	77	48	306	109	0	0.02
Alternative Site #2 : West Burton ASC BT Retrofit & CO_2 Capture : Waste / By-Products and Emissions								
Existing Plant	406	479	63	37	35	895	1.51	2.25
ASC BTR	342	568	54	33	31	754	0.70	0.59
ASC BTR Amine CO_2 Capture	431	451	68	43	152	143	0.15	<0.01
ASC BTR Oxyfuel CO_2 Capture	430	452	67	44	286	112	0	0.01

Notes:

1. Flue gas from amine absorber reheated via FGD GGH, the cross-leakage from which introduces the emissions quoted.

Table 2.10-2: ASC BT Retrofit & CO_2 Capture : Waste / By-Products and Emissions

2.11 Retrofit Plant Footprint

The footprint requirements of the CO_2 Capture Plant are dictated by equipment size and site access requirements for installation and maintenance. **Table 2.11-1** presents the estimated footprint for the retrofit options studied:-

	Subcritical Existing Unit	ASC BTR	ASC BTR Amine CO_2 Capture	ASC BTR Oxyfuel CO_2 Capture
Approx Unit Gross Capacity	500 – 660 MWe	615 – 660 MWe	540 – 600 MWe	630 - 660 MWe
Power Generation (m^2)	140,000	140,000	140,000	140,000
CO_2 Capture Plant (m^2)	-	-	23,000	18,700
CO_2 Compression Plant (m^2)	-	-	825	5,800

Table 2.11-1: Approximate Footprint Requirements of CO_2 Capture Plant

There is potential for layout optimisation and footprint reduction (of up to 20%), for example, with further clarification on scope of supply and reduction in access to major plant items. However, this benefit will need to be evaluated against the possible impact on capital and operating costs.

Site plans have been developed for each retrofit case based on retrofit to one boiler/turbine unit. In each case the retrofitted supercritical boiler and turbine plant is located within the boiler and turbine house, replacing the existing subcritical plant.

Ratcliffe: The capture plant location at Ratcliffe Power Station is feasible through utilisation of existing free space beyond the FGD plant.

Drax: A possible location of the capture plant at Drax Power Station may be to utilise the site of the existing Biomass Store and Yarrow Store including relocation of oil tanks as appropriate.

West Burton: The proposed location of the CO_2 capture plants at West Burton Power Station will require re-routing of the site overhead power lines, the cost implications of which have been taken into consideration in the economic analysis.

2.12 Balance of Retained Power Plant

With respect to the retained balance of power plant, the study identified the implications on equipment directly affected by the retrofit options considered. In order to assess the total costs associated with the retrofit, estimates have also been made to include significant items of life extension work for equipment not directly affected by retrofit, but required to be refurbished simply to meet the design basis requirement of 25 year design life following the retrofit.

2.13 Outline Scope of Retrofit Plant

Outline scope of equipment supplies proposed for the retrofit plant are summarised in the following tables:-

- **Table 2.13-1** ASC BT retrofit
- **Table 2.13-2** ASC BT Retrofit Amine CO_2 Capture; and
- **Table 2.13-3** ASC BT Retrofit Oxyfuel CO_2 Capture.

New Components Required	Components to Re-Use
ASC Boiler Island Furnace water wall Start-up system: separator and storage vessels Circulation pumps Superheaters Reheaters Steam temperature regulating system Economiser & recirculation system 100% HP steam bypass station RH pressure safety relief system Critical Piping - Main steam pipework - HP bypass pipework - Hot and cold reheat steam pipework - Feedwater pipework **DeNO$_X$ Plant** SCR (NOx ≤ 200 mg/Nm^3 @ 6%O_2) **ASC Steam Turbine Island** HP turbine module IP turbine module LP turbine (retrofit) Generator (for Ratcliffe & West Burton only) Generator transformer (for Ratcliffe & West Burton only) Condenser tubenest Condensate pumps Boiler feedwater pumps LP & HP feedwater heaters, deaerator HP & IP drains system Control oil system Turbine governing and protection system Attemperation spray pipework **BoP** Additional switchgear/ transformer Condensate polishing plant Chemical dosing system	**Coal & Ash Handling** Coal handling and stocking Ash handling and disposal **Boiler Island** Coal pulverisers / mills/ PF pipework Burners and windbox BOFA / SOFA systems Combustion management Sootblowers Regenerative airheaters Draught plant (FD / PA / ID / BUF fans upgrade, if required) Air and flue gas ductwork Bottom ash removal system ESP / fly ash removal systems Boiler structural steel and galleries Boiler house lifting hoists & man access Elevator **FGD & Handling Plant** FGD plant upgrade (SO_2 ≤ 200 mg/Nm^3 @ 6%O_2) **Steam Turbine Island** LP turbine hoods and frames Generator (for Drax only) Generator Transformer (for Drax only) Condenser shell Gland sealing system (upgrade) Lube oil system Turbine hall crane **BoP** Stack Boiler/ turbine foundations Switchgear and transformers Water treatment plant (upgrade) Cooling water supply system Refurbish existing remaining plant C&I upgrade, as appropriate Buildings

Table 2.13-1: ASC BT Retrofit – Outline Scope of Supply

New Components Required	Components to Re-Use
ASC Boiler Island Furnace water wall Start-up system: separator and storage vessels Circulation pumps Superheaters Reheaters Steam temperature regulating system Economiser & recirculation system 100% HP steam bypass station RH pressure safety relief system Critical Piping - Main steam pipework - HP bypass pipework - Hot and cold reheat steam pipework - Feedwater pipework **DeNO$_X$ Plant** SCR (NOx ≤ 200 mg/Nm^3 @ 6%O_2) **ASC Steam Turbine Island** HP turbine module IP turbine module LP turbine (retrofit) Generator (for Ratcliffe & West Burton only) Generator transformer (for Ratcliffe & West Burton only) Condenser tubenest Condensate pumps Boiler feedwater pumps LP & HP feedwater heaters, deaerator HP & IP drains system Control oil system Turbine governing and protection system Attemperation spray pipework Heat recovery and supply pipework Amine CO_2 capture plant steam extraction control & isolation valves **EFG+ CO_2 Capture Plant** 9000tpd (approx) amine based CO_2 capture unit Direct Contact Coolers 9000tpd (approx) CO_2 compression plant Heat recovery equipment Steam extraction pipework : IP/LP turbine cross-over to EFG+ plant. Condensate pipework : EFG+ plant to turbine island **BoP** Additional switchgear/ transformer Condensate polishing plant Chemical dosing system	**Coal & Ash Handling** Coal handling and stocking Ash handling and disposal **Boiler Island** Coal pulverisers / mills / PF pipework Burners and windbox BOFA / SOFA systems Combustion management Sootblowers Regenerative airheaters Draught plant (FD / PA / ID fans / BUF upgrade, if required) Air and flue gas ductwork Bottom ash removal system ESP / fly ash removal systems Boiler structural steel and galleries Boiler house lifting hoists & man access Elevator **FGD & Handling Plant** FGD plant upgrade or additional polisher (SO_x ≤ 30 mg/Nm^3 @ 6%O_2) **Steam Turbine Island** LP turbine hoods and frames Generator (for Drax only) Generator transformer (for Drax only) Condenser shell Gland sealing system (upgrade) Lube oil system Turbine hall crane **BoP** Stack Boiler / turbine foundations Switchgear and transformers Water treatment plant (upgrade) Cooling water supply system Refurbish existing remaining plant C&I upgrade, as appropriate Buildings

Table 2.13-2: ASC BT Retrofit Amine CO_2 Capture – Outline Scope of Supply

New Components Required	Components to Re-Use
ASC Boiler Island Furnace water wall Start-up system: separator and storage vessels Circulation pumps Superheaters Reheaters Steam temperature regulating system Economiser & recirculation system 100% HP steam bypass station RH pressure safety relief system Critical Piping - Main steam pipework - HP bypass pipework - Hot and Cold reheat steam pipework - Feedwater pipework **DeNO$_X$ Plant** SCR (NOx ≤ 200 mg/Nm^3 @ 6%O_2) for 100% Air Firing Capability **ASC Steam Turbine Island** HP turbine module IP turbine module LP turbine (retrofit) Generator (for Ratcliffe & West Burton only) Generator transformer (for Ratcliffe & West Burton only) Condenser tubenest Condensate pumps Boiler feedwater pumps LP & HP feedwater heaters, deaerator HP & IP drains system Control oil system Turbine governing and protection system Attemperation spray pipework Heat recovery and supply pipework **Oxyfuel CO_2 Capture Plant** 9500tpd (approx) Air Separation Units (ASUs) 500tonnes LOX storage and vaporisation system Oxygen heater Oxyfuel FGR and oxygen injection system Heat recovery equipment 9500tpd (approx) CO_2 purification and compression plant **BoP** Additional switchgear/ transformer Condensate polishing plant Chemical dosing system	**Coal & Ash Handling** Coal handling and stocking Ash handling and disposal **Boiler Island** Coal pulverisers / mills/ PF pipework Burners and windbox (burners as adapted for dual air / oxyfuel operation) BOFA / SOFA systems Combustion management Sootblowers Regenerative airheaters Draught plant (FD / PA / ID fans / BUF upgrade, if required) Air and flue gas ductwork Bottom ash removal system ESP / fly ash removal systems (upgrade) Boiler structural steel and galleries Boiler house lifting hoists & man access Elevator **FGD & Handling Plant** FGD plant upgrade (SO_2 ≤ 200 mg/Nm^3 @ 6%O_2) for 100% air-firing capability **Steam Turbine Island** LP turbine hoods and frames Generator (for Drax only) Generator transformer (for Drax only) Condenser shell Gland sealing system (upgrade) Lube oil system Turbine hall crane **BoP** Stack Boiler / turbine foundations Switchgear and transformers Water treatment plant (upgrade) Cooling water supply system Refurbish existing remaining plant C&I upgrade, as appropriate Buildings

Table 2.13-3: ASC BT Retrofit Oxyfuel CO_2 Capture – Outline Scope of Supply

2.14

Reliability, Availability, Maintainability (RAM)

The RAM assessment estimates reveal significant differences in anticipated availability for the retrofit options investigated with the CO_2 capture options returning lower availability figures than those estimated for Advanced Supercritical Boiler / Turbine retrofit.

Availability: Bypass or Capture:	High Capture	High Bypass	Low Capture	Low Bypass
Mature Plant Availability (%)				
ASC BTR	87.5	89.6	85.5	87.6
ASC BTR Amine CO_2 Capture	84.8	89.0	80.8	86.8
ASC BTR Oxyfuel CO_2 Capture	84.2	87.8	79.5	85.6
Average Availability (%) : First 8 Years				
ASC BTR	86.3	88.8	84.0	86.4
ASC BTR Amine CO_2 Capture	80.6	86.9	75.0	83.6
ASC BTR Oxyfuel CO_2 Capture	78.4	83.7	71.8	80.0

Notes:-

1. ‘High’ and ‘Low’ cases indicate the upper and lower bound availability.
2. ‘Bypass’ assumes the unit can still generate power when carbon capture or FGD is unavailable i.e. amine CO_2 capture plant bypass or FGD bypass or Oxyfuel air-firing mode of operation.
3. ‘Capture’ assumes the unit can only produce power when carbon capture and FGD are available.

Table 2.14-1: ASC BT Retrofit & CO_2 Capture : Plant Availability Estimates

Key factors contributing to the lower availability of the Oxyfuel CO_2 capture were considered as (i) requirement to maintain air ingress at acceptable levels for target CO_2 purity, (ii) safety requirements to mitigate Oxyfuel CO_2 rich flue gas out-leakage for the pressurised parts of the system operating in the boiler house area and (iii) boiler pressure part degradation as a result of recycling acid gases and operation under CO_2 rich flue gas conditions.

2.15 Health & Safety Considerations : CO_2 Capture Plant

The technologies associated with the production and handling of amines, handling of oxygen and the handling of CO_2 are mature and well understood. The associated hazards are recognised and effectively controlled by a well-developed framework of standards, codes of practice and guidance, widely used by other industry sectors. Hence health and safety risks from handling of these chemicals / gases in a power generation plant can also be managed sensibly.

Retrofit of CO_2 capture technologies to power generation plant will require a HAZOP study based on the following key aspects:-

- Greater Health and Safety to meet requirements of UK Control of Major Accident Hazards (COMAH) Regulations 1999 [8] and COMAH Amendment Regulations 2005 / EU Directive 96/82/EC [9]. Mitigation measures are required to be applied to CO_2 Capture Plant based on threshold of quantities of dangerous substances for both storage and process use (**Table 2.15-1**) which the power plant is required to take specific actions to control the risk.

Substance	Material Safety Data Sheet Hazard	Schedule 1 Reference Part No.	Lower Threshold Tonnes	Higher Threshold Tonnes
Carbon Dioxide (CO_2)	Asphyxiant	-		
Mono-Ethanol Amine (MEA)	Flammable	Part 3	5000	50000
Oxygen (O_2)	Oxidising	Part 2	200	2000

Table 2.15-1: UK COMAH Regulations : Threshold Quantities (CO_2, MEA, O_2)

Note: The safety or health risks associated with power generation plant incorporating CO_2 capture are not considered to be fundamentally any different from the requirements that are not already established in thermal generation plants or the petrochemical industry.

- Health and Safety issues related to CO_2 transportation.
- CO_2 transport via pipelines to the storage location, including safe transportability and considerations on shared CO_2 pipe lines.

2.16 Operability & Flexibility

Many fossil-fired plants operating in the UK are mid-merit. As a result, it is important that they are able to respond quickly to electricity market price signals. The suitability of a plant to operate in these conditions is determined by a number of factors including technical constraints such as the ability of plant to start-up, shutdown and ramp output up or down rapidly. Although, the project ground rules have specified that the capture plants (amine capture and Oxyfuel capture) should be designed for an 85% utilisation factor (ie base load operation), recent experience in the UK market suggests that the position of plants in the merit order can change significantly over the plant lifetime. In addition, the prospect of much greater penetration of renewable generation into the market than previously has been the case makes flexible operation of fossil plant more likely, either because of competition with excessive amounts of zero-marginal-cost generation or because of the need for reserve capacity. Therefore, the suitability of plant to operate as mid-merit plant should still be assessed, even for plant that are initially designed for base load operation.

The study of plant operability and flexibility concentrated on the impact of adding CO_2 capture to power plants since these are less well understood than differences between subcritical drum and once-through BENSON boilers. Work covering plant operability and flexibility has been reported in conference papers and a journal article [10, 11, 12, 13, 14, 15]. Further work is required to improve understanding of the potential positive and negative impacts on plant flexibility associated with CO_2 capture, but this study has not identified any show-stoppers.

Quantifying Plant Flexibility in Economic Analysis

The project guidelines for economic assessment suggested that the economic analysis should take account of the potential for pulverised coal-fired plants to "exploit inherent [flexibility] advantages of PF plant compared to other low-carbon options". The project has not undertaken quantitative economic work in this area, but a published paper [10] provides a qualitative overview of options for power plants to obtain additional value by flexible operation and, in particular, providing ancillary services to the electricity network. This paper discusses economic approaches to value changes in power plant flexibility and identifies a number of areas where further work is required including the need to improve estimates of the costs and benefits associated with different changes to power plant behaviour. It also discusses additional economic tools that might be required to allow more robust analysis to inform investment decisions regarding potential capital expenditure to improve plant flexibility. In particular, discounted cash flow techniques have limited ability to take account of real-time behaviour of power plants over the timescales that are relevant for maximising value from flexible operations. It seems likely that alternative methods might be required and it was concluded that:

"One approach is real options analysis, which includes specific recognition of flexibility within project valuation. Although this approach represents a significant improvement over many standard approaches which ignore the value of flexibility, it is still challenging to fully characterise risk and uncertainty, so it is expected that Monte-Carlo methods would be required in conjunction with real options."

Advanced Supercritical Power Plant without CO_2 Capture

The boiler design used for this project is of the once-through BENSON type [5]. The operational flexibility of the advanced supercritical power plant is regarded as being a major benefit. There is no loss of flexibility in moving from subcritical to advanced supercritical steam conditions and, in some respects, the once-through boiler design is more flexible than drum boiler designs. This is because, to control metal temperature differentials in thick section components such as the steam drum, temperature control at start-up and during load ramping is more critical.

However, in once-through boiler plant, given the absence of stored energy available from a boiler steam drum, consideration is required for the plant's ability to provide primary response to the electricity network - frequency response is a mandatory service demanded by the UK National Grid Electricity Transmission (NGET): the UK 'target' grid frequency is nominally 50Hz. Given further consideration, it is possible to develop the appropriate boiler / turbine control philosophies to meet the NGET requirements with once-through supercritical power plants.

Additionally it should be noted that water quality requirements for once-through boiler plant are more stringent than those for drum type boilers, which may have some impact on plant operability, particularly under a two-shift operation regime.

Potential Changes to Power Plant Flexibility with CO_2 Capture

Adding CO_2 capture technologies to coal-fired power generation plant will impact on plant flexibility, specifically start-up / shutdown time periods, ramp rates / load following capability and part load operation. **Table 2.16-1** summarises some important flexibility considerations and the current state of knowledge in these areas.

Both Post Combustion capture and Oxyfuel Combustion technologies are considered to have similar key flexibility constraints, for example turndown of the CO_2 compressor train applies to both technologies. With respect to Oxyfuel, to meet overall plant demands, the ASU plant flexibility can be improved through selection of the number of ASU trains and back-up in the form of liquid oxygen (LOX) storage, including a number of other methods. Although an ASU start up time to reach the design purity of oxygen after defrost is > 17 hours (hot plant) [16], the time required for restart of a cold plant would be about 2 to 3 hours [16] to reach full plant output at design oxygen purity. Hence, for Oxyfuel Combustion, the overall impact on plant flexibility can be minimised by selection of appropriate number of ASU trains and back-up in the form of liquid oxygen storage.

In addition to the various aspects of power plant operation noted in **Table 2.16-1**, it is important to understand the requirements of the systems downstream of the power plant. For example, CO_2 quality requirements for transport and storage systems should be defined and understood. The matching of CO_2 supply and demand also needs to be considered over various timescales potentially ranging from minutes and hours to the whole plant lifetime.

Flexibility Consideration or Option	**Relevance/Impact on Plant Performance**
Likely changes in start-up and shutdown procedures	Further work required to understand these, using integrated models and/or real operating experience. Start-up and shutdown times and costs can be important in determining what role plants can play within the electricity network, with obvious implications for plant economic performance.
Potential to change ramp rates for load following – could be faster or slower	Plant ramp rates are critical in determining whether a plant is suitable to provide response capacity. Hence changes in these could affect the services that could be offered to the electricity network. Further work is required to understand how various components of capture schemes and their interactions with the base plant could alter ramp rates, including dynamic simulation of CO_2 compression.
Part-load efficiency for power plants with CO_2 capture is not fully understood	Since some coal-fired plants are often operated at part load to offer response capacity to the network, it is important to establish if/how CO_2 capture affects power plant efficiency across the full range of outputs. Operating experience and/or integrated plant models are required to improve understanding in this area.
Can change plant efficiency by changing capture plant operation – increased capacity at times of high demand, depending on overall plant constraints	If plant efficiency can be increased by reducing CO_2 capture levels (or delaying energy intensive aspects of the CO_2 capture process) then extra capacity can be made available to the grid, possibly very quickly. However, this will depend on balance-of-plant constraints (see final row of the table). This could be a response/reserve service that would not require off-design operation for that service to be available to the network operator.
Can change plant efficiency by changing capture plant operation – reduced minimum stable generation at times of low demand	If energy intensive aspects of the CO_2 capture process are delayed (as above) then this will lead to a reduction in plant efficiency and, hence, output during times when these postponed energy intensive process are then undertaken. At times of low demand this could be useful for the system operator since it would reduce the minimum stable generation of the plant, leaving more capacity available for other plants with lower marginal costs, but without compromising the security and quality of electricity supply.
Fuel flexibility could affect CO_2 savings associated with the power plant and 'negative emissions electricity' might be possible	The importance of fuel flexibility is not expected to change, but adding CO_2 capture introduces a potential benefit due to capture of CO_2 from carbon neutral fuels; resulting in an overall net credit in CO_2 emissions released. Biomass removes CO_2 from the atmosphere as it grows and this would be permanently removed if the CO_2 re-released when it burns was captured and stored, rather than being emitted to the atmosphere.
Performance could vary depending on balance of plant constraints, not just capture technology characteristics	It is important to note that changes in particular aspects of power plant performance could be constrained by limitations of other parts of the system. For example, additional potential capacity can only be sold into the electricity network if the generator and grid connection are large enough. For CO_2 capture-ready plants where capture is retrofitted, it is expected that the plant would be appropriately sized, since balance of plant items would be sized for the initial plant without capture. It is not yet clear whether investment to provide this flexibility at a plant built with CO_2 capture from the beginning of its operations would be justified by the potential value of that flexibility.

Table 2.16-1: Some Potential changes to Power Plant Flexibility when CO_2 Capture is Added

2.17

Capture-Ready Power Plants

The fundamental requirement of a capture ready power plant is that:-

A design study for adding CO_2 capture is carried out to assess technical feasibility and cost-effective pre-investment options. Particular requirements of this study include:-

(i) Must demonstrate sufficient existing space on site and in critical access locations to add CO_2 capture plant and necessary interconnections.

(ii) Cost-effective pre-investment options for retrofitted areas of the plant should be applied (anything beyond this is not justified).

(iii) Identification of a reasonable route to CO_2 storage.

Space Requirements

The prime essential requirement for ASC PF Power Plant capture-ready features is allocation of sufficient additional space at appropriate locations within the power plant to accommodate the additional CO_2 capture equipment and to allow extension of Balance of Plant equipment to meet the additional requirements of the capture plant.

These essential requirements are:-

- space allocation for additional equipment and associated accessories required for CO_2 capture in future. Further space may be needed during construction, for storage of equipment and materials and for access to the existing plant.
- space allocation for modifications to the boiler and steam turbine island.
- space allocation for extension and addition of balance of plant systems, as appropriate, to meet the additional requirements of the capture plant.
- space for additional vehicle movement after capture equipment addition (eg deliveries of consumables).
- space allocation based on HAZOP studies, considering storage / handling of oxygen, amine based solvents and CO_2 processing.

Capture Ready Considerations

Some further considerations for Post Combustion capture-ready features and Oxyfuel Combustion capture-ready features for PF Power Plants are presented in **Tables 2.17-1** and **2.17-2** respectively.

A further detailed study on capture ready power plants has been recently completed by IEA GHG [17].

ASC Boiler Island	• No essential capture ready requirements foreseen.
DeNOx Plant (SCR)	• No essential capture ready requirements foreseen.
ESP	• No essential capture ready requirements foreseen.
DeSOx Plant (FGD)	• Sufficient space to accommodate additional polishing unit and associated duct work. Consideration of requirements on BUF.
ASC Turbine Island	• Provision in steam turbine for extraction of almost 50% of steam flow from IP turbine exhaust (IP-LP cross over pipe) for amine regeneration. • Provision to enable bypass of the required number of LP feedwater heaters. • Provisions in steam turbine building pipe racks / building support structure to enable routing / support of the steam pipework between steam turbine and amine CO_2 capture plant reboiler.
BoP :-	
Draught Plant / Flue Gas Ductwork	• Provision in ID fan discharge ducting to enable interconnection with additional draught fan. Sufficient space at the most appropriate location in this area for installing additional fan and associated ductwork. • Provision in FGD discharge ductwork to enable interconnection with additional polishing unit. • Provision in FGD GGH inlet ductwork to enable interconnection with amine CO_2 capture plant absorber vent flue gas ductwork. Sufficient space to accommodate routing of ductwork.
Raw Water Pre-treatment Plant / Water Treatment Plant / Cooling Water System / Waste Water Treatment Plant	• No essential capture-ready requirement foreseen, except for provisions for tie-ins.
Plant Pipe Racks	• Design of pipe rack structures to handle additional pipe loads. • Provisions in pipe racks to accommodate additional piping.
C&I	• Space/ provisions for extension of control room & space / provisions in cable floor to accommodate additional cables.
Electrical	• Space for additional Unit Auxiliary Transformer (UAT) • Provisions in bus ducts to feed the UAT and for power distribution to auxiliaries. • Provision in underground cable trenches / above ground cable trays to accommodate additional cables. • Space in extension of Low Voltage & High Voltage Switch Gear Room(s) to accommodate additional feeders / MCCs.
Compressed Air System	• Space for addition of compressed air system components / sizing of compressed air distribution headers / tie-ins.
Fire Fighting / Protection	• Space to accommodate new fire fighting system(s) for capture plant and provisions in the plant fire hydrant network for additional fire hydrant points.
Design, Planning Permission & Approvals	• Undertake study to ensure that all technical reasons that would prevent installation and operation of CO_2 capture plant have been identified and eliminated. • Given local drivers, obtain planning permissions and similar approvals for eventual retrofit of CO_2 capture plant, although this is not considered to be an essential capture ready requirement.
HAZOP & CO_2 Study	• Greater Health and Safety to meet requirements of UK Control of Major Accident Hazards (COMAH) Regulations 1999 [8] and COMAH Amendment Regulations 2005 / EU Directive 96/82/EC [9]. Mitigation measures are required to be applied to CO_2 Capture Plant based on threshold of quantities of dangerous substances for both storage and process use which the power plant is required to take specific actions to control the risk. Note: The safety or health risks associated with power generation plant incorporating CO_2 capture are not considered to be fundamentally any different from the requirements that are not already established in thermal generation plants or the petrochemical industry. • Health and Safety issues related to CO_2 transportation. • CO_2 transport via pipelines to the storage location, including safe transportability and considerations on shared CO_2 pipe lines.

Table 2.17-1: Capture Ready Considerations for Post Combustion Capture for PF Plant

ASC Boiler Island	The capture-ready plant will need to consider the following essential features (draught system):- • Adequate space in the boiler island to route the Oxyfuel FGR ducting, to accommodate change in duct sizes and to add maintenance platforms. • Adequate space in the boiler island to route oxygen injection pipework. • Adequate space for steam oxygen preheater and flue gas heat recovery plant. • Provisions / space in flue gas ducting enable take-off of Oxyfuel FGR ducting. • Provisions at FD fan inlet ductwork to enable interconnection with Oxyfuel FGR duct and addition of isolation dampers. • Provisions for tie-ins for the oxygen injection system into the existing combustion air system • Consideration for requirement of O_2 compatible materials in the combustion ductwork local to the proposed O_2 injection locations. • FD/PA/ID/BUF fans casing material selection giving considerations to Oxyfuel flue gas conditions (higher temperature / high SO_3 concentration in Oxyfuel flue gases). Note: Fans operate as SFGR/PFGR/ID/BUF respectively after capture retrofit. • Boiler design and draught plant considerations for achievable and maintainable minimum air ingress levels.
DeNOx Plant (SCR)	• No essential capture ready requirements foreseen.
ESP	• Combination of dry electrostatic precipitators and wet flue gas desulphurisation plant considered adequate, subject to modifications (SO_3 gas conditioning for improvement of dust resistivity) to correct deterioration in collection efficiency caused by the change to dust resistivity resulting from higher flue gas temperature.
DeSOx Plant (FGD)	• No essential capture ready requirements foreseen.
ASC Turbine Island	• Provision for process integration with ASU, CO_2 Purification & Compression plant and boiler flue gas systems. • Provision to enable bypass of the required number of LP / HP feedwater heaters.
BoP :-	
Draught Plant / Flue Gas Ductwork	• Provision in FGD ductwork to enable interconnection with CO_2 Purification & Compression System. Sufficient space to accommodate routing of ductwork.
Raw Water Pre-treatment Plant / Water Treatment Plant / Cooling Water System / Waste Water Treatment Plant	• No essential capture-ready requirement foreseen, except for provisions for tie-ins.
Plant Pipe Racks	• Design of pipe rack structures to handle additional pipe loads. • Provisions in pipe racks to accommodate additional piping.
C&I	• Space/ provisions for extension of control room & space / provisions in cable floor to accommodate cables.
Electrical	• Space for additional Unit Auxiliary Transformer (UAT) • Provisions in bus ducts to feed the UAT and for power distribution to auxiliaries. • Provision in underground cable trenches / above ground cable trays to accommodate additional cables. • Space for extension of Low Voltage & High Voltage Switch Gear to accommodate additional feeders.
Fire Fighting / Protection	• Space to accommodate new fire fighting system(s) for capture plant and provisions in the plant fire hydrant network for additional fire hydrant points.
Design, Planning Permission & Approvals	• See Table 2.17-1.
HAZOP & CO_2 Study	• See Table 2.17-1.

Table 2.17-2: Capture Ready Considerations for Oxyfuel CO_2 Capture for PF Plant

Effects on adding CO_2 capture to Capture-Ready ASC BTR Power Plant

The overall effects on adding CO_2 capture to capture-ready ASC BTR power plant are presented in the table below:

Description	ASC BTR Amine CO_2 Capture	ASC BTR Oxyfuel CO_2 Capture
Generator output	Reduces by some 12%	Increases by some 3.5%
Export power	Reduces by some 20%	Reduces by some 20%
ASC Boiler	Virtually unaffected	Virtually unaffected with appropriate flue gas recycle
HP turbine/ HP feedwater heaters/ IP turbine inlet	Virtually unaffected	Virtually unaffected
LP turbine mass flow rate	Reduces by up to 50%	Increases by some 10%
IP Turbine exhaust pressure	Reduces by some 50%	-
Main condenser heat rejection	Drops by some 40%	Increases by more than 20%
Plant heat rejection to cooling water	Increases by some 25%	Increases by some 40%
Condensate heating through heat recovery	By approximately 90°C (full condensate flow)	By approximately 140°C (full condensate flow)

Table 2.17-3: Effects of adding CO_2 Capture to Capture-Ready ASC BTR Power Plants

2.18 Economic Performance

The overall techno-economic performance of the retrofit carbon abatement technologies including specific investment, O&M costs, cost of electricity and cost of CO_2 avoidance for Ratcliffe, Drax and West Burton Power Plants are summarised below in **Table 2.18-1**. The economic assessment has been based on the following agreed key criteria:-

- UK domestic coal : coal price : £1.07/GJ
- Load Factor :Utilisation factor (85%) x Availability
- 10% discount rate
- 25 year design life extension post retrofit

Given the LCPD status of the existing unit, the economic assessment takes into consideration lost generation whilst the unit is off-load during the construction period. Sensitivities to fuel prices, discount rates and introduction of carbon tax (for uncaptured / emitted CO_2) and their relative impact on the overall cost of electricity have been investigated. No CO_2 credits have been assumed in the analysis including the benefit of emissions reduction due to capture of CO_2 from cofiring carbon neutral fuels.

The carbon capture retrofit plant include costs for CO_2 compression to 110bara but exclude costs associated with transport and storage of CO_2 as this depends on a number of factors including transport distance, method of transport and the type of storage reservoir. The economics are based on the amine CO_2 capture option capturing 85% of CO_2 emissions compared with 88% of the CO_2 emissions captured for Oxyfuel CO_2 capture.

Overall, ASC boiler / turbine retrofit is estimated to deliver an overall plant efficiency of 44% to 45%, LHV at a cost of electricity of 2.4 to 2.5p/kWh. Adding CO_2 capture technologies reduces this efficiency by some nine to ten percentage points and increases the cost of electricity by some 2.0 – 3.0p/kWh. The estimated cost of CO_2 capture and compression (excluding CO_2 transport and storage) is 36 - 45£/tonne of CO_2 emissions avoided relative to existing subcritical plant or 35 - 47£/tonne of CO_2 emissions avoided relative to ASC boiler / turbine retrofit.

The sensitivity of economic performance factors (cost of electricity and CO_2 avoidance cost) to variations in the base fuel price, discount rate, carbon tax/future CO_2 price was assessed. The assessment concluded:-

- **Fuel Price**: As would be expected, the change in cost of electricity could be almost directly deduced via a percentage change in the fuel component of the cost of electricity. A 100% increase in fuel price increases the cost of electricity by some 25% to 30% and the CO_2 avoidance cost (for carbon capture plant) by less than 10%.

- **Discount Rate**: A reduction in the financial discount rate reduces the capital cost component of the cost of electricity. Compared to the base 10% discount rate, a discount rate of 5% lowers the cost of electricity for the non-capture retrofit plant by some 10% and carbon capture retrofit plant by some 30%. The cost of CO_2 avoided is lower by some 30%.

- **Carbon Tax**: Similar costs of generation are achieved for the carbon capture and non-capture retrofit plant at a carbon tax level of about 36-45£/tonne.

Cross-comparison of the above economic results with a model developed using the Integrated Environmental Control Model (IECM) indicated that plant performance predicted by the engineering analysis carried out within the project is typical of that obtained by other studies and, given that significant cost escalations have occurred in recent years, investment required for a new build plant is higher than for retrofit to suitable existing plants.

		Reference Site : Ratcliffe Power Station			Alternative Site #1 : Drax Power Station			Alternative Site #2 : West Burton Power Station		
		ASC BTR	ASC BTR Amine CO_2 Capture	ASC BTR Oxyfuel CO_2 Capture	ASC BTR	ASC BTR Amine CO_2 Capture	ASC BTR Oxyfuel CO_2 Capture	ASC BTR	ASC BTR Amine CO_2 Capture	ASC BTR Oxyfuel CO_2 Capture
Plant Performance										
Fuel Heat Input (LHV)	MWt	1286	1286	1286	1393	1393	1396	1278	1278	1313
Gross Output	MWe	625	550	634	668	594	668	615	541	634
Net Output	MWe	577	459	448	613	493	476	568	451	452
Efficiency and Emissions										
Net Plant Efficiency	%, LHV	44.9%	35.7%	34.9%	44.0%	35.4%	34.1%	44.5%	35.3%	34.4%
CO_2 Emissions	g/kWh net	753	142	115	733	137	109	754	143	112
CO_2 Captured	g/kWh net	-	805	854	-	774	805	-	807	829
Economic Performance										
Power Generation Plant Investment including Life Extension	£ Million	360.7	387.0	402.2	358.2	382.6	403.3	356.6	408.2	435.4
Capture Plant Investment	£ Million	-	200.1	283.1	-	206.6	263.1	-	200.1	283.1
Total Investment Cost	£ Million	360.7	587.2	685.3	358.2	589.2	686.4	356.6	608.3	718.5
Specific Investment	£/kWe net	625.3	1280.0	1529.0	584.5	1194.7	1440.7	627.5	1349.5	1590.6
Fixed O&M Costs	£M/annum	19.8	28.2	30.4	19.8	29.0	32.6	19.5	29.9	33.4
Variable O&M Costs (@ 100% load factor)	£M/annum	45.9	47.3	44.9	49.2	50.6	47.1	45.0	46.4	44.2
Cost of Electricity	**p/kWh**	**2.50**	**4.73**	**5.38**	**2.37**	**4.47**	**5.08**	**2.52**	**4.98**	**5.56**
Cost of CO_2 Avoidance (relative to existing plant)	**£/tonne CO_2**	**38.7**	**37.0**	**44.2**	**40.1**	**35.9**	**42.9**	**36.5**	**39.6**	**45.4**
Cost of CO_2 Avoidance (relative to ASC BTR)	**£/tonne CO_2**	**-**	**36.5**	**45.1**	**-**	**35.2**	**43.4**	**-**	**40.3**	**47.4**

Notes
1. Power generation plant investment includes life extension of retained plant.
2. Investment costs (Year 2005-2006 cost basis) stated include owner's costs (5%), fees (2%) and contingencies (10%).
3. Cost of CO_2 avoidance relative to existing subcritical plant: 2.0p/kWh COE and CO_2 emissions of 869g/kWh (Ratcliffe), 825g/kWh (Drax) and 895g/kWh (West Burton).

Table 2.18-1: ASC BT Retrofit & CO_2 Capture : Overall Plant Performance Comparison

2.19 Overall ASC BTR Implementation Programme

Overall preliminary project implementation schedules were developed for each of the ASC BT retrofit options considering the requirements for:-

- Front End Engineering Design (FEED)
- Approval for authorisation / planning / IPPC application / Section 36 consent; as appropriate
- Detailed design & engineering
- Procurement, manufacture and supply
- Dismantle works
- Retrofit plant site construction / erection
- Commissioning up to commercial operation

The schedules for the retrofit carbon capture options, ASC BTR Amine and ASC BTR Oxyfuel, were based upon the schedule for ASC BTR but with some added elements to allow for the extra design and build requirements for the additional plant items associated with CO_2 capture plant.

The overall programme duration required to complete ASC BT retrofit is estimated at approximately 56 months (from contract award to unit return to commercial operation). The overall programme duration for ASC BT with CO_2 capture is estimated at 56 to 58 months. The programme duration to complete the intrusive site works is 25 months (from unit off-line to unit return to service).

Special consideration must be given to the various planning consents required for retrofit. In particular Section 36 application is required and likely to represent a major challenge for expansion of the power plant sites for CO_2 capture plant.

For capture plant retrofit, greater health and safety is necessary to meet the requirements of the UK Control of Major Accident Hazards (COMAH) regulations based on the threshold of quantities of certain substances for both on-site storage and process use. Adoption of a top-tier status under COMAH will require extra safety measures on behalf on the operator; including the publication of a safety report, an on-site and off-site emergency plan. The site must also provide certain information to the public concerning these activities.

There are a number of practical aspects to consider with retrofitting carbon abated clean coal technologies to an existing power generation unit; these are associated mainly with the operational status of the surrounding station. Key considerations are access and egress, materials lay-down, Construction Design & Management (CDM) regulations and the increased on-site workforce. These aspects will require careful pre-planning prior to demolition and construction of the retrofit plant.

3. RECOMMENDATIONS

Over the next five to six years, investment in capture-ready carbon abated clean coal power plants (retrofits and new-build) can make a major contribution to filling UK's large generation gap by 2015 of at least 20GWe due to the closure of opted-out coal fired power stations. Against concerns for security of supplies, the level of investment in coal fired plant is recognised in the recent UK Government 2007 Energy White Paper (EWP).

Carbon abated clean coal power plants, available today with guarantees, will reduce dependence on imported expensive natural gas that would imbalance the generation portfolio. Clean coal technology brings reductions in specific CO_2 emissions compared to the plants replaced at a cost of electricity less than that from new-build gas-fired power stations and can be fitted later with carbon capture and storage (CCS) when this becomes available.

In parallel, the UK Government's commitment to support a full-scale (at least 300 MWe) first-of-class CCS project (to be selected by competition as launched in November 2007) is an important step to early demonstration of the technology over the period 2008 – 2014. The benefits of demonstration include potential reductions in the cost of the technology as a result of learning-by-doing.

Beyond 2015, capture-ready coal-fired power plants are to be retrofitted with CCS and any further coal power plants constructed with CCS incorporated [as accepted by EWP, development and deployment of CCS has been recognised as a component of European energy policy by the Council of the European Union which supports European Commission proposals to encourage a CCS demonstration plan involving up to 12 demonstration plants operating in Europe by 2015, with the aim that all new coal-fired power plants be fitted with CO_2 capture from 2020 onwards].

Together, these actions will demonstrate a practical commitment by the UK to CO_2 emission reductions from fossil fuel power plant using technologies suitable for both developing and developed countries. This will position the UK at the forefront of these technologies taking a leading role in their commercialisation and roll-out world-wide.

4. RESULTS AND CONCLUSIONS

4.1 Results

The work undertaken under the project has:-

- Demonstrated the technical feasibility of Advanced Supercritical Retrofit capture-ready plant to UK power plant fleet.
- Demonstrated it is technically feasible to retrofit carbon capture technologies of Post Combustion or Oxyfuel Combustion to an existing coal-fired power plant. However, currently in most UK power plants there is insufficient space available to fit carbon capture equipment to all units of the power plant and insufficient cooling capacity. Further considerations are required to address these key issues, particularly in securing the appropriate space required beyond the power station fence.
- Demonstrated that Advanced Supercritical Retrofits and Advanced Supercritical retrofits with Carbon Capture (subject to carbon tax / future CO_2 price) are economically viable in terms of the Cost of Electricity generated.

Overall, based on a 25 year plant design life extension, advanced supercritical retrofit at the UK power plants considered are estimated to deliver overall plant thermal efficiencies of 44 - 45% net, LHV at a cost of electricity of 2.4 to 2.5p/kWh. The retrofit plant can reduce carbon dioxide emissions by around 16% compared to the average UK power plant. The plants can be designed for enhanced biomass cofiring – up to 20%, giving a further 20% reduction in carbon dioxide emissions and can be made capture ready. However, the overall performance depends on various technical and economic factors, including fuel price.

Adding CO_2 capture technologies to achieve large reductions in CO_2 emissions of >85% reduces the plant efficiency by some nine to ten percentage points and increases the cost of electricity by some 2.0 to 3.0p/kWh. The estimated cost of CO_2 capture and compression (excluding CO_2 transport and storage) is 36 - 45£/tonne of CO_2 emissions avoided for the UK power plants considered.

The specific investment (Year 2005-2006 cost basis) of the ASC BTR plant with maximum plant electrical output by retaining the same fuel heat input rate as per the existing plant is estimated at 625£/kWe net. For ASC BTR with CO_2 capture, the specific investment required based on amine based Post Combustion technology is estimated at 1195-1280£/kWe net compared to Oxyfuel Combustion of 1440-1530£/kWe net.

RAM assessment of Post Combustion and Oxyfuel Combustion carbon capture technologies show similar availabilities when mature – availability is expected to be some 80% – 85% (capture mode operation) or 86% - 89%

(capture plant by-passed) in comparison with 86% – 90% for ASC retrofit plant without CO_2 capture.

This study has identified a number of areas where adding CO_2 capture may affect plant operating flexibility. Although further work is required to improve understanding of the potential positive and negative impacts on plant flexibility associated with CO_2 capture, the study has not identified any technical show-stoppers.

The overall programme duration required to complete an advanced supercritical boiler/turbine retrofit is estimated at approximately 56 months (from contract award to unit return to commercial operation). The overall programme duration for the retrofit plant with CO_2 capture is estimated at 56 to 58 months. The programme duration to complete the intrusive site works is 25 months (from unit off-line to unit return to service).

4.2 Conclusions

Retrofit of carbon abated clean coal technologies (CATs) is a practical reality with no technical or physical show stoppers being identified in the course of the study.

Advanced supercritical boiler/turbine (ASC BTR) technology is available now with the appropriate guarantees for retrofitting to coal-fired power plant to improve efficiency, reduce fuel costs and reduce carbon dioxide emissions.

When CO_2 capture and storage becomes economic or mandatory the retrofit routes studied are likely to be amongst the best and most economic options for existing pulverised fuel power generation plant. The project consortium members are well positioned to exploit the opportunities worldwide.

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