Programme Area: Carbon Capture and Storage

Project: Benchmark Refresh

Title: Task 5 Report: Independent Capture Plant

Abstract:

This report describes development of a new benchmark for an alternative commercial CCGT model with an Independent Capture Plant (ICP), in order to examine the feasibility, cost, schedule and efficiency penalty for a “commercially distinct” post-combustion carbon capture plant. The report describes the results from a base case and two sensitivity cases: ·The base case consists of a CCGT plus ICP configured for 90% capture using an amine system but where the CCGT is unaffected by the capture plant. In this case the capture plant operates independently of the CCGT and is self-sufficient in steam and power; ·The first sensitivity case investigates the use of power import from the CCGT. The steam demand for the ICP is met with a package steam boiler; The second sensitivity case investigates the effect of importing both power and steam from the CCGT. This is considered to represent a retrofit scenario, where the ICP is built next to an existing CCGT. This report documents the assumptions used and presents the technical and economic performance for the above cases, as compared with the Task 1 CCGT Benchmark cases both with and without capture (see Deliverable D2.1).

Context:

This project refreshed and extended techno-economic studies of current generation (benchmark) CO2 capture technologies for gas fired power stations and provided comparable information on one or more next generation technologies. It produced a new benchmark incorporating exhaust gas recycle and provided robust, independent and directly comparable technology assessments of specific technologies being considered for further demonstration.

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WP6 - CCS Benchmark Refresh 2013
Task 5 Report

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1. EXECUTIVE SUMMARY

1.1 Introduction

The ETI has engaged Amec Foster Wheeler to execute its CCS Benchmark Refresh 2013 Project. The main purpose of this further study work is to provide additional benchmarking and performance analysis of next generation carbon capture technologies building upon those evaluated and reported in previous phases of CCS study work that Amec Foster Wheeler has executed with ETI.

1.2 Scope

Task 5: Independent Capture Plant

This task involves development of a new benchmark for an alternative commercial CCGT model with an Independent Capture Plant (ICP), in order to examine the feasibility, cost, schedule and efficiency penalty for a "commercially distinct" post-combustion carbon capture plant.

Task 5 involves a base case and two sensitivity cases:

- The base case consists of a CCGT plus ICP configured for 90% capture using an amine system as in WP6 Task 1, but where the CCGT is unaffected by the capture plant.

  In this case the capture plant operates independently of the CCGT and is self-sufficient in steam and power, having its own GT/HRSG and (if required) additional steam raising capability. The ICP is configured to capture 90% of the CO_2 from its own GT/HRSG/steam-raising in addition to the 90% capture from CCGT flue gas. The GT selected for the ICP is sized to satisfy the ICP parasitic power load.

- The first sensitivity case investigates the effect of power import from the CCGT. The steam demand for the ICP is met with a package steam boiler. The ICP is configured to capture 90% of the CO_2 from its own steam boiler.

- The second sensitivity case investigates the effect of importing both power and steam from the CCGT. This is considered to represent a retrofit scenario, where the ICP is built next to an existing CCGT, making it distinct from the WP Task 1 integrated plant case which was considered new-build. In this case, no GT/HRSG or steam boiler is required in the ICP.

This Task 5 Report documents the assumptions used and presents the technical and economic performance for the above cases, as compared with the Task 1 CCGT Benchmark cases both with and without capture. Table 1-1 highlights the plant configuration of the Independent Capture Plant cases along with the Task 1 CCGT Benchmark cases.

Table 1-1 Plant Configuration of Benchmark Task 1 Cases and CCGT with ICP Cases

	Benchmark Task 1	Benchmark Task 1	ICP Base Case	ICP Sensitivity Case 1	ICP Sensitivity Case 2
	0% CCS	90% CCS	90% CCS	90% CCS	90% CCS
Main Power Plant	CCGT : a) Two MHI M701F5 gas turbines, each with own HRSG b) Common single STG	CCGT : a) Two MHI M701F5 gas turbines, each with own HRSG b) Common single STG with LP steam extraction for Capture Plant	CCGT : a) Two MHI M701F5 gas turbines, each with own HRSG b) Common single STG	CCGT : a) Two MHI M701F5 gas turbines, each with own HRSG b) Common single STG	CCGT : a) Two MHI M701F5 gas turbines, each with own HRSG b) Common single STG modified for LP steam extraction
Carbon Capture Plant	n/a	Integrated capture plant with power and steam from CCGT plant.	Independent capture plant self-sufficient in steam and power a) Single Alstom GT11N2 gas turbine, with HRSG producing LP steam only b) Small power import from grid c) Supplementary LP steam generated in a package steam boiler	Independent capture plant self-sufficient in steam. a) Power imported from CCGT plant b) LP steam generated using package steam boiler	Independent capture plant with steam and power imported from CCGT plant. This case represents a retrofit scenario of Benchmark Task 1 90% case considering ICP is built next to an existing CCGT.
Tie-in between CCGT and capture plant	n/a	Fully integrated new build installation	Flue gas duct	a) Flue gas duct b) Electrical tie-in	a) Flue gas duct b) Electrical tie-in c) Steam/condensate tie-in
Existing Steam Turbine modification	n/a	n/a	n/a	n/a	Existing steam turbine within CCGT needs to be modified to extract LP steam.
CCGT Shut down requirement for ICP	n/a	n/a	All tie-ins within scheduled 2-week shutdown of CCGT plant	All tie-ins within scheduled 2-week shutdown of CCGT plant	4 weeks CCGT plant shut down required for tie-ins

1.3 Task 5 – Independent Capture Plant

1.3.1 Independent Capture Plant Performance Results

Table 1-2 Technical Performance Figures for CCGT with ICP Cases

		Benchmark Task 1	Benchmark Task 1	ICP Base Case	ICP Sensitivity Case 1	ICP Sensitivity Case 2
		0% CCS	90% CCS	90% CCS	90% CCS	90% CCS
		100% Load	100% Load	100% Load	100% Load	100% Load
Power						
CCGT gross installed capacity	MWe	1068.0	967.9	1068.0	1068.0	967.9
Gas Turbine (s)	MWe	739.0	739.0	739.0	739.0	739.0
Steam Turbine	MWe	328.9	228.9	328.9	328.9	228.9
Others	MWe	0.0	0.0	0.0	0.0	0.0
CCGT auxiliary loads	MWe	22.4	20.0	22.4	22.4	20.0
CCGT Power Island	MWe	15.6	13.2	15.6	15.6	13.2
Others	MWe	6.8	6.8	6.8	6.8	6.8
CCGT Net Power Export	MWe	1045.6	947.9	1045.6	1045.6	947.9
ICP Gross Power	MWe	0.0	0.0	112.7	0.0	0.0
Gas Turbine	MWe	0.0	0.0	112.7	0.0	0.0
Power Import from Grid	MWe	0.0	0.0	2.0	0.0	0.0
Capture Plant auxiliary loads	MWe	0.0	77.1	114.7	98.7	81.2
ICP GT	MWe	0.0	0.0	1.8	0.0	0.0
Flue Gas Blower	MWe	0.0	37.2	52.5	43.1	37.2
Acid Gas Removal/DCC	MWe	0.0	2.8	3.9	3.7	2.8
CO_2 compression	MWe	0.0	31.7	43.7	39.8	31.7
Others	MWe	0.0	5.3	12.9	12.2	6.5
CCGT+ICP Net Power Export	MWe	1045.6	870.8	1043.5	946.9	869.6
Plant Net Efficiency (LHV)	%	58.3	48.6	42.4	42.2	48.5
Heat Rate	kJ/kWh	6172.1	7410.6	8485.8	8523.9	7421.0
CC Energy Penalty	%	-	9.7	15.9	16.1	9.8
Flows						
Total fuel feed rate	tpd	3264.1	3264.1	4478.7	4082.4	3264.1
Flue gas to the Capture Plant	t/hr	-	5127.1	6838.6	5777.3	5127.4
Water consumption	tpd	204	204	367.0	350	204
Cooling water (once through)	tpd	1,219,104	1,851,274	2,954,572	2,825,568	2,455,128
Carbon Balance						
Total carbon in feeds	tpd	2400.3	2400.3	3293.4	3002.0	2400.3
Total carbon captured	tpd	0.0	2159.4	2969.6	2709.3	2159.4
Carbon capture rate	%	0.0	90.0	90.2	90.2	90.0
Total CO_2 captured	tpd	0.0	7913.0	10882.0	9928.1	7913.0
Total CO_2 emitted	tpd	8795.6	882.6	1186.6	1072.7	882.6
CO_2 emissions	g CO_2 /kWh_{Net}	350.5	42.2	47.4	47.2	42.3

Table 1-3 Economic Performance Figures for CCGT with ICP cases

		Benchmark Task 1	Benchmark Task 1	ICP Base Case	ICP Sensitivity Case 1	ICP Sensitivity Case 2
		0% CCS	**90% CCS**	**90% CCS**	**90% CCS**	**90% CCS**
		100% Load	**100% Load**	**100% Load**	**100% Load**	**100% Load**
Total CAPEX	GB£M	547.5	997.2	1345.1	1178.8	1013.6
CCGT Power Island	GB£M	474.5	474.5	474.5	474.5	474.5
CCGT U&O	GB£M	73.0	73.0	73.0	73.0	73.0
Capture Plant Power Block	GB£M	0.0	0.0	131.6	51.8	0.0
Capture Plant Tie-ins	GB£M	0.0	0.0	10.0	13.4	16.5
Acid Gas Removal Unit	GB£M	0.0	322.9	467.0	405.5	322.9
CO_2 compression	GB£M	0.0	61.5	76.2	71.6	61.5
Capture Plant U&O	GB£M	0.0	65.2	112.7	88.9	65.1
CAPEX efficiency	GB£/kW_{Net}	523.6	1145.1	1289.0	1244.9	1169.5
Total OPEX – incl. fuel	GB£M p.a.	296.6	313.4	428.3	388.9	315.1
Total OPEX – excl. fuel	GB£M p.a.	28.3	45.1	60.1	53.3	46.8
OPEX – incl. fuel	GB£ p.a. / kW_{Net}	283.7	359.9	410.4	410.7	363.6
OPEX – excl. fuel	GB£ p.a. / kW_{Net}	27.1	51.8	57.6	56.3	54.0
Levelised Cost of Electricity						
CO_2 emission cost = £0 / te CO_2	£ / MWh_{Net}	47.7	69.1	78.7	77.8	70.1
CO_2 emission cost = £20 / te CO_2	£ / MWh_{Net}	54.7	70.0	79.6	78.7	71.0
CO_2 emission cost = £40 / te CO_2	£ / MWh_{Net}	61.7	70.8	80.5	79.7	71.8
CO_2 emission cost = £60 / te CO_2	£ / MWh_{Net}	68.7	71.7	81.5	80.6	72.7
Cost of CO_2 Captured CO_2 emission cost = £ 0 / te CO_2	£ / te CO_2	n/a	56.8	71.3	69.0	59.1
Cost of CO_2 Avoided CO_2 emission cost = £ 0 / te CO_2	£ / te CO_2	n/a	69.7	102.3	99.3	72.9

1.3.2 Performance Analysis of Independent Capture Plant

Table 1-2 summarises the key technical performance figures for the Independent Capture Plant cases compared with the WP6 Task 1 benchmark cases, with and without 90% CO_2 capture.

The impacts of commercially independent capture plant on the overall performance of the CCGT power plant with 90% carbon capture can be summarised as follows:

ICP Base Case

The CCGT with an independent carbon capture plant, self-sufficient in steam and power, with its own GT/HRSG and a package steam boiler, suffers from an overall 6.2% drop in efficiency compared to the CCGT with an integrated capture plant. The overall plant capacity has increased approximately ~37% compared to the CCGT with an integrated capture plant due to the fuel consumed by the Alstom gas turbine and the package steam boiler used to produce the power and steam for the ICP.

Although the increase in capacity alone would not be expected to affect the overall plant efficiency, the following table shows the contributing factors leading to the efficiency drop for the ICP Base Case:

Table 1-4 Efficiency drop and contributing factors for ICP Base Case

Contributing Factors	Efficiency drop from Task 1 90% CCS, % Point
Less power produced for a given amount of fuel due to less efficient ICP GT (33.3%) compared to CCGT Gas Turbine (41%)	-1.2
Fuel used in the ICP duct burner and steam boiler to produce steam only. This fuel energy is not translated to produce power, hence overall drop in the electrical efficiency	-5.4
Efficiency gain from the CCGT compared to integrated case as no steam is being extracted from the CCGT steam turbine	+0.8
Parasitic load increased disproportionately due to higher flue gas temperature to the GT and package boiler blowers, higher DCC cooling water demand and duplication of offsite systems	-0.4
Overall Efficiency drop, %	-6.2

ICP Sensitivity Case 1

ICP Sensitivity Case 1 suffers from an overall 6.4% drop in efficiency compared to the CCGT with an integrated capture plant. The following table shows the breakdown of the efficiency drop and their contributing factors:

Table 1-5 Efficiency drop and contributing factors for Sensitivity 1

Contributing Factors	Efficiency drop from Task 1 90% CCS, % Point
Fuel used in the steam boiler to produce steam for reboiler. This fuel energy is not translated to produce power, hence overall drop in the electrical efficiency	-8.3
Efficiency gain from the CCGT compared to integrated case as no steam is being extracted from the CCGT steam turbine	+2.0
Parasitic load increased disproportionately due to higher flue gas temperature to the package boiler blowers, higher DCC cooling water demand and duplication of offsite systems	-0.1
Overall Efficiency drop, %	-6.4

ICP Sensitivity Case 2

As ICP Sensitivity Case 2 is a retrofit scenario of WP Task 1 integrated plant case, plant capacity is similar to WP Task 1 integrated plant case. Table 1-2 shows the similarity between the technical data of the two cases.

The only difference in the technical performance is the offsite power demand. As the capture plant is commercially separated from the CCGT plant, offsites such as buildings, demin water plant etc. are duplicated which leads to the higher offsite power demand of the overall plant. Hence the net power output is decreased slightly which is reflected in the 0.1% decrease in net efficiency and the increase in heat rate and carbon efficiency.

1.3.3 Economic Analysis of Independent Capture Plant

Capital Cost Variation

For the ICP cases, the CCGT plant capacity remains the same as the WP6 Task 1, hence the CCGT power island capital cost for all cases are the same as shown in Table 1-3.

The 35% increase in the capital cost of the ICP Base Case compared to the Task 1 integrated capture plant is due several factors:

- The added cost of the capture plant power block which includes an Alstom GT/HRSG and package boiler.
- The capture plant capacity has increased by approximately 33% which requires four trains of DCC and absorber columns and three trains of stripper columns compared to three trains of DCC and absorber columns and two trains of stripper columns for the Task 1 integrated case.
- In addition to the increased volumetric flow entering the Acid Gas Removal unit, the flue gas temperature has also increased from 93°C to 131°C, resulting in a bigger gas-gas exchanger and a bigger DCC cooler exchanger.
- The ICP case includes an independent exhaust stack.
- The addition of flue gas tie-in costs.
- The increase of cooling load and duplication of offsites in the capture plant resulting in higher U&O costs.

For similar reasons, the capital cost of the ICP Sensitivity Case 1 increased by 18% compared to the Task 1 integrated capture plant.

ICP Sensitivity Case 2 is a retrofit case of WP6 Task 1 integrated capture plant. The ICP capture plant is commercially separated from the CCGT, hence it requires tie-ins for flue gas, electrical systems, steam and condensate, duplication in offsites facilities and modification of existing steam turbine to install extraction pipe and control systems. These factors increase the capital cost for this retrofit case by ~1.6% compared to the integrated capture plant.

Operating Cost Variation

The significant increase in operating costs for the ICP Base Case and Sensitivity Case 1 shown in Table 1-3 is mostly due to the increase in fuel requirement.

The ICP Base Case fuel demand is approximately 37% higher than WP6 Task 1 integrated capture plant due to the fuel requirement for the capture plant Power Island to produce power and steam and the package boiler to meet the additional steam demand.

For Sensitivity Case 1, the capture plant Power Island is not required, as power is being imported from the CCGT plant. However, two package boilers are required to produce the entire steam demand for the stripper column. Overall, fuel demand for this case is less than the ICP Base Case, though it is still ~25% higher than the integrated capture plant of Task 1.

In addition to the fuel cost, there is also an increase in the fixed operating costs for both the ICP Base Case and Sensitivity Case 1, since several of these are related to the total capital cost.

As the independent capture plant is commercially separated from the CCGT power plant, more personnel are required than for the integrated plant which increases the direct labour cost and hence fixed cost for all the ICP cases.

Levelised Cost of Electricity Variation with Independent Capture Plant

Since both the total capital and the total operating costs increase significantly for the ICP Base Case and Sensitivity Case 1, so does the levelised cost of electricity (LCOE). The LCOE increases by 14.1% and 12.5% for the ICP Base Case and Sensitivity Case 1 respectively. For the retrofit case (Sensitivity Case 2), LCOE increases slightly by 1.4% compared to the Task 1 integrated capture plant. The difference is due to the higher fixed operating cost for the retrofit case, mainly related to the direct labour cost.

Overall, these results imply that there is a significant penalty associated with operating the capture plant as a commercially distinct entity and that if opportunities to integrate the capture plant with the CCGT are not able to be realised commercially, this penalty is likely to increase the levelised cost of electricity by well over 10%.

2. INTRODUCTION

The Energy Technologies Institute (ETI) is a public private partnership between global industry members - BP, Caterpillar, EDF, E.ON, Rolls-Royce and Shell with the UK government. The ETI brings together projects that accelerate the development of affordable, clean, secure technologies needed to help the UK meet its legally binding 2050 targets. The ETI's mission is to accelerate the development, demonstration and eventual commercial deployment of a focused portfolio of energy technologies, which will increase energy efficiency, reduce greenhouse gas emissions and help achieve energy and climate change goals.

The ETI has engaged Amec Foster Wheeler to execute its CCS Benchmark Refresh 2013 Project. The main purpose of this further study work is to provide additional benchmarking and performance analysis of next generation carbon capture technologies building upon those evaluated and reported in previous phases of CCS study work that Amec Foster Wheeler has executed with ETI.

2.1 Scope of Study

The scope of the CCS Benchmark Refresh 2013 Project is presented in five distinct tasks over three phases.

Phase A – Benchmark Refresh

Task 1: Combined Cycle Gas Turbine (CCGT) Benchmark Refresh

Task 2: Exhaust Gas Recycle Benchmark

Phase B – Technology Assessments

Task 3: Inventys Technology Refresh

Task 4: (Optional) Alternative Next Generation Technology Assessment

Phase C – Continuation of Technology Assessments

Task 5: Independent Capture Plant (ICP)

2.2 Scope of Phase C

2.2.1 Task 5: Independent Capture Plant

This task involves development of a new benchmark for an alternative commercial CCGT model with an Independent Capture Plant (ICP), in order to examine the feasibility, cost, schedule and efficiency penalty for a "commercially distinct" post-combustion carbon capture plant.

Task 5 involves a base case and two sensitivity cases:

- The base case consists of a CCGT plus ICP configured for 90% carbon capture using an amine system as in WP6 Task 1, but where the CCGT is unaffected by the capture plant.

  The Task 1 unabated benchmark CCGT is used as the basis for the plant sizing, and performance results are compared against the Task 1 performance both unabated and with an integrated CCS plant.

  In this case the capture plant operates independently of the CCGT and is self-sufficient in steam and power, having its own GT/HRSG and a package steam boiler. No steam turbine is used. The ICP is configured to capture

90% of the CO_2 from the CCGT flue gas as well as its own GT/HRSG and steam boiler flue gas. The GT selected for the ICP is sized to satisfy the ICP parasitic power load.

Capital costs include for independent infrastructure costs (e.g. control room and other buildings). The capital cost of interconnections (flue gas) with the CCGT is included in the ICP cost. The duration and cost of CCGT downtime for ICP tie-ins is estimated. LCOE is calculated for the system as a whole (CCGT + ICP), which gives a comparison against the WP6 Task 1 unabated plant and integrated plant cases.

- The first sensitivity case investigates the effect of power import from the CCGT. The steam demand for the ICP is met with a package steam boiler. The ICP is configured to capture 90% of the CO_2 from the CCGT flue gas as well as its own steam boiler flue gas.

  The capital cost of connections with the CCGT (flue gas and electrical) is included in the ICP cost. The duration and cost of CCGT downtime for ICP tie-ins is estimated. LCOE is calculated for the system as a whole (CCGT + ICP), which gives a comparison against the other cases.

- The second sensitivity case investigates the effect of importing both power and steam from the CCGT. This is considered to represent a retrofit scenario, where the ICP is built next to an existing CCGT, making it distinct from the WP Task 1 integrated plant case which was considered new-build.

  In this case, no GT/HRSG or steam boiler is required in the ICP. The capital cost of interconnections with the CCGT (flue gas, electrical, steam and condensate) and modifications to the existing steam turbine required due to steam extraction for the ICP stripper is included in the ICP cost. The duration and cost of CCGT downtime for ICP tie-ins and steam turbine modification is estimated. LCOE is calculated for the system as a whole (CCGT + ICP), which gives a comparison against the other cases.

As far as practical, the same benchmark scale, technical basis, capex assumptions and capture rate (90%) as Task 1 are used. Performance data tables include a calculated value for carbon efficiency ($gCO_{2\ emitted}$ /kWh).

Technical Development

The updated WP1 CCGT case from Task 1 was used as the basis for technical development of a new benchmark for an alternative commercial CCGT model with an Independent Capture Plant (ICP) in Task 5.

The process simulation model was modified to make the CCGT and ICP operationally and commercially independent of each other, incorporating additional equipment to generate steam and power for the ICP as required.

The process model was used to generate a revised heat and material balance (at 100% load only) for each of the CCGT + ICP Cases. Utility requirements, specifically steam and power are taken into account in the overall process performance.

- Base Case – CCGT + ICP self-sufficient in power and steam
- Sensitivities:
  - ICP self-sufficient in steam, power from CCGT
  - ICP with steam and power from CCGT

Technical performance data for CCGT + ICP case have been generated for 90% capture of both CCGT & ICP emissions. A sized equipment list has been generated for the ICP as the basis of the revised capital cost estimate, although the equipment list for the core CCGT plant does not vary for Task 5.

Cost Estimate

Equipment factored capital cost estimates have been produced for each evaluation case, based on the sized equipment list. The estimates have been produced on a consistent basis with the WP1 cost estimate (UK£, 2009 Q1 basis, ±40% accuracy) and are presented as a breakdown of costs at a main unit / block level.

Operating cost estimates have been produced for each evaluation case based on the combination of technical definition and capital cost estimate.

ETI have provided assumed prices for imported electricity and cost of CCGT downtime as follows:

- Imported electricity = 6p/kWh (positioned between wholesale and large industrial user, towards wholesale)
- Downtime per day = £120k/d (sum of all fixed)

Techno-Economic Assessment Report

This Phase C Report documents the assumptions used and presents the technical and economic performance for the above cases, as compared with the Task 1 CCGT Benchmark cases both with and without capture, including:

- Process description and block level process flow scheme drawings;
- Heat and material balance for key streams at 100% load;
- Summary of scheme performance figures on a block-by-block level at 100% load including:
    - Overall gross and net power output figures;
    - Individual block power demand figures;
    - Overall CO_2 capture (quantity and capture level);
    - Overall thermal efficiency (LHV basis);
    - Feedstock composition and feed rate;
    - Utility summary;
    - Assumed entry conditions for CO_2 compression system.
- ±40% Equipment factored CAPEX estimate, including a breakdown of costs at a main unit / block level. Estimate basis Q1 2009 UK£;
- Operating cost estimate, including contribution of adsorbents, catalysts and chemicals costs, maintenance (factored from CAPEX), direct labour and general overheads.

The report includes a section on key assumptions and uncertainties, and includes comparisons between the Task 5 and Task 1 cases.

3. TASK 5 – INDEPENDENT CAPTURE PLANT

3.1 ICP Base Case

3.1.1 Introduction

The overall process scheme was based upon:

- A commercially separate CCGT power plant - assumed to be identical to the unabated reference plant from WP6 Task 1 - a natural gas fired combined cycle gas turbine (CCGT) using two Mitsubishi Heavy Industries (MHI) M701F5 gas turbines featuring dry low NOx (DLN) burners, each with downstream heat recovery steam generator (HRSG), and common single steam turbine generator (STG);
- An Independent Capture Plant (ICP) – a CO_2 capture unit and CO_2 compression and dehydration unit. Power demand for the ICP is met with a natural gas fired gas turbine (GT) using an Alstom GT11N2 50 Hz gas turbine, along with a small grid import. LP steam demands are met through recovering waste heat from the GT in a HRSG, supplemented by additional LP Steam generated in a package steam boiler. The CO_2 capture unit is designed to capture 90% of the CO_2 from the CCGT, internal GT and package steam boiler.

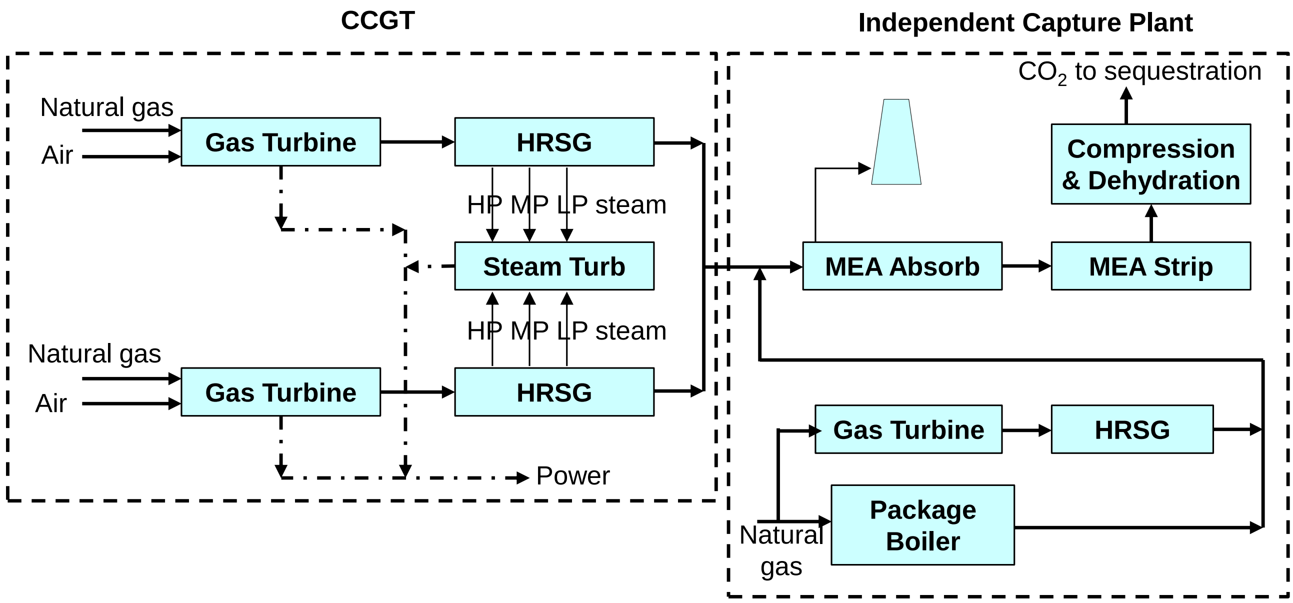


Figure 3-1 CCGT with Independent Capture Plant – Base Case

The natural gas feed rate for the GTs was set to ensure full utilisation of the gas turbines with the supporting and downstream equipment items sized to process the generated gas turbine exhaust gas and the package boiler flue gas. The process conditions, including stream flows, pressures, temperatures and compositions, were produced to reflect this sizing basis.

Key features of the configuration include:

- CCGT – comprising two parallel trains, each with one MHI M701F5 50 Hz gas turbine and one HRSG, connected to a single condensing steam turbine, using seawater cooling.
- Acid Gas Removal Unit – CO_2 removal scheme developed using in-house information on the basis of an MEA-based process such as Fluor Econamine FG+ CO_2 recovery technology.
- CO_2 Compression and Drying Units – dehydration and multi-stage compression to 150 barg.
- Internal power and steam generation – comprising a single Alstom GT11N2 50 Hz gas turbine and one HRSG producing LP steam only. Supplementary steam to satisfy the demand of the capture plant is generated in a package steam boiler.

The carbon capture scheme is configured with four trains of MEA absorption, three trains of stripping and two trains of CO_2 compression and drying. The absorption trains are sized based upon the maximum size of the absorption column in the region of 15m diameter (larger column diameters up to 20m have been suggested where the vessel can be constructed on-site). The number of stripping trains was selected based upon the heat input required for the stripper reboilers with a maximum total reboiler duty of approximately 150 MW_{th} per train (this is based upon 3 x 50 MW_{th} reboilers located around the column base). The number of CO_2 compression trains was selected based upon in-house knowledge of commercially available equipment and to keep a consistent order of compressor size with other benchmark cases (from WP1).

The lean/rich solvent exchanger, also known as the cross-over exchanger, is another very large and key equipment item in the post-combustion carbon capture scheme. This duty is most commonly met using a plate and frame type heat exchanger in the smaller scale plants currently in operation. A feature of this type of exchanger is its relative simplicity of scale up, achieved by adding frames and increasing the area of each frame. While it is unlikely that a heat exchanger of this type has yet been operated at the scale required for the benchmark cases, previous Amec Foster Wheeler work with technology providers has shown that the sizes envisaged in this study are not infeasible. This case was calculated to require 3 x 20167m^2 heat transfer surface area exchangers with a duty of 105MW each.

3.1.2 Process Description

<u>CCGT</u>

The CCGT in this case is assumed to be a commercially separate plant, identical to the unabated CCGT case in WP6 Task 1.

<u>ICP Internal Power & Steam</u>

The internal power island is based on a single Alstom GT11N2 50 Hz natural gas fed gas turbine, with its own heat recovery steam generator (HRSG) configured to generate superheated LP steam. Natural gas is received from across the plant battery limits via a metering station and fed to the GT.

The GT exhaust gases flow to the HRSG, with additional duct firing. The thermal energy of the exhaust gases is used to raise and superheat LP steam required for the stripper reboiler.

The coil sequence in the ICP HRSG is summarised as follows:

- LP Superheater
- LP Evaporator
- LP Economiser

The LP steam generated by the ICP HRSG is not sufficient to meet the stripper reboiler steam demand. Supplementary LP steam is generated using a gas-fired package boiler to meet the demand. Natural gas, received at the plant battery limits via a metering station, is fed to the package boiler.

Condensate from the stripper reboiler is deaerated using LP steam in the deaerator. BFW from the deaerator meets the requirement for both HRSG and package boiler.

The LP BFW pumps pump the BFW from the deaerator to approximately 600 kPa. Approximately 240 t/hr of BFW is routed to the package boiler whereas the rest passes through the LP Economiser and into the LP Steam Drum. Water from the LP Steam Drum passes through the LP Evaporator generating LP steam, which is returned to the LP Steam Drum before entering the LP Superheater. The superheated LP steam is then used to supply the heat required for the Stripper Reboiler in the Acid Gas Removal Unit (AGRU).

In the ICP case, the HRSG is producing only LP steam for the Stripper Reboiler. Condensate returned from the reboiler is at a temperature of 133°C, which limits the amount of heat that can be extracted from the flue gas. Thus, the flue gas leaves the HRSG at a temperature of 148°C. Note that this is significantly higher than for Task 1, where the flue gas exiting the HRSG was at approximately 93°C. In Task 1, condensate from the vacuum steam condenser is first heated from 25°C to 55°C using hot condensate before entering the final economiser stage in the HRSG. Due to the availability of such a low temperature stream, more heat extraction is possible from the flue gas in Task 1. There are no other lower temperature streams available that can be used to improve the efficiency of the ICP HRSG economiser.

CO_2 Removal

The flue gases from the CCGT HRSG, ICP GT/HRSG and package boiler are at near atmospheric pressure; hence requiring pressure boosting using blowers to overcome the pressure drop in the direct contact cooler (DCC) and absorption column in the capture plant. Four blowers have been used in total; two physically located in the CCGT boundary to raise the pressure of the HRSG flue gas, whereas two blowers are within the ICP boundary, servicing the ICP GT/HRSG and package boiler flue gas respectively. The energy demand and the cost of all four blowers are considered to be part of the ICP parasitic demand and cost as they are only needed to overcome the pressure drop of the independent capture plant.

The flue gas streams from the four blowers are combined to form a single stream at approximately 130°C and 1.25 bara before it passes through the four train recuperative gas-gas exchangers. To keep the flue gas temperature from the gas-gas exchanger to the DCC column the same as in the Task 1 integrated case (82°C), the decarbonised exhaust gas leaves the exchanger at 93°C. This results in a higher energy loss through the stack, compared to the Task 1 integrated case, where the exhaust gas to the stack is at 80°C. The hot inlet flue gas increases the duty and the size of the gas-gas exchangers in the ICP plant.

Note that if the exhaust flue gas was kept at the same temperature as in Task 1 (80°C), then the flue gas to the DCC column would be hotter (96°C) which would increase the load to the DCC cooling system in order to maintain the required inlet temperature to the absorber column at 50°C.

In the DCC column, much of the water present in the flue gas stream condenses as the gas is cooled to approximately 50°C. The condensate is recirculated through a cooler and returned to the contact tower. A small quantity of sodium hydroxide is added to the recirculating water in order to ensure that the remaining SO_2 in the flue gas is removed to meet the <10 ppm specification to prevent excessive solvent losses.

The flue gas entering the DCC has a higher water vapour content compared to Task 1 integrated case, so less heat is removed through vaporisation into the flue gas and more heat must be removed into the cooling water through the circulating water stream, increasing the size of piping / equipment in this loop. The larger gas-gas exchanger and DCC have a significant impact on the CAPEX of the ICP section.

In the lower portion of the absorption column the flue gas is contacted with semi-lean and then lean amine which absorbs approximately 90% of the CO_2 content of the flue gas. This section also incorporates an extraction and cooling loop in order to ensure cooler conditions which are more favourable to CO_2 absorption. In the top of the column the flue gas is washed with water to prevent solvent losses to the atmosphere.

The CO_2-rich solvent stream exits the bottom of the absorber column and is pumped to approximately 5 bara. The stream is then split, with approximately 25% of the flow passing through two stages of heating against warmer solvent streams before being flashed at a pressure of 1.3 bara. The semi lean solvent from the flash drum is then cooled against rich solvent and returned to the absorption column with the cooled extracted solvent. The remaining rich solvent is heated against lean solvent in the cross-over exchanger and introduced to the stripper column.

In the stripper column the CO_2 desorbs from the rich solvent as it is heated producing a stream of hot lean solvent from the bottom of the stripper. This lean solvent is cooled against rich solvent and returned to the absorption column. The stripper overheads are cooled to 30°C, condensing a significant quantity of water, some of which is returned to the stripper as reflux with the rest being sent to treatment or recovery.

<u>CO_2 Compression and Drying</u>

The acid gas resulting from the semi lean amine flash is compressed in the first of eight compression stages, after which it is cooled and passed through a knock out drum. After the first compression stage the main CO_2 stream from the stripper column is added to the flashed acid gas stream for all the subsequent compression steps. Between each of the first four steps is a cooler and knock out drum, and the CO_2 is compressed up to a pressure of 25 bara.

The CO_2 is then dried by molecular sieve adsorption to reach the specification of <50 ppmv moisture. Two dehydration vessels are required since one bed will be in use whilst the second bed will be in regeneration. The regeneration cycle uses a slipstream of dried gas exiting the operating molecular sieve bed. The gas is heated using the returning regeneration gas exiting the molecular sieve bed in regeneration. It is further heated under temperature control in an electric heater before entering the bed in a counter flow direction. The wet gas leaving the bed is cooled against incoming gas, any condensed water is separated in a knock out drum before it is passed through a fines filter and returned upstream of the 3rd stage compressor.

The absorbent regeneration process takes several hours. When complete the heater is bypassed and the bed is cooled down over several hours before return to operation.

The final three compression stages include intercoolers and an aftercooler and result in a final CO_2 product at specification of 150 barg and 30°C.

Balance of Plant

The key balance of plant requirements for this scheme are the cooling water supply systems. The DCC, CO_2 removal unit and CO_2 compression and drying units require a significant quantity of cooling medium. Where this cannot be supplied using heat integration within or between the process units, cooling water is required. This cooling water is supplied as fresh cooling water in a closed circuit. The fresh water system is cooled against sea water.

Facilities are also required for storage and make-up of the MEA based solvent to the CO_2 removal system. Reuse and treatment of the numerous, mainly small water streams produced from the cooling of water-saturated gas streams are integrated with the units where possible. Streams containing contaminants such as MEA are routed to an effluent treatment system.

3.1.3 Plant Performance

The plant performance for this case was assessed at 100% load, as summarised in the table below:

Table 3-1 Performance Figures for CCGT with ICP Base Case

		100% Load
Power		
CCGT gross installed capacity	MWe	1068.0
Gas Turbine (s)	MWe	739.0
Steam Turbine	MWe	328.9
Others	MWe	0.0
CCGT auxiliary loads	MWe	22.4
CCGT Power Island	MWe	15.6
Others	MWe	6.8
CCGT Net Power Export	MWe	1045.6
ICP Gross Power	MWe	112.7
Gas Turbine	MWe	112.7
Power Import from Grid	MWe	2.0
ICP auxiliary loads	MWe	114.7
ICP GT	MWe	1.8
Flue Gas Blower	MWe	52.5
Acid Gas Removal/DCC	MWe	3.9
CO_2 compression	MWe	43.7
Others	MWe	12.9
CCGT+ICP Net Power Export	MWe	1043.5
Net Efficiency (LHV)	%	42.4
Heat Rate	kJ/kWh	8485.8
Flows		
Total fuel feed rate	tpd	4478.7
Water consumption	tpd	367.0
Cooling water (once through)	tpd	2,954,572
Carbon Balance		
Total carbon in feeds	tpd	3293.4
Total carbon captured	tpd	2969.6
Carbon capture rate	%	90.2
Total CO_2 captured	tpd	10882.0
Total CO_2 emitted	tpd	1186.6
CO_2 emissions	g CO_2/kWh_{Net}	47.4

3.1.4 Capital Cost, Operating Cost and Economics

The economic results are outlined in the table below:

Table 3-2 Economic Figures for CCGT with ICP Base Case

		100% Load
Total CAPEX	GB£M	1345.1
CCGT Power Island	GB£M	474.5
CCGT U&O	GB£M	73.0
ICP Power Block	GB£M	131.6
ICP Tie-ins	GB£M	10.0
ICP Acid Gas Removal	GB£M	467.0
CO_2 compression	GB£M	76.2
ICP U&O	GB£M	112.7
CAPEX efficiency	GB£/kW_{Net}	1289.0
Total OPEX – incl. fuel	GB£M p.a.	428.3
Total OPEX – excl. fuel	GB£M p.a.	60.1
OPEX – incl. fuel	GB£ p.a. / kW_{Net}	410.4
OPEX – excl. fuel	GB£ p.a. / kW_{Net}	57.6
Levelised Cost of Electricity		
CO_2 emission cost = £0 / te CO_2	£ / MWh_{Net}	78.7
CO_2 emission cost = £20 / te CO_2	£ / MWh_{Net}	79.6
CO_2 emission cost = £40 / te CO_2	£ / MWh_{Net}	80.5
CO_2 emission cost = £60 / te CO_2	£ / MWh_{Net}	81.5
Cost of CO_2 Captured		
CO_2 emission cost = £ 0 / te CO_2	£ / te CO_2	71.3
Cost of CO_2 Avoided		
CO_2 emission cost = £ 0 / te CO_2	£ / te CO_2	102.3

3.1.5 Key Features, Assumptions and Uncertainties

Many features and assumptions have already been discussed in the preceding sections; hence are only briefly summarised below:

- ICP and CCGT are assumed to be 100m apart.
- Only connection between two independent plants is the flue gas ducting.
- Grid connections required to import approximately 2 MW power to the ICP.
- ICP Gas Turbine and HRSG with duct firing has been modelled using GT-PRO software. Alstom GT11N2 50 Hz natural gas fed gas turbine performance data generated by the model has been compared with the GTW 2013 performance data. Both data are in good agreement.
- Duct firing has been included to boost the steam production. Flue gas temperature within HRSG after duct firing is assumed to be 820°C which is limited by the material of construction of HRSG.
- ICP HRSG pressure drop is assumed to be as same as CCGT HRSG which is 0.02 bar.
- Polytropic efficiency of the flue gas blower is assumed to be 85%.
- Motor efficiencies for blowers, pumps and compressors are all assumed to be 95%.
- BFW make-up in the ICP is assumed to be 1% of the total water circulation rate.

- Typical figures for pressure drop have been assumed throughout the scheme in order to arrive at a reasonable pressure profile in the absence of specifics such as plot layout and elevations.

To install the flue gas duct between the two independent plants, CCGT plant needs to be shut down for a certain period of time. Advice from the construction and maintenance experts within Amec Foster Wheeler on the timescale requirement have been summarised below:

- CCGT shutdown for general maintenance: 14 days every 2 years for minor inspection
- Flue gas ducting and necessary support structure between two commercially independent plant boundaries can be installed within the schedule shutdown period of 2 weeks.

From the above information, it can be assumed that no extra CCGT down time is required for the flue gas ducting installation for the ICP Base Case scenario.

3.2 ICP Sensitivity Case 1 – Imported Power

3.2.1 Introduction

The overall process scheme was based upon:

- A commercially separate CCGT power plant – as described in Section 3.1.1.
- An Independent Capture Plant (ICP) – a CO_2 capture unit and CO_2 compression and dehydration unit. Power demand for the ICP is imported from the CCGT plant. LP steam demands are met by package steam boiler. The CO_2 capture unit is designed to capture 90% of the CO_2 from the CCGT and package steam boiler flue gas.

Key features of the configuration described in the Section 3.1.1 are true for this case as well.

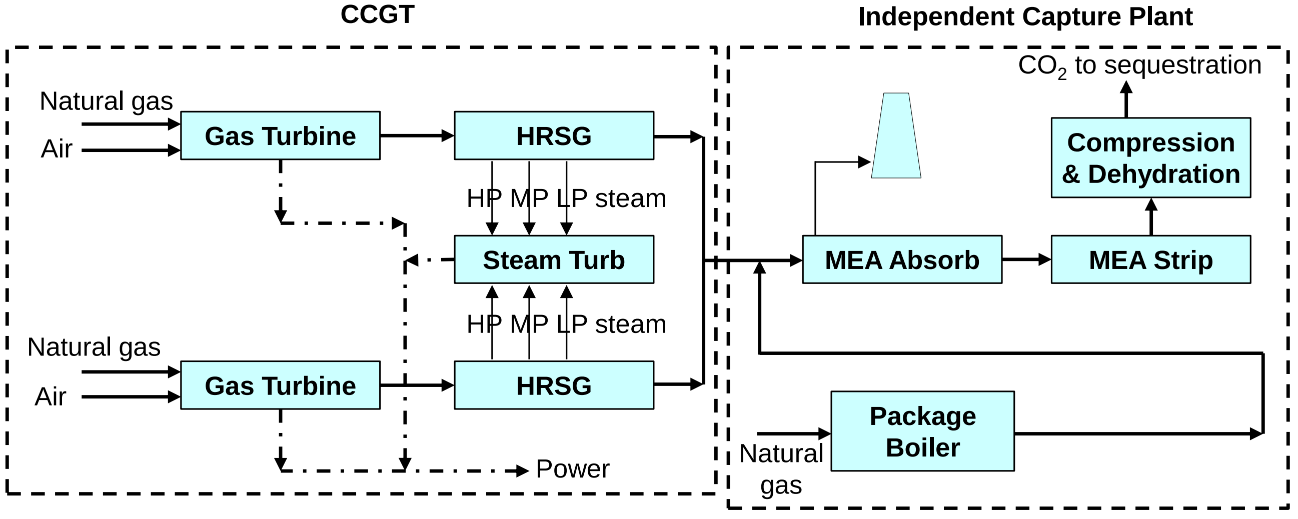


Figure 3-2 CCGT with Independent Capture Plant – Sensitivity Case 1

3.2.2 Process Description

The process description of this scheme is similar to Section 3.1.2 apart from that the internal power island comprised with Alstom GT with HRSG is not required for this case.

The package boiler in this sensitivity case is sized for the total steam demand required for stripping the CO_2 from the solvent.

3.2.3 Plant Performance

The plant performance for this case was assessed at 100% load, as summarised in the table below:

Table 3-3 Performance Figures for CCGT with ICP Sensitivity Case 1 (imported power from CCGT)

Power		**100% Load**
CCGT gross installed capacity	MWe	1068.0
Gas Turbine (s)	MWe	739.0
Steam Turbine	MWe	328.9
Others	MWe	0.0
CCGT auxiliary loads	MWe	22.4
CCGT Power Island	MWe	15.6
Others	MWe	6.8
CCGT Net Power Export	MWe	1045.6
ICP Gross Power	MWe	0.0
Gas Turbine	MWe	0.0
Power Import from Grid	MWe	0.0
ICP auxiliary loads	MWe	98.7
ICP GT	MWe	0.0
Flue Gas Blower	MWe	43.1
Acid Gas Removal/DCC	MWe	3.7
CO_2 compression	MWe	39.8
Others	MWe	12.2
CCGT+ICP Net Power Export	MWe	946.9
Net Efficiency (LHV)	%	42.2
Heat Rate	kJ/kWh	8523.9
Flows		
Total fuel feed rate	tpd	4082.4
Flue gas to Capture Plant	t/hr	5777.3
Water consumption	tpd	350
Cooling water (once through)	tpd	2825568
Carbon Balance		
Total carbon in feeds	tpd	3002.0
Total carbon captured	tpd	2709.3
Carbon capture rate	%	90.2
Total CO_2 captured	tpd	9928.1
Total CO_2 emitted	tpd	1072.7
CO_2 emissions	g CO_2/kWh$_{Net}$	47.2

3.2.4 Capital Cost, Operating Cost and Economics

The economic results are outlined in the table below:

Table 3-4 Economic Figures for CCGT with ICP Sensitivity Case 1

		100% Load
Total CAPEX	GB£M	1178.8
CCGT Power Island	GB£M	474.5
CCGT U&O	GB£M	73.0
ICP Power Block	GB£M	51.8
ICP Tie-ins	GB£M	13.4
ICP Acid Gas Removal	GB£M	405.5
CO_2 compression	GB£M	71.6
ICP U&O	GB£M	88.9
CAPEX efficiency	GB£/kW$_{Net}$	1244.9
Total OPEX – incl. fuel	GB£M p.a.	388.9
Total OPEX – excl. fuel	GB£M p.a.	53.3
OPEX – incl. fuel	GB£ p.a. / kW$_{Net}$	410.7
OPEX – excl. fuel	GB£ p.a. / kW$_{Net}$	56.3
Levelised Cost of Electricity		
CO_2 emission cost = £0 / te CO_2	£ / MWh$_{Net}$	77.8
CO_2 emission cost = £20 / te CO_2	£ / MWh$_{Net}$	78.7
CO_2 emission cost = £40 / te CO_2	£ / MWh$_{Net}$	79.7
CO_2 emission cost = £60 / te CO_2	£ / MWh$_{Net}$	80.6
Cost of CO_2 Captured		
CO_2 emission cost = £ 0 / te CO_2	£ / te CO_2	69.0
Cost of CO_2 Avoided		
CO_2 emission cost = £ 0 / te CO_2	£ / te CO_2	99.3

3.2.5 Key Assumptions and Uncertainties

As power required for the ICP is imported from the CCGT plant, the Alstom GT which was used to generate power for the ICP Base Case is not required for this sensitivity case. No grid power import is required for this case.

An electrical tie-in is required between the two independent plants to import power from the CCGT. According to the electrical experts within Amec Foster Wheeler, electrical tie-ins can be installed within the CCGT scheduled shutdown period of 2 weeks. Therefore, it can be concluded that no extra CCGT down time is required for both flue gas ducting and electrical tie-in installation for the ICP Sensitivity Case 1.

The steam required for the stripper units is generated using a package steam boiler within the ICP. All other assumptions (apart from the Alstom GT/HRSG and grid power) reported in Section 3.1.5, along with the timeframe requirement for the flue gas duct installation, is true for this case as well.

3.3 ICP Sensitivity Case 2 – Imported Steam & Power

3.3.1 Introduction

The overall process scheme was based upon:

- A commercially separate CCGT power plant – as described in the Section 3.1.1.
- An Independent Capture Plant (ICP) – a CO_2 capture unit and CO_2 compression and dehydration unit. Power demand for the ICP is imported from the CCGT plant. LP steam demands for the stripper unit are also met by LP steam imported from the CCGT plant. The CO_2 capture unit is designed to capture 90% of the CO_2 from the CCGT flue gas.

This case is considered to represent a retrofit scenario, where the ICP is built next to an existing CCGT, making it distinct from the WP Task 1 integrated plant case which was considered new-build.

Key features of the configuration described in the Section 3.1.1 are true for this case as well.

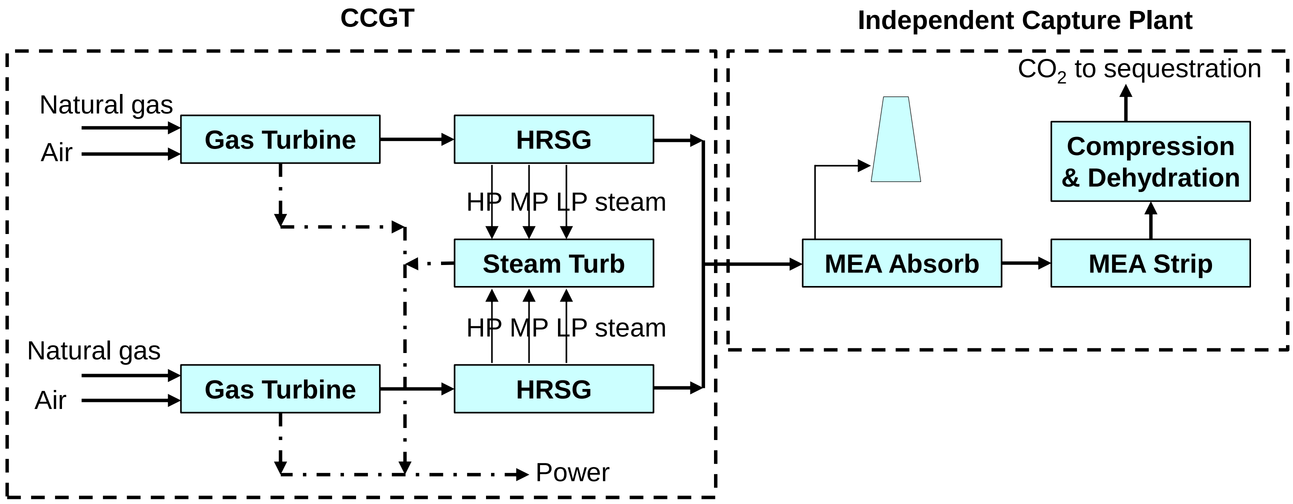


Figure 3-3 CCGT with Independent Capture Plant – Sensitivity Case 2

3.3.2 Process Description

The process description of this scheme is similar to Section 3.1.2 apart from that the internal power island, comprised of the Alstom GT with HRSG, and also the package boiler are not required for this case.

3.3.3 Plant Performance

The plant performance for this case was assessed at 100% load, as summarised in the table below:

Table 3-5 Performance Figures for CCGT with ICP Sensitivity Case 2 (imported power and steam from CCGT)

		100% Load
Power		
CCGT gross installed capacity	MWe	968.0
Gas Turbine (s)	MWe	739.0
Steam Turbine	MWe	228.9
Others	MWe	0.0
CCGT auxiliary loads	MWe	20.0
CCGT Power Island	MWe	13.2
Others	MWe	6.8
CCGT Net Power Export	MWe	947.9
ICP Gross Power	MWe	0.0
Gas Turbine	MWe	0.0
Power Import from Grid	MWe	0.0
ICP auxiliary loads	MWe	81.2
ICP GT	MWe	0.0
Flue Gas Blower	MWe	37.2
Acid Gas Removal/DCC	MWe	2.8
CO_2 compression	MWe	31.7
Others	MWe	6.5
CCGT+ICP Net Power Export	MWe	869.6
Net Efficiency (LHV)	%	48.5
Heat Rate	kJ/kWh	7421.0
Flows		
Total fuel feed rate	tpd	3264.1
Flue gas to capture plant	t/hr	5127.4
Water consumption	tpd	204
Cooling water (once through)	tpd	2455128
Carbon Balance		
Total carbon in feeds	tpd	2400.3
Total carbon captured	tpd	2159.4
Carbon capture rate	%	90.0
Total CO_2 captured	tpd	7913.0
Total CO_2 emitted	tpd	882.6
CO_2 emissions	g CO_2/kWh_{Net}	42.3

3.3.4 Capital Cost, Operating Cost and Economics

The economic results are outlined in the table below:

Table 3-6 Economic Figures for CCGT with ICP Sensitivity Case 2

		100% Load
Total CAPEX	GB£M	1013.6
CCGT Power Island	GB£M	474.5
CCGT U&O	GB£M	73.0
ICP Power Block	GB£M	0.0
ICP Tie-ins	GB£M	16.5
ICP Acid Gas Removal	GB£M	322.9
CO_2 compression	GB£M	61.5
ICP U&O	GB£M	65.1
CAPEX efficiency	GB£/kW_{Net}	1169
Total OPEX – incl. fuel	GB£M p.a.	315.1
Total OPEX – excl. fuel	GB£M p.a.	46.8
OPEX – incl. fuel	GB£ p.a. / kW_{Net}	363.6
OPEX – excl. fuel	GB£ p.a. / kW_{Net}	54.0
Levelised Cost of Electricity CO_2 emission cost = £0 / te CO_2 CO_2 emission cost = £20 / te CO_2 CO_2 emission cost = £40 / te CO_2 CO_2 emission cost = £60 / te CO_2	 £ / MWh_{Net} £ / MWh_{Net} £ / MWh_{Net} £ / MWh_{Net}	 70.1 71.0 71.8 72.7
Cost of CO_2 Captured CO_2 emission cost = £ 0 / te CO_2	 £ / te CO_2	 59.1
Cost of CO_2 Avoided CO_2 emission cost = £ 0 / te CO_2	 £ / te CO_2	 72.9

3.3.5 Key Assumptions and Uncertainties

Both power and steam required for the ICP are imported from the CCGT plant for this case. Therefore, the Alstom GT with HRSG and package boiler needed for the base case is not required for this sensitivity case. All other assumptions reported in Section 3.1.5 are true for this case.

As mentioned before, this case represents a retrofit scenario, where the ICP is built next to an existing CCGT, being integrated to import power and steam from the CCGT. Electrical and steam tie-ins are required between the two independent plants along with the flue gas ducting.

The CCGT HRSG has been highly integrated to generate three steam levels (HP/MP/LP) to maximise power generation using a steam turbine. The existing steam turbine in the CCGT plant is a non-extracting condensing turbine utilising all steam produced by the HRSG to generate power. For this sensitivity case, the low pressure (LP) steam required for the capture plant is approximately 495 t/h, which will be supplied by the HRSG/steam turbine of the CCGT. Hence, the existing steam turbine in the CCGT needs to be either replaced by an extracting steam turbine or modified to extract LP steam required from the MP-LP interconnection.

Experts on rotating equipment within Amec Foster Wheeler advise that the existing steam turbine can be modified to extract the required LP steam.

- The extraction turbine will always require a minimum flow to the turbine exhaust. This flow is used to carry away heat from the windage losses generated by the turbine's post extraction stages. Cooling steam will typically not be less than 10% of design flow.

- Extraction of 495 t/h of LP steam for this sensitivity case corresponds to ~70% LP steam between MP and LP section of the turbine; 30% LP steam will flow to LP turbine to generate power.
- Therefore, the LP section can potentially run with this 30% throughput without any need of changing the LP section of the turbine (assuming the steam turbine has a split casing setup which is a feature of most large steam turbines).

Amec Foster Wheeler contacted steam turbine vendors to understand the turbine functionality and also to support the above findings.

Siemens were very helpful and offered their expert opinion on the steam turbine configuration. The suggestions and advice received from Siemens are summarised below:

- This high amount of steam can only be extracted in the case where a control device in front of the LP-turbine is available, i.e. extraction control flaps in the overcross pipe to the LP-turbine.
- A pipe connection of 2x DN900 (2x 36 inch NPS) is required to extract approximately 500t/h of LP steam of 4 bara.
- LP-turbine will then run in throttle mode operation.
- Therefore, it should in principle be possible to extract steam from the existing LP-turbine.
- The erosion may be a little bit higher due to lower steam flow through the LP section; that shouldn't be an issue due to reheat application.
- A change of the LP-turbine blade design might be beneficial for reducing the throttle losses in the expansion section.

The statement from Siemens clearly supports the advice provided by the in-house experts. Therefore, it is considered that the existing steam turbine within CCGT can be modified to an extracting steam turbine which can run with low throughput of LP steam.

It can be noted that the steam turbine design for this case does not consider any efficiency reduction of the LP turbine due to steam extraction. However, in reality the efficiency of the LP section of the non-extracting steam turbine will drop due to LP steam extraction which in turn will reduce the overall power output from the steam turbine. Significant vendor input would be required to understand the efficiency change and this has not been quantified for this report.

To install the steam extraction pipe, condensate return pipe to steam condenser and electrical / steam / condensate / flue gas tie-ins between the two independent plants, the CCGT plant needs to be shut down for a certain timeframe. These modifications and installations could be done partly during the scheduled CCGT shutdown period to avoid extensive down time of the CCGT and losing valuable exportable power.

It has been discussed in previous sections that flue gas ducting and electrical tie-ins can be installed within the scheduled shutdown of 2 weeks of the CCGT plant. Advice from electrical and steam turbine experts within Amec Foster Wheeler clearly states that further shutdown time on top of the scheduled shutdown would be necessary for steam turbine modifications for this case.

- Steam and condensate tie-ins between two commercially independent plants boundary can be installed within the schedule shutdown period of 2 weeks.
- Time required to install the steam extraction line and setup the control system to modify the existing steam turbine: approximately 4 weeks.
- LP turbine blade design change is an internal change to the turbine section and potentially might require further extension of the shutdown period. This modification has not been considered in this study.
- Therefore, it is considered that 2 weeks CCGT downtime would be necessary for steam turbine modification/extraction line on top of 2 weeks normal shutdown.

4. EVALUATION BASES

4.1 Technical Evaluation Basis

The Basis of Design document given in Attachment 1 has been used as the technical basis on which each option has been evaluated, including:

- plant location;
- site conditions;
- plant capacity;
- plant (climatic) operating conditions;
- feedstock, product and utility availability and specifications; and
- environmental emissions basis.

CO_2 Capture Rate

Each carbon dioxide abated case will be designed to achieve a target carbon capture level of at least 90%, defined as:

$$CO_2 \text{ Capture Rate (\%)} = \frac{100 \text{ x Moles carbon contained in the } CO_2 \text{ product}}{\text{Moles carbon contained in the natural gas feed}}$$

4.2 Capital Cost Estimating Basis

Introduction

The estimates contained within this study report have been based on the technical definition for each of the benchmark cases considered. The estimate methodology is largely based on in-house data, available from previous work undertaken by Amec Foster Wheeler for similar plants.

For all of the cases reported the source estimate data has been adjusted to provide figures on a consistent and comparable 1st quarter 2009 (1Q2009) UK Basis.

Estimates prepared using this methodology and associated qualifications/exclusions are normally considered to have an accuracy of +/-40%.

Currency

The estimates are reported in GB Pounds (GB£).

When in-house data is available in a different currency, the following currency conversion rates have been used for conversion:

Base Currency	Exchange Rate
GB£ 1	US$ 1.53
GB£ 1	€ 1.12

Basis

Equipment estimates are developed using Amec Foster Wheeler's indexed Aspentech Capital Cost Estimator (ACCE) estimating programme and in-house data for more complex specialist equipment.

All other costs, including bulks associated with the project are factored from the equipment costs.

No site specific costs have been included. Consistent with the Basis of Design, the site has been assumed to be a generic site clear and level and free from underground obstructions. These estimates reflect a 1Q2009 UK site basis with no allowance for future escalation.

Format

The Work Breakdown Structure (WBS) used for the estimates is as follows:

- CCGT Power Block
- CCGT Utilities & Offsites
- ICP Acid Gas Removal Unit
- ICP Power Block
- ICP Tie-ins
- ICP Utilities & Offsites
- ICP CO_2 Compression and Dehydration

The ICP Utilities & Offsites area includes the following major items, as appropriate:

- Interconnecting piping
- Electrical Switchgear/Transformers
- 275 kV cables to new switchyard
- DCS system
- Seawater Intake/Pumping/Outfall System
- Demineralised Water system
- BFW Chemical Injection
- Condensate Polishing Package
- Water treatment
- Cooling water
- Flare Package
- N_2 Package
- Instrument/Utility Air Package
- Firefighting system

Major Equipment

The majority of equipment item costs have been generated using the ACCE estimating program indexed to reflect Amec Foster Wheeler's experience of market conditions.

For some specialised major equipment items not covered by the ACCE database, costs have been based on in-house data and published cost data from licensors.

The supplier/licensor budget prices received for previous works carried out by Amec Foster Wheeler mainly include the following units/equipment:

- Dehydration Package;
- CCGT Power Island including the following
    - HRSG
    - Steam Turbine
    - Gas Turbine
- ICP Power Island including the following
    - Package Boiler

Gas Turbine World cost data has been used for the estimation purpose of the following items

- Alstom Gas Turbine in ICP
- HRSG in ICP

Direct Bulk Materials

The estimated material costs reflect worldwide procurement, therefore no allowance for possible savings by local purchasing of direct materials and associated reductions in shipping costs have been made.

The bulk material costs have been factored from the major equipment costs using factors derived from a more detailed study for a very similar plant. These costs include the following:

- Piping
- Instruments
- Electricals
- Catalysts & Chemicals

Direct Material & Labour Contracts

Costs are allowed based on factors derived from earlier similar projects. Costs include the following:

- Tankage
- Civil, Steelwork & Buildings
- Protective cover

Labour only contracts

Costs are allowed based on factors derived from earlier similar projects. Costs include the following.

- Equipment erection
- Piping Fabrication & Erection
- E&I Installation
- Scaffolding
- Pre-commissioning trade labour assistance

Indirect Costs

Costs are allowed based on factors derived from earlier similar projects. Costs include the following.

- Temporary facilities
- Heavy Lifts
- Commissioning
- Vendor's engineers

EPC Contracts

Costs are allowed based on factors derived from earlier similar projects. Costs include the following.

- Engineering services (including FEED engineering)
- Construction Management

CCGT Downtime information specified by ETI

- CCGT Downtime per day = £120k/d (sum of all fixed)

Escalation

The estimates have been escalated depending on the date of the reference project, based on Amec Foster Wheeler experience. No allowance has been made for future escalation.

Land Costs

Land costs have been included as specified by ETI at a rate of 5% of the total installed costs for all cases

Owner's Costs

Owner's costs have been included as specified by ETI at a rate of 10% of the total installed costs for all cases.

Contingency

Contingency has been included as specified by ETI at a rate of 25% of the total installed costs for all cases.

Exclusions

The following costs have been specifically excluded from the capital cost estimates:

- Import Duties;
- Capital / Insurance Spares;
- Financing;
- Royalties & Process Guarantees;
- Piling;
- Removal of unseen/unidentified underground obstructions;
- Operating costs (which are covered separately);
- Statutory Authority & Utility Company costs & permits;
- Currency Fluctuations;
- PMC Costs;
- Contractors Fees;
- Contractors All Risk Insurance;
- Taxes;
- Metal pricing movements.

4.3 Operating and Maintenance Cost Estimating Basis

Introduction

Operating and Maintenance (O&M) costs include the following:

- Chemicals;
- Catalyst;
- Solvents;
- Direct labour;
- Maintenance;
- Administration and General Overheads.

O&M costs are generally allocated as variable and fixed costs. Variable operating costs are directly proportional to the amount of kilowatt-hours produced and are referred to as incremental costs. They may be expressed in £/kWh. Fixed operating costs are essentially independent of the quantity of kilowatt-hours produced. They may be expressed in £/h or £/year.

4.3.1 Variable Costs

The variable costs include the consumption of catalysts, chemicals and solvents. These costs are annual, based on the expected equivalent availability of the plant. The variable costs mainly include the following:

- Fuel (natural gas);

  A natural gas price of £265/t has been assumed.

- Default import electricity price = 6p/kWh (positioned between wholesale and large industrial user, towards wholesale)
- Solvent (MEA) consumption within the Acid Gas Removal Unit;
- Chemicals for water/steam treatment and waste water treatment; and
- Waste disposal.

CO_2 Emissions Costs

In addition, any costs associated with CO_2 emissions will impact the operating costs of the facility. LCOE has been calculated for each case using emissions costs of £0/te, £20/te, £40/te and £60/te.

4.3.2 Fixed Costs

The fixed costs mainly include the following:

- Direct labour;
- Administration and general overheads;
- Maintenance.

Direct Labour

The yearly cost of the direct labour has been calculated assuming an average cost equal to £50,000 / year for each individual. The number of personnel engaged for the CCGT has been evaluated on the basis of the following tables.

Table 4-1– Personnel of Combined Cycle Gas Turbine plants

Operation	**Total**	**Notes**
Area Responsible	1	daily position
Assistant Area Responsible	1	daily position
Electrical Assistant	5	1 shift position
Shift Supervisor	5	1 shift position
Control Room Operator	10	2 shift position
Field Operator	10	2 shift position
Subtotal	**32**	
Maintenance		
Mechanical group	3	daily position
Instrument group	3	daily position
Electrical group	2	daily position
Subtotal	**8**	
Laboratory		
Superintendent + Analysts	**4**	daily position
Total	**40**	

It has been assumed that the number of personnel required for the independent capture plant is similar to the CCGT plant. Hence, the total number of personnel requirement for the overall plant i.e. Combined Cycle Gas Turbine plants with independent post-combustion CO_2 capture plant has been considered as 80.

Administration and General Overheads

These costs include all other Company services not directly involved in the operation of the Complex, such as:

- Management;
- Personnel services;
- Technical services;
- Clerical staff.

These services vary widely from company to company and are also dependent on the type and complexity of the operation.

Based on EPRI, Technical Assessment Guide for the Power Industry, an amount equal to 30% of the direct labour cost has been considered.

Maintenance

A precise evaluation of the cost of maintenance would require a breakdown of the costs amongst the numerous components and packages of the Complex.

Since these costs are all strongly dependent on the type of equipment selected and statistical maintenance data provided by the selected Supplier, this type of evaluation of the maintenance cost is premature at this stage of the study.

For this reason, the annual maintenance cost of the Complex has been estimated as a percentage of the installed capital cost of the facilities.

Different percentage factors have been applied to the different units, based on the following criteria:

- 2.5% for gaseous and liquid handling units;
- 1.7% for utilities and offsites;
- 5.0% for the Power Island (to take into account the gas turbine maintenance cost based on the assumption of a Long Term Service Agreement with the selected gas turbine manufacturer).

4.4 Economic Basis

For the purposes of economic modelling and calculation of the Levelised Cost of Electricity (LCOE), the following assumptions have been made for all cases.

- A plant availability of 85% has been assumed, which equates to an on-stream time of 7446 hr per year. A reduced availability has been taken into account for year 1 (65%) and year 2 (75%).
- Combined costs of insurance and local taxes have been assumed at 2% of the Total Installed Cost.
- Capital Expenditure has been assumed to be spread over a three year period in the following spread:
    - Year -3 = 25%
    - Year -2 = 45%
    - Year -1 = 30%
- A discount rate of 10% has been assumed.
- A project life of 20 years has been assumed.
- All costs associated with transport and storage of CO_2 has been assumed to be outside of the scope of the calculated LCOE.

CO_2 Emissions Costs

In addition, any costs associated with CO_2 emissions will impact the economics of the facility. LCOE has been calculated for each case using emissions costs of £0/te, £20/te, £40/te and £60/te.

5. ASSESSMENT OF THE EFFECT OF INDEPENDENT CAPTURE PLANT

5.1 Plant Performance

Overall plant performance data for the ICP Base Case and two sensitivity cases along with the WP6 Task 1 benchmark cases are shown in the following table.

Table 5-1 Comparison of Performance Figures between Task 1 and CCGT with ICP

		Benchmark Task 1	Benchmark Task 1	ICP Base Case	ICP Sensitivity Case 1	ICP Sensitivity Case 2
		0% CCS	90% CCS	90% CCS	90% CCS	90% CCS
		100% Load	100% Load	100% Load	100% Load	100% Load
Power						
CCGT gross installed capacity	MWe	1068.0	967.9	1068.0	1068.0	967.9
Gas Turbine (s)	MWe	739.0	739.0	739.0	739.0	739.0
Steam Turbine	MWe	328.9	228.9	328.9	328.9	228.9
Others	MWe	0.0	0.0	0.0	0.0	0.0
CCGT auxiliary loads	MWe	22.4	20.0	22.4	22.4	20.0
CCGT Power Island	MWe	15.6	13.2	15.6	15.6	13.2
Others	MWe	6.8	6.8	6.8	6.8	6.8
CCGT Net Power Export	MWe	1045.6	947.9	1045.6	1045.6	947.9
ICP Gross Power	MWe	0.0	0.0	112.7	0.0	0.0
Gas Turbine	MWe	0.0	0.0	112.7	0.0	0.0
Power Import from Grid	MWe	0.0	0.0	2.0	0.0	0.0
Capture Plant auxiliary loads	MWe	0.0	77.1	114.7	98.7	81.2
ICP GT	MWe	0.0	0.0	1.8	0.0	0.0
Flue Gas Blower	MWe	0.0	37.2	52.5	43.1	37.2
Acid Gas Removal/DCC	MWe	0.0	2.8	3.9	3.7	2.8
CO_2 compression	MWe	0.0	31.7	43.7	39.8	31.7
Others	MWe	0.0	5.3	12.9	12.2	6.5
CCGT+ICP Net Power Export	MWe	1045.6	870.8	1043.5	946.9	869.6
Plant Net Efficiency (LHV)	%	58.3	48.6	42.4	42.2	48.5
Heat Rate	kJ/kWh	6172.1	7410.6	8485.8	8523.9	7421.0
CC Energy Penalty	%	-	9.7	15.9	16.1	9.8
Flows						
Total fuel feed rate	tpd	3264.1	3264.1	4478.7	4082.4	3264.1
Flue gas to the Capture Plant	t/hr	-	5127.1	6838.6	5777.3	5127.4
Water consumption	tpd	204	204	367.0	350	204
Cooling water (once through)	tpd	1,219,104	1,851,274	2,954,572	2,825,568	2,455,128
Carbon Balance						
Total carbon in feeds	tpd	2400.3	2400.3	3293.4	3002.0	2400.3
Total carbon captured	tpd	0.0	2159.4	2969.6	2709.3	2159.4
Carbon capture rate	%	0.0	90.0	90.2	90.2	90.0
Total CO_2 captured	tpd	0.0	7913.0	10882.0	9928.1	7913.0
Total CO_2 emitted	tpd	8795.6	882.6	1186.6	1072.7	882.6
CO_2 emissions	g CO_2 /kWh_{Net}	350.5	42.2	47.4	47.2	42.3

5.1.1 Technical Comparison of ICP Base Case with Benchmark Task 1 Cases

It is evident from Table 5-2 that fuel flow rate to the ICP Base Case is approximately 37% higher than the CCGT with an integrated capture plant. This is due to the fuel consumed by the Alstom gas turbine, duct burner in the HRSG and package steam boiler used to produce the power and steam for the ICP. Although the increase in capacity alone would not be expected to affect the overall plant efficiency, it can be seen from Table 5-2 that the CCGT with an independent carbon capture plant capturing 90% carbon suffers from an overall 6.2% drop in efficiency compared to the CCGT with an integrated capture plant.

Table 5-2 Comparison of Performance Figures between Task 1 and CCGT with ICP Base Case

		Benchmark Task 1	Benchmark Task 1	Benchmark Task 1- Scaled up by 37%	ICP Base Case
		0% CCS	90% CCS	90% CCS	90% CCS
		100% Load	100% Load	137% Load	100% Load
Power					
CCGT gross installed capacity	MWe	1068.0	967.9	1328.1	1068.0
Gas Turbine (s)	MWe	739.0	739.0	1014.1	739.0
Steam Turbine	MWe	328.9	228.9	314.1	328.9
CCGT auxiliary loads	MWe	22.4	20.0	27.5	22.4
CCGT Power Island	MWe	15.6	13.2	18.1	15.6
Others	MWe	6.8	6.8	9.4	6.8
CCGT Net Power Export	MWe	1045.6	947.9	1300.6	1045.6
CCGT Efficiency (LHV)	**%**	**58.3**	**52.9**	**52.9**	**58.3**
ICP Gross Power	MWe	0.0	0.0	0.0	112.7
Gas Turbine	MWe	0.0	0.0	0.0	112.7
Power Import from Grid	MWe	0.0	0.0	0.0	2.0
Capture Plant auxiliary loads	MWe	0.0	77.1	105.7	114.7
ICP GT	MWe	0.0	0.0	0.0	1.8
Flue Gas Blower	MWe	0.0	37.2	51.1	52.5
Acid Gas Removal/DCC	MWe	0.0	2.8	3.8	3.9
CO_2 compression	MWe	0.0	31.7	43.5	43.7
Others	MWe	0.0	5.3	7.3	12.9
CCGT+ICP Net Power Export	MWe	1045.6	870.8	1194.9	1043.5
Plant Net Efficiency (LHV)	**%**	**58.3**	**48.6**	**48.6**	**42.4**
CC Energy Penalty	%	-	9.7	9.7	15.9
Fuel Flows					
Total fuel feed rate	tpd	3264.1	3264.1	4478.7	4478.7
Fuel to CCGT	tpd	3264.1	3264.1	4478.7	3264.1
Fuel to ICP GT	tpd	-	-	-	625.9
Fuel to ICP Duct Burner	tpd	-	-	-	269.3
Fuel to ICP Steam Boiler	tpd	-	-	-	319.4

In the Task 1 CCGT (0% CCS) case, fuel is used to produce power in the GT and 3-level steam (HP/MP/LP) in the HRSG. The steam is used in the steam turbine to produce more power, making the system 58.3% efficient (electrical). This arrangement maximises the power generation for a given amount of fuel input.

In the Task 1 Integrated CCGT with 90% CCS case, steam is extracted from the MP-LP section of the Steam Turbine to be used in the stripper reboiler. This reduces the power production from the steam turbine, making the overall system 52.9% efficient (electrical).

In the ICP Base Case, the CCGT is similar to the Task 1 CCGT (0% CCS) as no power or steam is being used from the CCGT plant to the independent capture plant. The Independent Capture Plant has an arrangement of producing its own power and steam. Fuel is used to produce power in a small Alstom GT to satisfy the parasitic load of the capture plant. The LP steam produced by the HRSG extracting energy from the hot GT flue gas is not sufficient to satisfy the stripper reboiler demand. Therefore, a duct burner in the HRSG and a steam boiler are used to satisfy the overall steam demand. Fuel used in the duct burner (269 tpd) and the steam boiler (319 tpd) is used to produce LP steam only, which is then totally consumed by the stripper reboiler. In this arrangement, fuel energy associated with the generation of the LP steam is considered to be an energy loss from the overall system, as it hasn't been translated into power. This makes the ICP section's power and steam generation facility only 17% electrically efficient, which is much lower than the integrated capture plant's power and steam generation efficiency (52.9%).

This less efficient power and steam generation scheme of the ICP has a major impact on the overall plant efficiency. This loss of efficiency may be broken down into contributing factors, including:

- The Alstom GT used in the ICP section is ~33% efficient which is much lower than the MHI M701F5 GT (~41%) used in the CCGT section. This lower efficiency translates to 29 MW less power generation from the Alstom GT, compared to 142 MW from the MHI GT using same fuel feed rate. This lower power generation contributes to a 1.2% efficiency reduction in the ICP Base Case.
- 5.4% electrical efficiency loss is due to the fuel energy used to produce LP steam only (using a duct burner and steam boiler) which is not translated to the power.
- There is a 0.8% electrical efficiency gain due to more power being generated by the ICP CCGT steam turbine compared to the Task 1 integrated CCGT, as no steam is being extracted from the CCGT steam turbine.
- The parasitic demand for the CCGT+ICP Base Case has increased disproportionately compared to the capacity, leading to a further 0.4% decrease in efficiency. The main contributors to the higher parasitic load are explained below:
  - ICP GT and Package Boiler Flue Gas Blowers:

    As explained in the Section 3.1.2, the flue gas leaving the ICP HRSG is much hotter (148°C) than the Task 1 CCGT HRSG flue gas (93°C). This higher temperature flue gas increases the blower power requirement (higher actual volumetric flow rate) for the ICP GT flue gas blower compared to the CCGT flue gas blower. The flue gas from the package steam boiler is at a higher temperature (130°C) as well, requiring a higher parasitic load for the blower.

- Acid Gas Removal Process parasitic demand:

  The CO_2 loading in the flue gas to the DCC/capture plant has been increased by ~37% due to the increased capacity. However, the parasitic demand for the DCC/capture plant has increased by ~39%. This discrepancy is mainly due to the higher DCC cooling water circulation requirement which increases the parasitic load of the DCC pump (discussed in the Section 3.1.2).

- Offsite and Utilities:

  As explained above, the increased cooling water demand for the capture plant results in higher power demand for the closed loop cooling circuit. As the capture plant is commercially independent of the CCGT plant, offsites such as buildings, demin water plant, etc. are duplicated leading to higher O&U power demand for the overall plant.

Table 5-3 lists the breakdown of the efficiency drop and their contributing factors as discussed above:

Table 5-3 Efficiency Drop and Contributing Factors for ICP Base Case

Contributing Factors	Efficiency drop from Task 1 90% CCS, % Point
Less power produced for a given amount of fuel due to less efficient ICP GT (33.3%) compared to CCGT Gas Turbine (41%)	-1.2
Fuel used in the ICP duct burner and steam boiler to produce steam only. This fuel energy is not translated to produce power, hence overall drop in the electrical efficiency	-5.4
Efficiency gain from the CCGT compared to integrated case as no steam is being extracted from the CCGT steam turbine	+0.8
Parasitic load increased disproportionately due to higher flue gas temperature to the GT and package boiler blowers, higher DCC cooling water demand and duplication of offsite systems	-0.4
Overall Efficiency drop, %	-6.2

5.1.2 Technical Comparison of ICP Sensitivity Case 1 with Benchmark Task 1 Cases

It is clear from Table 5-4 below, that fuel flow rate to the ICP Sensitivity Case 1 has increased approximately 25% compared to the integrated capture plant. This is due to the fuel used by the package steam boilers to produce steam for the ICP CO_2 stripper. As mentioned earlier, this increase in capacity shouldn't affect the overall efficiency of the plant; however, it is evident from Table 5-4 that ICP Sensitivity Case 1 suffers from an overall 6.4% point drop in efficiency compared to the CCGT with an integrated capture plant.

In ICP Sensitivity Case 1, the CCGT is similar to the Task 1 (0% CCS) CCGT in terms of both GT and steam turbine power output as no steam is being extracted for the capture plant. However, the capture plant parasitic demand is satisfied by the CCGT. Therefore, the net plant power export is less than for Task 1 (0% CCS).

The Independent Capture Plant has an arrangement for producing its own steam to be consumed by the stripper reboiler using package boilers. In this arrangement, fuel energy associated with the generation of the LP steam is an energy loss from the overall system, as it hasn't been translated into power. The steam generation scheme used in the capture plant has an impact on the overall electrical efficiency of the plant.

Table 5-4 Comparison of Performance Figures between Task 1 and CCGT with ICP Sensitivity Case1

		Benchmark Task 1	Benchmark Task 1	Benchmark Task 1- Scaled up by 25%	ICP Sensitivity Case 1
		0% CCS	90% CCS	90% CCS	90% CCS
		100% Load	100% Load	125% Load	100% Load
Power					
CCGT gross installed capacity	MWe	1068.0	967.9	1210.6	1068.0
Gas Turbine (s)	MWe	739.0	739.0	924.3	739.0
Steam Turbine	MWe	328.9	228.9	286.3	328.9
CCGT auxiliary loads	MWe	22.4	20.0	25.1	22.4
CCGT Power Island	MWe	15.6	13.2	16.5	15.6
Others	MWe	6.8	6.8	8.5	6.8
CCGT Net Power Export	MWe	1045.6	947.9	1185.5	1045.6
CCGT Efficiency (LHV)	**%**	**58.3**	**52.9**	**52.9**	**58.3**
Capture Plant auxiliary loads	MWe	0.0	77.1	96.4	98.7
Flue Gas Blower	MWe	0.0	37.2	46.4	43.1
Acid Gas Removal/DCC	MWe	0.0	2.8	3.5	3.7
CO_2 compression	MWe	0.0	31.7	39.7	39.8
Others	MWe	0.0	5.3	6.6	12.2
CCGT+ICP Net Power Export	MWe	1045.6	870.8	1089.1	946.9
Plant Net Efficiency (LHV)	**%**	**58.3**	**48.6**	**48.6**	**42.2**
CC Energy Penalty	%	-	9.7	9.7	16.1
Fuel Flows					
Total fuel feed rate	tpd	3264.1	3264.1	4082.4	4082.4
Fuel to CCGT	tpd	3264.1	3264.1	4082.4	3264.1
Fuel to ICP Steam Boiler	tpd	-	-	-	818.3

The contributing factors leading to the overall efficiency drop are as follows:

- 8.3% electrical efficiency loss is due to the fuel energy used to produce LP steam, using the steam boiler, which is not translated to the power.
- There is a 2.0% electrical efficiency gain due to more power being generated by the ICP CCGT steam turbine, since no steam is extracted from the CCGT steam turbine.
- The parasitic demand for the CCGT+ICP Sensitivity Case 1 has increased disproportionately by ~28% compared to the capacity which has increased by ~25%. The higher parasitic load led to a 0.1% decrease in overall plant net electrical efficiency. Causes for increase in the parasitic load are the same as noted in Section 5.1.1 above.

The following table shows the breakdown of the efficiency drop and their contributing factors as discussed above:

Table 5-5 Efficiency Drop and Contributing Factors for Sensitivity Case 1

Contributing Factors	Efficiency drop from Task 1 90% CCS, % Point
Fuel used in the steam boiler to produce steam for reboiler. This fuel energy is not translated to produce power, hence overall drop in the electrical efficiency	-8.3
Efficiency gain from the CCGT compared to integrated case as no steam is being extracted from the CCGT steam turbine	+2.0
Parasitic load increased disproportionately due to higher flue gas temperature to the package boiler blowers, higher DCC cooling water demand and duplication of offsite systems	-0.1
Overall Efficiency drop, %	-6.4

5.1.3 Technical Comparison of ICP Sensitivity Case 2 with Benchmark Task 1 Cases

As ICP Sensitivity Case 2 is a retrofit scenario of WP Task 1 integrated plant case, plant capacity is similar to WP Task 1 integrated plant case. Table 5-1 shows the similarity between the technical data of the two cases.

The only difference in the technical performance is the offsite power demand. As the capture plant is commercially separated from the CCGT plant, offsites such as buildings, demin water plant etc. are duplicated which leads to the higher offsite power demand of the overall plant. Hence the net power output is decreased slightly which is reflected in the 0.1% decrease in net efficiency and the increase in heat rate and carbon efficiency.

5.1.4 Energy Flow Diagrams for Task 1 and ICP Cases

Figure 5-1, Figure 5-2, Figure 5-3 and Figure 5-4 represent the energy distribution for the Task 1 0% CCS, Task 1 integrated capture plant with 90% CCS, ICP Base Case and ICP Sensitivity Case 1 respectively.

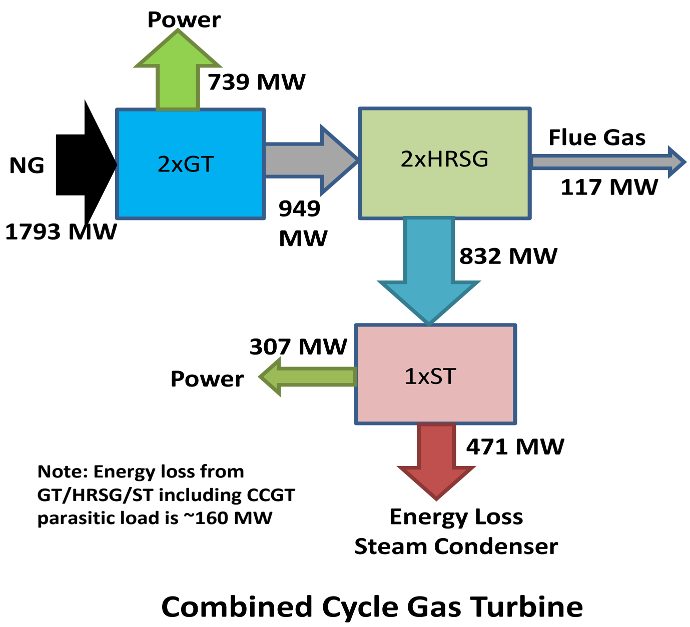


Figure 5-1 Energy Flow Diagram for Task 1 0% CCS Case

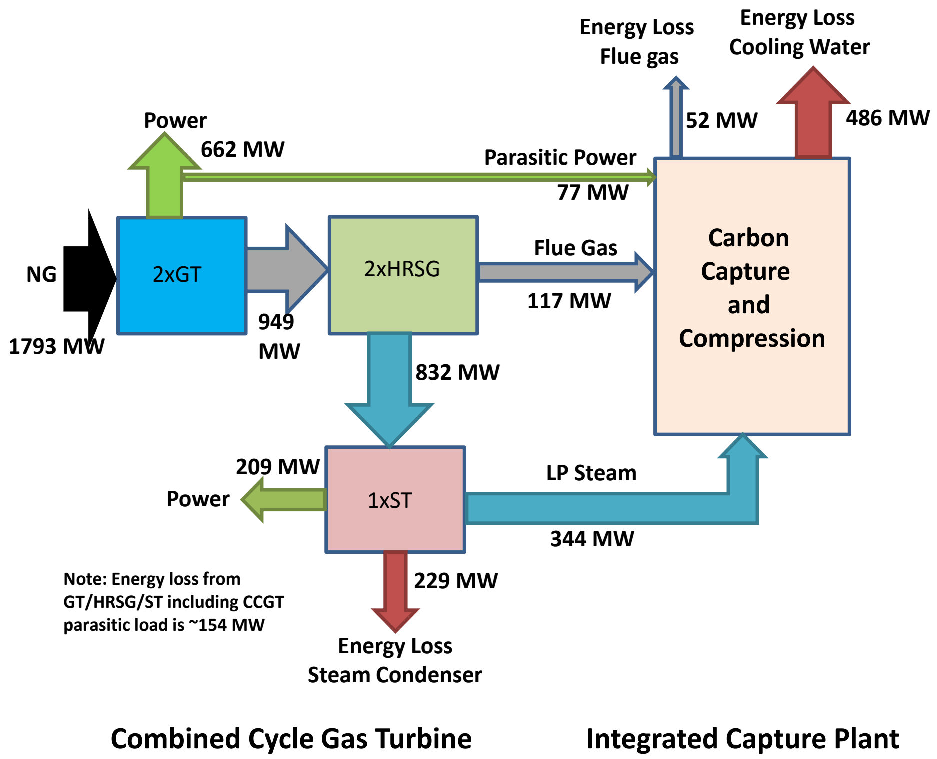


Figure 5-2 Energy Flow Diagram for Task 1 90% CCS Case

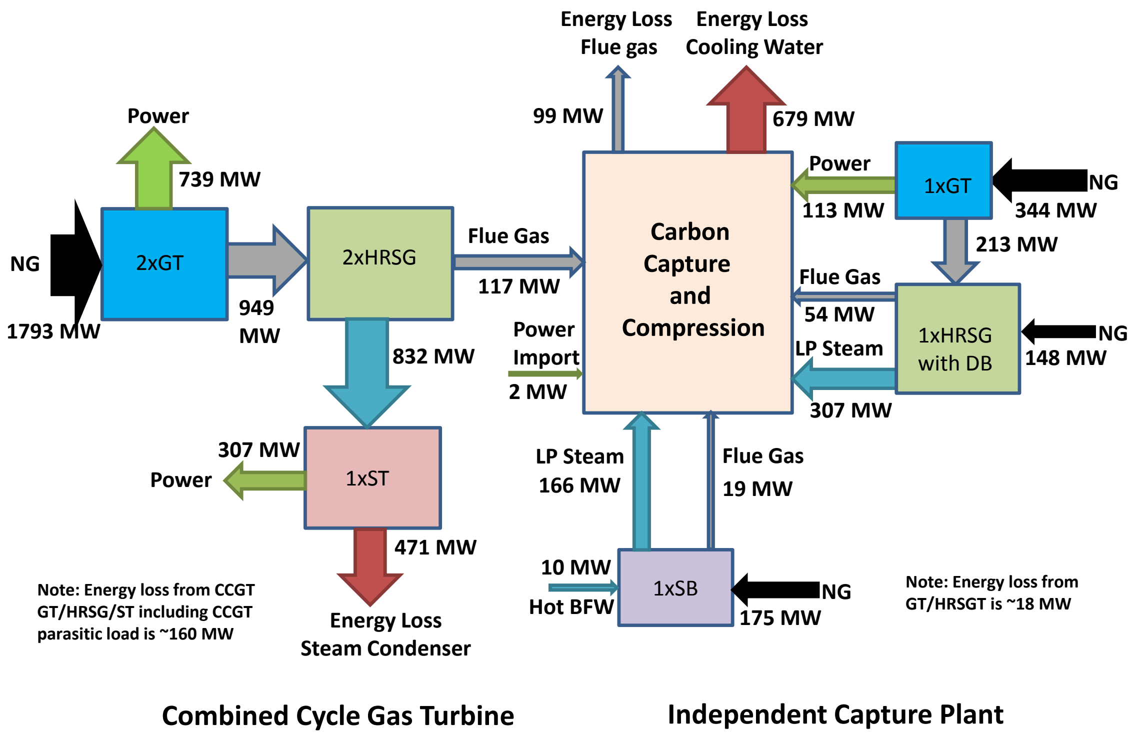


Figure 5-3 Energy Flow Diagram for ICP Base Case

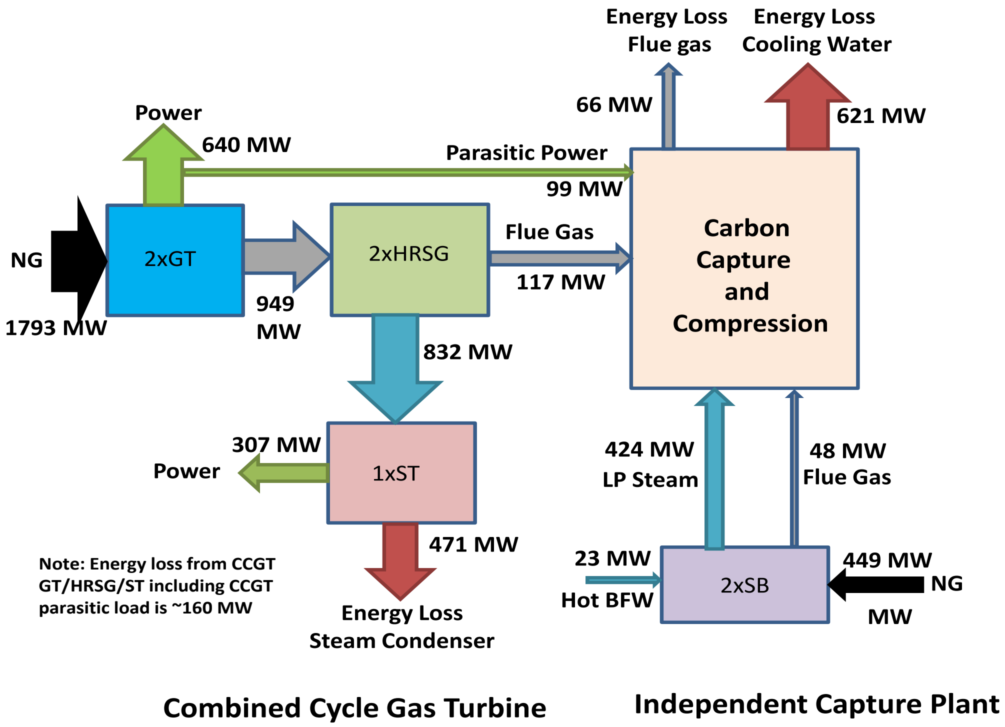


Figure 5-4 Energy Flow Diagram for ICP Sensitivity Case1

The Task 1 integrated case (Figure 5-2) has similar fuel energy input to Task 1 0% CCS (Figure 5-1), but the energy loss from the overall system is 23% (922 MW) higher than for Task 1 0% CCS (747 MW). This energy loss is associated with the steam to reboiler and capture plant parasitic power loss, reducing the net exportable power and plant electrical efficiency.

Figure 5-3 clearly demonstrates the two distinct sections of the ICP Base Case namely the CCGT and Independent Capture Plant. The only connection between these two sections is the flue gas from the CCGT directed to the capture plant for CO_2 removal. The CCGT section has similar fuel energy input (1793 MW), associated energy losses (747 MW) and power production (1046 MW) as the Task 1 0% CCS case (Figure 5-1). The ICP section also requires fuel energy input to produce power and steam to satisfy its own parasitic demand and reboiler steam demand. The overall energy input to the ICP Base Case is 2460 MW which is 37% higher than the Task 1 integrated case (Figure 5-2). Although the capacity increase is not expected to affect the overall plant efficiency and % energy losses, it can be noted from Figure 5-3 that the overall energy loss from the ICP Base Case is 53% (1414 MW) higher than for the Task 1 integrated case. This increase can be attributed to the following factors:

- The energy loss from the steam condenser for the ICP Base Case has nearly doubled compared to the Task 1 integrated case. This accounts for 50% of the increase in the energy loss for the ICP Base Case.
- The energy loss through the stack for the ICP Base Case has increased due to the higher exhaust temperature (explained in the Section 3.1.2).

- The energy loss associated with the cooling water has increased slightly as the cooling water demand in the DCC section is higher for the ICP Base Case (explained in the Section 5.1.1).

These energy losses are reflected in the lower efficiency of the ICP Base Case.

In the ICP Sensitivity Case 1 (Figure 5-4), the capture plant is partly integrated with the CCGT as the parasitic power for the capture plant has been taken from the CCGT section. The fuel energy input to the CCGT section is the same as for the Task 1 integrated case, but the overall fuel flow to the plant is higher due to fuel consumption to produce steam for the stripper reboiler. The overall energy input to the ICP Sensitivity Case 1 is 2242 MW, which is 25% higher than for the Task 1 integrated case energy input. It is generally expected that the overall energy loss from the ICP Sensitivity Case 1 should be around 25% higher than the Task 1 integrated case as well; however it can be noted that the energy loss is ~30% higher, which can be attributed to the higher energy loss from the steam condenser and cooling water. These energy losses account for the lower efficiency of the ICP Sensitivity Case 1.

It can be concluded from the above analysis that the overall losses from the CCGT with capture plant increases as it becomes commercially independent, which is reflected in the lower net power generation for the ICP cases. Overall, these results imply that there is a significant penalty associated with operating the capture plant as a commercially distinct entity and that if opportunities to integrate the capture plant with the CCGT are not able to be realised commercially, this penalty is likely to increase the levelised cost of electricity by more than 10%.

5.2 Economic Performance

Overall plant economic data for the ICP Base Case and two sensitivity cases along with the WP6 Task 1 benchmark cases are shown in Table 5-6, below.

Table 5-6 Comparison of Economic Performance Figures between Task 1 and CCGT with ICP

		Benchmark Task 1	Benchmark Task 1	ICP Base Case	ICP Sensitivity Case 1	ICP Sensitivity Case 2
		0% CCS	90% CCS	90% CCS	90% CCS	90% CCS
		100% Load	100% Load	100% Load	100% Load	100% Load
Total CAPEX	GB£M	547.5	997.2	1345.1	1178.8	1013.6
CCGT Power Island	GB£M	474.5	474.5	474.5	474.5	474.5
CCGT U&O	GB£M	73.0	73.0	73.0	73.0	73.0
Capture Plant Power Block	GB£M	0.0	0.0	131.6	51.8	0.0
Capture Plant Tie-ins	GB£M	0.0	0.0	10.0	13.4	16.5
Acid Gas Removal Unit	GB£M	0.0	322.9	467.0	405.5	322.9
CO_2 compression	GB£M	0.0	61.5	76.2	71.6	61.5
Capture Plant U&O	GB£M	0.0	65.2	112.7	88.9	65.1
CAPEX efficiency	GB£/kW_{Net}	523.6	1145.1	1289.0	1244.9	1169.5
Total OPEX – incl. fuel	GB£M p.a.	296.6	313.4	428.3	388.9	315.1
Total OPEX – excl. fuel	GB£M p.a.	28.3	45.1	60.1	53.3	46.8
OPEX – incl. fuel	GB£ p.a. / kW_{Net}	283.7	359.9	410.4	410.7	363.6
OPEX – excl. fuel	GB£ p.a. / kW_{Net}	27.1	51.8	57.6	56.3	54.0
Levelised Cost of Electricity						
CO_2 emission cost = £0 / te CO_2	£ / MWh_{Net}	47.7	69.1	78.7	77.8	70.1
CO_2 emission cost = £20 / te CO_2	£ / MWh_{Net}	54.7	70.0	79.6	78.7	71.0
CO_2 emission cost = £40 / te CO_2	£ / MWh_{Net}	61.7	70.8	80.5	79.7	71.8
CO_2 emission cost = £60 / te CO_2	£ / MWh_{Net}	68.7	71.7	81.5	80.6	72.7
Cost of CO_2 Captured CO_2 emission cost = £ 0 / te CO_2	£ / te CO_2	n/a	56.8	71.3	69.0	59.1
Cost of CO_2 Avoided CO_2 emission cost = £ 0 / te CO_2	£ / te CO_2	n/a	69.7	102.3	99.3	72.9

5.2.1 Capital Cost Variation with Independent Capture Plant

For the ICP Base Case, the CCGT plant capacity remains the same as in Task 1, hence the CCGT power island capital cost listed in Table 5-6 is the same. This is true for the CCGT section costs in the sensitivity cases as well.

However, the overall CAPEX of the ICP Base Case has increased by 35% compared to the Task 1 integrated capture plant, due to the following factors:

- The added cost of the capture plant power block, which includes the Alstom GT / HRSG and package boiler.
- The capture plant capacity has increased by approximately 33%, which requires four trains of DCC and absorber columns and three trains of stripper columns compared to three trains of DCC and absorber columns and two trains of stripper columns for the Task 1 integrated case.
- The Acid Gas Removal (AGR) unit equipment cost has increased disproportionately (~45%) compared to the capacity increase. Table 5-7 compares the cost of the AGR unit for the Task 1 integrated case and ICP Base Case.
    - ➢ In the ICP Base Case, the CCGT flue gas blowers are considered as part of the ICP power block; hence their cost is not included in the AGR unit. The CCGT flue gas blowers are part of the AGR unit for the Task 1 integrated case.
    - ➢ Other contributing factors leading to the AGR unit cost increase are a bigger gas-gas exchanger, bigger DCC cooler exchanger and an exhaust stack in the capture plant (not required for the Task 1 integrated case).
- The addition of flue gas tie-in costs.
- The increase of cooling load and duplication of offsites in the capture plant results in the U&O cost for the overall plant increasing by 35%.

Table 5-7 Comparison of Acid Gas Removal Unit CAPEX between Task 1 Integrated Case and ICP Base Case

		Benchmark Task 1	Benchmark Task 1 – 33% scaled up cost	ICP Base Case	Delta Cost
		90% CCS	90% CCS	90% CCS	
Acid Gas Removal Unit cost					
Total CAPEX	GB£M	98.7	131.2	142.7	
CAPEX without Flue gas Blowers in AGR unit cost	GB£M	88.0	117.0	142.7	25.7
Main Contributing factor for ICP Base Case CAPEX increase					
Gas-gas exchanger	GB£M	6.5	8.6	13.2	4.6
DCC Cooler	GB£M	0.8	1.1	2.5	1.4
Exhaust gas stack in the capture plant	GB£M	-	-	18.0	18.0

The capital cost of the ICP Sensitivity Case 1 increased by 18% compared to the Task 1 integrated capture plant due to following factors:

- The added cost of capture plant package boilers to produce steam for the stripper.
- The capture plant capacity has increased by approximately 13% which requires four trains of DCC / absorbers and three trains of stripper columns.
- AGR unit equipment cost has increased disproportionately (~26%) compared to the capacity increase. Major contributing factors leading to the AGR unit cost increase are a bigger gas-gas exchanger, bigger DCC cooler exchanger and an exhaust stack in the capture plant (not required for the Task 1 integrated case).
- The addition of flue gas and electrical tie-in costs.
- The increase of overall U&O cost is due to higher cooling loading and offsite duplication.

ICP Sensitivity Case 2 is a retrofit case of WP6 Task 1 integrated capture plant. The Independent Capture Plant is commercially separated from the CCGT, hence it requires tie-ins for flue gas, electrical systems, steam and condensate, duplication in offsites facilities and modification of the existing steam turbine to install extraction pipes and control systems. These factors increase the capital cost for this retrofit case by 1.6% compared to the integrated capture plant.

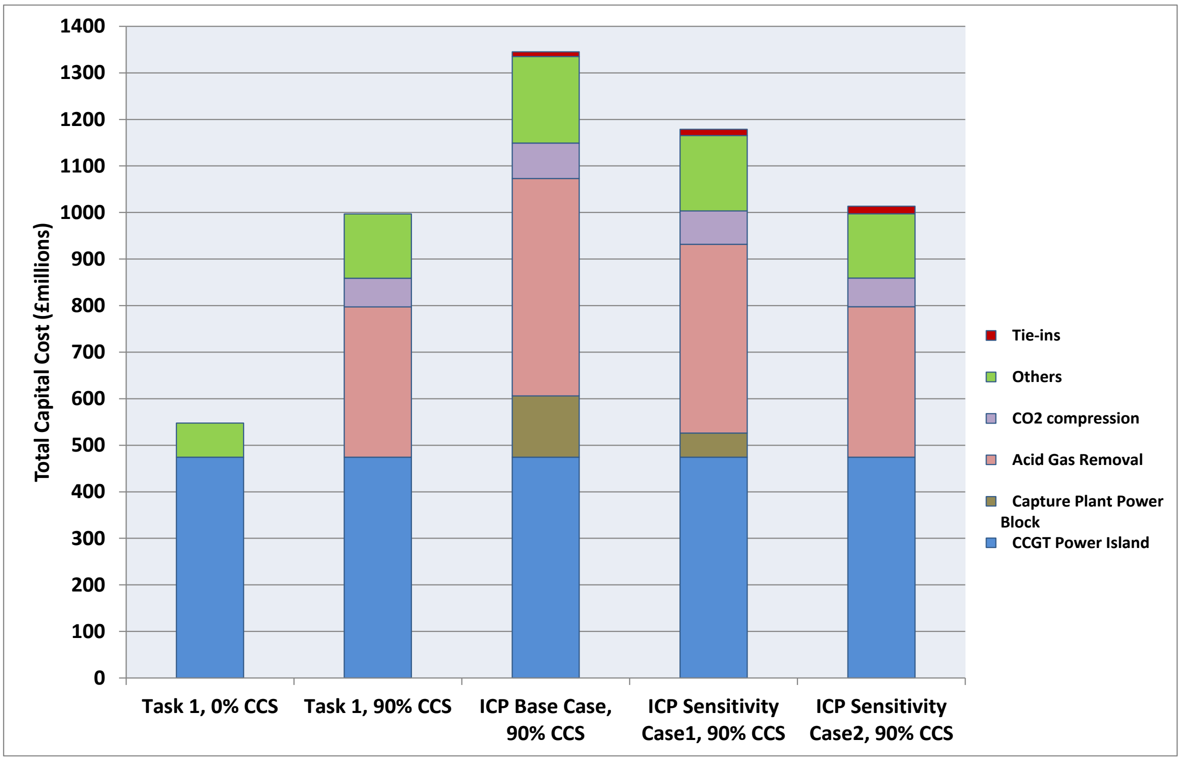


Figure 5-5 Capital Cost Comparison between Task 1 Cases and ICP Cases

5.2.2 Operating Cost Variation with Independent Capture Plant

The significant increase in operating costs for the ICP Base Case and Sensitivity Case 1 shown in **Error! Reference source not found.** is mostly due to the increase in fuel requirement.

ICP Base Case fuel demand is approximately 37% higher than WP6 Task 1 integrated capture plant due to the fuel requirement for the capture plant Power Island to produce power and steam, and the package boiler to meet the additional steam demand.

For the Sensitivity Case 1, the capture plant Power Island is not required, as power is being imported from the CCGT plant. However, two package boilers are required to produce the entire steam demand of the stripper column. Overall, fuel demand for this case is less than for the ICP Base Case, though it is still ~25% higher than the integrated capture plant of Task 1.

In addition to the fuel cost, there is also an increase in the fixed operating costs for both the ICP Base Case and Sensitivity Case 1, since several of these are related to the total capital cost. As the independent capture plant is commercially separated from the CCGT power plant, more personnel are required than for the integrated plant which increases the direct labour cost and hence fixed cost for all the ICP cases.

5.2.3 Levelised Cost of Electricity Variation with Independent Capture Plant

Since both the total capital and the total operating costs increased significantly for the ICP Base Case and Sensitivity Case 1, so does the levelised cost of electricity (LCOE). The LCOE increases by 14.1% and 12.5% for the ICP Base Case and Sensitivity Case 1 respectively.

For the retrofit case (Sensitivity Case 2), LCOE increases slightly by 1.4% compared to the Task 1 integrated capture plant. The difference is due to the higher fixed operating cost for the retrofit case, mainly down to direct labour cost.

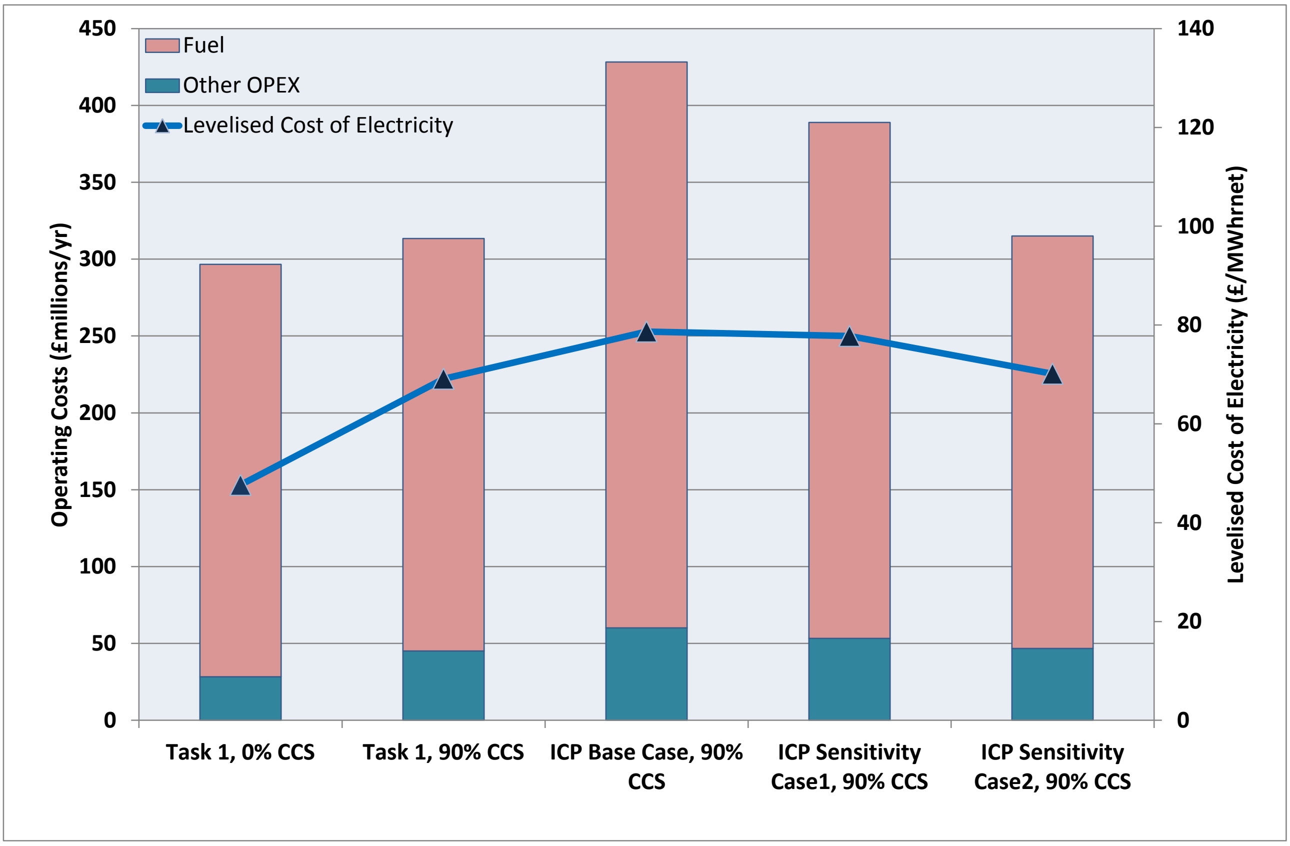


Figure 5-6 Operating Cost and LCOE Comparison between Task 1 Cases and ICP Cases

6. REFERENCES

1. Gas Turbine World, 2013.

ATTACHMENT 1
BASIS OF DESIGN

Contract No.:	1.17.13058
Client's Name:	The Energy Technologies Institute
Project Title:	Hydrogen Storage and Flexible Turbine Systems
Project Location:	Generic UK

REVISION	**Rev O1 (Draft)**				
DATE	26 July 2013				
ORIG. BY	T. Abbott	Tim Abbott			
CHKD BY	S. Ferguson	Ferguson			
APP. BY	T. Abbott	Tim Abbott			

WP6 - CCS Benchmark Refresh 2013
Basis of Design

CONTENTS

1. INTRODUCTION

The ETI has engaged Foster Wheeler to execute its CCS Benchmark Refresh 2013 Project. The main purpose of this further study work is to provide additional benchmarking and performance analysis of next generation carbon capture technologies building upon those evaluated and reported in previous phases of CCS study work that Foster Wheeler has executed with ETI.

This purpose of this Basis of Design document is to provide a clear and consistent basis on which to evaluate each option in support of the study.

2. PLANT LOCATION

The site is assumed to be a green field coastal location on the NE coast of the UK, with adjacent deep sea access.

3. SITE CONDITION

An assumed clear level obstruction (both under and above ground) free site is considered, without the need for any required special civil works.

4. PLANT CAPACITY

Each case will be designed to produce electric energy (800 MWe nominal gross capacity without CO_2 capture) to be delivered to the UK National grid. For each of the Benchmarks considered, the design capacity will vary, determined by the full design capacity of key equipment items, for example, in the case of CCGT schemes the full ”appetite” of the selected gas turbines.

5. PLANT OPERATING CONDITIONS

The following climatic conditions marked (*) shall be considered reference conditions for plant performance evaluation across all WP6 cases. Individual case deliverables will be produced at reference conditions only.

Atmospheric pressure:		1013 mbar (*)
Relative humidity:	average:	average 60% (*)
		maximum: 95%
		minimum: 40%
Ambient temperatures:		average 10°C (*)
		summer 30°C
		minimum -10°C

6. CARBON DIOXIDE CAPTURE RATE

Each carbon dioxide abated case will be designed to achieve a target carbon capture level of at least 90%, defined as:

$$CO_2 \text{ Capture Rate (\%)} = \frac{100 \times \text{Moles carbon contained in the } CO_2 \text{ product}}{\text{Moles carbon contained in the natural gas feed}}$$

7. FEEDSTOCK, PRODUCT AND UTILITY SUPPLIES

The streams available at plant battery limits are the following:

- Natural gas;
- CO_2 product;
- Sea water supply;
- Sea water return;
- Plant/raw/potable water; and
- Chemicals (including amine).

Other utilities, including demineralised water, boiler feed water, instrument and plant air, oxygen and nitrogen will be generated within the complex where necessary and will be available for use at the required conditions.

8. FEEDSTOCK SPECIFICATIONS

8.1 Natural Gas

Natural gas NTS connection is available.

Natural gas feedstock specification (as NTS spec):

H_2S Content	Not more than 5 mg/m^3
Total Sulphur Content	Not more than 50 mg/m^3
Hydrogen Content	Not more than 0.1% (molar)
Oxygen Content	Not more than 0.001% (molar)
Hydrocarbon Dewpoint	Not more than -2^{o}C, at any pressure up to 85 bar(g)
Water Dewpoint	Not more than -10^{o}C, at 85 bar(g) (or the actual delivery pressure)
Wobbe Number (real gross dry)	Between 48.14 MJ/m^3 and 51.41 MJ/m^3 (at standard temperature and pressure) and in compliance with ICF and SI limits as listed below
Incomplete Combustion Factor	Not more than 0.48
Soot Index	Not more than 0.60
Gross Calorific Value (real gross dry)	Between 36.9 MJ/m^3 and 42.3 MJ/m^3 (at standard temperature and pressure) and in compliance with ICF and SI limits described above, subject to a 1 MJ/m^3 variation.
Inerts	Not more than 7.0mol%, subject to: Carbon Dioxide content – not more than 2.0mol% Nitrogen content – not more than 5.0mol%

Contaminants	Gas shall not contain solid or liquid material which may interfere with the integrity or operation of pipes or any gas appliance within the meaning of the Regulation 2(1) of the Gas Safety (Use of) Regulations 1998 that a consumer could reasonably be expected to operate.
Delivery Temperature	Between 1°C and 38°C
Odour	Gas delivered shall have no odour that might contravene the statutory obligation "not to transmit or distribute any gas at a pressure below 7 bar(g) which does not possess a distinctive and characteristic odour".

8.2 Back up fuel/power

Natural gas (as detailed in section 8.1) is available for back-up fuel.

National Grid electrical grid connection is available for "black start" power requirement scenarios.

9. PRODUCT SPECIFICATIONS

9.1 Carbon Dioxide

Carbon dioxide produced from the plant will be dried and compressed to 150 bar(g) for export from the facility. Product carbon dioxide conditions will be:

Pressure:	150 bar(g)
Temperature:	$\leq$ 30°C

The target carbon dioxide export specification is based on the requirements for EOR.

H_2O	< 50 ppmv
CO_2	> 97 vol%
SO_2	< 50 ppm
H_2S	< 50 ppm
CO	< 3 vol%
Ar	< 3 vol%
O_2	100 ppmv
N_2	< 3 vol%
H_2	< 3 vol%
CH_4	< 2 vol%
COS	< 50ppm

9.2 Power

Power will be generated from the complex at 275 kV and will be transmitted to an assumed existing HV substation for connection onto the UK National Grid. It is assumed that National Grid electrical grid connection is available.

Electric Power

Net Power Output	800 MWe nominal capacity
Voltage	275 kV
Frequency	50 Hz

10. UTILITY SUPPLIES

10.1 Seawater cooling system

The primary cooling system is sea water in a once through system. Services will include the steam turbine condenser and the seawater/closed loop interchanger. Seawater supply assumed to be clear filtered and chlorinated, without suspended solids and organic matter. Seawater supply from a new intake and a seawater outfall will be required as part of the complex.

The following seawater conditions marked (*) shall be considered reference conditions for plant performance evaluation across all WP6 cases. Individual case deliverables will be produced at reference conditions only.

Seawater conditions:

Average supply temperature:	10°C (*)
Average return temperature:	18°C (*)
Operating pressure at Condenser inlet:	3 bar(g)
Maximum allowable ΔP for Condenser:	0.7 bar

10.2 Closed loop water cooling system

The secondary cooling system is a closed loop, seawater cooled cooling water system. All cooling services, with the exception of the steam turbine vacuum condenser, will be placed on this system. This system cools the closed loop water against seawater. The make-up water to the system shall be demineralised water stabilized and conditioned.

The following closed loop water conditions marked (*) shall be considered reference conditions for plant performance evaluation across all WP6 cases. Individual case deliverables will be produced at reference conditions only.

Closed loop cooling water conditions:

Average supply temperature:	14°C (*)
Average return temperature:	24°C (*)
Seawater/closed loop water interchanger ΔT:	4°C (*)
Operating pressure at users:	3.0 bar(g)
Maximum allowable ΔP for users:	1.5 bar

11. ENVIRONMENTAL EMISSION BASIS

The overall gaseous emissions basis for the study cases are as follows:

	CCGT(2)
NOx (as NO_2),mg/Nm^3:	≤ 50
Particulate, mg/Nm^3:	≤ 5
CO, mg/Nm^3:	≤ 20

Notes:

(1) @ 6% O_2 vol dry

(2) @ 15% O_2 vol dry

12. OUTLINE SCHEME DESCRIPTIONS

12.1 Natural Gas CCGT Power Plant with Amine Solvent Post-Combustion CO_2 Capture

The overall process scheme will be based upon a natural gas fired combined cycle gas turbine (CCGT) using two Frame F class gas turbines, each with downstream heat recovery steam generator (HRSG), and common single steam turbine generator (STG), CO_2 capture unit and CO_2 compression and dehydration unit.

In this case this natural gas feed rate will be set to ensure full utilisation of the gas turbines with the supporting and downstream equipment items sized to process the generated gas turbine exhaust gas. The process conditions, including stream flows, pressures, temperatures and compositions, will be produced to reflect this sizing basis. Key features of the configuration include:

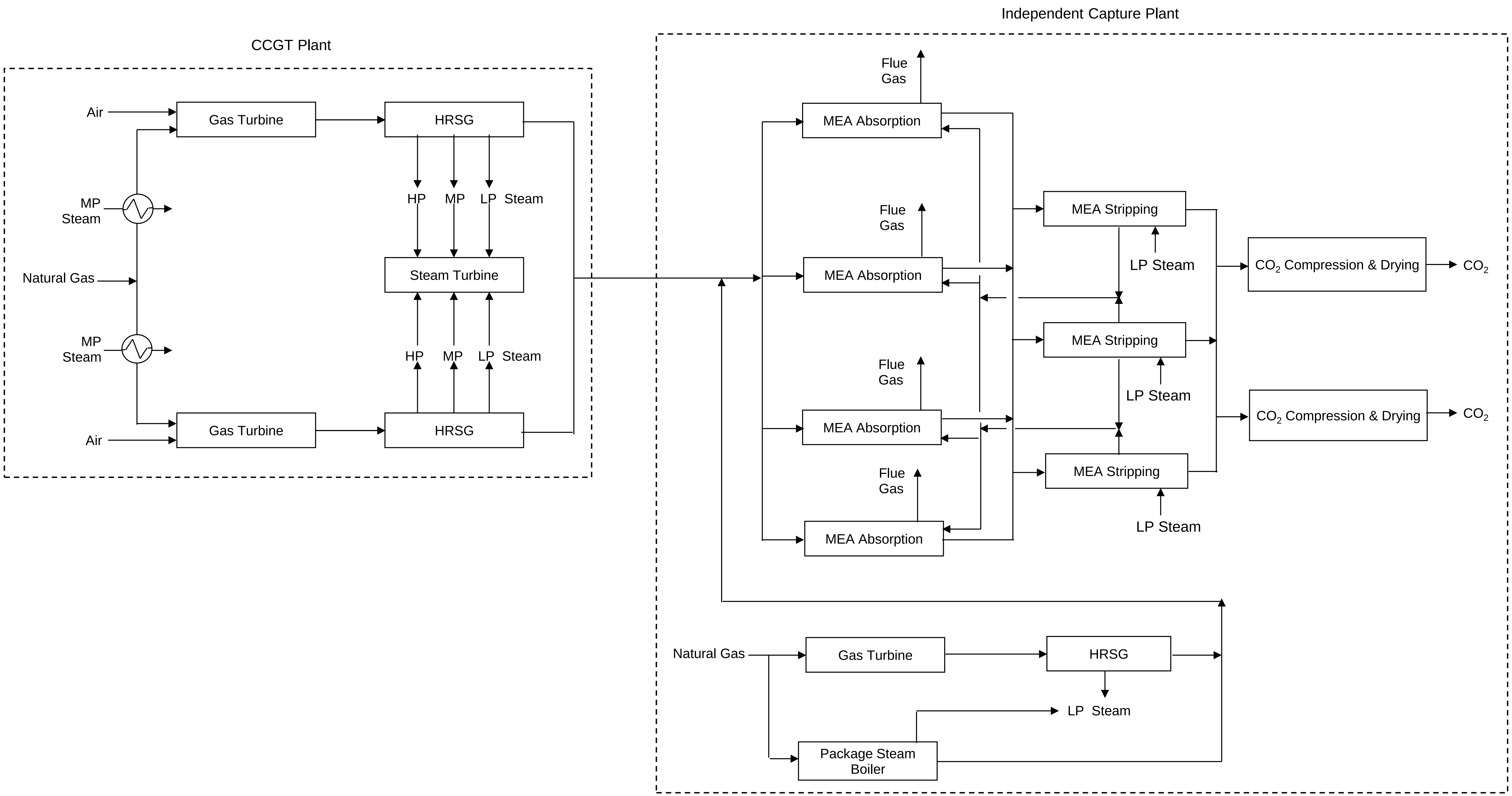
- Power Island Unit – comprising of two parallel trains, each with one F class 50 Hz gas turbine and one heat recovery steam generator (HRSG), connected to a single condensing steam turbine, using seawater cooling.
- Acid Gas Removal Unit – carbon dioxide removal scheme developed using in-house information on the basis of an MEA-based process such as Fluor Econamine carbon dioxide recovery technology.
- Carbon Dioxide Compression and Drying Units – dehydration and compression to 150 barg based on in-house knowledge of commercially available equipment.

12.2 Natural Gas CCGT Power Plant without CO_2 Capture

An equivalent Natural Gas CCGT without CO_2 capture will be developed. This will be based upon the same configuration as above, with the exclusion of the AGR and CO_2 compression and drying units. The case will use the same natural gas feed rate as the Natural Gas CCGT Power Plant with CO_2 capture case.

ATTACHMENT 2
HEAT AND MATERIAL BALANCES

1. CCGT with ICP - Base Case
2. CCGT with ICP Sensitivity Case 1 – Imported Power
3. CCGT with ICP Sensitivity Case 2 – Imported Steam & Power



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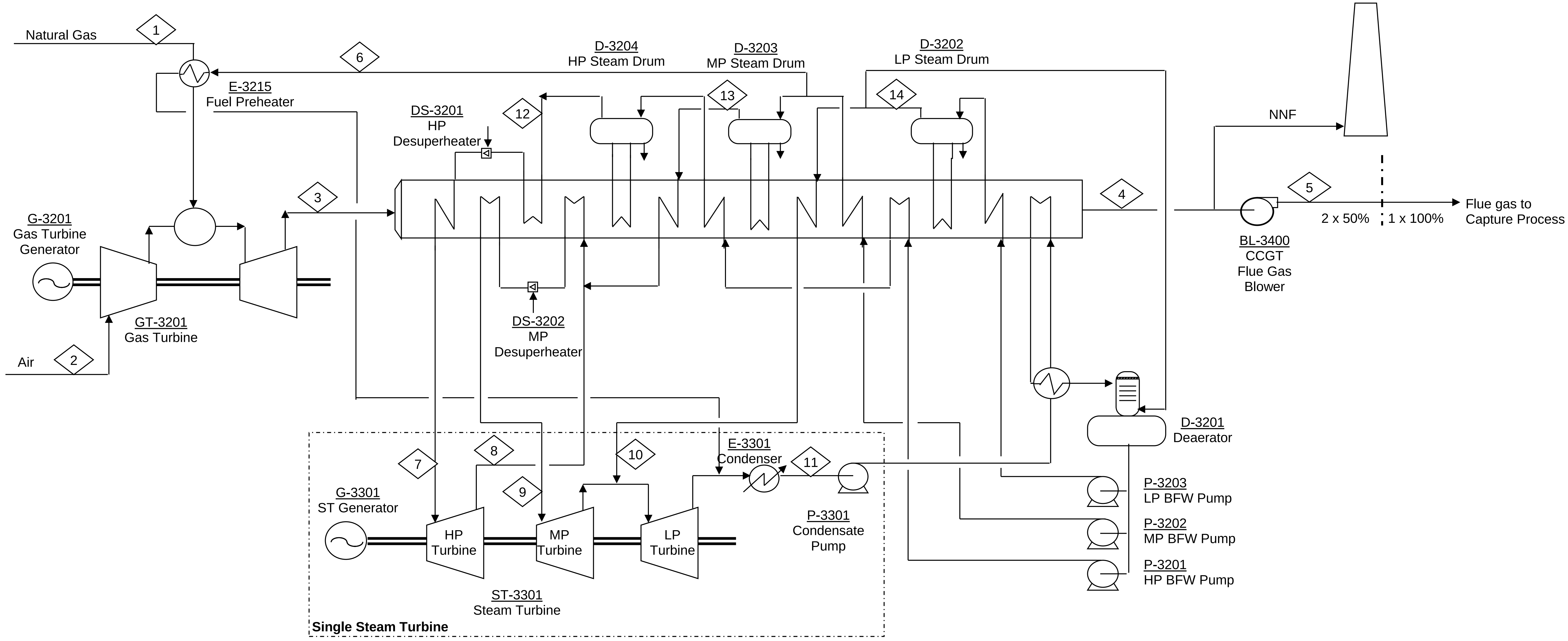
REVISIONS

CCS BENCHMARK REFRESH 2013	
BLOCK FLOW DIAGRAM	CASE: CCGT and Independent Capture Plant with 90% Post Combustion CO2 Capture
amec foster wheeler	DWG. NO.: XXXX-XX-XXX — REV: O1



2 GTs each with own HRSG, deaerator and BFW pumps in parallel
with a single ST and condenser
Flows shown below are for the full facility capacity

Stream Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Pressure (kPa)	3447	101	105	103	125	2918	13980	2801	2689	417	3.5	13980	2918	435
Temperature (°C)	1	10	613	93	116	212	566	327	566	203	24	337	232	147
Mass rate (kg/h)	136002	4991402	5127404	5127404	5127404	83253	598255	598255	698991	64623	846867	598255	100737	84262
Mole % Oxygen	0.00	20.82	11.01	11.01	11.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Nitrogen	1.47	77.60	74.18	74.18	74.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % CO2	0.68	0.03	4.64	4.64	4.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Methane	87.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Hydrogen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Argon	0.00	0.93	0.89	0.89	0.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Ethane	7.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Propane	2.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % H2O	0.00	0.61	9.29	9.29	9.29	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Molar rate (kmol/hr)	7419	173009	180723	180723	180723	4620	33199	33199	38790	3586	33200	33200	5590	4676

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CCS BENCHMARK REFRESH 2013

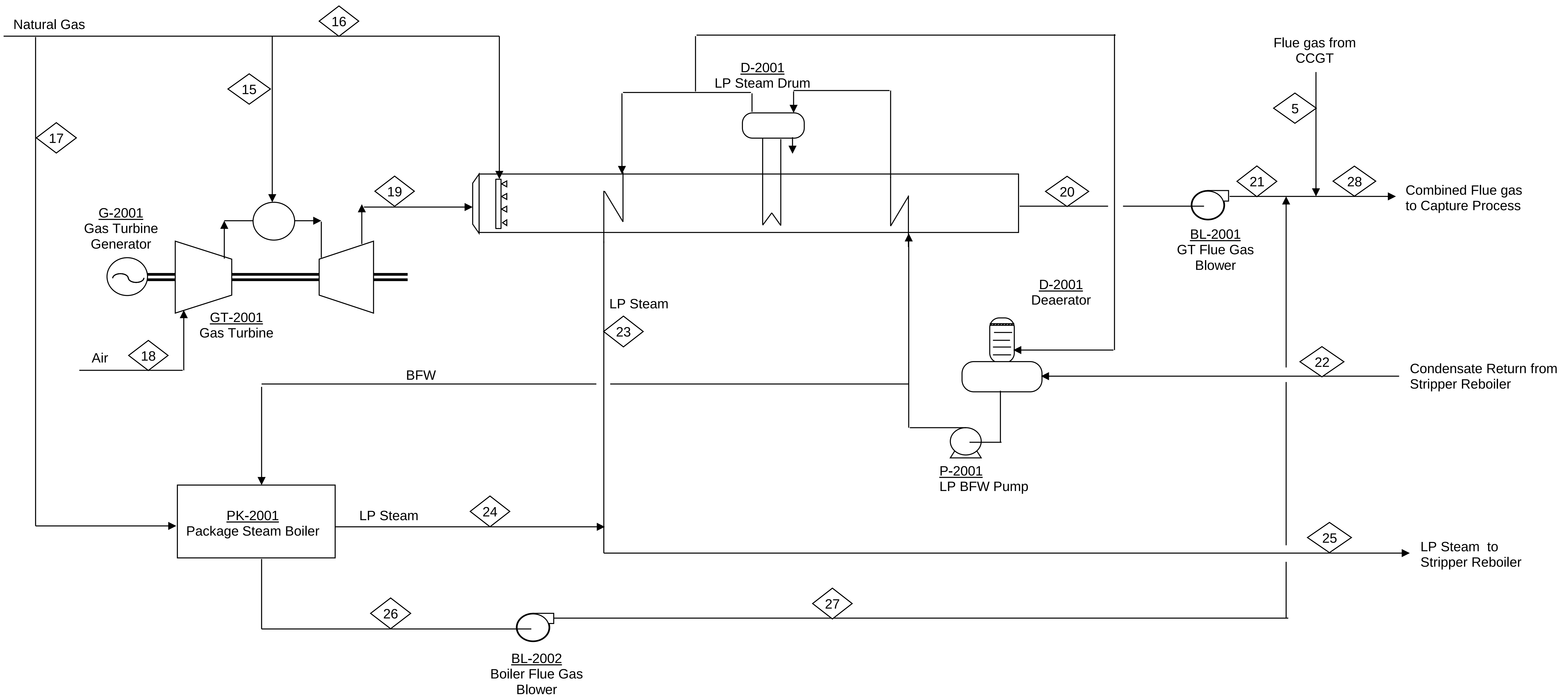
UNIT 3200/3300/3400
CCGT Power Generation

amec foster wheeler

CASE:
CCGT and Independent Capture Plant with 90% Post Combustion CO2 Capture

DWG NO.: XXXX-XX-XXX

REV: O1



1 GT with duct firing, HRSG, deaerator and BFW pump
1 Auxiliary Package Steam Boiler
Flows shown below are for the full facility capacity

Stream Name	15	16	17	18	19	20	21	22	23	24	25	26	27	28		
Pressure (kPa)	3447	3447	3447	101	104	102	125	400	417	417	417	101	125	125		
Temperature (°C)	1	1	1	10	529	148	176	133	293	293	293	130	157	131		
Mass rate (kg/h)	26080	11220	13309	1420200	1446300	1457500	1457500	677880	441200	236680	677880	253657	253657	6838561		
Mole % Oxygen	0.00	0.00	0.00	20.82	14.10	11.34	11.34	0.00	0.00	0.00	0.00	1.72	1.72	10.73		
Mole % Nitrogen	1.47	1.47	1.47	77.60	75.23	74.29	74.29	0.00	0.00	0.00	0.00	70.82	70.82	74.07		
Mole % CO2	0.68	0.68	0.68	0.03	3.18	4.48	4.48	0.00	0.00	0.00	0.00	8.98	8.98	4.77		
Mole % Methane	87.08	87.08	87.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Mole % Hydrogen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Mole % Argon	0.00	0.00	0.00	0.93	0.91	0.89	0.89	0.00	0.00	0.00	0.00	0.85	0.85	0.89		
Mole % Ethane	7.83	7.83	7.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Mole % Propane	2.94	2.94	2.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Mole % H2O	0.00	0.00	0.00	0.61	6.58	9.00	9.00	100.00	100.00	100.00	100.00	17.63	17.63	9.54		
Molar rate (kmol/hr)	1423	612	726	49226	50676	51338	51341	37618	24484	13134	37618	9106	9106	241170		

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01	09/06/15	FIRST ISSUE	RR	TA	TA

REVISIONS

CCS BENCHMARK REFRESH 2013

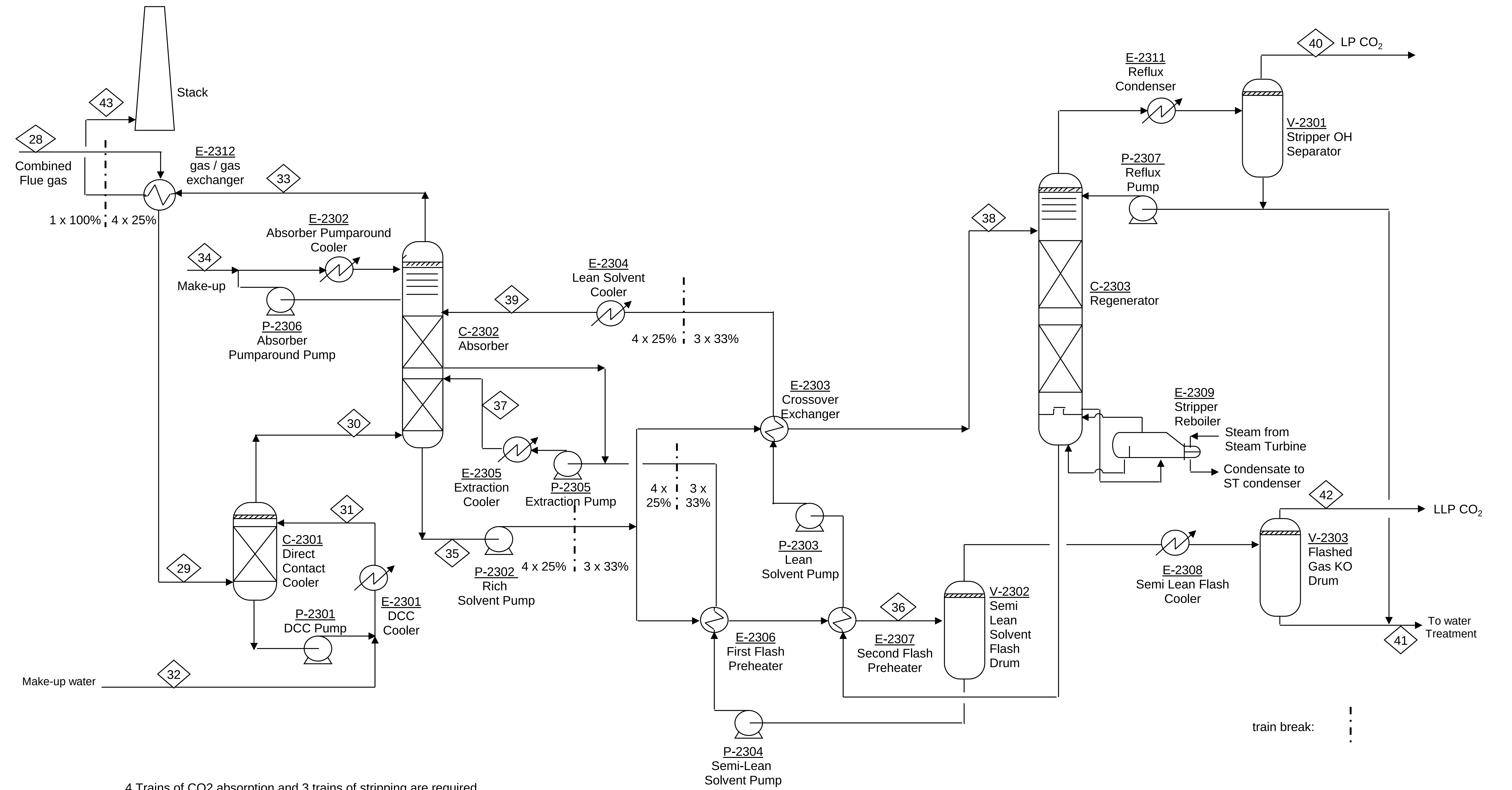
UNIT 2000
ICP Power and Steam Generation

amec foster wheeler

CASE:
CCGT and Independent Capture Plant with 90% Post Combustion CO2 Capture

DWG. NO.: XXXX-XX-XXX

REV: O1



4 Trains of CO2 absorption and 3 trains of stripping are required
Flows shown below are for the full facility capacity

Stream	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
Pressure (kPa)	115	110	415	485	103	110	110	130	348	453	140	138	110	110	102
Temperature (°C)	82	50	30	50	41	10	52	103	30	93	30	30	32	35	96
Mass rate (kg/h)	6838561	6918403	504000	79842	6182919	89280	10707682	3212305	9925713	7495378	6897600	402790	172495	58011	6182919
Mole % CO2	4.77	4.68	0.00	0.00	0.50	0.00	5.01	5.01	3.89	5.01	2.25	96.88	0.06	94.80	0.50
Mole % Oxygen	10.73	10.54	0.00	0.00	11.64	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	11.64
Mole % Nitrogen	74.07	72.73	0.00	0.00	80.34	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.07	80.34
Mole % Argon	0.89	0.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % MEA	0.00	0.00	0.00	0.00	0.00	0.00	10.77	10.77	11.16	10.77	11.53	0.00	0.49	0.00	0.00
Mole % H2O	9.54	11.17	100.00	100.00	7.52	100.00	84.22	84.22	84.96	84.22	86.22	3.09	99.45	5.12	7.52
Molar rate (kmol/hr)	241170	245602	27976	4432	222361	4956	447011	134103	416509	312908	292713	9323	9457	1360	222361

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CCS BENCHMARK REFRESH 2013

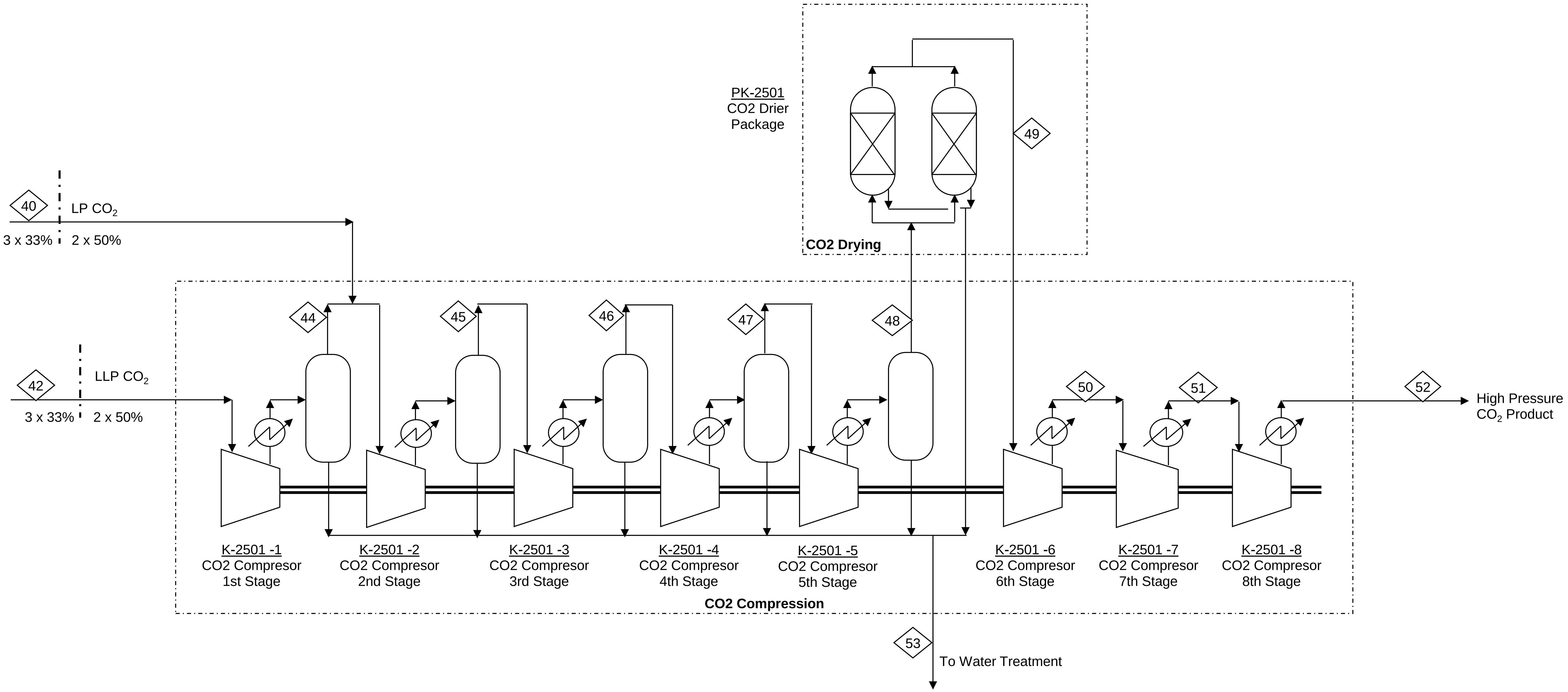
UNIT 2300
Acid Gas Removal

amec foster wheeler

CASE:
CCGT and Independent Capture Plant with 90% Post Combustion CO2 Capture

DWG. NO.: XXXX-XX-XXX

REV: O1



2 Trains of CO2 Compression and Drying are Required
Flows shown below are for the full facility capacity

Stream Name	44	45	46	47	48	49	50	51	52	53
Pressure (kPa)	138	270	530	1140	2490	2390	5490	9990	15090	138
Temperature (°C)	24	24	24	24	24	25	24	55	30	24
Mass rate (kg/h)	57271	456477	455467	505307	505034	504657	454191	454191	454191	6477
Mole % CO2	97.74	98.83	99.36	99.65	99.78	99.96	99.96	99.96	99.96	0.24
Mole % Oxygen	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00
Mole % Nitrogen	0.07	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.00
Mole % MEA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % H2O	2.17	1.13	0.60	0.31	0.18	0.00	0.00	0.00	0.00	99.76
Molar rate (kmol/hr)	1319	10443	10387	11504	11489	11468	10322	10322	10322	358

REV	DATE	TITLE	BY	CHK	APP
01	09/06/15	FIRST ISSUE	RR	TA	TA

REVISIONS

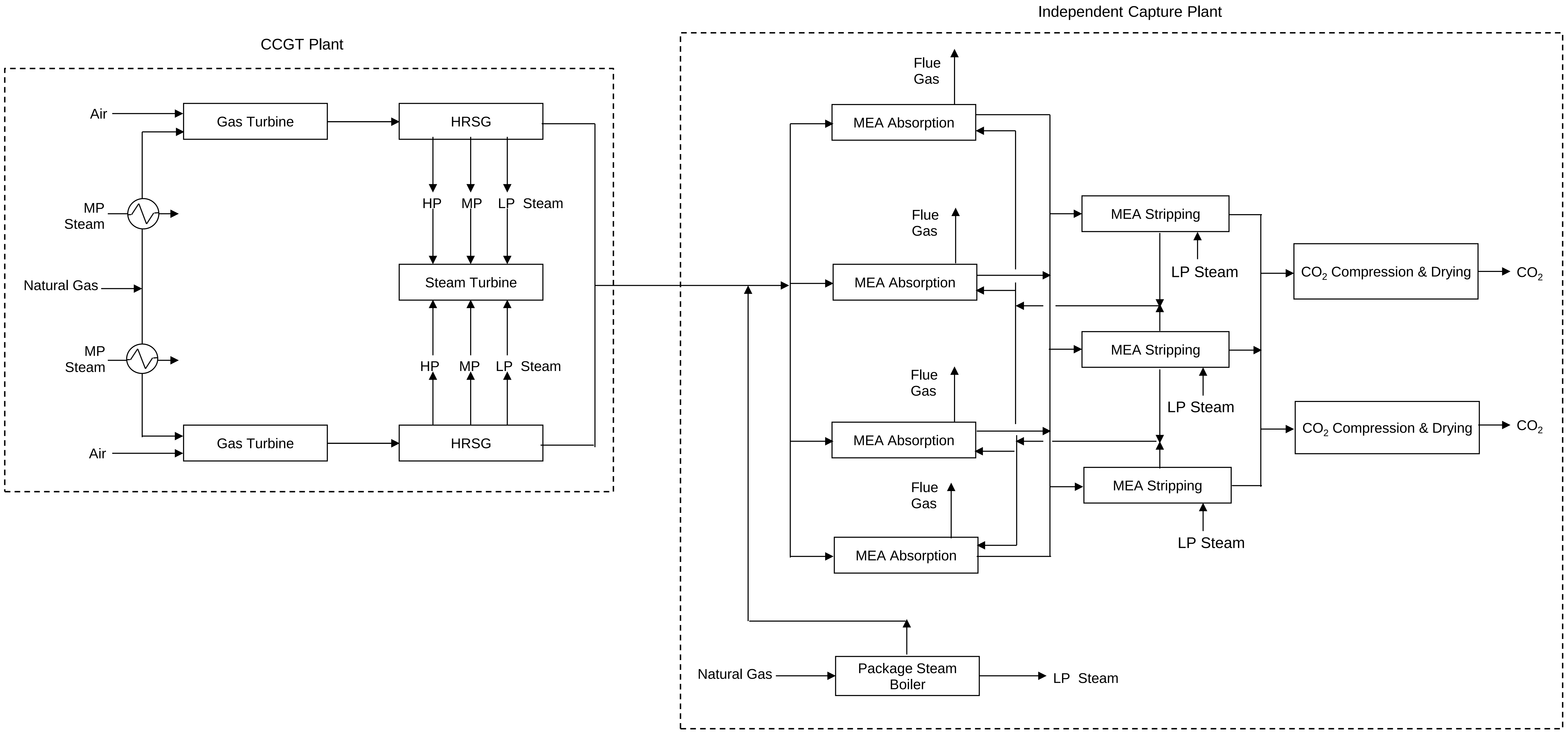
CCS BENCHMARK REFRESH 2013

UNIT 2500
CO_2 Compression and Drying

amec foster wheeler

CASE:
CCGT and Independent Capture Plant with 90% Post Combustion CO2 Capture

DWG. NO.: XXXX-XX-XXX
REV: O1



01	09/06/15	FIRST ISSUE	RR	TA	TA	
REV	DATE	TITLE	BY	CHK	APP	

REVISIONS

CCS BENCHMARK REFRESH 2013

BLOCK FLOW DIAGRAM

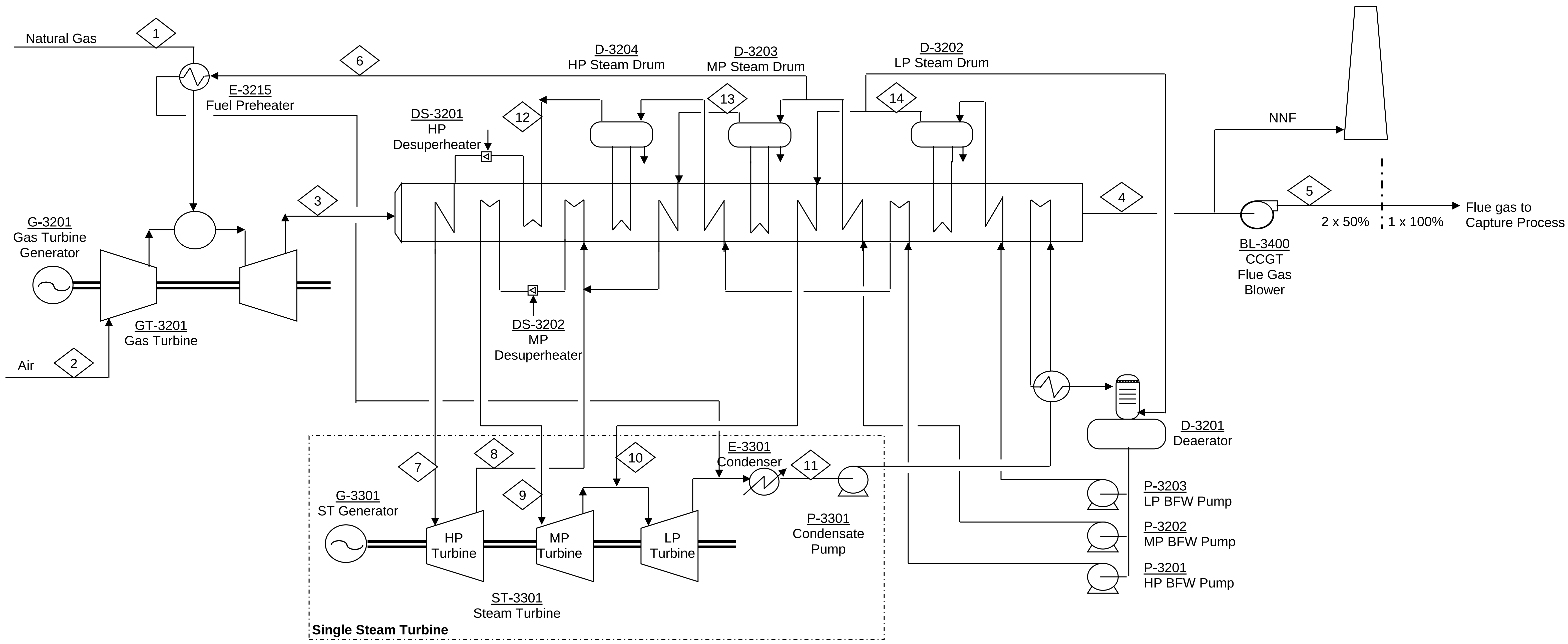
amec foster wheeler

CASE:

CCGT and ICP Sensitivity Case1 with 90% Post Combustion CO2 Capture

DWG. NO.: XXXX-XX-XXX

REV: O1



2 GTs each with own HRSG, deaerator and BFW pumps in parallel
with a single ST and condenser
Flows shown below are for the full facility capacity

Stream Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Pressure (kPa)	3447	101	105	103	125	2918	13980	2801	2689	417	3.5	13980	2918	435
Temperature (°C)	1	10	613	93	116	212	566	327	566	203	24	337	232	147
Mass rate (kg/h)	136002	4991402	5127404	5127404	5127404	83253	598255	598255	698991	64623	846867	598255	100737	84262
Mole % Oxygen	0.00	20.82	11.01	11.01	11.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Nitrogen	1.47	77.60	74.18	74.18	74.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % CO2	0.68	0.03	4.64	4.64	4.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Methane	87.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Hydrogen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Argon	0.00	0.93	0.89	0.89	0.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Ethane	7.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Propane	2.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % H2O	0.00	0.61	9.29	9.29	9.29	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Molar rate (kmol/hr)	7419	173009	180723	180723	180723	4620	33199	33199	38790	3586	33200	33200	5590	4676

REV	DATE	TITLE	BY	CHK	APP
01	09/06/15	FIRST ISSUE	RR	TA	TA

REVISIONS

CCS BENCHMARK REFRESH 2013

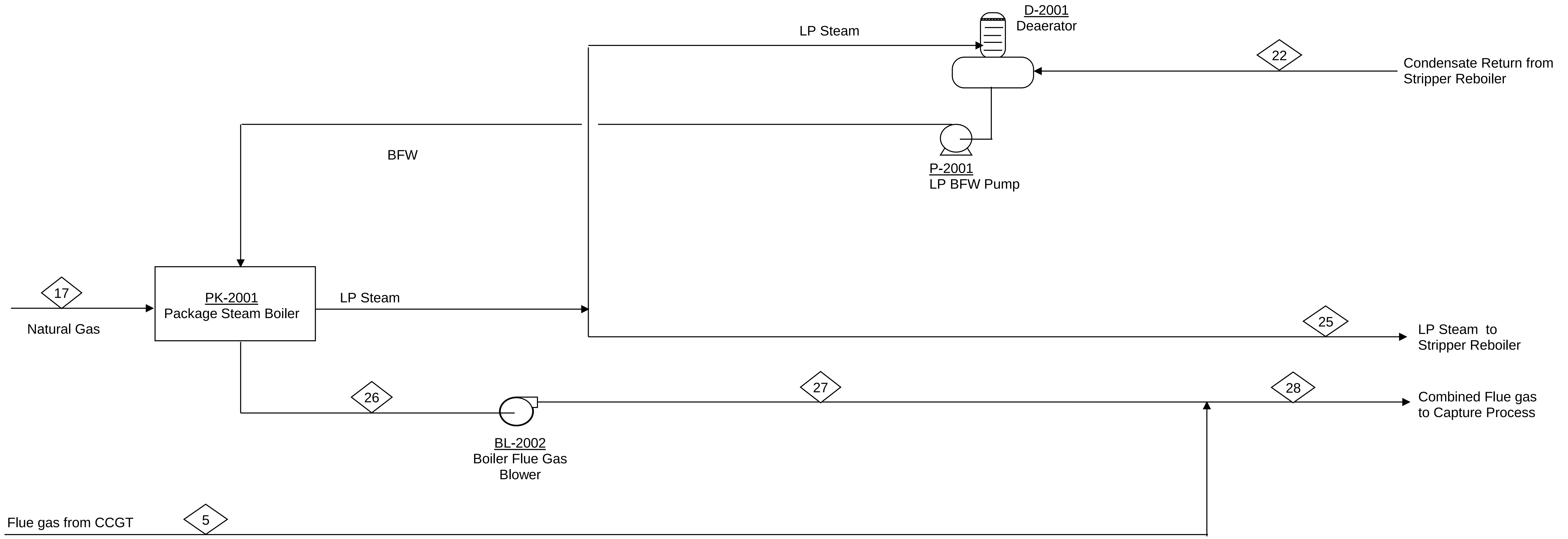
UNIT 3200/3300/3400
CCGT Power Generation

CASE:
CCGT and ICP Sensitivity Case1 with 90% Post Combustion CO2 Capture

amec foster wheeler

DWG NO.: XXXX-XX-XXX

REV: O1



1 Auxiliary Package Steam Boiler, deaerator and BFW pump
Flows shown below are for the full facility capacity

Stream Name	17	22	25	26	27	28	
Pressure (kPa)	3447	400	417	101	125	125	
Temperature (°C)	1	133	293	130	157	121	
Mass rate (kg/h)	34098	606960	606960	649865	649865	5777269	
Mole % Oxygen	0.00	0.00	0.00	1.72	1.72	9.95	
Mole % Nitrogen	1.47	0.00	0.00	70.82	70.82	73.79	
Mole % CO2	0.68	0.00	0.00	8.98	8.98	5.14	
Mole % Methane	87.08	0.00	0.00	0.00	0.00	0.00	
Mole % Hydrogen	0.00	0.00	0.00	0.00	0.00	0.00	
Mole % Argon	0.00	0.00	0.00	0.85	0.85	0.88	
Mole % Ethane	7.83	0.00	0.00	0.00	0.00	0.00	
Mole % Propane	2.94	0.00	0.00	0.00	0.00	0.00	
Mole % H2O	0.00	100.00	100.00	17.63	17.63	10.24	
Molar rate (kmol/hr)	1860	33683	33683	23329	23329	204052	

01	09/06/15	FIRST ISSUE	RR	TA	TA	
REV	DATE	TITLE	BY	CHK	APP	

REVISIONS

CCS BENCHMARK REFRESH 2013

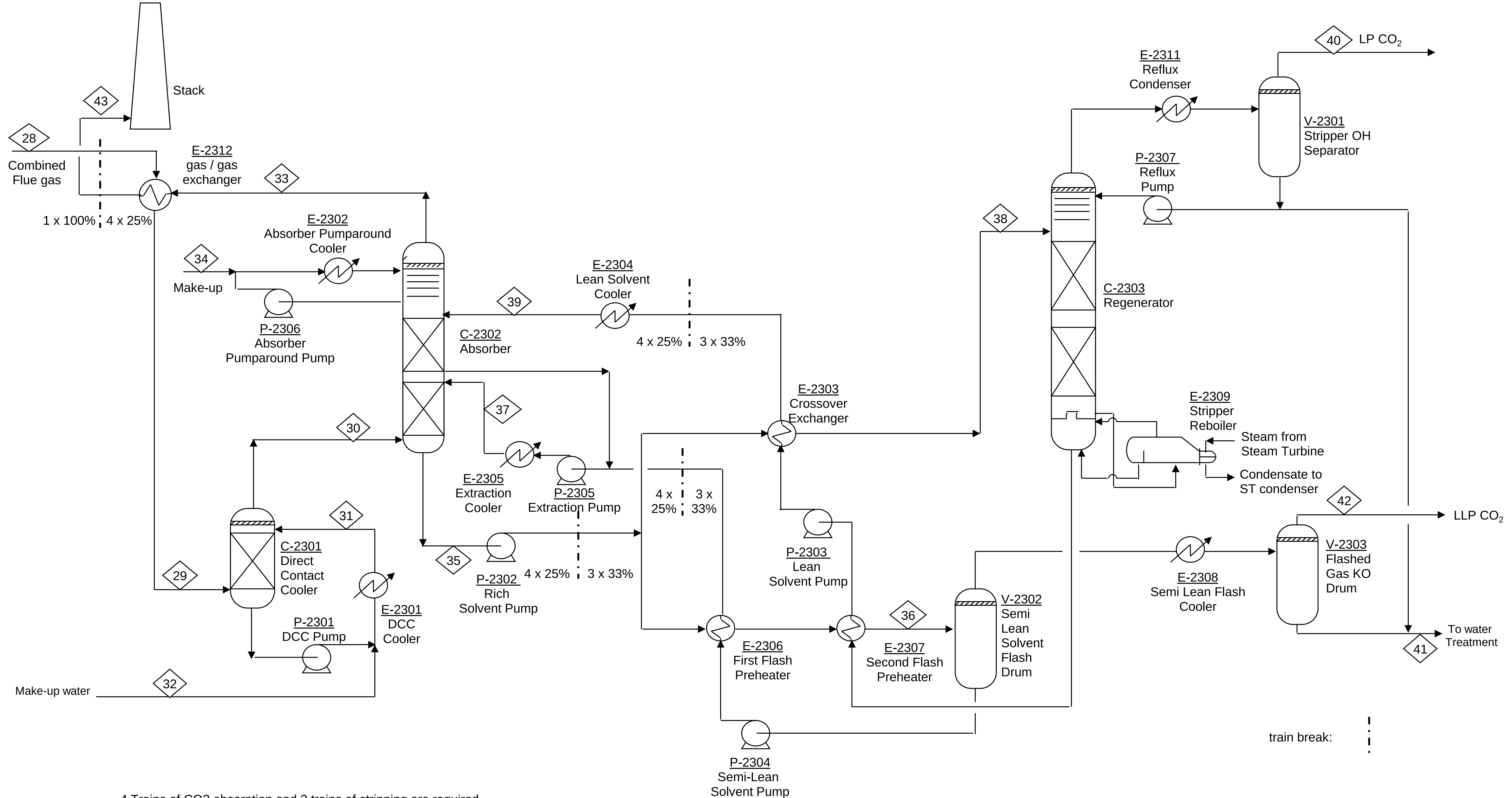
UNIT 2000
ICP Steam Generation

amec foster wheeler

CASE:
CCGT and ICP Sensitivity Case1 with 90% Post Combustion CO2 Capture

DWG. NO.: XXXX-XX-XXX

REV: O1



4 Trains of CO2 absorption and 3 trains of stripping are required
Flows shown below are for the full facility capacity

Stream	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
Pressure (kPa)	115	110	415	485	103	110	110	130	348	453	140	138	110	110	102
Temperature (°C)	82	50	30	52	40	10	52	103	30	93	30	30	32	35	86
Mass rate (kg/h)	5777269	5815780	1152000	38511	5148514	82800	9779475	2933843	9044013	6845633	6300000	365395	160676	54342	5148514
Mole % CO2	5.14	5.08	0.00	0.00	0.49	0.00	5.04	5.04	3.87	5.04	2.25	96.88	0.06	94.80	0.49
Mole % Oxygen	9.95	9.84	0.00	0.00	10.96	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	10.96
Mole % Nitrogen	73.79	73.02	0.00	0.00	81.32	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.07	81.32
Mole % Argon	0.88	0.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % MEA	0.00	0.00	0.00	0.00	0.00	0.00	10.77	10.77	11.16	10.77	11.53	0.00	0.50	0.00	0.00
Mole % H2O	10.24	11.17	100.00	100.00	7.23	100.00	84.19	84.19	84.97	84.19	86.22	3.09	99.44	5.12	7.23
Molar rate (kmol/hr)	204052	206190	63945	2138	185163	4596	408094	122428	379582	285666	267353	8458	8807	1274	185163

REV	DATE	TITLE	BY	CHK	APP
01	09/06/15	FIRST ISSUE	RR	TA	TA

REVISIONS

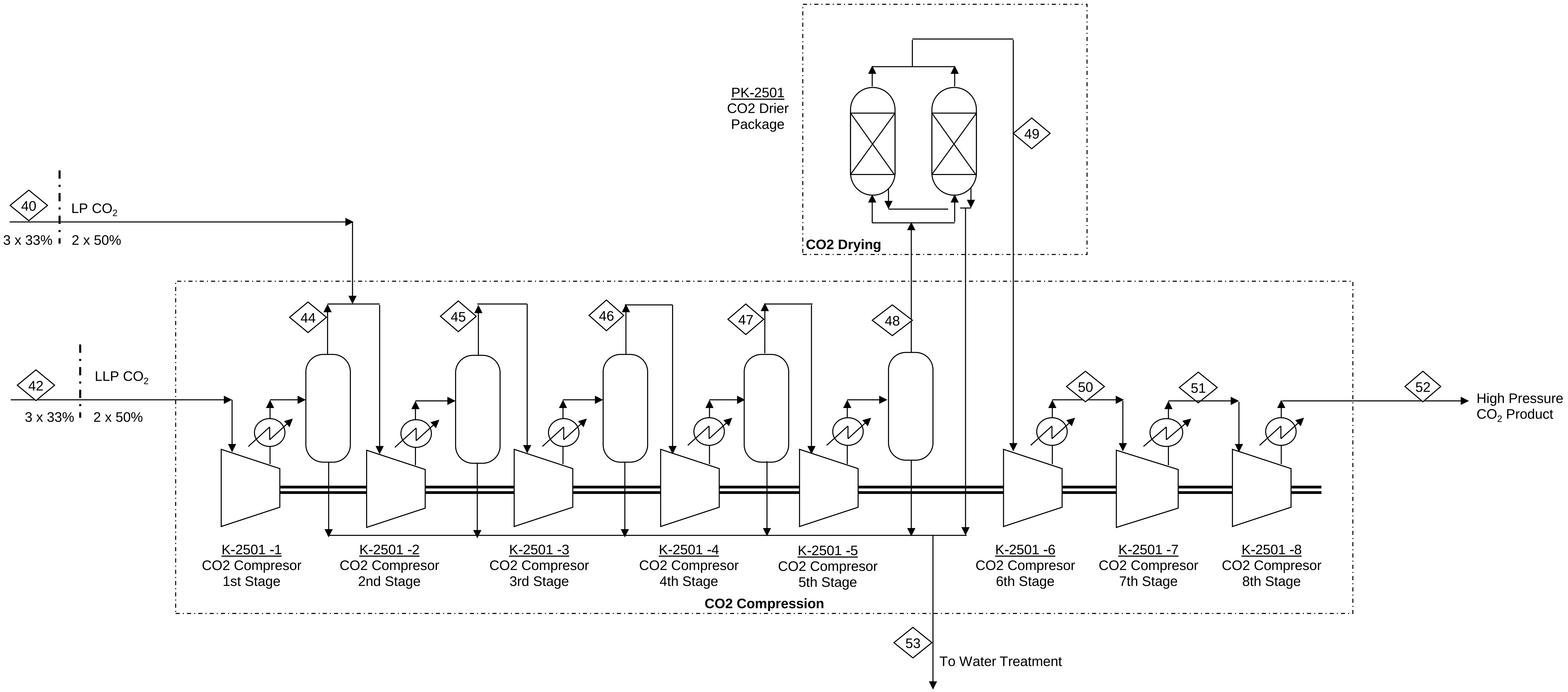
CCS BENCHMARK REFRESH 2013

UNIT 2300
Base Case Acid Gas Removal

CASE:
CCGT and ICP Sensitivity Case1 with 90% Post Combustion CO2 Capture

amec foster wheeler

DWG. NO.: XXXX-XX-XXX
REV: O1



2 Trains of CO2 Compression and Drying are Required
Flows shown below are for the full facility capacity

Stream Name	44	45	46	47	48	49	50	51	52	53
Pressure (kPa)	138	270	530	1140	2490	2390	5490	9990	15090	138
Temperature (°C)	24	24	24	24	24	25	24	55	30	24
Mass rate (kg/h)	53649	415786	414866	460336	460087	459744	413770	413770	413770	5914
Mole % CO2	97.75	98.83	99.36	99.65	99.78	99.96	99.96	99.96	99.96	0.24
Mole % Oxygen	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00
Mole % Nitrogen	0.07	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.00
Mole % MEA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % H2O	2.17	1.13	0.60	0.31	0.18	0.00	0.00	0.00	0.00	99.76
Molar rate (kmol/hr)	1235	9512	9461	10480	10467	10448	9403	9403	9403	327

REV	DATE	TITLE	BY	CHK	APP
01	09/06/15	FIRST ISSUE	RR	TA	TA

REVISIONS

CCS BENCHMARK REFRESH 2013

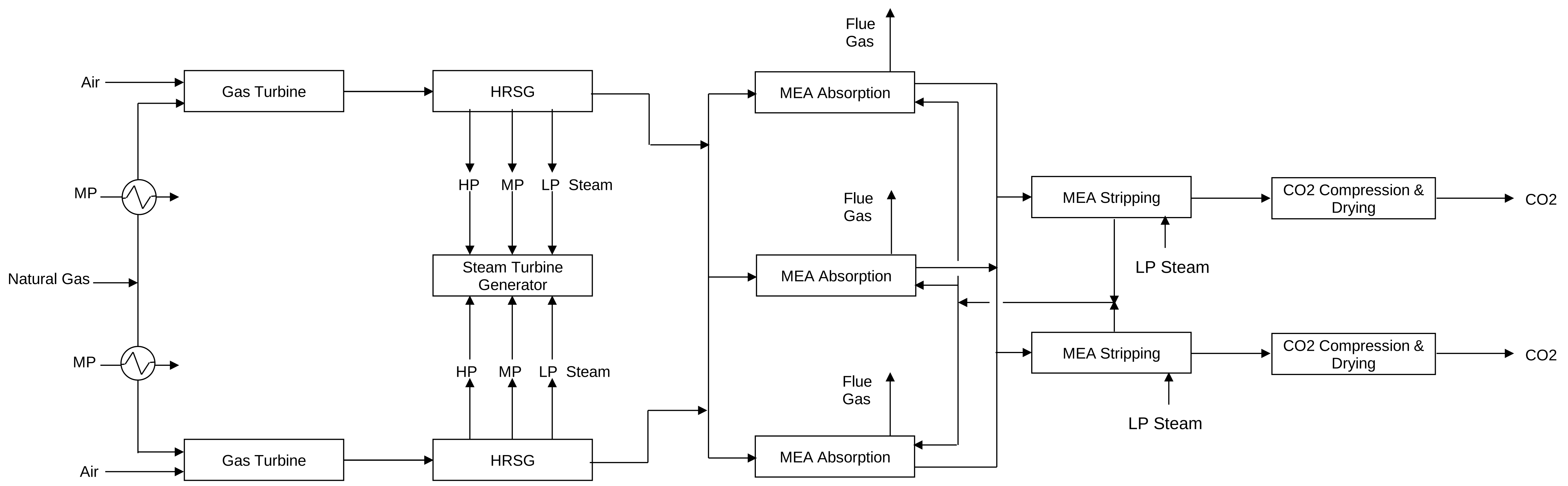
UNIT 2500
CO_2 Compression and Drying

amec foster wheeler

CASE:
CCGT and ICP Sensitivity Case1 with 90% Post Combustion CO2 Capture

DWG. NO.: XXXX-XX-XXX

REV: O1



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01	09/08/13	FIRST ISSUE	SEF	TA	TA	
REV	DATE	TITLE	BY	CHK	APP	

REVISIONS

CCS BENCHMARK REFRESH 2013

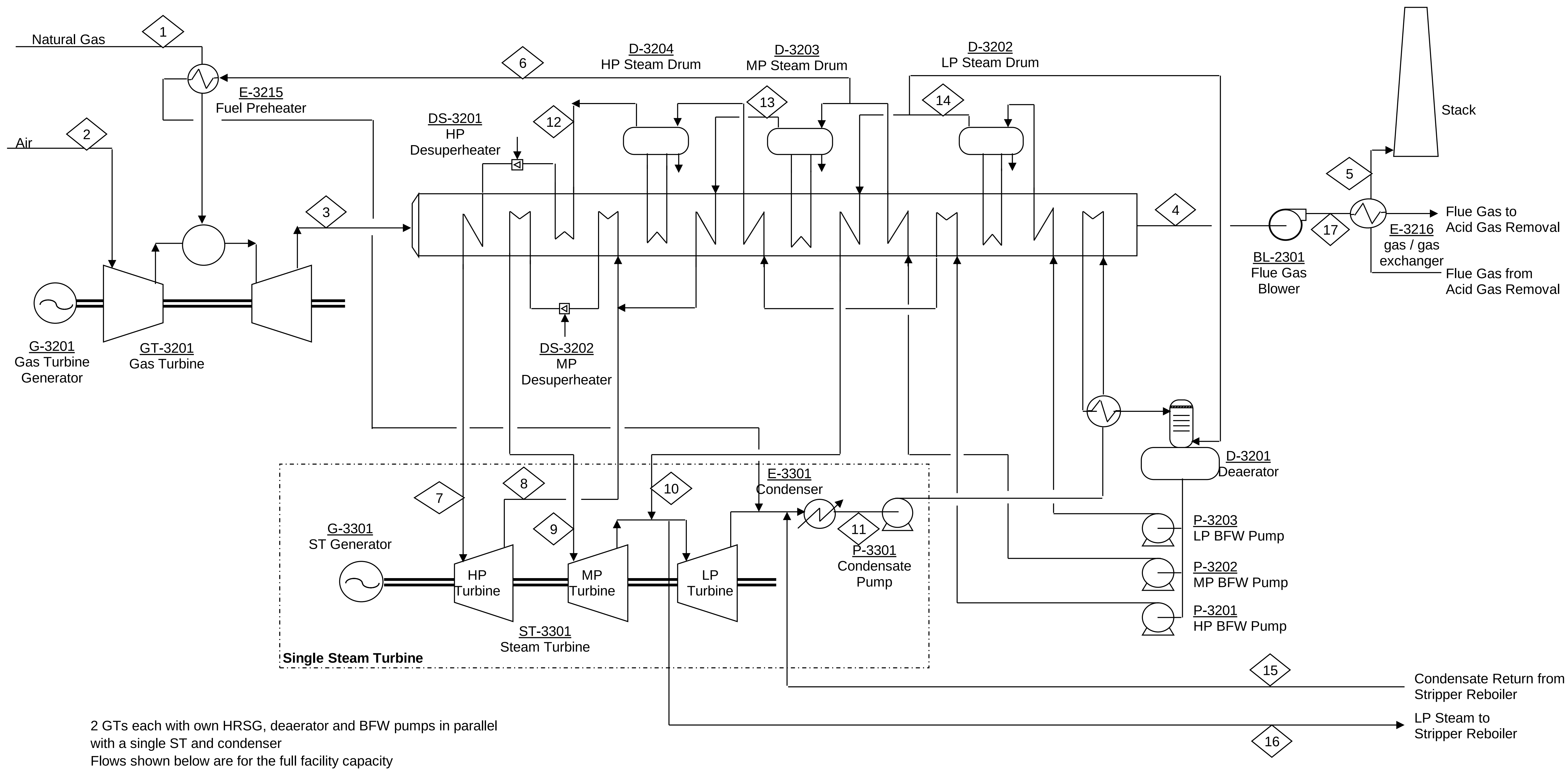
BLOCK FLOW DIAGRAM

FOSTER WHEELER ENERGY

CASE: Natural Gas Combined Cycle Power Plant with 90% Post Combustion CO2 Capture

DWG. NO.: XXXX-XX-XXX

REV: A1



2 GTs each with own HRSG, deaerator and BFW pumps in parallel
with a single ST and condenser
Flows shown below are for the full facility capacity

Stream Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Pressure (kPa)	3447	101	105	103	102	2918	13980	2801	2689	417	3.5	13980	2918	435	400	417
Temperature (°C)	1.0	10.0	613.4	93.3	80.0	212.3	566.0	327.0	565.6	203.4	24.5	336.5	232.3	146.6	133.5	292.6
Mass rate (kg/h)	136002	4991402	5127404	5127404	4660576	83254	598254	598254	698991	64623	846868	598254	100737	84262	493200	493200
Mole % Oxygen	0.00	20.82	11.01	11.01	11.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Nitrogen	1.47	77.60	74.18	74.18	79.96	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % CO2	0.68	0.03	4.64	4.64	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Methane	87.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Hydrogen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Argon	0.00	0.93	0.89	0.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Ethane	7.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % Propane	2.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % H2O	0.00	0.61	9.29	9.29	7.67	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Molar rate (kmol/hr)	7419	173009	180723	180723	167647	4620	33199	33199	38790	3586	46996	33199	5590	4676	27370	27370

REV	DATE	TITLE	BY	CHK	APP
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CCS BENCHMARK REFRESH 2013

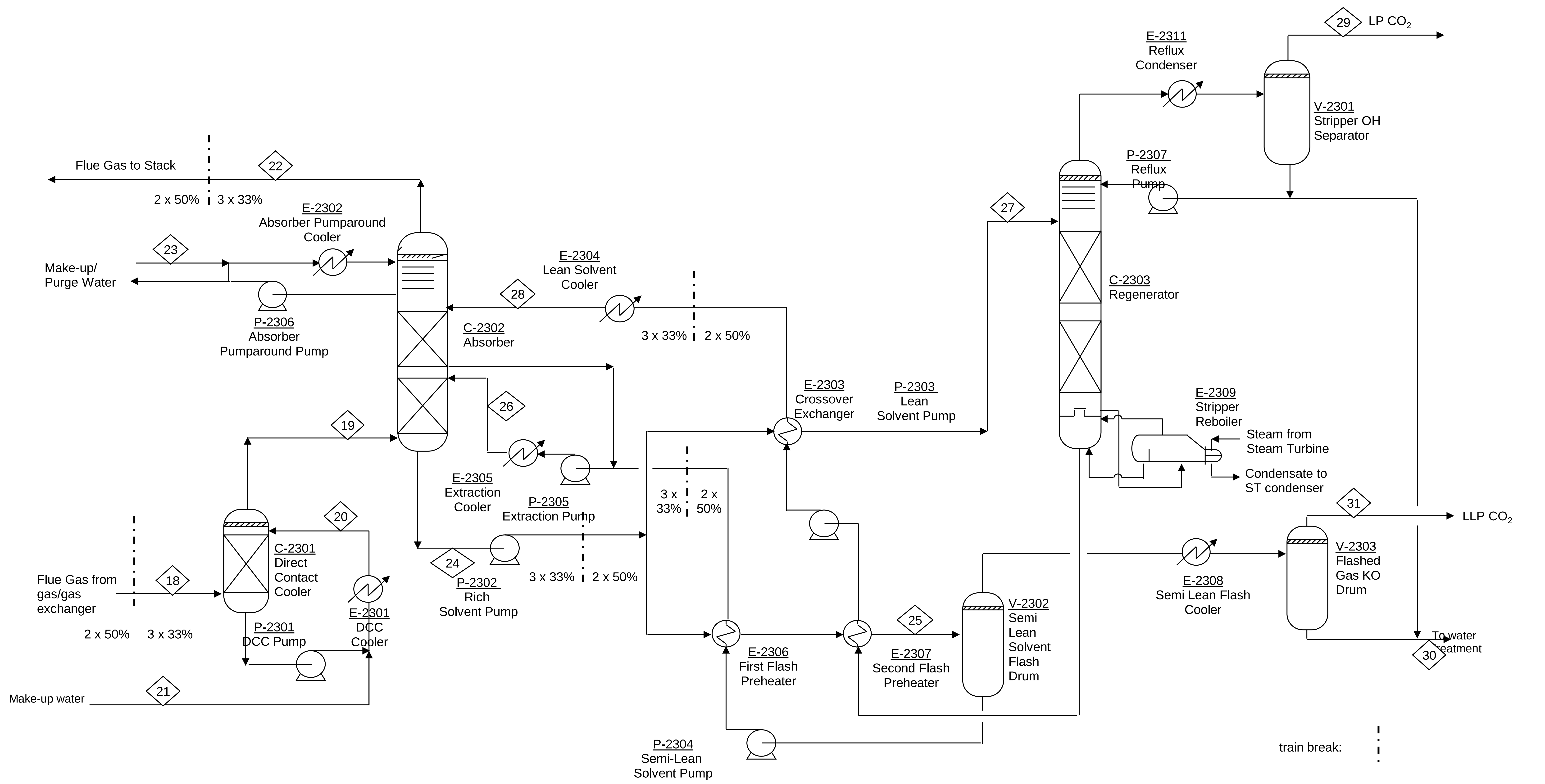
UNIT XXXX
Power Generation

FOSTER WHEELER ENERGY

CASE: Natural Gas Combined Cycle Power Plant with 90% Post Combustion CO2 Capture

DWG. NO.: XXXX-XX-XXX

REV: A1



3 Trains of CO2 absorption, 2 trains of stripping and 2 trains of compression are required
Flows shown below are for the full facility capacity

Stream	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Pressure (kPa)	125	115	110	415	485	103	110	110	130	348	453	140	138	110	110
Temperature (°C)	116.4	82.0	49.8	30.0	50.1	41.3	10.0	51.8	103.0	30.0	93.0	30.0	30.0	32.4	35.0
Mass rate (kg/h)	5127404	5127404	5195652	144000	68247	4660622	64800	7803777	2341133	7228467	5462644	5029200	292212	125118	42060
Mole % CO2	4.64	4.64	4.54	0.00	0.00	0.50	0.00	5.00	5.00	3.98	5.00	2.25	96.88	0.06	94.80
Mole % Oxygen	11.01	11.01	10.78	0.00	0.00	11.87	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02
Mole % Nitrogen	74.17	74.17	72.65	0.00	0.00	79.96	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.07
Mole % Argon	0.89	0.89	0.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % MEA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.77	10.77	11.17	10.77	11.53	0.00	0.49	0.00
Mole % H2O	9.29	9.29	11.15	100.00	100.00	7.67	100.00	84.22	84.22	84.85	84.22	86.22	3.09	99.45	5.12
Molar rate (kmol/hr)	180723	180723	184511	7993	3788	167650	3597	325748	97724	302968	228023	213424	6764	6859	986

REV	DATE	TITLE	BY	CHK	APP
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CCS BENCHMARK REFRESH 2013

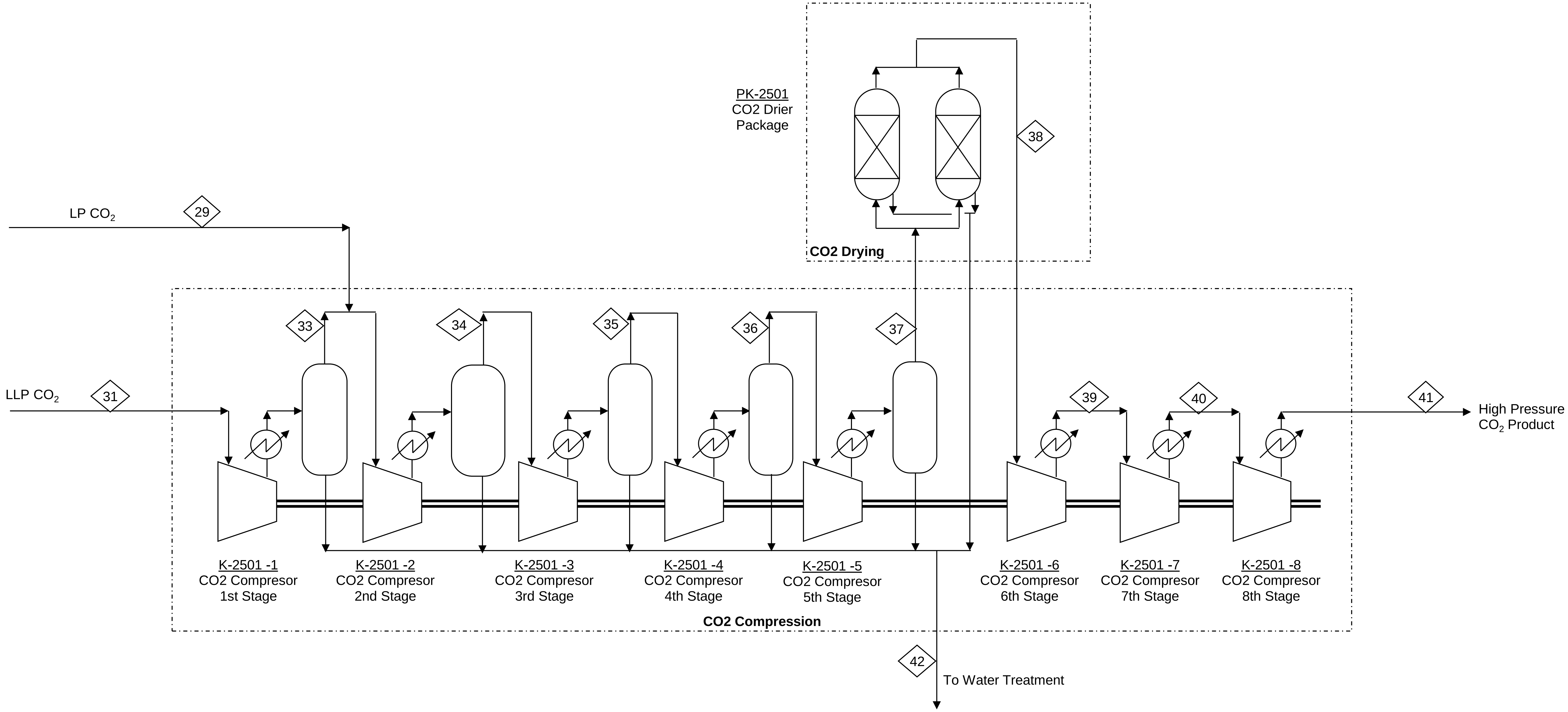
UNIT XXXX
ACID GAS REMOVAL & CO_2 Compr.

FOSTER WHEELER ENERGY

CASE: Natural Gas Combined Cycle Power Plant with 90% Post Combustion CO2 Capture

DWG. NO.: XXXX-XX-XXX

REV.: A1



Flows shown below are for the full facility capacity

Stream Name	33	34	35	36	37	38	39	40	41	42
Pressure (kPa)	138	270	530	1140	2490	2390	5490	9990	15090	138
Temperature (°C)	24.0	24.0	24.0	24.0	24.0	25.0	24.0	55.0	30.0	23.9
Mass rate (kg/h)	41523	331136	330403	366901	366702	366429	329786	329786	329786	4701
Mole % CO2	97.74	98.83	99.36	99.65	99.78	99.96	99.96	99.96	99.96	0.24
Mole % Oxygen	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00
Mole % Nitrogen	0.07	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.00
Mole % MEA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole % H2O	2.17	1.13	0.60	0.31	0.18	0.00	0.00	0.00	0.00	99.76
Molar rate (kmol/hr)	956	7576	7535	8353	8342	8327	7494	7494	7494	260

A1	24/09/13	ISSUED FOR DESIGN	SEF	RR	TA
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REV	DATE	TITLE	BY	CHK	APP

REVISIONS

CCS BENCHMARK REFRESH 2013

UNIT XXXX

ACID GAS REMOVAL & CO_2 Compr.

FOSTER WHEELER ENERGY

CASE:

Natural Gas Combined Cycle Power Plant with 90% Post Combustion CO2 Capture

DWG. NO.: XXXX-XX-XXX

REV: A1

ATTACHMENT 3
UTILITY SUMMARIES

1. CCGT with ICP - Base Case
2. CCGT with ICP Sensitivity Case 1 – Imported Power
3. CCGT with ICP Sensitivity Case 2 – Imported Steam & Power

AMEC FOSTER WHEELER ENERGY LIMITED
UTILITIES BALANCE SUMMARY

CCGT without CO_2 Capture - 100% GT Load

CLIENT:	The Energy Technologies Institute				
CONTRACT:	13191	REV	O1		SHEET
NAME:	CCS Benchmark Refresh - Task 5	DATE	09/06/2015		1 OF 1
		ORIG. BY	RR		
		APP. BY	TA		

	DESCRIPTION	ELECTRIC POWER (kW)	Steam (T/h)			Condensate	Sea Cooling water	Fresh Cooling water	Process Water	Demin water	BFW	REMARKS	REV
		Electric Oper. Load	HP Steam 139 barg	MP Steam 26 barg	LP Steam 3 barg	T/h	T/h	T/h	T/h	T/h	T/h		
	Process Units												
	Acid Gas Removal Unit (MEA)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a		
	CO_2 Compression & Drying	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a		
	Process Units Total	0	0	0	0	0	0	0	0	0	0		
	Power Island												
	Gas Turbine (Note 1)	-8060	0	0	0	0	0	0	0	0	0		
	HRSGs	0	598.3	699.0	64.6	-846.9	0	0	0	8.5	0		
	Steam Turbine (Note 2)	-6469	-598.3	-699.0	-64.6	846.9	-49053	0	0	0	0		
	Power Generation Units (Note 3)	1067991	0.0	0.0	0.0	0.0	0.0	0	0	0	0		
	Power Island Total	1053463	0	0	0	0	-49053	0	0	8.5	0		
	Offsites & Utilities												
	Demin Plant	-25								-8.5			
	Sea Cooling Water	-5608					49053						
	Fresh Cooling Water	0											
	Utility water	0											
	Fire Water System	-40											
	Condensate Treatment	-58											
	Waste Water Treatment	-100											
	Flare	0											
	Storage	0											
	Buildings	-1000											
	Others	0											
	Offsites & Utilities Total	-6831	0	0	0	0	49053	0	0	-8.5	0		
	Grand Total	**1046631**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**		

NOTES
1. Includes auxiliary and transformer losses.
2. Includes Steam and water cycle balance of plant and transformer losses.
3. Net of generator losses

AMEC FOSTER WHEELER ENERGY LIMITED
UTILITIES BALANCE SUMMARY

ICP Base Case with 90% CO_2 Capture

CLIENT: The Energy Technologies Institute
CONTRACT: 13191
NAME: CCS Benchmark Refresh - Task 5

REV	O1					SHEET
DATE	09/06/2015					1 OF 1
ORIG. BY	RR					
APP. BY	TA					

DESCRIPTION	ELECTRIC POWER (kWh/h)	Steam (T/h)			Condensate	Sea Cooling water	Fresh Cooling water	Process Water	Demin water	BFW	REMARKS	REV
	Electric Oper. Load	HP Steam 139 barg	MP Steam 26 barg	LP Steam 3 barg	T/h	T/h	T/h	T/h	T/h	T/h		
Process Units												
Acid Gas Removal Unit (MEA)	-56384	0	0	-678	678	0	-52710	0	0	0	Note 3	
CO_2 Compression & Drying	-43706	0	0	0	0	0	-6560	0	0	0		
Process Units Total	-100089	0	0	-678	678	0	-59269	0	0	0		
Power Island												
Gas Turbine (Note 1)	-1763	0	0	0	0	0	0	0	0	0		
HRSGs	0	0	0	441	-441	0	0	0	-6.8	0		
BFW Pump	-108											
Package Steam Boiler	0			237	-237							
Power Generation Units (Note 2)	112682	0	0	0	0	0	0	0	0	0		
Power Island Total	110811	0	0	678	-678	0	0	0	-6.8	0		
Offsites & Utilities												
Demin Plant	-25								6.8			
Sea Cooling Water	-8517					74054						
Fresh Cooling Water	-3414					-74054	59269					
Utility water	-12							0				
Fire Water System	-40											
Condensate Treatment	-58											
Waste Water Treatment	-100											
Flare	0											
Storage	0											
Buildings	-600											
Others	0											
Offistes & Utilities Total	-12766	0	0	0	0	0	59269	0	6.8	0		
Grand Total	**-2044**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**		

NOTES
1. Includes auxiliary and transformer losses.
2. Net of generator losses
3. 84 tph intermittent LPS required during solvent reclaimation mode.

AMEC FOSTER WHEELER ENERGY LIMITED
UTILITIES BALANCE SUMMARY

ICP Sensitivity Case 1 with 90% CO_2 Capture

CLIENT:	The Energy Technologies Institute											
CONTRACT:	13191	REV			O1						SHEET	
NAME:	CCS Benchmark Refresh - Task 5	DATE			09/06/2015						1 OF 1	
		ORIG. BY			RR							
		APP. BY			TA							

	DESCRIPTION	ELECTRIC POWER (kWh/h)	Steam (T/h)			Condensate	Sea Cooling water	Fresh Cooling water	Process Water	Demin water	BFW	REMARKS	REV
		Electric Oper. Load	HP Steam 139 barg	MP Steam 26 barg	LP Steam 3 barg	T/h	T/h	T/h	T/h	T/h	T/h		
	Process Units												
	Acid Gas Removal Unit (MEA)	-46710	0	0	-607	607	0	-48982	0	0	0	Note 3	
	CO_2 Compression & Drying	-39791	0	0	0	0	0	-5985	0	0	0		
	Process Units Total	-86501	0	0	-607	607	0	-54967	0	0	0		
	Power Island												
	Gas Turbine (Note 1)	0	0	0	0	0	0	0	0	0	0		
	HRSGs	0	0	0	0	0	0	0	0	6.1	0		
	BFW Pump	-269											
	Package Steam Boiler	0			607	-607							
	Power Generation Units (Note 2)	0	0	0	0	0	0	0	0	0	0		
	Power Island Total	-269	0	0	607	-607	0	0	0	6	0		
	Offsites & Utilities												
	Demin Plant	-25								-6.1			
	Sea Cooling Water	-7899					68679						
	Fresh Cooling Water	-3165					-68679	54967					
	Utility water	-12							0				
	Fire Water System	-40											
	Condensate Treatment	-58											
	Waste Water Treatment	-100											
	Flare	0											
	Storage	0											
	Buildings	-600											
	Others	0											
	Offsites & Utilities Total	-11899	0	0	0	0	0	54967	0	-6.1	0		
	Grand Total	**-98669**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**		

NOTES 1. Includes auxiliary and transformer losses.
2. Net of generator losses
3. 84 tph intermittent LPS required during solvent reclaimation mode.

AMEC FOSTER WHEELER ENERGY LIMITED
UTILITIES BALANCE SUMMARY

ICP Sensitivity Case 2 with 90% CO_2 Capture

CLIENT: The Energy Technologies Institute
CONTRACT: 13191
NAME: CCS Benchmark Refresh - Task 5

REV	O1					SHEET
DATE	09/06/2015					1 OF 1
ORIG. BY	RR					
APP. BY	TA					

DESCRIPTION	ELECTRIC POWER (kWh/h)	Steam (T/h)			Condensate	Sea Cooling water	Fresh Cooling water	Process Water	Demin water	BFW	REMARKS	REV
	Electric Oper. Load	HP Steam 139 barg	MP Steam 26 barg	LP Steam 3 barg	T/h	T/h	T/h	T/h	T/h	T/h		
Process Units												
Acid Gas Removal Unit (MEA)	-40023	0	0	-495	495	0	-37846	0	0	0	Note 3	
CO_2 Compression & Drying	-31731	0	0	0	0	0	-4768	0	0	0		
Process Units Total	-71754	0	0	-495	495	0	-42614	0	0	0		
Power Island												
Gas Turbine (Note 1)	0	0	0	0	0	0	0	0	0	0		
HRSGs	0	0	0	0	0	0	0	0	0.0	0		
BFW Pump	0											
Package Steam Boiler	0			0	0							
Power Generation Units (Note 2)	0	0	0	0	0	0	0	0	0	0		
Power Island Total	0	0	0	0	0	0	0	0	0	0		
Offsites & Utilities												
Demin Plant	-25								0.0			
Sea Cooling Water	-3246					53244						
Fresh Cooling Water	-2451					-53244	42614					
Utility water	-12							0				
Fire Water System	-40											
Condensate Treatment	-58											
Waste Water Treatment	-100											
Flare	0											
Storage	0											
Buildings	-600											
Others	0											
Offsites & Utilities Total	-6532	0	0	0	0	0	42614	0	0.0	0		
Grand Total	**-78286**	**0**	**0**	**-495**	**495**	**0**	**0**	**0**	**0**	**0**		

NOTES
1. Includes auxiliary and transformer losses.
2. Net of generator losses
3. 84 tph intermittent LPS required during solvent reclaimation mode.

ATTACHMENT 4
EQUIPMENT LISTS

1. CCGT with ICP – Base Case
2. CCGT with ICP – Imported Power Items
3. CCGT with ICP – Imported Steam & Power Items

amec foster wheeler	CLIENT: ETI PROJECT TITLE: CCS BENCHMARK REFRESH 2013 CONTRACT: 13191	REVISION	O1			
		DATE	Apr-15			
		BY	RR			
		CHECKED	TA			
		APPROVED	TA			

CASE: Independent Capture Plant Base Case with 90% Post Combustion CO2 Capture

Train	Item	Description	Specification	Remarks
1	GT-2001	Gas Turbine (1 x 100% Train)	112.68 MWe Output Turbine generator	Alstom GT11N2 machine
1		Duct Burner (1)		
1		HRSG (1 x 100% Train)	316 MW Duty (3 Coils)	
1	D-2001	Deaerator (1 x 100% Train)	689 tph	part of HRSG package
1	P-2001 A/B	LP BFW Pumps (2 x 100% Train)	102.4 kW 686.5 m3/h, 2.49 bara suction, 5.8 bara discharge, CS	
1	D-2001	LP Steam Drum (1 x 100% Train)	442 tph	part of HRSG package
1		Stack (1 x 100%)	6182.9 tph flue gas @ 96 oC and 1.02 bara	
1	PK-2001	Package Steam Boiler	236.7 tph LP Steam @ 293 oC and 4.17 bara	

amec foster wheeler

EQUIPMENT LIST - CCGT with Independent Capture Plant (Base Case)

		REV	BY	APPROVED	DATE
UNIT NAME:	MEA Unit & CO2 Compression	ORIG			
		01	RR	TA	01/04/2015
UNIT No.:	2300/2500	02	RR	TA	11/09/2015
		03			
CLIENT:	The Energies Technology Institute				
PROJECT:	CCS BENCHMARK REFRESH 2013				
CONTRACT	13191				
DOCUMENT No.:					
CASE SUMMARY	Independent Capture Plant with 90% Post Combustion CO2 Capture				

NOTES

amec foster wheeler	**EQUIPMENT LIST FOR COMPRESSORS**	**Rev.**	**ORIG**	**REV 01**	**REV 02**	
	Client: The Energies Technology Institute **Contract No:** 13191	**Ch'd**	RR			**SHEET** 2 **of** 8
	Description: CCS BENCHMARK REFRESH 2013	**App.**	TA			
	Unit No: 2300/2500 MEA Unit & CO2 Compression	**Date**	01/04/2015			

EQUIPMENT NUMBER	DESCRIPTION	COMPRESSOR TYPE(1)/ SUB-TYPE	No.off x DUTY %	DRIVE TYPE OP./SPARE	ACTUAL CAPACITY m^3/hr	Cp/Cv INLET/ OUTLET	DIFF. PRESS. bar	PRESSURE INLET/OUTLET bara bara	TURB.DRIVE STEAM PRESS. barg	COMPRESSIBILITY INLET/OUTLET	POWER EST/RATED kW	MATERIAL CASING	MOLECULAR WEIGHT	REMARKS	REV
1/2 BL-3400	CCGT Flue Gas Blower	Blower	2 x 50%	electric	2,663,257	1.379 / 1.376	0.22	1.03 / 1.25	n/a	0.999 / 0.999	17683	304 SS	28.4	**Unit 3400 CCGT Mods**	
BL-2001	GT Flue Gas Blower	Blower	1 x 100%	electric	881,442	1.372 / 1.369	0.23	1.02 / 1.25	n/a	1.000 / 1.000	6172	305 SS	28.4	**Unit 2000 ICP Power Island**	
BL-2002	Boiler Flue Gas Blower	Blower	1 x 100%	electric	150,582	1.361 / 1.358	0.24	1.01 / 1.25	n/a	0.999 / 0.999	1082	306 SS	27.9	**Unit 2000 ICP Power Island**	
1/2 K-2501-1	CO2 Compressor Stage 1	Centrifugal	2 x 50%	electric	15,744	1.287 / 1.278	0.4	1.1 / 1.5	n/a	0.994 / 0.994	179	304 SS	42.7		
1/2 K-2501-2	CO2 Compressor Stage 2	Centrifugal	2 x 50%	electric	96,220	1.286 / 1.272	1.4	1.4 / 2.8	n/a	0.992 / 0.991	3448	304 SS	43.2		
1/2 K-2501-3	CO2 Compressor Stage 3	Centrifugal	2 x 50%	electric	47,047	1.296 / 1.284	2.7	2.7 / 5.4	n/a	0.985 / 0.983	3226	304 SS	43.7		
1/2 K-2501-4	CO2 Compressor Stage 4	Centrifugal	2 x 50%	electric	23,483	1.313 / 1.304	6.2	5.3 / 11.5	n/a	0.970 / 0.966	3569	CS	43.8		
1/2 K-2501-5	CO2 Compressor Stage 5	Centrifugal	2 x 50%	electric	11,649	1.360 / 1.362	13.6	11.4 / 25.0	n/a	0.934 / 0.928	3867	CS	43.9		
1/2 K-2501-6	CO2 Compressor Stage 6	Centrifugal	2 x 50%	electric	4,598	1.493 / 1.512	31.1	23.9 / 55.0	n/a	0.859 / 0.856	3428	CS	44.0		
1/2 K-2501-7	CO2 Compressor Stage 7	Centrifugal	2 x 50%	electric	1,398	2.883 / 2.439	45.1	54.9 / 100.0	n/a	0.602 / 0.645	1721	CS	44.0		
1/2 K-2501-8	CO2 Compressor Stage 8	Centrifugal	2 x 50%	electric	705	4.318 / 2.887	51.1	99.9 / 151.0	n/a	0.500 / 0.578	1094	CS	44.0		

Notes: **1. AC - Air Compressor GC - Gas Compressor FN - Fan**

	EQUIPMENT LIST FOR VESSELS				Rev.	ORIG	REV 01	REV 02	
	Client:	The Energies Technology Institute	Contract No:	13191	Ch'd	RR			SHEET 3 of 8
	Description:	CCS BENCHMARK REFRESH 2013			App.	TA			
	Unit No:	2300/2500	MEA Unit & CO2 Compression		Date	01/04/2015			

EQUIPMENT NUMBER	DESCRIPTION	VESSEL TYPE(1)/ SUB-TYPE	No.off x DUTY %	DIMENSIONS ID m	DIMENSIONS HEIGHT T/T m	TOTAL VOLUME m^3	V/H (2)	DESIGN CONDITIONS TEMP ^oC	DESIGN CONDITIONS PRESS barg	DESIGN CONDITIONS VACUUM FVPRESS bara	INTERNALS TYPE/No.OFF PACKED VOL. m^3 / PACKED HGT mm	MATERIALS OF CONST'N SHELL MAT./LINING/ CA	MATERIALS OF CONST'N INTERNALS MAT./LINING/ CA	REMARKS	REV
1/2/3/4 C-2301	Direct contact cooler	TW	4 x 25%	14.82	29.64	5965	V	107	3.5	1.013	Random Packing 916 10000	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding	Packing: 10m Mellapak 250X	
1/2/3/4 C-2302	Absorption Column	TW	4 x 25%	15.56	27.00	6123	V	75	3.5	1.013	Random Packing 2670 / 390 14000 / 2000	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding	Packing: 14m Mellapak 250X / 2m Mellapak 250Y	
1/2/3 C-2303	Stripper Column	TW	3 x 33%	7.29	17.20	819	V	143	3.5	1.013	Trays / 14	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2/3 V-2301	Stripper OH Separator	VT	3 x 33%	3.43	6.86	74	V	55	3.5	1.013	Wire Mesh Pad 0.92 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2/3 V-2302	Semi-Lean Solvent Flash Drum	VT	3 x 33%	2.56	5.12	31	V	128	3.5	1.013	Wire Mesh Pad 0.34 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2/3 V-2303	Flashed Gas KO Pot	VT	3 x 33%	1.44	2.88	5.5	V	60	3.5	1.013	Wire Mesh Pad 0.16 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2 V-2501	CO2 Compressor Stage 1 KO Pot	VT	2 x 50%	1.62	3.24	7.8	V	49	3.5	1.013	Wire Mesh Pad 0.21 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2 V-2502	CO2 Compressor Stage 2 KO Pot	VT	2 x 50%	3.78	7.56	99.0	V	49	3.5	1.013	Wire Mesh Pad 1.12 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2 V-2503	CO2 Compressor Stage 3 KO Pot	VT	2 x 50%	3.19	6.38	59.5	V	49	4.7	1.013	Wire Mesh Pad 0.80 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2 V-2504	CO2 Compressor Stage 4 KO Pot	VT	2 x 50%	2.76	5.52	38.5	V	49	11.4	1.013	Wire Mesh Pad 0.60 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		

Notes:

1. TW - Single Diameter Tower DDT - Double Diameter Tower HT - Horizontal Tank AT - Agitated Tank VT - Vertical Tank

2. V - Vertical H - Horizontal

amec foster wheeler	**EQUIPMENT LIST FOR VESSELS**		**Rev.**	**ORIG**	**REV 01**	**REV 02**	
	Client: The Energies Technology Institute	**Contract No:** 13191	**Ch'd**	RR			**SHEET** 4 **of** 8
	Description: CCS BENCHMARK REFRESH 2013		**App.**	TA			
	Unit No: 2300/2500	MEA Unit & CO2 Compression	**Date**	01/04/2015			

EQUIPMENT NUMBER	DESCRIPTION	VESSEL TYPE(1)/ SUB-TYPE	No.off x DUTY %	DIMENSIONS ID m	DIMENSIONS HEIGHT T/T m	TOTAL VOLUME m^3	V/H (2)	DESIGN CONDITIONS TEMP ^oC	DESIGN CONDITIONS PRESS barg	DESIGN CONDITIONS VACUUM FVPRESS bara	INTERNALS TYPE/No.OFF PACKED VOL. m^3 / PACKED HGT mm	MATERIALS OF CONST'N SHELL MAT./LINING/ CA	MATERIALS OF CONST'N INTERNALS MAT./LINING/ CA	REMARKS	REV
1/2 V-2305	CO2 Compressor Stage 5 KO Pot	VT	2 x 50%	2.24	4.48	20.6	V	49	26.3	1.013	Wire Mesh Pad 0.39 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2 D-2501 A/B	Dehydration Bed #1 & 2	VT	4 x 25%								Molecular Sieve / /			By Drier Package Vendor	

Notes:
1. TW - Single Diameter Tower DDT - Double Diameter Tower HT - Horizontal Tank AT - Agitated Tank VT - Vertical Tank
2. V - Vertical H - Horizontal

PROJECT No.: 13191

EQUIPMENT LIST FOR HEAT EXCHANGERS		Rev.	ORIG	REV 01	REV 02	SHEET 5 of 8
Client:	The Energies Technology Institute — Contract No: 13191	Ch'd	RR			
Description:	CCS BENCHMARK REFRESH 2013	App.	TA			
Unit No:	2300/2500 MEA Unit & CO2 Compression	Date	01/04/2015			

EQUIPMENT NUMBER	DESCRIPTION	EXCHANGER TYPE(1)/ SUB-TYPE	No.off x DUTY %	No.OF SHELLS (ST)	TEMA TYPE(ST)/ HEADER CONST(AC) (2)	RATE(3) kg/hr	DUTY MW	HEAT T'FER AREA(6) m^2	DESIGN CONDITIONS COLDSIDE(4) TEMP/PRESS ^oC / barg	DESIGN CONDITIONS HOTSIDE TEMP/PRESS ^oC /barg	MATERIAL PLATE/ SHELL	MATERIAL TUBE(ST/AC) HEAD(AC)	No.OF BAYS/FANS (AC)	FAN TYPES (5)	TOTAL FAN POWER kW	REMARKS	REV
1/2/3/4 E-2312	Gas/Gas Heat Exchanger	HE	4 x 25%	1	n/a	1709640	24.9	27679	121 / 4.7	156 / 3.5	CS	CS	n/a		n/a	like a combustion air preheater	
1/2/3/4 E-2301	DCC Cooler	HE	4 x 25%	1	n/a	258935	3.1	2482	49 / 4.7 (tubeside)	75 / 3.5	CS with 3mm min 304L cladding	316L	n/a		n/a		
1/2/3/4 E-2302	Absorber Pump Around Cooler	HE	4 x 25%	1	n/a	9228	0.2	14	49 / 4.7 (tubeside)	66 / 3.5	CS	CS	n/a		n/a		
1/2/3 E-2303	Cross Over Exchanger	HE	3 x 33%	1	n/a	2498459	105.0	20167	118 / 5.3	125 / 6.5	316L	316L	n/a		n/a	Plate & Frame	
1/2/3/4 E-2304	Lean Solvent Cooler	HE	4 x 25%	4	n/a	4193803	50.1	2990	49 / 4.7 (tubeside)	83 / 5.5	316L	316L	n/a		n/a	Plate & Frame	
1/2/3/4 E-2305	Extraction Cooler	HE	4 x 25%	4	n/a	5166646	61.8	3871	49 / 4.7 (tubeside)	80 / 4.2	316L	316L	n/a		n/a	Plate & Frame	
1/2/3 E-2306	First Flash Preheater	HE	3 x 33%	4	n/a	1070768	33.8	10119	108 / 4.2 (tubeside)	128 / 5.3	316L	316L	n/a		n/a		
1/2/3 E-2307	Second Flash Preheater	HE	3 x 33%	4	n/a	1070768	47.4	5503	128 / 3.5 (tubeside)	143 / 5.2	316L	316L	n/a		n/a		
1/2/3 E-2308	Semi Lean Flash Cooler	HE	3 x 33%	4	n/a	1640919	19.6	486	49 / 4.7 (tubeside)	128 / 3.5	316L	316L	n/a		n/a		
1/2/3 E-2309 A/B/C	Stripper Reboiler	RB	9 x 11%	3	n/a	865398	52.5	1274	143 / 3.5	325 / 4.7 (tubeside)	316L	316L	n/a		n/a		
1/2/3 E-2310	Solvent Reclaimer	RB	3 x 33%	1	n/a	70033	30.6	210	174 / 3.5	173 / 6.2 (tubeside)	CS with 3mm min 304L cladding	316L	n/a		n/a	intermittent duty	

Notes:

1. C - Condenser HE - Heat Exchanger RB - Reboiler STB - Steam Boiler 2. For Air Coolers CP - Cover Plate PT - Plug Type MT - Manifold Type BT - Billet Type

3. Rate = Total Fluid Entering Coldside And Applies To Condensers, Boilers And Heaters. 4. Coldside Design Temp Equals Design Air Temp. For Air Coolers 5. I - Induced F - Forced

6. For Air-Coolers, this is Bare Tube Area

PROJECT No.: 13191

EQUIPMENT LIST FOR HEAT EXCHANGERS

Client: The Energies Technology Institute **Contract No:** 13191
Description: CCS BENCHMARK REFRESH 2013
Unit No: 2300/2500 MEA Unit & CO2 Compression

Rev.	ORIG	REV 01	REV 02
Ch'd	RR		
App.	TA		
Date	01/04/2015		

EQUIPMENT NUMBER	DESCRIPTION	EXCHANGER TYPE(1)/ SUB-TYPE	No.off x DUTY %	No.OF SHELLS (ST)	TEMA TYPE(ST)/ HEADER CONST(AC) (2)	RATE(3) kg/hr	DUTY MW	HEAT T'FER AREA(6) m^2	DESIGN CONDITIONS COLDSIDE(4) TEMP/PRESS °C / barg	DESIGN CONDITIONS HOTSIDE TEMP/PRESS °C /barg	MATERIAL PLATE/ SHELL	MATERIAL TUBE(ST/AC) HEAD(AC)	No.OF BAYS/FANS (AC)	FAN TYPE (5)	TOTAL FAN POWER kW	REMARKS	REV
1/2/3 E-2311	Reflux Cooler	HE	3 x 33%	2	n/a	3100250	37.1	1054	49 / 4.7 (tubeside)	116 / 3.5	CS with 3mm min 304L cladding	316L	n/a	n/a	n/a		
1/2 E-2501	CO2 Compressor Stage 1 Cooler	HE	2 x 50%	1	n/a	42929	0.5	125	49 / 4.7 (tubeside)	49 / 3.5	CS with 3mm min 304L cladding	316L	n/a	n/a	n/a		
1/2 E-2502	CO2 Compressor Stage 2 Cooler	HE	2 x 50%	1	n/a	422321	5.1	831	49 / 4.7 (tubeside)	115 / 3.5	CS with 3mm min 304L cladding	316L	n/a	n/a	n/a		
1/2 E-2503	CO2 Compressor Stage 3 Cooler	HE	2 x 50%	1	n/a	311971	3.7	664	49 / 4.7 (tubeside)	107 / 6.1	CS with 3mm min 304L cladding	316L	n/a	n/a	n/a		
1/2 E-2504	CO2 Compressor Stage 4 Cooler	HE	2 x 50%	1	n/a	393148	4.7	768	49 / 4.7 (tubeside)	115 / 12.2	CS with 3mm min 304L cladding	316L	n/a	n/a	n/a		
1/2 E-2505	CO2 Compressor Stage 5 Cooler	HE	2 x 50%	1	n/a	419839	5.0	802	49 / 4.7 (tubeside)	117 / 26.5	CS with 6mm CA	316L	n/a	n/a	n/a		
1/2 E-2506	CO2 Compressor Stage 6 Cooler	HE	2 x 50%	1	n/a	556715	6.7	987	49 / 4.7 (tubeside)	125 / 59	CS with 6mm CA	316L	n/a	n/a	n/a		
1/2 E-2507	CO2 Compressor Stage 7 Cooler	HE	2 x 50%	1	n/a	263734	3.2	280	49 / 4.7 (tubeside)	100 / 105	CS with 6mm CA	316L	n/a	n/a	n/a		
1/2 E-2508	CO2 Product Cooler	HE	2 x 50%	1	n/a	873465	10.4	1377	49 / 4.7 (tubeside)	110 / 158	CS with 6mm CA	316L	n/a	n/a	n/a		
1/2 E-2509	Regen. Gas Electric Heater	HE	2 x 50%													By Drier Package Vendor	
1/2E-2510	Regen. Gas Feed/Product Exchanger	HE	2 x 50%													By Drier Package Vendor	

Notes:
1. C - Condenser HE - Heat Exchanger RB - Reboiler STB - Steam Boiler 2. For Air Coolers CP - Cover Plate PT - Plug Type MT - Manifold Type BT - Billet Type
3. Rate = Total Fluid Entering Coldside And Applies To Condensers, Boilers And Heaters. 4. Coldside Design Temp Equals Design Air Temp. For Air Coolers 5. I - Induced F - Forced
6. For Air-Coolers, this is Bare Tube Area

PROJECT No.: 13191

amec foster wheeler

EQUIPMENT LIST FOR PUMPS

Client:	The Energies Technology Institute	**Contract No:**	13191		
Description:	CCS BENCHMARK REFRESH 2013				
Unit No:	2300/2500	MEA Unit & CO2 Compression			

Rev.	**ORIG**	**REV 01**	**REV 02**
Ch'd	RR		
App.	TA		
Date	01/04/2015		

EQUIPMENT NUMBER	**DESCRIPTION**	**PUMP TYPE(1)/ SUB-TYPE**	**No.off x DUTY %**	**DRIVE TYPE (2) OP./SPARE**	**DESIGN CAPACITY m^3/hr**	**PUMP EFFIC'Y %**	**DIFF PRESSURE kPa**	**TURB. DRIVE STEAM P barg**	**OPERATING CONDS TEMP ^oC**	**OPERATING CONDS SG**	**OPERATING CONDS VISC'Y cP**	**DESIGN CONDITIONS TEMP ^oC**	**DESIGN CONDITIONS PRESS barg**	**POWER EST/RATED kW**	**MATERIAL CASING/ROTOR**	**REMARKS**	**REV**
1/2/3\4 P-2301 A/B	DCC Cooler Pump	Centrifugal	8 x 25%	electric	118		379		50	0.988	0.540	75	5.35	16.4	316L SS / 316L SS	number of items tbc	
1/2/3/4 P-2302 A/B/C/D	Rich Solvent Pump	Centrifugal	16 x 8.3%	electric	934		352		52	1.05	1.090	77	5.00	122	CS / CS	number of items tbc	
1/2/3 P-2303 A/B/C/D	Lean Solvent Pump	Centrifugal	12 x 11%	electric	860		419		99	1.00	0.436	124	6.57	133	316L SS / 316L SS	number of items tbc	
1/2/3 P-2304 A/B/C	Semi-Lean Solvent Pump	Centrifugal	9 x 16.7%	electric	556		224		103	1.013	0.427	128	3.59	46	CS / CS	number of items tbc	
1/2/3\4 P-2305 A/B/C/D	Extraction Pump	Centrifugal	16 x 8.3%	electric	878		252		55	1.036	1.025	80	3.63	82	CS / CS	number of items tbc	
1/2/3/4 P-2306 A/B	Absorber Pumparound Pump	Centrifugal	8 x 25%	electric	10		126		41	0.993	0.674	66	1.97	0.04	316L SS / 316L SS	number of items tbc	
1/2/3 P-2306 A/B	Stripper Reflux Pump	Centrifugal	6 x 33%	electric	52		147		30	1.052	0.845	55	2.70	1.8	316L SS / 316L SS	number of items tbc	

Notes: **1. Differential pressure to be confirmed after column design**

	EQUIPMENT LIST FOR PACKAGE EQUIPMENT				Rev.	ORIG	REV 01	REV 02	
amec foster wheeler	Client:	The Energies Technology Institute	Contract No:	13191	Ch'd	RR			SHEET 8 of 8
	Description:	CCS BENCHMARK REFRESH 2013			App.	TA			
	Unit No:	2300/2500	MEA Unit & CO2 Compression		Date	01/04/2015			

EQUIPMENT NUMBER	DESCRIPTION	EQUIPMENT TYPE(1)/ SUB-TYPE	No.off x DUTY %	DRIVE TYPE (2) OP./SPARE	DIMENSIONS DIAM./HGT/ LENGTH mm	AREA mm^2	CAPACITY m^3	FLOW kg/hr	PRESS OPER./DIFF. barg / bar	DESIGN CONDS. TEMP/PRESS °C / barg	POWER EST/RATED kW	MATERIAL BODY/CA	COOL.TOWER WBT °C / APP °C / CWT °C (3)	REMARKS	REV
1/2/3/4 F-2301	DCC Circulation Water Filter	F	4 x 25%				11	106039	3.85 / 0.7			Shell: 304L SS Internals: 304 SS		Packing = Activated Carbon	
1/2/3/4 F-2302	Absorber Wash Water Filter	F	4 x 25%				9.3	9228	0.122 / 0.1			Shell: 304L SS Internals: 304 SS		Packing = Activated Carbon	
1/2/3/4 F-2303	Lean Solvent Filter	F	4 x 25%				106	105049	0.387 / 0.1			Shell: 304L SS Internals: 304 SS		Packing = Activated Carbon	
1/2 F-2501	Dehydration Fines Filter	F	2 x 50%											By Drier Package Vendor	
1/2 F-2502	Regeneration Fines Filter	F	2 x 50%											By Drier Package Vendor	
1/2 PK-2301	Soda Ash Injection Package		2 x 50%												
1/2 PK-2501	CO2 Drier Package	Mol Sieve	2 x 50%				4845 m3/h	252517 kg/h 0.075 wt% water	24.9 / 0.9					Product spec <50 ppmv water	

Notes:

1. AD - Air Dryer CRY - Crystallizer CTW - Cooling Tower D - Dryer DC - Dust Collector DD - Drum Dryer E - Evaporator EG - Electrical Generator EJ - Ejector F - Filter FLR - Flare Stack HU - Heating Unit RD - Rotary Dryer RU - Refrigeration Unit STK - Stack TDS - Tray Drying System WFE - Wiped Film Evaporator WTS - Water Treatment System

2. VFD - Variable Frequency Motor Driver

3. WBT - Wet Bulb Temperature APP - Approach Temperature CWT - Cooling Water Inlet Temperature

PROJECT No.: 13191

CASE: ICP Sensitivity Case with 90% Post Combustion CO2 Capture

Train	Item	Description	Specification	Remarks
1	D-2001	Deaerator (1 x 100% Train)	608 tph	
1	P-2001 A/B	LP BFW Pumps (2 x 100% Train)	280 kW 657.5 m3/h, 3 bara suction, 14.5 bara discharge, CS	
1		Stack (1 x 100%)	5148.5 tph flue gas @ 85.5 oC and 1.02 bara	
1	PK-2001	Package Steam Boiler	607 tph LP Steam @ 293 oC and 4.17 bara	

EQUIPMENT LIST - CCGT with Independent Capture Plant Sensitivity Case 1

REV	BY	APPROVED	DATE
ORIG			
01	RR	TA	15/04/2015
02	RR	TA	11/09/2015
03			

UNIT NAME:	MEA Unit & CO2 Compression
UNIT No.:	2300/2500
CLIENT:	The Energies Technology Institute
PROJECT:	CCS BENCHMARK REFRESH 2013
CONTRACT	13191
DOCUMENT No.:	
CASE SUMMARY	ICP Sensitivity 1 with 90% Post Combustion CO2 Capture

NOTES

	EQUIPMENT LIST FOR COMPRESSORS	Rev.	ORIG	REV 01	REV 02	
	Client: The Energies Technology Institute **Contract No:** 13191	Ch'd	RR			SHEET 2 of 8
	Description: CCS BENCHMARK REFRESH 2013	App.	TA			
	Unit No: 2300/2500 MEA Unit & CO_2 Compression	Date	15/04/2015			

EQUIPMENT NUMBER	DESCRIPTION	COMPRESSOR TYPE(1)/ SUB-TYPE	No.off x DUTY %	DRIVE TYPE OP./SPARE	ACTUAL CAPACITY m^3/hr	Cp/Cv INLET/ OUTLET	DIFF. PRESS. bar	PRESSURE INLET/OUTLET bara / bara	TURB.DRIVE STEAM PRESS. barg	COMPRESSIBILITY INLET/OUTLET	POWER EST/RATED kW	MATERIAL CASING	MOLECULAR WEIGHT	REMARKS	REV
1/2 BL-3400	CCGT Flue Gas Blower	Blower	2 x 50%	electric	2,663,257	1.379 / 1.376	0.22	1.03 / 1.25	n/a	0.999 / 0.999	17683	304 SS	28.4	**Unit 3400 CCGT Mods**	
BL-2002	Boiler Flue Gas Blower	Blower	1 x 100%	electric	385,540	1.361 / 1.358	0.24	1.01 / 1.25	n/a	0.999 / 0.999	2770	306 SS	27.9	**Unit 2000 ICP Power Island**	
1/2 K-2501-1	CO_2 Compressor Stage 1	Centrifugal	2 x 50%	electric	14,748	1.287 / 1.278	0.4	1.1 / 1.5	n/a	0.994 / 0.994	167	304 SS	42.7		
1/2 K-2501-2	CO_2 Compressor Stage 2	Centrifugal	2 x 50%	electric	87,634	1.286 / 1.272	1.4	1.4 / 2.8	n/a	0.992 / 0.991	3140	304 SS	43.2		
1/2 K-2501-3	CO_2 Compressor Stage 3	Centrifugal	2 x 50%	electric	42,853	1.296 / 1.284	2.7	2.7 / 5.4	n/a	0.985 / 0.983	2939	304 SS	43.7		
1/2 K-2501-4	CO_2 Compressor Stage 4	Centrifugal	2 x 50%	electric	21,390	1.313 / 1.304	6.2	5.3 / 11.5	n/a	0.970 / 0.966	3251	CS	43.8		
1/2 K-2501-5	CO_2 Compressor Stage 5	Centrifugal	2 x 50%	electric	10,612	1.360 / 1.362	13.6	11.4 / 25.0	n/a	0.934 / 0.928	3522	CS	43.9		
1/2 K-2501-6	CO_2 Compressor Stage 6	Centrifugal	2 x 50%	electric	4,189	1.493 / 1.512	31.1	23.9 / 55.0	n/a	0.859 / 0.856	3123	CS	44.0		
1/2 K-2501-7	CO_2 Compressor Stage 7	Centrifugal	2 x 50%	electric	1,274	2.883 / 2.439	45.1	54.9 / 100.0	n/a	0.602 / 0.645	1568	CS	44.0		
1/2 K-2501-8	CO_2 Compressor Stage 8	Centrifugal	2 x 50%	electric	642	4.318 / 2.887	51.1	99.9 / 151.0	n/a	0.500 / 0.578	997	CS	44.0		

Notes: **1. AC - Air Compressor GC - Gas Compressor FN - Fan**

	EQUIPMENT LIST FOR VESSELS	Rev.	ORIG	REV 01	REV 02	
	Client: The Energies Technology Institute **Contract No:** 13191	Ch'd	RR			SHEET 3 of 8
	Description: CCS BENCHMARK REFRESH 2013	App.	TA			
	Unit No: 2300/2500 MEA Unit & CO2 Compression	Date	15/04/2015			

EQUIPMENT NUMBER	DESCRIPTION	VESSEL TYPE(1)/ SUB-TYPE	No.off x DUTY %	DIMENSIONS ID m	DIMENSIONS HEIGHT T/T m	TOTAL VOLUME m^3	V/H (2)	DESIGN CONDITIONS TEMP ^oC	DESIGN CONDITIONS PRESS barg	DESIGN CONDITIONS VACUUM FVPRESS bara	INTERNALS TYPE/No.OFF PACKED VOL. m^3 / PACKED HGT mm	MATERIALS OF CONST'N SHELL MAT./LINING/ CA	MATERIALS OF CONST'N INTERNALS MAT./LINING/ CA	REMARKS	REV
1/2/3/4 C-2301	Direct contact cooler	TW	4 x 25%	13.62	27.24	4630	V	107	3.5	1.013	Random Packing 711 10000	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding	Packing: 10m Mellapak 250X	
1/2/3/4 C-2302	Absorption Column	TW	4 x 25%	14.26	27.00	5071	V	75	3.5	1.013	Random Packing 2240 / 320 14000 / 2000	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding	Packing: 14m Mellapak 250X / 2m Mellapak 250Y	
1/2/3 C-2303	Stripper Column	TW	3 x 33%	6.97	17.20	744	V	143	3.5	1.013	Trays / 14	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2/3 V-2301	Stripper OH Separator	VT	3 x 33%	3.27	6.54	64	V	55	3.5	1.013	Wire Mesh Pad 0.84 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2/3 V-2302	Semi-Lean Solvent Flash Drum	VT	3 x 33%	2.47	4.94	28	V	128	3.5	1.013	Wire Mesh Pad 0.32 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2/3 V-2303	Flashed Gas KO Pot	VT	3 x 33%	1.39	2.78	4.9	V	60	3.5	1.013	Wire Mesh Pad 0.15 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2 V-2501	CO2 Compressor Stage 1 KO Pot	VT	2 x 50%	1.57	3.14	7.1	V	49	3.5	1.013	Wire Mesh Pad 0.19 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2 V-2502	CO2 Compressor Stage 2 KO Pot	VT	2 x 50%	3.61	7.22	86.2	V	49	3.5	1.013	Wire Mesh Pad 1.02 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2 V-2503	CO2 Compressor Stage 3 KO Pot	VT	2 x 50%	3.04	6.08	51.5	V	49	4.7	1.013	Wire Mesh Pad 0.73 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2 V-2504	CO2 Compressor Stage 4 KO Pot	VT	2 x 50%	2.64	5.28	33.7	V	49	11.4	1.013	Wire Mesh Pad 0.55 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		

Notes:
1. TW - Single Diameter Tower DDT - Double Diameter Tower HT - Horizontal Tank AT - Agitated Tank VT - Vertical Tank
2. V - Vertical H - Horizontal

	EQUIPMENT LIST FOR VESSELS				Rev.	ORIG	REV 01	REV 02	
amec foster wheeler	Client:	The Energies Technology Institute	Contract No:	13191	Ch'd	RR			SHEET 4 of 8
	Description:	CCS BENCHMARK REFRESH 2013			App.	TA			
	Unit No:	2300/2500	MEA Unit & CO2 Compression		Date	15/04/2015			

EQUIPMENT NUMBER	DESCRIPTION	VESSEL TYPE(1)/ SUB-TYPE	No.off x DUTY %	DIMENSIONS ID m	DIMENSIONS HEIGHT T/T m	TOTAL VOLUME m^3	V/H (2)	DESIGN CONDITIONS TEMP ^oC	DESIGN CONDITIONS PRESS barg	DESIGN CONDITIONS VACUUM FVPRESS bara	INTERNALS TYPE/No.OFF PACKED VOL. m^3 / PACKED HGT mm	MATERIALS OF CONST'N SHELL MAT./LINING/ CA	MATERIALS OF CONST'N INTERNALS MAT./LINING/ CA	REMARKS	REV
1/2 V-2305	CO2 Compressor Stage 5 KO Pot	VT	2 x 50%	2.14	4.28	18.0	V	49	26.3	1.013	Wire Mesh Pad 0.36 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		
1/2 D-2501 A/B	Dehydration Bed #1 & 2	VT	4 x 25%								Molecular Sieve / /			By Drier Package Vendor	

Notes:
1. TW - Single Diameter Tower DDT - Double Diameter Tower HT - Horizontal Tank AT - Agitated Tank VT - Vertical Tank
2. V - Vertical H - Horizontal

PROJECT No.: 13191

	EQUIPMENT LIST FOR HEAT EXCHANGERS	Rev.	ORIG	REV 01	REV 02	
amec foster wheeler	Client: The Energies Technology Institute Contract No: 13191	Ch'd	RR			SHEET 5 of 8
	Description: CCS BENCHMARK REFRESH 2013	App.	TA			
	Unit No: 2300/2500 MEA Unit & CO2 Compression	Date	15/04/2015			

EQUIPMENT NUMBER	DESCRIPTION	EXCHANGER TYPE(1)/ SUB-TYPE	No.off x DUTY %	No.OF SHELLS (ST)	TEMA TYPE(ST)/ HEADER CONST(AC) (2)	RATE(3) kg/hr	DUTY MW	HEAT T'FER AREA(6) m^2	DESIGN CONDITIONS COLDSIDE(4) TEMP/PRESS °C / barg	DESIGN CONDITIONS HOTSIDE TEMP/PRESS °C /barg	MATERIAL PLATE/ SHELL	MATERIAL TUBE(ST/AC) HEAD(AC)	No.OF BAYS/FANS (AC)	FAN TYPES (5)	TOTAL FAN POWER kW	REMARKS	REV
1/2/3/4 E-2312	Gas/Gas Heat Exchanger	HE	4 x 25%	1	n/a	1444317	17.0	11699	111 / 4.7	146 / 3.5	CS	CS	n/a		n/a	like a combustion air preheater	
1/2/3/4 E-2301	DCC Cooler	HE	4 x 25%	1	n/a	622124	7.4	5838	49 / 4.7 (tubeside)	77 / 3.5	CS with 3mm min 304L cladding	316L	n/a		n/a		
1/2/3/4 E-2302	Absorber Pump Around Cooler	HE	4 x 25%	1	n/a	9195	0.2	14	49 / 4.7 (tubeside)	66 / 3.5	CS	CS	n/a		n/a		
1/2/3 E-2303	Cross Over Exchanger	HE	3 x 33%	1	n/a	2281878	95.8	19391	118 / 5.3	124 / 6.5	316L	316L	n/a		n/a	Plate & Frame	
1/2/3/4 E-2304	Lean Solvent Cooler	HE	4 x 25%	4	n/a	3783918	45.2	2711	49 / 4.7 (tubeside)	82 / 5.5	316L	316L	n/a		n/a	Plate & Frame	
1/2/3/4 E-2305	Extraction Cooler	HE	4 x 25%	4	n/a	4707333	56.3	3527	49 / 4.7 (tubeside)	80 / 4.2	316L	316L	n/a		n/a	Plate & Frame	
1/2/3 E-2306	First Flash Preheater	HE	3 x 33%	4	n/a	977948	30.9	9241	108 / 4.2 (tubeside)	128 / 5.3	316L	316L	n/a		n/a		
1/2/3 E-2307	Second Flash Preheater	HE	3 x 33%	4	n/a	977948	43.8	5311	128 / 3.5 (tubeside)	143 / 5.2	316L	316L	n/a		n/a		
1/2/3 E-2308	Semi Lean Flash Cooler	HE	3 x 33%	4	n/a	1535631	18.4	455	49 / 4.7 (tubeside)	128 / 3.5	316L	316L	n/a		n/a		
1/2/3 E-2309 A/B/C	Stripper Reboiler	RB	9 x 11%	3	n/a	788910	47.0	1140	143 / 3.5	325 / 4.7 (tubeside)	316L	316L	n/a		n/a		
1/2/3 E-2310	Solvent Reclaimer	RB	3 x 33%	1	n/a	63975	25.9	192	174 / 3.5	173 / 6.2 (tubeside)	CS with 3mm min 304L cladding	316L	n/a		n/a	intermittent duty	

Notes:

1. C - Condenser HE - Heat Exchanger RB - Reboiler STB - Steam Boiler 2. For Air Coolers CP - Cover Plate PT - Plug Type MT - Manifold Type BT - Billet Type

3. Rate = Total Fluid Entering Coldside And Applies To Condensers, Boilers And Heaters. 4. Coldside Design Temp Equals Design Air Temp. For Air Coolers 5. I - Induced F - Forced

6. For Air-Coolers, this is Bare Tube Area

PROJECT No.: 13191

	EQUIPMENT LIST FOR HEAT EXCHANGERS		Rev.	ORIG	REV 01	REV 02	
amec foster wheeler	Client: The Energies Technology Institute	Contract No: 13191	Ch'd	RR			SHEET 6 of 8
	Description: CCS BENCHMARK REFRESH 2013		App.	TA			
	Unit No: 2300/2500 MEA Unit & CO2 Compression		Date	15/04/2015			

EQUIPMENT NUMBER	DESCRIPTION	EXCHANGER TYPE(1)/ SUB-TYPE	No.off x DUTY %	No.OF SHELLS (ST)	TEMA TYPE(ST)/ HEADER CONST(AC) (2)	RATE(3) kg/hr	DUTY MW	HEAT T'FER AREA(6) m^2	DESIGN CONDITIONS COLDSIDE(4) TEMP/PRESS °C / barg	DESIGN CONDITIONS HOTSIDE TEMP/PRESS °C /barg	MATERIAL PLATE/ SHELL	MATERIAL TUBE(ST/AC) HEAD(AC)	No.OF BAYS/FANS (AC)	FAN TYPE (5)	TOTAL FAN POWER kW	REMARKS	REV
1/2/3 E-2311	Reflux Cooler	HE	3 x 33%	2	n/a	2640658	31.6	905	49 / 4.7 (tubeside)	115 / 3.5	CS with 3mm min 304L cladding	316L	n/a	n/a	n/a		
1/2 E-2501	CO2 Compressor Stage 1 Cooler	HE	2 x 50%	1	n/a	40209	0.5	117	49 / 4.7 (tubeside)	49 / 3.5	CS with 3mm min 304L cladding	316L	n/a	n/a	n/a		
1/2 E-2502	CO2 Compressor Stage 2 Cooler	HE	2 x 50%	1	n/a	384387	4.6	757	49 / 4.7 (tubeside)	115 / 3.5	CS with 3mm min 304L cladding	316L	n/a	n/a	n/a		
1/2 E-2503	CO2 Compressor Stage 3 Cooler	HE	2 x 50%	1	n/a	284161	3.4	605	49 / 4.7 (tubeside)	107 / 6.1	CS with 3mm min 304L cladding	316L	n/a	n/a	n/a		
1/2 E-2504	CO2 Compressor Stage 4 Cooler	HE	2 x 50%	1	n/a	358169	4.3	699	49 / 4.7 (tubeside)	115 / 12.2	CS with 3mm min 304L cladding	316L	n/a	n/a	n/a		
1/2 E-2505	CO2 Compressor Stage 5 Cooler	HE	2 x 50%	1	n/a	382474	4.6	731	49 / 4.7 (tubeside)	117 / 26.5	CS with 6mm CA	316L	n/a	n/a	n/a		
1/2 E-2506	CO2 Compressor Stage 6 Cooler	HE	2 x 50%	1	n/a	507172	6.1	900	49 / 4.7 (tubeside)	125 / 59	CS with 6mm CA	316L	n/a	n/a	n/a		
1/2 E-2507	CO2 Compressor Stage 7 Cooler	HE	2 x 50%	1	n/a	240265	2.9	255	49 / 4.7 (tubeside)	100 / 105	CS with 6mm CA	316L	n/a	n/a	n/a		
1/2 E-2508	CO2 Product Cooler	HE	2 x 50%	1	n/a	795727	9.5	1254	49 / 4.7 (tubeside)	110 / 158	CS with 6mm CA	316L	n/a	n/a	n/a		
1/2 E-2509	Regen. Gas Electric Heater	HE	2 x 50%													By Drier Package Vendor	
1/2E-2510	Regen. Gas Feed/Product Exchanger	HE	2 x 50%													By Drier Package Vendor	

Notes:
1. C - Condenser HE - Heat Exchanger RB - Reboiler STB - Steam Boiler 2. For Air Coolers CP - Cover Plate PT - Plug Type MT - Manifold Type BT - Billet Type
3. Rate = Total Fluid Entering Coldside And Applies To Condensers, Boilers And Heaters. 4. Coldside Design Temp Equals Design Air Temp. For Air Coolers 5. I - Induced F - Forced
6. For Air-Coolers, this is Bare Tube Area

PROJECT No.: 13191

amec foster wheeler

EQUIPMENT LIST FOR PUMPS

Client: The Energies Technology Institute	**Contract No:** 13191	**Rev.**	**ORIG**	**REV 01**	**REV 02**
Description: CCS BENCHMARK REFRESH 2013		**Ch'd**	RR		
Unit No: 2300/2500 MEA Unit & CO2 Compression		**App.**	TA		
		Date	15/04/2015		

EQUIPMENT NUMBER	DESCRIPTION	PUMP TYPE(1)/ SUB-TYPE	No.off x DUTY %	DRIVE TYPE (2) OP./SPARE	DESIGN CAPACITY m^3/hr	PUMP EFFIC'Y %	DIFF PRESSURE kPa	TURB. DRIVE STEAM P barg	OPERATING CONDS TEMP / SG / VISC'Y ^oC		cP	DESIGN CONDITIONS TEMP/PRESS ^oC	barg	POWER EST/RATED kW	MATERIAL CASING/ROTOR	REMARKS	REV
1/2/3\4 P-2301 A/B	DCC Cooler Pump	Centrifugal	8 x 25%	electric	310		434		52	0.987	0.531	77	6.06	43.1	316L SS / 316L SS	number of items tbc	
1/2/3/4 P-2302 A/B/C/D	Rich Solvent Pump	Centrifugal	16 x 8.3%	electric	853		352		52	1.051	1.091	77	5.00	112	CS / CS	number of items tbc	
1/2/3 P-2303 A/B/C/D	Lean Solvent Pump	Centrifugal	12 x 11%	electric	785		419		99	1.00	0.438	124	6.58	121	316L SS / 316L SS	number of items tbc	
1/2/3 P-2304 A/B/C	Semi-Lean Solvent Pump	Centrifugal	9 x 16.7%	electric	507		224		103	1.013	0.427	128	3.59	42	CS / CS	number of items tbc	
1/2/3\4 P-2305 A/B/C/D	Extraction Pump	Centrifugal	16 x 8.3%	electric	800		252		55	1.036	1.025	80	3.63	75	CS / CS	number of items tbc	
1/2/3/4 P-2306 A/B	Absorber Pumparound Pump	Centrifugal	8 x 25%	electric	10		126		41	0.993	0.684	66	1.97	0.04	316L SS / 316L SS	number of items tbc	
1/2/3 P-2306 A/B	Stripper Reflux Pump	Centrifugal	6 x 33%	electric	44		147		30	1.052	0.845	55	2.70	1.5	316L SS / 316L SS	number of items tbc	

Notes: **1. Differential pressure to be confirmed after column design**

EQUIPMENT LIST FOR PACKAGE EQUIPMENT

Client:	The Energies Technology Institute	**Contract No:**	13191		
Description:	CCS BENCHMARK REFRESH 2013				
Unit No:	2300/2500	MEA Unit & CO_2 Compression			

Rev.	ORIG	REV 01	REV 02
Ch'd	RR		
App.	TA		
Date	15/04/2015		

SHEET 8 **of** 8

EQUIPMENT NUMBER	DESCRIPTION	EQUIPMENT TYPE(1)/ SUB-TYPE	No.off x DUTY %	DRIVE TYPE (2) OP./SPARE	DIMENSIONS DIAM./HGT/ LENGTH mm	AREA mm^2	CAPACITY m^3	FLOW kg/hr	PRESS OPER./DIFF. barg / bar	DESIGN CONDS. TEMP/PRESS °C / barg	POWER EST/RATED kW	MATERIAL BODY/CA	COOL.TOWER WBT °C / APP °C / CWT °C (3)	REMARKS	REV
1/2/3/4 F-2301	DCC Circulation Water Filter	F	4 x 25%				28	278372	3.85 / 0.7			Shell: 304L SS Internals: 304 SS		Packing = Activated Carbon	
1/2/3/4 F-2302	Absorber Wash Water Filter	F	4 x 25%				9.3	9195	0.122 / 0.1			Shell: 304L SS Internals: 304 SS		Packing = Activated Carbon	
1/2/3/4 F-2303	Lean Solvent Filter	F	4 x 25%				96	95962	0.387 / 0.1			Shell: 304L SS Internals: 304 SS		Packing = Activated Carbon	
1/2 F-2501	Dehydration Fines Filter	F	2 x 50%											By Drier Package Vendor	
1/2 F-2502	Regeneration Fines Filter	F	2 x 50%											By Drier Package Vendor	
1/2 PK-2301	Soda Ash Injection Package		2 x 50%												
1/2 PK-2501	CO_2 Drier Package	Mol Sieve	2 x 50%				4414 m3/h	230044 kg/h 0.075 wt% water	24.9 / 0.9					Product spec <50 ppmv water	

Notes:

1. AD - Air Dryer CRY - Crystallizer CTW - Cooling Tower D - Dryer DC - Dust Collector DD - Drum Dryer E - Evaporator EG - Electrical Generator EJ - Ejector F - Filter FLR - Flare Stack HU - Heating Unit RD - Rotary Dryer RU - Refrigeration Unit STK - Stack TDS - Tray Drying System WFE - Wiped Film Evaporator WTS - Water Treatment System

2. VFD - Variable Frequency Motor Driver

3. WBT - Wet Bulb Temperature APP - Approach Temperature CWT - Cooling Water Inlet Temperature

FOSTER WHEELER ENERGY	CLIENT: ETI JECT TITLE: CCS BENCHMARK REFRESH 2013 CONTRACT: 13191	REVISION	0	1	2	3
		DATE	Jun-15			
		BY	RR			
		CHECKED	TA			
		APPROVED				

CASE: NGCC POWER PLANT WITH 90% POST COMBUSTION CO_2 CAPTURE AND 0% EXHAUST GAS RECYCLE

Train	Item	Description	Specification	Remarks
1 - 2	GT-3201	Gas Turbine (2 x 50% Train)	369.52 MWe Output Turbine generator	MHI M701F5 machine
1 - 2		HRSG (2 x 50% Train)	409.76 MW Duty (14 Coils)	
1 - 2	D-3201	Deaerator (2 x 50% Train)	436.75 tph	part of HRSG package
1 - 2	P-3201 A/B	HP BFW Pumps (4 x 50% Train)	1443.3 kW, 330.6 m3/h, 28.4 barg suction, 139.0 barg discharge, CS	
1 - 2	P-3202 A/B	MP BFW Pumps (4 x 50% Train)	445.46 kW 431.8 m3/h, 3.34 barg suction, 28.4 barg discharge, CS	
1 - 2	P-3203 A/B	LP BFW Pumps (4 x 50% Train)	38.5 kW 477.9 m3/h, 2.49 barg suction, 3.34 barg discharge, CS	
1 - 2	D-3204	HP Steam Drum (2 x 50% Train)	299.13 tph	part of HRSG package
1 - 2	D-3203	MP Steam Drum (2 x 50% Train)	50.37 tph	part of HRSG package
1 - 2	D-3202	LP Steam Drum (2 x 50% Train)	42.13 tph	part of HRSG package
1 - 2	E-3215	Fuel Gas Preheater (2 x 50% Train)	8871 kW Duty, 68004 kg/h process stream flow, 326 m2 heat transfer area, Carbon Steel	
1 - 2	E-3216	Gas / Gas Exchanger (2 x 50% Train)	26330 kW Duty, 26.33MW, 2330288 kg/h flow, 16531 m3 heat transfer area	
1	E-3301	Vacuum Condenser (1 x 100% Train)	846.86 tph condensate; 3.5 kPa (abs), 470.51 MW, 48,556 m2 heat transfer area, Carbon Steel	REF. duty = 371.8 MW
1	P-3301 A/B/C	Condensate Pumps (1 x 100% Train)	423.43 tph condensate, 420.5 m3/h, 115.9 kW, -0.978 barg suction, 5.53 barg discharge, CS	
1	ST-3301	Steam Turbine (1 x 100% Train)	229.25 MWe Output Turbine generator; 140 bar, 566 ^oC; 27 bar, 565 ^oC; 4.2 bar, 292 ^oC	
1 - 2	Z-3201	Stack (2 x 50%)		part of HRSG package

FOSTER WHEELER
ENERGY LTD
READING

EQUIPMENT LIST - CCGT with Independent Capture Plant Sensitivity Case 2

REV	BY	APPROVED	DATE
ORIG			
01	RR		10/06/2015
02			
03			

UNIT NAME: MEA Unit & CO_2 Compression

UNIT No.: 100

CLIENT: The Energies Technology Institute

PROJECT: CCS BENCHMARK REFRESH 2013

CONTRACT 13191

DOCUMENT No.:

CASE SUMMARY Natural Gas Combined Cycle Power Plant with 90% Post Combustion CO_2 Capture

NOTES

FOSTER WHEELER ENERGY LTD.	EQUIPMENT LIST FOR COMPRESSORS	Rev.	ORIG	REV 01	REV 02	
	Client: The Energies Technology Institute **Contract No:** 13191	Ch'd	SEF			SHEET 2 of 8
	Description: CCS BENCHMARK REFRESH 2013	App.	SEF			
	Unit No: 2300/2500 MEA Unit & CO2 Compression	Date	10/06/2015			

EQUIPMENT NUMBER	DESCRIPTION	COMPRESSOR TYPE(1)/ SUB-TYPE	No.off x DUTY %	DRIVE TYPE OP./SPARE	ACTUAL CAPACITY m^3/hr	Cp/Cv INLET/ OUTLET	DIFF. PRESS. bar	PRESSURE INLET/OUTLET bara bara	TURB.DRIVE STEAM PRESS. barg	COMPRESSIBILITY INLET/OUTLET	POWER EST/RATED kW	MATERIAL CASING	MOLECULAR WEIGHT	REMARKS	REV
1/2 BL-2301	Flue Gas Blower	Blower	2 x 50%	electric	2,663,319	1.379 / 1.376	0.22	1.04 / 1.25	n/a	0.999 / 0.999	17683	304 SS	28.37		01
1/2 K-2501-1	CO2 Compressor Stage 1	Centrifugal	2 x 50%	electric	11,402	1.284 / 1.278	0.38	1.10 / 1.48	n/a	0.994 / 0.994	129	304 SS	42.67		01
1/2 K-2501-2	CO2 Compressor Stage 2	Centrifugal	2 x 50%	electric	69,830	1.286 / 1.272	1.4	1.38 / 2.80	n/a	0.992 / 0.991	2502	304 SS	43.23		01
1/2 K-2501-3	CO2 Compressor Stage 3	Centrifugal	2 x 50%	electric	34,143	1.296 / 1.284	2.7	2.7 / 5.4	n/a	0.985 / 0.983	2341	304 SS	43.71		01
1/2 K-2501-4	CO2 Compressor Stage 4	Centrifugal	2 x 50%	electric	17,042	1.313 / 1.304	6.2	5.3 / 11.5	n/a	0.970 / 0.966	2590	CS	43.85		01
1/2 K-2501-5	CO2 Compressor Stage 5	Centrifugal	2 x 50%	electric	8,462	1.360 / 1.362	14	11.4 / 25.0	n/a	0.934 / 0.928	2809	CS	43.92		01
1/2 K-2501-6	CO2 Compressor Stage 6	Centrifugal	2 x 50%	electric	3,340	1.493 / 1.512	31	23.9 / 55.0	n/a	0.859 / 0.856	2490	CS	#REF!		01
1/2 K-2501-7	CO2 Compressor Stage 7	Centrifugal	2 x 50%	electric	1,016	2.883 / 2.439	45	54.9 / 100.0	n/a	0.602 / 0.645	1250	CS	44.00		01
1/2 K-2501-8	CO2 Compressor Stage 8	Centrifugal	2 x 50%	electric	512	4.318 / 2.887	51	99.9 / 151.0	n/a	0.500 / 0.578	795	CS	44.00		01

Notes: **1. AC - Air Compressor GC - Gas Compressor FN - Fan**

FOSTER WHEELER ENERGY LTD.	EQUIPMENT LIST FOR VESSELS	Rev.	ORIG	REV 01	REV 02	
	Client: The Energies Technology Institute Contract No: 13191	Ch'd	SEF			SHEET 3 of 8
	Description: CCS BENCHMARK REFRESH 2013	App.	SEF			
	Unit No: 2300/2500 MEA Unit & CO2 Compression	Date	10/06/2011			

EQUIPMENT NUMBER	DESCRIPTION	VESSEL TYPE(1)/ SUB-TYPE	No.off x DUTY %	DIMENSIONS ID m	HEIGHT T/T m	TOTAL VOLUME m^3	V/H (2)	DESIGN CONDITIONS TEMP ^oC	PRESS barg	VACUUM FVPRESS bara	INTERNALS TYPE/No.OFF PACKED VOL. m^3 / PACKED HGT mm	MATERIALS OF CONST'N SHELL MAT./LINING/ CA	INTERNALS MAT./LINING/ CA	REMARKS	REV
1/2/3 C-2301	Direct contact cooler	TW	3 x 33%	14.77	29.53	5901.24	V	107	3.5	1.013	Random Packing 916 10000	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding	Packing: 10m Mellapak 250X	01
1/2/3 C-2302	Absorption Column	TW	3 x 33%	15.58	27.00	6134	V	75	3.5	1.013	Random Packing 2670 / 390 14000 / 2000	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding	Packing: 14m Mellapak 250X / 2m Mellapak 250Y	01
1/2 C-2303	Stripper Column	TW	2 x 50%	7.51	17.20	872	V	143	3.5	1.013	Trays / 14	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		01
1/2 V-2301	Stripper OH Separator	VT	2 x 50%	3.53	7.06	81	V	55	3.5	1.013	Wire Mesh Pad 0.98 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		01
1/2 V-2302	Semi-Lean Solvent Flash Drum	VT	2 x 50%	2.61	5.22	33	V	128	3.5	1.013	Wire Mesh Pad 0.54 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		01
1/2 V-2303	Flashed Gas KO Pot	VT	2 x 50%	1.44	2.88	5.5	V	60.0	3.5	1.013	Wire Mesh Pad 0.16 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		01
1/2 V-2501	CO2 Compressor Stage 1 KO Pot	VT	2 x 50%	1.33	2.66	4.3	V	49.0	3.5	1.013	Wire Mesh Pad 0.14 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		01
1/2 V-2502	CO2 Compressor Stage 2 KO Pot	VT	2 x 50%	3.18	6.36	58.9	V	49	3.5	1.013	Wire Mesh Pad 0.79 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		01
1/2 V-2503	CO2 Compressor Stage 3 KO Pot	VT	2 x 50%	2.40	4.80	25.3	V	49	4.7	1.013	Wire Mesh Pad 0.45 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		01
1/2 V-2504	CO2 Compressor Stage 4 KO Pot	VT	2 x 50%	2.00	4.00	14.7	V	49	11.4	1.013	Wire Mesh Pad 0.31 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		01

Notes: **1. TW - Single Diameter Tower DDT - Double Diameter Tower HT - Horizontal Tank AT - Agitated Tank VT - Vertical Tank**

2. V - Vertical H - Horizontal

FOSTER WHEELER ENERGY LTD.	EQUIPMENT LIST FOR VESSELS				Rev.	ORIG	REV 01	REV 02	
	Client:	The Energies Technology Institute	Contract No:	13191	Ch'd	SEF			SHEET 4 of 8
	Description:	CCS BENCHMARK REFRESH 2013			App.	SEF			
	Unit No:	2300/2500	MEA Unit & CO2 Compression		Date	10/06/2011			

EQUIPMENT NUMBER	DESCRIPTION	VESSEL TYPE(1)/ SUB-TYPE	No.off x DUTY %	DIMENSIONS ID m	DIMENSIONS HEIGHT T/T m	TOTAL VOLUME m^3	V/H (2)	DESIGN CONDITIONS TEMP ^oC	DESIGN CONDITIONS PRESS barg	DESIGN CONDITIONS VACUUM FVPRESS bara	INTERNALS TYPE/No.OFF PACKED VOL. m^3 / PACKED HGT mm	MATERIALS OF CONST'N SHELL MAT./LINING/ CA	MATERIALS OF CONST'N INTERNALS MAT./LINING/ CA	REMARKS	REV
1/2 V-2305	CO2 Compressor Stage 5 KO Pot	VT	2 x 50%	1.60	3.20	7.5	V	49	26.3	1.013	Wire Mesh Pad 0.20 100	CS with 3mm min 304L cladding	CS with 3mm min 304L cladding		01
1/2 D-2501 A/B	Dehydration Bed #1 & 2	VT	4 x 25%								Molecular Sieve			By Drier Package Vendor	

Notes: **1. TW - Single Diameter Tower DDT - Double Diameter Tower HT - Horizontal Tank AT - Agitated Tank VT - Vertical Tank**
2. V - Vertical H - Horizontal

FOSTER WHEELER ENERGY LTD.

EQUIPMENT LIST FOR HEAT EXCHANGERS

Client: The Energies Technology Institute **Contract No:** 13191
Description: CCS BENCHMARK REFRESH 2013
Unit No: 2300/2500 MEA Unit & CO2 Compression

Rev.	ORIG	REV 01	REV 02
Ch'd	SEF		
App.	SEF		
Date	10/06/2015		

EQUIPMENT NUMBER	DESCRIPTION	EXCHANGER TYPE(1)/ SUB-TYPE	No.off x DUTY %	No.OF SHELLS (ST)	TEMA TYPE(ST)/ HEADER CONST(AC) (2)	RATE(3) kg/hr	DUTY MW	HEAT T'FER AREA(6) m^2	DESIGN CONDITIONS COLDSIDE(4) TEMP/PRESS ^oC / barg	DESIGN CONDITIONS HOTSIDE TEMP/PRESS ^oC /barg	MATERIAL PLATE/ SHELL	MATERIAL TUBE(ST/AC) HEAD(AC)	No.OF BAYS/FANS (AC)	FAN TYPES (5)	TOTAL FAN POWER kW	REMARKS	REV
1/2 E-3216	Gas/Gas Heat Exchanger	HE	2 x 50%	1	n/a	2563702	26.3	16531	105.0 / 4.7	141.4 / 3.5	CS	CS	n/a		n/a	like a combustion air preheater	01
1/2/3 E-2301	DCC Cooler	HE	3 x 33%	1	n/a	96676	1.2	934	49.0 / 4.7 (tubeside)	75.1 / 3.5	CS with 3mm min 304L cladding	316L	n/a		n/a		01
1/2/3 E-2302	Absorber Pump Around Cooler	HE	3 x 33%	1	n/a	12321	0.3	18	49.0 / 4.7 (tubeside)	66.8 / 3.5	CS	CS	n/a		n/a		01
1/2 E-2303	Cross Over Exchanger	HE	2 x 50%	1	n/a	2731311	114.9	21867	118.0 / 5.3	124.7 / 6.5	316L	316L	n/a		n/a	Plate & Frame	01
1/2/3 E-2304	Lean Solvent Cooler	HE	3 x 33%	4	n/a	4076281	48.7	2906	49.0 / 4.7 (tubeside)	82.8 / 5.5	316L	316L	n/a		n/a		01
1/2/3 E-2305	Extraction Cooler	HE	3 x 33%	4	n/a	4972952	59.5	3737	49.0 / 4.7 (tubeside)	79.6 / 4.2	316L	316L	n/a		n/a		01
1/2 E-2306	First Flash Preheater	HE	2 x 50%	4	n/a	1170562	37.0	11080	108.0 / 4.2 (tubeside)	128.1 / 5.3	316L	316L	n/a		n/a		01
1/2 E-2307	Second Flash Preheater	HE	2 x 50%	4	n/a	1170562	51.6	5957	128.0 / 3.5 (tubeside)	142.7 / 5.2	316L	316L	n/a		n/a		01
1/2 E-2308	Semi Lean Flash Cooler	HE	2 x 50%	4	n/a	1782565	21.3	528	49.0 / 4.7 (tubeside)	128.0 / 3.5	316L	316L	n/a		n/a		01
1/2 E-2309 A/B/C	Stripper Reboiler	RB	6 x 17%	3	n/a	946212	57.4	1391	142.7 / 3.5	325.0 / 4.7 (tubeside)	316L	316L	n/a		n/a		01
1/2 E-2310	Solvent Reclaimer	RB	2 x 50%	1	n/a	76581	34.5	230	173.9 / 3.5	172.9 / 6.2 (tubeside)	CS with 3mm min 304L cladding	316L	n/a		n/a	intermittent duty	01

Notes:
1. C - Condenser HE - Heat Exchanger RB - Reboiler STB - Steam Boiler 2. For Air Coolers CP - Cover Plate PT - Plug Type MT - Manifold Type BT - Billet Type
3. Rate = Total Fluid Entering Coldside And Applies To Condensers, Boilers And Heaters. 4. Coldside Design Temp Equals Design Air Temp. For Air Coolers 5. I - Induced F - Forced
6. For Air-Coolers, this is Bare Tube Area

FOSTER WHEELER ENERGY LTD.	EQUIPMENT LIST FOR HEAT EXCHANGERS		Rev.	ORIG	REV 01	REV 02	
	Client: The Energies Technology Institute	Contract No: 13191	Ch'd	SEF			SHEET 6 of 8
	Description: CCS BENCHMARK REFRESH 2013		App.	SEF			
	Unit No: 2300/2500 MEA Unit & CO2 Compression		Date	10/06/2015			

EQUIPMENT NUMBER	DESCRIPTION	EXCHANGER TYPE(1)/ SUB-TYPE	No.off x DUTY %	No.OF SHELLS (ST)	TEMA TYPE(ST)/ HEADER CONST(AC) (2)	RATE(3) kg/hr	DUTY MW	HEAT T'FER AREA(6) m^2	DESIGN CONDITIONS COLDSIDE(4) TEMP/PRESS ^oC / barg	DESIGN CONDITIONS HOTSIDE TEMP/PRESS ^oC /barg	MATERIAL PLATE/ SHELL	MATERIAL TUBE(ST/AC) HEAD(AC)	No.OF BAYS/FANS (AC)	FAN TYPE (5)	TOTAL FAN POWER kW	REMARKS	REV
1/2 E-2311	Reflux Cooler	HE	2 x 50%	2	n/a	3389602	40.5	1151	49.0 / 4.7 (tubeside)	115.8 / 3.5	CS with 3mm min 304L cladding	316L	n/a	n/a	n/a		01
1/2 E-2501	CO2 Compressor Stage 1 Cooler	HE	2 x 50%	1	n/a	31094	0.4	91	49.0 / 4.7 (tubeside)	84.7 / 3.5	CS with 3mm min 304L cladding	316L	n/a	n/a	n/a		01
1/2 E-2502	CO2 Compressor Stage 2 Cooler	HE	2 x 50%	1	n/a	306447	3.7	603	49.0 / 4.7 (tubeside)	114.5 / 3.5	CS with 3mm min 304L cladding	316L	n/a	n/a	n/a		01
1/2 E-2503	CO2 Compressor Stage 3 Cooler	HE	2 x 50%	1	n/a	226364	2.7	481	49.0 / 4.7 (tubeside)	107.3 / 6.1	CS with 3mm min 304L cladding	316L	n/a	n/a	n/a		01
1/2 E-2504	CO2 Compressor Stage 4 Cooler	HE	2 x 50%	1	n/a	285572	3.4	557	49.0 / 4.7 (tubeside)	115.2 / 12.2	CS with 3mm min 304L cladding	316L	n/a	n/a	n/a		01
1/2 E-2505	CO2 Compressor Stage 5 Cooler	HE	2 x 50%	1	n/a	304910	3.6	582	49.0 / 4.7 (tubeside)	117.5 / 26.5	CS with 6mm CA	316L	n/a	n/a	n/a		01
1/2 E-2506	CO2 Compressor Stage 6 Cooler	HE	2 x 50%	1	n/a	404316	4.8	717	49.0 / 4.7 (tubeside)	125.4 / 59	CS with 6mm CA	316L	n/a	n/a	n/a		01
1/2 E-2507	CO2 Compressor Stage 7 Cooler	HE	2 x 50%	1	n/a	191536	2.3	203	49 / 4.7 (tubeside)	100.0 / 105	CS with 6mm CA	316L	n/a	n/a	n/a		01
1/2 E-2508	CO2 Product Cooler	HE	2 x 50%	1	n/a	634358	7.6	999	49.0 / 4.7 (tubeside)	109.9 / 158	CS with 6mm CA	316L	n/a	n/a	n/a		01
1/2 E-2509	Regen. Gas Electric Heater	HE	2 x 50%													By Drier Package Vendor	
1/2E-2510	Regen. Gas Feed/Product Exchanger	HE	2 x 50%													By Drier Package Vendor	

Notes: **1. C - Condenser HE - Heat Exchanger RB - Reboiler STB - Steam Boiler 2. For Air Coolers CP - Cover Plate PT - Plug Type MT - Manifold Type BT - Billet Type**

3. Rate = Total Fluid Entering Coldside And Applies To Condensers, Boilers And Heaters. 4. Coldside Design Temp Equals Design Air Temp. For Air Coolers 5. I - Induced F - Forced

6. For Air-Coolers, this is Bare Tube Area

PROJECT No.: 13191

FOSTER WHEELER ENERGY LTD.	EQUIPMENT LIST FOR PUMPS		Rev.	ORIG	REV 01	REV 02	
	Client:	The Energies Technology Institute Contract No: 13191	Ch'd	SEF			SHEET 7 of 8
	Description:	CCS BENCHMARK REFRESH 2013	App.	SEF			
	Unit No:	2300/2500 MEA Unit & CO2 Compression	Date	10/06/2015			

EQUIPMENT NUMBER	DESCRIPTION	PUMP TYPE(1)/ SUB-TYPE	No.off x DUTY %	DRIVE TYPE (2) OP./SPARE	DESIGN CAPACITY m^3/hr	PUMP EFFIC'Y %	DIFF PRESSURE kPa	TURB. DRIVE STEAM P barg	OPERATING CONDS TEMP / SG / VISC'Y °C		cP	DESIGN CONDITIONS TEMP/PRESS °C	barg	POWER EST/RATED kW	MATERIAL CASING/ROTOR	REMARKS	REV
1/2/3 P-2301 A/B	DCC Cooler Pump	Centrifugal	6 x 33%	electric	28		379		50.0	0.988	0.544	75.0	5.35	3.9	316L SS / 316L SS	number of items tbc	01
1/2/3 P-2302 A/B/C/D	Rich Solvent Pump	Centrifugal	12 x 11%	electric	851		352		52.0	1.05	1.093	77.0	5.00	119	CS / CS	number of items tbc	01
1/2/3 P-2303 A/B/C/D	Lean Solvent Pump	Centrifugal	8 x 16.5%	electric	943		418		103.5	0.993	0.411	128.5	6.57	146	316L SS / 316L SS	number of items tbc	01
1/2/3 P-2304 A/B/C	Semi-Lean Solvent Pump	Centrifugal	6 x 25%	electric	608		224		103.0	1.013	0.427	128.0	3.59	50	CS / CS	number of items tbc	01
1/2/3 P-2305 A/B/C/D	Extraction Pump	Centrifugal	12 x 11%	electric	851		252		51.6	1.039	1.107	76.6	3.64	80	CS / CS	number of items tbc	01
1/2/3 P-2306 A/B	Absorber Pumparound Pump	Centrifugal	6 x 33%	electric	14		126		41.8	0.993	0.669	66.8	1.97	0.05	316L SS / 316L SS	number of items tbc	01
1/2 P-2306 A/B	Stripper Reflux Pump	Centrifugal	4 x 50%	electric	57		147		30.0	1.052	0.844	55.0	2.70	1.9	316L SS / 316L SS	number of items tbc	01

Notes: **1. Differential pressure to be confirmed after column design**

FOSTER WHEELER ENERGY LTD.	EQUIPMENT LIST FOR PACKAGE EQUIPMENT				Rev.	ORIG	REV 01	REV 02	
	Client:	The Energies Technology Institute	Contract No:	13191	Ch'd	SEF			SHEET 8 of 8
	Description:	CCS BENCHMARK REFRESH 2013			App.	SEF			
	Unit No:	2300/2500	MEA Unit & CO2 Compression		Date	10/06/2015			

EQUIPMENT NUMBER	DESCRIPTION	EQUIPMENT TYPE(1)/ SUB-TYPE	No.off x DUTY %	DRIVE TYPE (2) OP./SPARE	DIMENSIONS DIAM./HGT/ LENGTH mm	AREA mm^2	CAPACITY m^3	FLOW kg/hr	PRESS OPER./DIFF. barg / bar	DESIGN CONDS. TEMP/PRESS ^oC / barg	POWER EST/RATED kW	MATERIAL BODY/CA	COOL.TOWER WBT ^oC / APP ^oC / CWT ^oC (3)	REMARKS	REV
1/2 F-2301	DCC Circulation Water Filter	F	2 x 50%				3	25251	3.85 / 0.7			Shell: 304L SS Internals: 304 SS		Packing = Activated Carbon	01
1/2 F-2302	Absorber Wash Water Filter	F	2 x 50%				12.4	12321.1	0.122 / 0.1			Shell: 304L SS Internals: 304 SS		Packing = Activated Carbon	01
1/2 F-2303	Lean Solvent Filter	F	2 x 50%				103	102108	0.387 / 0.1			Shell: 304L SS Internals: 304 SS		Packing = Activated Carbon	01
1/2 F-2501	Dehydration Fines Filter	F	2 x 50%											By Drier Package Vendor	
1/2 F-2502	Regeneration Fines Filter	F	2 x 50%											By Drier Package Vendor	
1/2 PK-2301	Soda Ash Injection Package		2 x 50%												01
1/2 PK-2501	CO2 Drier Package	Mol Sieve	2 x 50%				3519 m3/h	183420 kg/h 0.075 wt% water	24.9 / 0.9					Product spec <50 ppmv water	01

Notes:

1. AD - Air Dryer CRY - Crystallizer CTW - Cooling Tower D - Dryer DC - Dust Collector DD - Drum Dryer E - Evaporator EG - Electrical Generator EJ - Ejector F - Filter FLR - Flare Stack HU - Heating Unit RD - Rotary Dryer RU - Refrigeration Unit STK - Stack TDS - Tray Drying System WFE - Wiped Film Evaporator WTS - Water Treatment System

2. VFD - Variable Frequency Motor Driver

3. WBT - Wet Bulb Temperature APP - Approach Temperature CWT - Cooling Water Inlet Temperature

ATTACHMENT 5
CAPITAL COST ESTIMATES

1. CCGT with ICP – Base Case
2. CCGT with ICP - Imported Power
3. CCGT with ICP - Imported Steam & Power

Project No : 13191
Client : ETI
Project : WP6 - CCS Study
Location : UK

Rev : '1'
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Independent Capture Plant - Base Case

COST CODE	DESCRIPTION		Independent Capture Plant (ICP)						CCGT			
			Unit 2300	Unit 2000		Unit 2500			Unit 32/33/3400			
			Independent Capture Plant (ICP)	Independent Capture Plant Power Block	Tie-ins (Electrical & Ducting	CO2 Compression (to 150 Bar)	ICP U&O	**Independent Capture Plant (ICP) Sub-Total**	CCGT Power Block	CCGT U&O	**CCGT Sub-Total**	**Overall Total**
			Million's GBP	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**
	MAJOR EQUIPMENT		142.7	53.0	0.17	25.9	9.80	**231.5**	190.9	8.5	**199.4**	**430.9**
	DIRECT BULK MATERIALS		49.6	16.0	4.71	6.6	13.20	**90.1**	57.6	10.6	**68.2**	**158.3**
	DIRECT MATERIAL & LABOUR CONTRACTS		16.5	6.0	0.23	1.1	20.10	**43.9**	21.8	18.5	**40.3**	**84.2**
	LABOUR ONLY CONTRACTS		67.3	8.9	1.44	11.5	22.70	**111.8**	32.1	8.3	**40.4**	**152.2**
	INDIRECTS		21.2	6.1	0.20	3.5	4.30	**35.3**	21.9	3.0	**24.9**	**60.2**
	EPC CONTRACTS		36.3	4.1	0.39	5.9	10.40	**57.0**	14.6	3.3	**17.9**	**74.9**
	INSTALLED COST		333.6	94.0	7.14	54.5	80.5	**569.7**	338.9	52.2	**391.1**	**960.8**
	LAND COSTS	5%	16.7	4.7	0.36	2.7	4.0	**28.5**	16.9	2.6	**19.6**	**48.0**
	OWNERS COSTS	10%	33.4	9.4	0.71	5.4	8.1	**57.0**	33.9	5.2	**39.1**	**96.1**
	CONTINGENCY	25%	83.4	23.5	1.79	13.6	20.1	**142.4**	84.7	13.0	**97.8**	**240.2**
	TOTAL PROJECT COST		467.0	131.6	10.00	76.2	112.7	**797.6**	474.5	73.0	**547.5**	**1,345.1**

Notes
1) Major Equipment is inclusive of costs up to FOB
2) Direct Bulk Materials includes Piping, Instrumentation, Electrical, Catalyst & Chemicals, Spares and Shipping costs
3) Direct Material & Labour Contracts includes Civil, Steelwork, Building and Protective Cover
4) Labour Only Contracts includes Mechanical, Electrical & Instrumentation, Pre-commisioning Trade Labour Support and Scaffolding Labour costs
5) Indirects includes Temporary Facilities, Heavy Lifts, Commissioning Services and Vendors Engineers
6) EPC Contracts covers Engineering, Procurement and Construction Management
7) Costs are instantaneous 1 Q 2009

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Client : ETI
Project : WP6 - CCS Study
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Independent Capture Plant - Sensitivity Case 1

COST CODE	DESCRIPTION		*Independent Capture Plant - Sensitivity Case1*						*CCGT*			
			Unit 2300	**Unit 2000**		**Unit 2500**		**Independent Capture Plant (ICP) Sub-Total**	**Unit 32/33/3400**		**CCGT Sub-Total**	**Overall Total**
			Independent Capture Plant (ICP)	Independent Capture Plant Power Block	Tie-ins (Electrical & Ducting	CO2 Compression (to 150 Bar)	ICP U&O		CCGT Power Block	CCGT U&O		
			Million's GBP	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**
	MAJOR EQUIPMENT		123.9	20.9	0.84	24.3	7.50	**177.4**	190.9	8.5	**199.4**	**376.8**
	DIRECT BULK MATERIALS		43.1	6.3	4.78	6.2	10.20	**70.6**	57.6	10.6	**68.2**	**138.8**
	DIRECT MATERIAL & LABOUR CONTRACTS		14.3	2.4	1.52	1.0	15.00	**34.2**	21.8	18.5	**40.3**	**74.5**
	LABOUR ONLY CONTRACTS		58.4	3.5	1.66	10.8	18.80	**93.1**	32.1	8.3	**40.4**	**133.6**
	INDIRECTS		18.4	2.4	0.27	3.3	3.30	**27.7**	21.9	3.0	**24.9**	**52.6**
	EPC CONTRACTS		31.6	1.6	0.52	5.5	8.70	**47.9**	14.6	3.3	**17.9**	**65.8**
	INSTALLED COST		289.7	37.0	9.59	51.2	63.5	**450.9**	338.9	52.2	**391.1**	**842.0**
	LAND COSTS	5%	14.5	1.9	0.5	2.6	3.2	**22.5**	16.9	2.6	**19.6**	**42.1**
	OWNERS COSTS	10%	29.0	3.7	1.0	5.1	6.4	**45.1**	33.9	5.2	**39.1**	**84.2**
	CONTINGENCY	25%	72.4	9.3	2.4	12.8	15.9	**112.7**	84.7	13.0	**97.8**	**210.5**
	TOTAL PROJECT COST		405.5	51.8	13.4	71.6	88.9	**631.3**	474.5	73.0	**547.5**	**1,178.8**
										6%		

Notes

1) Major Equipment is inclusive of costs up to FOB
2) Direct Bulk Materials includes Piping, Instrumentation, Electrical, Catalyst & Chemicals, Spares and Shipping costs
3) Direct Material & Labour Contracts includes Civil, Steelwork, Building and Protective Cover
4) Labour Only Contracts includes Mechanical, Electrical & Instrumentation, Pre-commisioning Trade Labour Support and Scaffolding Labour costs
5) Indirects includes Temporary Facilities, Heavy Lifts, Commissioning Services and Vendors Engineers
6) EPC Contracts covers Engineering, Procurement and Construction Management
7) Costs are instantaneous 1 Q 2009

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Independent Capture Plant - Sensitivity 2

COST CODE	DESCRIPTION	Independent Capture Plant (ICP)							CCGT			
		Unit 2300	Unit 2000			Unit 2500			Unit 32/33/3400			
		Independent Capture Plant (ICP)	Independent Capture Plant Power Block	Tie-ins (Electrical, Ducting & Piping)	Steam Extraction Tie-in	CO2 Compression (to 150 Bar)	ICP U&O	**Independent Capture Plant (ICP) Sub-Total**	CCGT Power Block	CCGT U&O	**CCGT Sub-Total**	**Overall Total**
		Million's GBP	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**	**Million's GBP**
	MAJOR EQUIPMENT	98.7		0.84		20.9	5.30	**125.7**	190.9	8.5	**199.4**	**325.1**
	DIRECT BULK MATERIALS	34.3		5.20	0.07	5.3	7.30	**52.2**	57.6	10.6	**68.2**	**120.4**
	DIRECT MATERIAL & LABOUR CONTRACTS	11.4		2.17	0.16	0.9	10.40	**25.0**	21.8	18.5	**40.3**	**65.3**
	LABOUR ONLY CONTRACTS	46.5		2.60	0.16	9.3	14.40	**72.9**	32.1	8.3	**40.4**	**113.4**
	INDIRECTS	14.7		0.34	0.10	2.9	2.40	**20.3**	21.9	3.0	**24.9**	**45.2**
	EPC CONTRACTS	25.1		0.64	0.12	4.7	6.70	**37.3**	14.6	3.3	**17.9**	**55.2**
	INSTALLED COST	230.7		11.78	0.61	44.0	46.5	**333.5**	338.9	52.2	**391.1**	**724.6**
	LAND COSTS 5%	11.5		0.59	0.03	2.2	2.3	**16.7**	16.9	2.6	**19.6**	**36.2**
	OWNERS COSTS 10%	23.1		1.18	0.06	4.4	4.7	**33.4**	33.9	5.2	**39.1**	**72.5**
	CONTINGENCY 25%	57.7		2.95	0.15	11.0	11.6	**83.4**	84.7	13.0	**97.8**	**181.2**
	TOTAL PROJECT COST	322.9		16.49	0.85	61.5	65.1	**466.9**	474.5	73.0	**547.5**	**1,014.5**

Notes
1) Major Equipment is inclusive of costs up to FOB
2) Direct Bulk Materials includes Piping, Instrumentation, Electrical, Catalyst & Chemicals, Spares and Shipping costs
3) Direct Material & Labour Contracts includes Civil, Steelwork, Building and Protective Cover
4) Labour Only Contracts includes Mechanical, Electrical & Instrumentation, Pre-commisioning Trade Labour Support and Scaffolding Labour costs
5) Indirects includes Temporary Facilities, Heavy Lifts, Commissioning Services and Vendors Engineers
6) EPC Contracts covers Engineering, Procurement and Construction Management
7) Costs are instantaneous 1 Q 2009

ATTACHMENT 6
OPERATING COST ESTIMATES

Maintenance Costs

Task 5 – Independent Capture Plant

Complex Section	Maint %	ICP Base Case 100% Load		ICP Sensitivity Case 1 - Power from CCGT 100% Load		ICP Sensitivity Case 2 - Power and Steam from CCGT 100% Load	
		Capital Cost	Maint. p.a	Capital Cost	Maint. p.a	Capital Cost	Maint. p.a
		UK£ (Million)		UK£ (Million)		UK£ (Million)	
AGR + CO2 Compression	2.5%	388	10	341	9	275	7
CCGT + ICP Power Island	5.0%	433	22	376	19	339	17
Common Facilities (offsites and utilities) and Tie-in	1.7%	140	2	125	2	111	2
TOTAL		961	**33.7**	842	**29.4**	724	**25.7**
		Overall Maint. % =		Overall Maint. % =		Overall Maint. % =	
		3.51		3.50		3.55	

Total Operating and Maintenance Costs

Task 5 – Independent Capture Plant

	Task 5 - CCGT + ICP		
	ICP Base Case 100% Load	ICP Sensitivity Case 1 - Power from CCGT 100% Load	ICP Sensitivity Case 2 - Power and Steam from CCGT 100% Load
	Million UK£ p.a	Million UK£ p.a	Million UK£ p.a
Fixed Costs			
Direct Labour	4.00	4.00	4.00
Administration / General Overheads	1.20	1.20	1.20
Maintenance	33.72	29.45	25.69
Insurance & Local Taxes Allowance	19.22	16.84	14.48
SUB TOTAL	**58.1**	**51.5**	**45.4**
Variable Costs			
Feedstock	368.2	335.6	268.4
Solvent, Catalysts and Chemicals	1.94	1.77	1.41
Waste Disposal	0.00	0.00	0.00
TOTAL	**428.3**	**388.9**	**315.1**
Total (Ex Fuel)	60.1	53.3	46.8