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Performance Evaluation of a Supercritical CO_2 Power Cycle Coal Gasification Plant

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Abstract

In many areas of the world, carbon intensity limits are being proposed for electrical power generation which current state of the art coal fueled power generation technologies cannot meet without the addition of carbon capture technology. Conventional technologies that reduce the carbon emissions intensity of coal-derived power generation place a significant burden on both the installed plant cost and the overall efficiency of the power generation process due to the added capital and parasitic operating costs of the carbon capture plant. Direct, oxy-fired Brayton power cycles using supercritical CO_2 (sCO_2) as the working fluid offer the opportunity to generate power from coal-derived syngas while facilitating straightforward capture of the CO_2 generated as part of the thermodynamic power cycle, and not simply added on.

A 500MWe conventional, integrated-gasification combined-cycle (IGCC) plant design was modelled using AspenPlus and was then modified by replacing the combustion turbine and heat recovery steam generator driven steam turbine with a direct, oxy-fired sCO_2 Brayton power cycle to investigate the performance of the system against the conventional arrangement with pre-combustion carbon capture installed. A number of cases were investigated, looking at the impact of varying degrees of integration between the Brayton cycle and the gasification unit. This paper will summarize the plant performance achieved for the cases developed in comparison to the conventional IGCC plant case with and without carbon capture applied.

Introduction

Recent regulations introduced in the US have focused on reducing the quantity of carbon dioxide being released into the atmosphere by large stationary sources, such as power stations. Under the Clean Air Act (CAA) 111(b), newly constructed plants are mandated to limit emissions of CO_2 to no greater than 1400 lb/MWh[1].

Existing plants can reduce their CO_2 emissions by installing carbon capture and storage (CCS) technologies however separating the CO_2 from the flue gas is energy intensive. The subsequent reduction in net power output, coupled with the capital costs of installing such a system leaves CCS power generation uncompetitive against unabated natural gas combined cycle plants in those geographies where natural gas is readily available.

There have been three primary approaches to reducing emissions of CO_2 from coal-fired power plants: Pre-combustion Capture, Post Combustion Capture and Oxycombustion Capture. In pre-combustion capture an Integrated Gasification Combined Cycle (IGCC) is utilized where the coal is processed in a gasifier to produce a syngas fuel where the carbon dioxide can be extracted prior to the final combustion and subsequent power generation. In Post Combustion Capture (PCC) processes, conventional

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combustion of directly fired fuel using air is carried out before contacting the resultant flue gas with a solvent to capture the relatively dilute CO_2. The third alternative, oxycombustion capture (OCC), avoids diluent nitrogen in the power system by removing the nitrogen content prior to the combustion step. This facilitates the production of a relatively concentrated stream of CO_2 flue gas which can be directly captured and purified.

Conventional pre-combustion capture technology involves the use of a water-gas shift reaction step to convert the syngas from being rich in carbon monoxide and water to being rich in hydrogen and carbon dioxide. The carbon dioxide can then be captured from the syngas during the acid gas removal process leaving a hydrogen rich fuel gas that when combusted within the gas turbine resultants in a flue gas which is dominated by moisture with only limited levels of carbon dioxide being present.

In contrast to the IGCC with capture strategy described above, the system investigated in this paper utilizes a conventional coal gasification system coupled to a supercritical carbon dioxide (sCO_2) Brayton cycle which replaces the conventional power generation components of the IGCC, namely the air breathing gas turbine and the heat recovery steam generator (HRSG) which is coupled to a steam turbine generator.

Approach

This work focused on initially bringing together a completely conventional Baseline coal gasification process (without any CO_2 capture) and a direct, oxy-fired supercritical CO_2 (sCO_2) Brayton cycle which burns the syngas produced by the gasifier. Although there is little or no integration between the gasification plant and the sCO_2 cycle, Test Case 1 explores the performance possible when there is no development risk applied to the conventional gasification plant. In addition to this case, two more Test Cases were investigated – the first simply substituted the gasification island fuel transport gas from the conventional nitrogen to CO_2 and the second did the same but investigated increasing the purity of the oxygen being fed to the gasifier and the sCO_2 burner.

The Baseline IGCC arrangement utilizes an HRSG on the gas turbine exhaust to generate steam for additional power generation, for moderation steam in the gasifier and to provide heating duties for goal drying and syngas processing, see Figure 1. The gasification section also generates steam from the syngas leaving the gasifier module in the ‘syngas cooler’ heat exchanger. This steam is combined with the HRSG generated saturated steam for efficient utilization in the Rankine power cycle.

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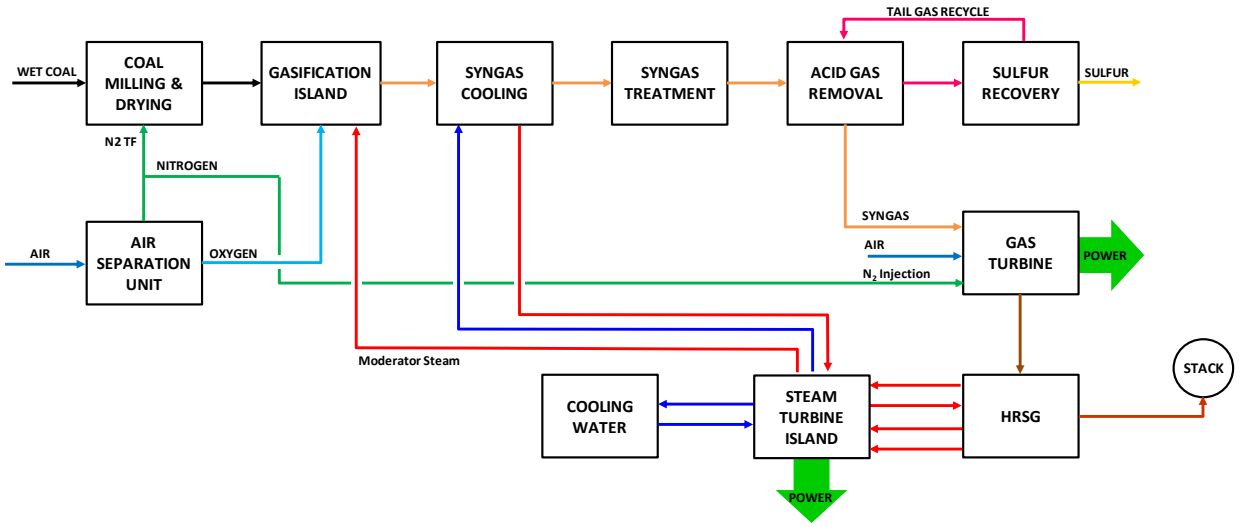

Figure 1
Baseline IGCC without Carbon Capture

When the sCO_2 Brayton cycle is substituted for the gas turbine and HRSG, the syngas cooling arrangement needs to be modified to a standalone steam cycle whereby both main steam and reheat duties are carried out by the syngas cooler (which typically only generates saturated main steam). Since the only heat input to this cycle is from the syngas cooler unit, the steam turbine is smaller than the original IGCC unit which also has steam from the HRSG. This modified steam cycle arrangement is shown in Figure 2.

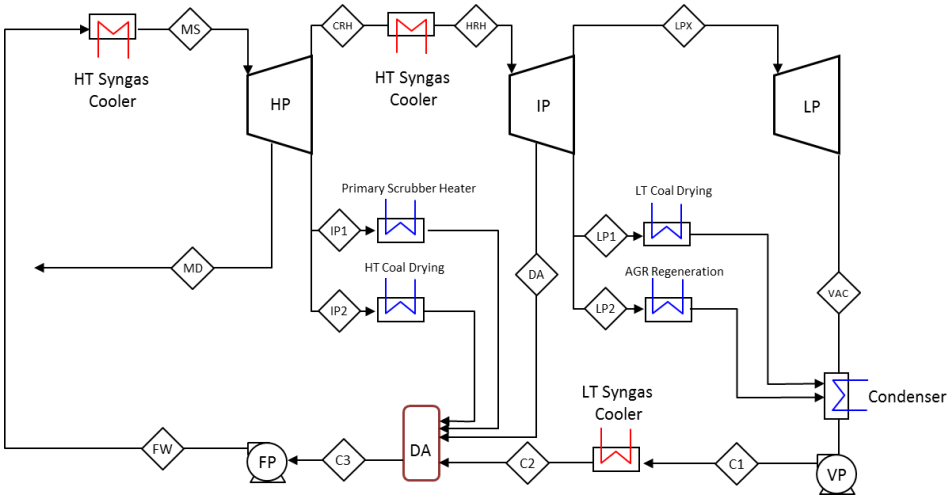

Figure 2
Test Cases Syngas Cooler with CHP Steam Cycle

Converting the steam system is the only structural change to the gasification process in the first case. The gasification unit produces essentially the same syngas composition as it does in the conventional IGCC plant. The block flow diagram of the gasification process with the sCO_2 Brayton cycle added is shown in Figure 3. The Air Separation Unit (ASU) also needs to be increased in size in this case since the sCO_2 Brayton cycle combustion requires oxygen feed whereas the original gas turbine used air as a source of oxygen.

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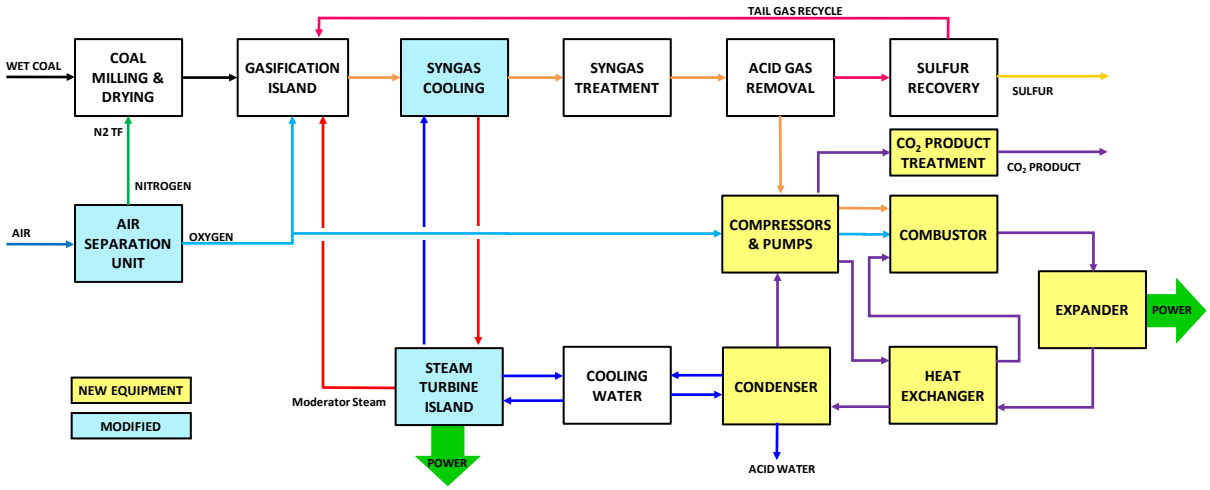

Figure 3
Test Case 1 - Gasification with sCO_2 Brayton Cycle

In contrast, Test Case 2 changes the overall feed to the gasifier by substituting CO_2 for the N_2 transfer fluid, thereby modifying the balance of gasification reactions. The quantity of CO_2 needed to perform this duty was matched volumetrically to the original nitrogen volume, thus a higher massflow was needed due to the higher density of the CO_2 at the same process conditions. Additionally, the moderation steam quantity being fed to the gasifier is eliminated in this case as the CO_2 transport fluid moderates the gasifier temperature. Test Case 3 investigates has the same process arrangement as Test Case 2 except the oxygen purity from the ASU is upgraded to 99.5% from the original 95% to further reduce the nitrogen and argon accumulation in the Brayton cycle working fluid.

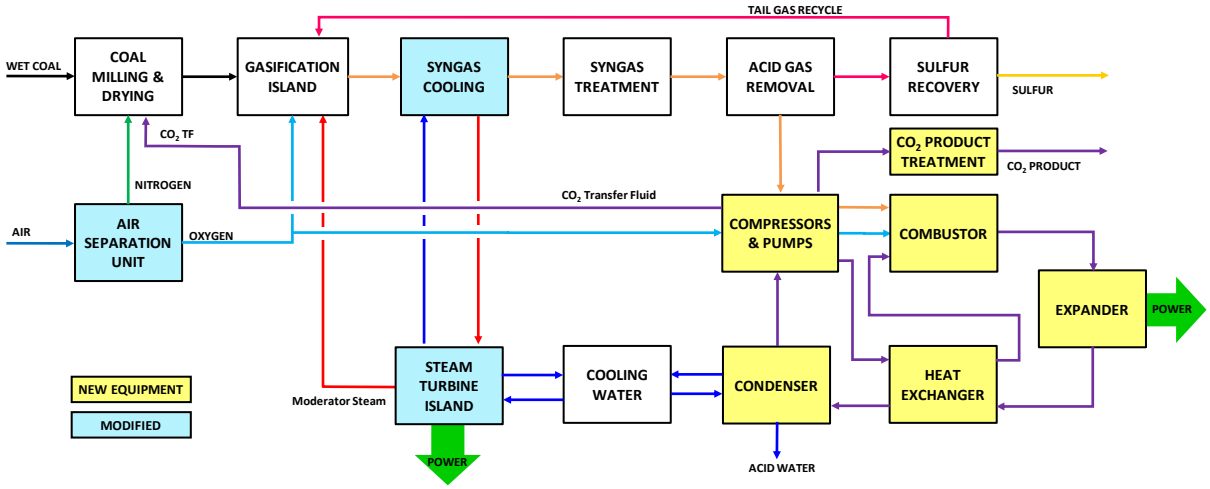

Figure 4
Test Cases 2 and 3 - Gasification with sCO_2 Brayton Cycle (CO_2 Transfer Fluid)

The purpose of these cases is to investigate the impact on the overall performance of the process both in terms of plant output and in CO_2 product purity. The resultant cooled syngas compositions exiting the AGR stage are presented in Table 1.

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Table 1
Syngas Composition

Case		Test Case 1		Test Case 2		Test Case 3	
Transfer Fluid		Nitrogen		CO_2		CO_2	
Oxygen Purity		95%		95%		99.5%	
Fuel Flowrate lb/hr (kg/hr)		601,700 (272,942)		601,700 (272,942)		601,700 (272,942)	
Oxygen Feed lb/hr (kg/hr)*		314,340 (142,590)		324,481 (147,190)		308,000 (139,714)	
Syngas Output lb/hr (kg/hr)		827,585 (375,407)		855,709 (388,165)		838,577 (380,393)	
Composition (v%)		Wet	Dry	Wet	Dry	Wet	Dry
Carbon Monoxide	CO	58.32	58.40	68.32	68.38	69.59	69.65
Hydrogen	H_2	27.91	27.95	22.58	22.60	22.71	22.73
Nitrogen	N_2	11.21	11.23	1.06	1.06	0.50	0.50
Water	H_2O	0.15	-	0.09	-	0.09	-
Carbon Dioxide	CO_2	1.56	1.56	6.56	6.57	6.94	6.95
Argon	Ar	0.86	0.86	1.39	1.39	0.17	0.17

*Oxygen flow basis is at purity level

The impact of substituting the transfer fluid from nitrogen to CO_2 is significant with the resultant nitrogen concentration being reduced to one tenth of the original level.

When this syngas is combusted in the sCO_2 Brayton Cycle, the resultant composition of the cycle working fluid is a function largely of the nitrogen and argon content of the syngas as well as the composition of the combustion oxygen and the degree of excess oxygen needed to achieve complete combustion. The composition of the working fluid entering the expander for all cases can be compared in Table 2. The expander inlet pressure was set to 4350 psia (300 bara) and the expansion was carried out on a 10:1 ratio. The overall circulation ratio of the working fluid was determined by balancing the heat exchanger inlet temperature at 1300°F (704°C) and the expander outlet temperature at 1400°F (760°C) to take cognizance of the thermal limitations of advanced materials.

The density of cooled CO_2 above 1071 psia (73.9 bara) can be as high as 46.8 lb/ft^3 (750 kg/m^3), making it behave more like a liquid when further compressed which requires far less energy than compressing a diatomic gas mixture such as air, as is the case in a conventional gas turbine arrangement. In contrast to this 'liquid like' behavior, the impure CO_2 fluid in Case 1 only shows a small reduction in compression power as it passes through the CO_2 critical pressure with the reduction continuing until 2300 psia (158 bara).

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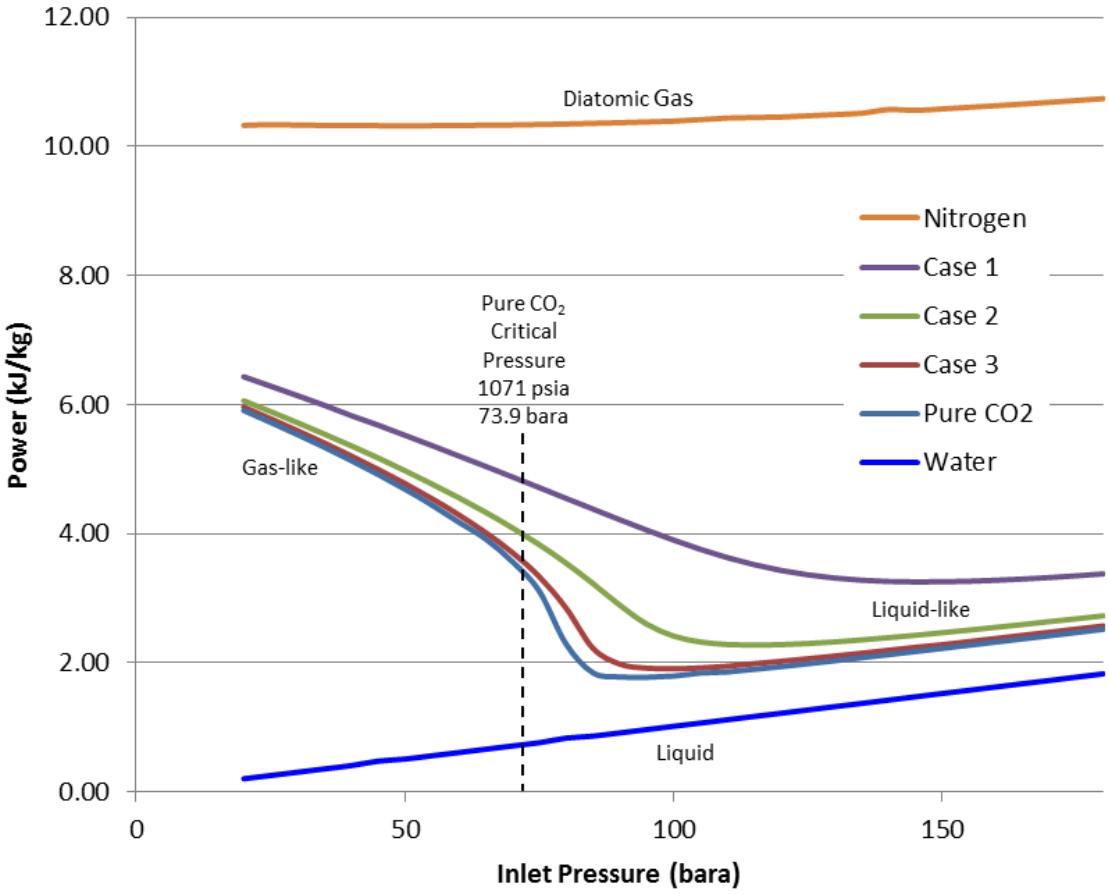

Figure 5
Specific Power to Compress for Fixed Pressure Ratio

As the CO_2 purity increases, the compression power is reduced and the pressure at which the greatest reduction occurs lowers towards the pure CO_2 characteristics. In Test Case 3 nitrogen enters the power cycle working fluid mainly as nitrogen in the coal syngas. Nitrogen and argon in the power cycle working fluid is limited by using high purity oxygen (HPO). The behavior is almost identical to the pure CO_2 case (Figure 5) with only a slight deflection in the apparent critical pressure.

Table 2
Brayton Cycle Working Fluid Composition at Expander Inlet

Location (Inlet)		Test Case 1		Test Case 2		Test Case 3	
Composition (v%)		Wet	Dry	Wet	Dry	Wet	Dry
Oxygen	O_2	0.57	0.59	0.55	0.57	0.57	0.59
Nitrogen	N_2	15.39	15.92	2.17	2.23	0.66	0.68
Water	H_2O	3.30	-	2.66	-	2.68	-
Carbon Dioxide	CO_2	77.54	80.19	90.87	93.36	95.61	98.24
Argon	Ar	3.19	3.30	3.73	3.84	0.47	0.48

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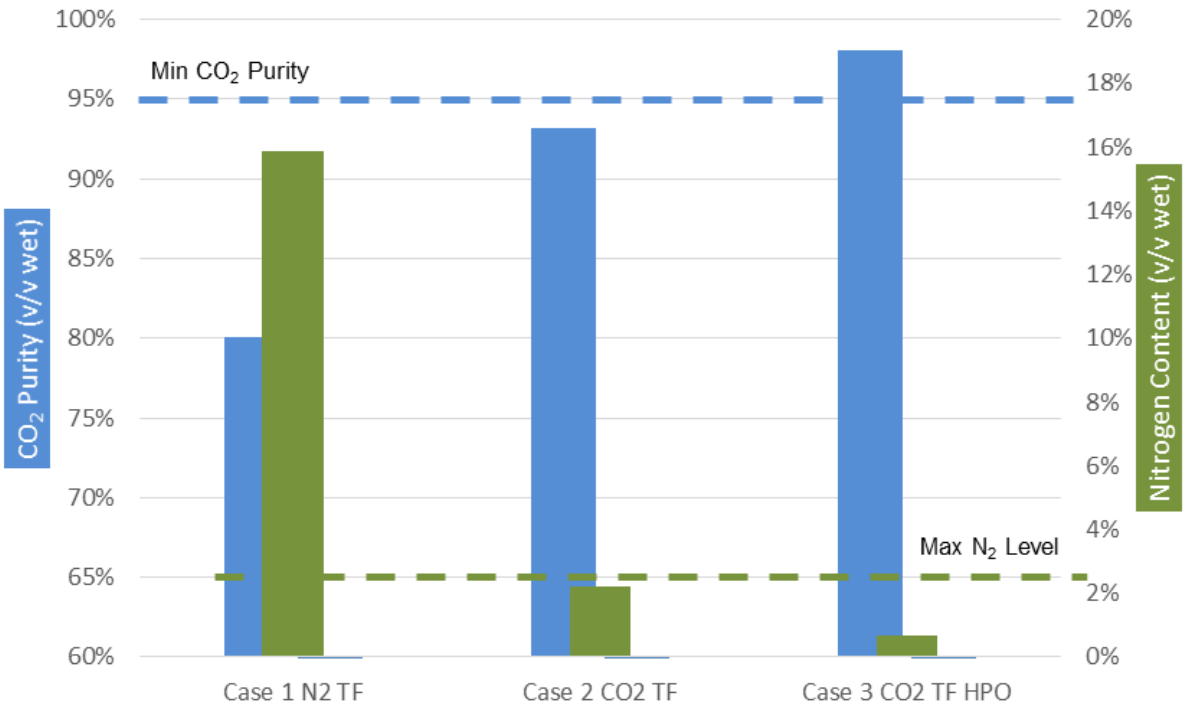

Figure 6
CO_2 Product Purity

Results

The performance results are presented in Table 3. It is clear that the impure CO_2 Case 1 generates slightly more power than the CO_2 transport fluid Cases 2 and 3. The power consumption from the CO_2 pumps, which pump the working fluid from 1235 psia (85 bara) to 4350 psia (300 bara), is significantly higher than the higher purity cases (over 50% higher than the highest purity case).

However, the gross power generated by the expander makes up for this additional pumping power, resulting in a higher overall net output. Despite this, the nitrogen transport fluid case is unlikely to be a viable case, since the CO_2 purity is very low at 80% volume which isn't compliant with typical pipeline specifications for CO_2 export[2] and would result in a significant reduction of the geological storage potential[3] if not further purified.

Cases 1 and 2 are not currently viable as the CO_2 produced is not of sufficient purity to meet export requirements. Case 3 exceeds the purity requirements and as such it would be beneficial for this process to utilize an ASU which has sufficient separation stages in the cold distillation system to generate higher purity oxygen than is commonly applied to oxycombustion processes.

The capture rate of the sCO_2 process is near unity, with only fugitive emissions of CO_2 leaving the plant via the dissolved gases within condensate from the syngas scrubbers and the Brayton cycle condenser.

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Table 3
Performance Results

Case		IGCC w/o Capture	sCO_2 Case 1	sCO_2 Case 2	sCO_2 Case 3
Transfer Fluid		N_2	N_2	CO_2	CO_2
Oxygen Purity	v%	95	95	95	99.5
Fuel Input	MWth	1470	1470	1470	1470
GT/Expander Power	MWe	464	922	864	846
Steam Turbine Power	MWe	235	52.3	58.4	59.3
CO_2 Compression	MWe	-	95.0	86.3	83.2
CO_2 Pumps	MWe	-	113.6	87.2	72.4
Fuel Compression	MWe	-	46.6	43.4	42.7
Oxygen Supply (ASU/Comp)	MWe	74.4	91.1	90.7	92.5
Gasifier Auxiliary	MWe	16.2	16.2	16.2	16.2
Plant Auxiliary	MWe	19.3	14.7	14.9	14.8
Net Power Exported*	MWe	587.9	596.0	582.4	582.6
CO_2 Emission	lb/MWh	1770	11.6	12.9	13.6
CO_2 Emission	g/kWh	803	5.3	5.9	6.2
CO_2 Product Flow	lb/h	-	1,211,335	1,092,124	1,046,597
CO_2 Product Flow	kg/h	-	549,483	495,407	474,755
CO_2 Product Purity	v% wet	-	80.1	93.2	98.1
Overall Plant Efficiency		**40.0**	**40.5**	**39.6**	**39.6**
Capture Rate	**%**	**0**	**99.5**	**99.3**	**99.2**

* Generator efficiency included

Key findings from this assessment:

- Substitution of a conventional air breathing gas turbine with heat recovery steam generator for a supercritical CO_2 Brayton Cycle does not significantly impact the resultant power output.
- Application of the supercritical CO_2 Brayton cycle facilitates full carbon capture with no reduction in power output.

It is anticipated that with a greater degree of integration between the gasification process and the sCO_2 process (such as eliminating the Rankine cycle), could yield benefit in overall performance as well as reducing capital costs.

Conclusions

The Supercritical CO_2 Brayton cycle potentially offers a competitive way to utilize coal without reducing the overall power output whilst delivering near zero GHG emissions from the process. The system investigated here was only minimally integrated with the gasifier unit as the objective was to keep the

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'proven' gasifier components as standard as possible, thus removing uncertainty from that area of the process.

Despite minimal integration and with little change to the gasification process, the performance of the sCO_2 Brayton Cycle power block with near complete carbon capture is essentially the same as the conventional IGCC without carbon capture. It is reasonable to anticipate that the performance of the sCO_2 process would exceed the IGCC Baseline case as new flow sheets are identified which increased thermal integration between the sCO_2 Brayton cycle and the gasifier cooling systems.

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Author Biography

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Mr. Hume has had over 15 years experience in carrying out modeling and analysis of power plant systems and associated environmental control systems. He has also managing a two year R&D demonstration project on Post Combustion Capture where he defined testing objectives, developed the test program and arranged the personnel to carry out the different tests and conduct analysis of the performance results. Since joining EPRI in 2014 he has focused on advanced power cycles and the testing of carbon capture processes.

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