Reference Number: 89243319CFE000015 Coal-Based Power Plants of the Future.

Title of Project: Allam Cycle Zero Emission Coal Power
Concept Area of Interest: Inherently Capture

Company
8 Rivers Capital, LLC
406 Blackwell Street
Durham, NC 27701
American Tobacco Campus
Crowe Building - Fourth Floor

DUNS Number: 829549307
Business Size: Small Business

Subcontractors
WSP UK Limited
WSP House
70 Chancery Lane, London
WC2A 1AF

DUNS Number: 28-906-0493
Business Size: Large Business

Institute of Gas Technology (GTI)
1700 S Mount Prospect Rd
Des Plaines, IL 60018-1804

DUNS Number – 045060753
Business Size: Other Than Small Business (Not-For-Profit Concern)

Date of Proposal: July 15th, 2019

Table of Contents

BUSINESS CASE

Market Scenario

Allam Cycle Coal can create a business case for coal to thrive in the most difficult economic and regulatory conditions. The technology can enable new zero emission coal generation both globally and domestically, using American technology and American coal. This is because the Allam Cycle coal power system has the potential to produce electricity at a lower cost than conventional coal and natural gas plants, with natural gas seen as the key competitor for new-build dispatchable power. And, the system includes full carbon capture (>97%) and eliminates all other air emissions. This inherent emissions capture provides an additional revenue stream to the Allam Cycle coal plant, and future-proofs it against environmental regulations.

Coal Type: For this scenario, we assume the use of Powder River Basin (PRB) Coal. Given the abundance of natural gas, and a desire to be conservative, we used the High Oil and Gas Resource case from EIA, which projects a market average of $2.90 / MMBTU gas in 2025, and $1.62 /MMBTU coal at mine mouth and $2.64 coal delivered cost.[i] To adjust this projection for PRB coal we assume that the mine mouth price remains at $.70 / MMBTU for PRB coal, given that EIA has mine mouth coal prices changing by <2%,while keeping 2025 delivery costs the same. This led to a net $1.72/ MMBTU delivered coal cost. We also show a case at $2.68/MMBTU delivered cost, which uses the same methodology for Illinois Basin coal's 2019 price point.[ii]

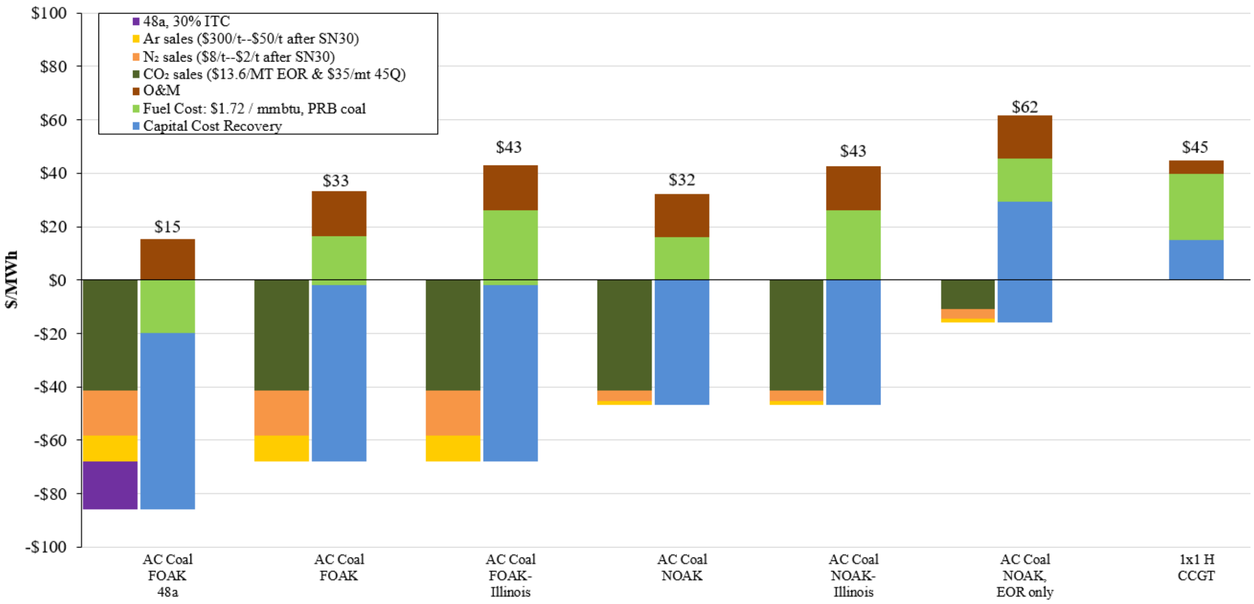
Renewables Penetration: Using the EIA base case, renewables penetration is expected to grow from 18% to 31% of domestic power generation by 2050, with 73% of that power coming from intermittent solar and wind. The direct impact of renewables on Allam Cycle coal will be felt in terms of fluctuations in power prices and resulting dispatch of the plant. Our analysis doesn't attempt to predict future power prices and power market structure, and instead compares the price competitiveness of the facility to other dispatchable power plants. If Allam Cycle coal is the lowest marginal cost option for dispatchable power, it will be competitive.

The second related impact is capacity factor. Modeling of system economics shows that a minimum 40% capacity factor is required for an Allam Cycle Coal plant to remain economic, given its high relative CAPEX and reduced revenues at this level. However, given the lower marginal cost of production of the Allam Cycle due to additional byproduct revenues, we expect this plant to dispatch ahead of all other fossil plants, and to maintain a high capacity factor even with the 31% renewables projected by EIA, and above. As shown later in Figure 1, with current value of CO_2, Allam Cycle coal can bid into the dispatch order at a low marginal bid, ensuring it runs at high capacity factor. With future plants that have lower byproduct revenues and only $15 / MT from CO_2 (from EOR or a future carbon price), the marginal bid would still be low enough to be the first fossil source in the dispatch stack.

CO_2 Constraint: We assume a base case CO_2 value of $48.6 / MT, which can be currently realized in the US market through the 45Q tax credit ($35 post-tax value)) combined with $13.6 / MT CO_2 sales for enhanced oil recovery (EOR). Then we model a no 45Q case that models a $13.6 / MT CO_2 value. This value can be realized in the US or the Middle East with EOR, or through energy policy, like the industrial carbon price in Alberta ($15 / MT)[iii], the cap and trade system in Europe ($29 / MT)[iv], or the Korean emission trading system ($20 / MT).[v] The same CO_2 value could be achieved through policy schemes like clean energy standards or cap and trade, and have the same functional impact on the competitiveness of the Allam Cycle. This model doesn't include the cost of CO_2 transport and sequestration, which is expected to range from $5-$20 / MT depending on the specific site. But as will be shown, the economic advantage of Allam Cycle coal is large enough to withstand those additional CO_2 costs.

Domestic Market Applicability: As shown in Figure 1, Allam Cycle Coal's (AC Coal's) levelized cost of electricity in the US can out compete new combined cycle plants, which is the main competition for new dispatchable generation. The first-of-a-kind plant (FOAK) is projected to cost $33 / MWH after coproduct sales, 27% lower than CCGT and half the price of an unabated supercritical coal plant. This is possible because of industrial gas sales, which amount to revenue of $68 / MWH: $41.5 of that revenue from CO_2 sales, a quarter of which comes from sale of CO_2 for Enhanced Oil Recovery (EOR) and three quarters of which comes from the 45Q. The remaining $26.5 comes from Argon and Nitrogen from the air separation process, which are valuable industrial feedstocks for uses like arc welding and fertilizers.

Figure 1: Levelized Cost Comparison In The US Market



The Allam Cycle is modeled with a 36 month construction time compared to 31 months for CCGT.

Natural gas is priced at $2.90 / MMBTU and PRB coal at $1.72 / MMBTU.[vi] Cost data for other technologies is taken from NETL baselines 2011 Vol 3.[vii] The assumptions across cases are: A levelized capital recovery rate of 10.2%; effective tax rate of 25.7%; 45Q and 48A are not taxed; 8.3% nominal discount rate; no escalation or inflation except for 2% natural gas price escalation; 40 year economic life; and 85% capacity factor. 2018 is the cost reference year.

Allam Cycle coal outcompetes Supercritical Pulverized Coal (SC-PC in Figure 2) and H-class Combined Cycle Gas Turbines (CCGT) because of a mixture of its high inherent efficiency, manageable capital costs, and its multiple revenue streams. Figure 1 shows different sensitivity cases for CO_2 value, by product revenue, tax credit status, technology maturity, and coal price.

As more plants are built, it is assumed that the revenues from Argon and Nitrogen sales will decline, as shown. Capital costs will also decline as learnings from early plants improve the overall design and constructability. Without 45Q, a Nth of a kind plant (NOAK) will produce electricity at $62 / MWH, cheaper than SC-PC, but more expensive than CCGT with $2.90 / MMBTU gas. It would still be extremely competitive when natural gas prices are above $5 / MMBTU as is common globally, and in any domestic scenarios when the total CO_2 value is greater than $30 / MT between EOR and carbon policies.

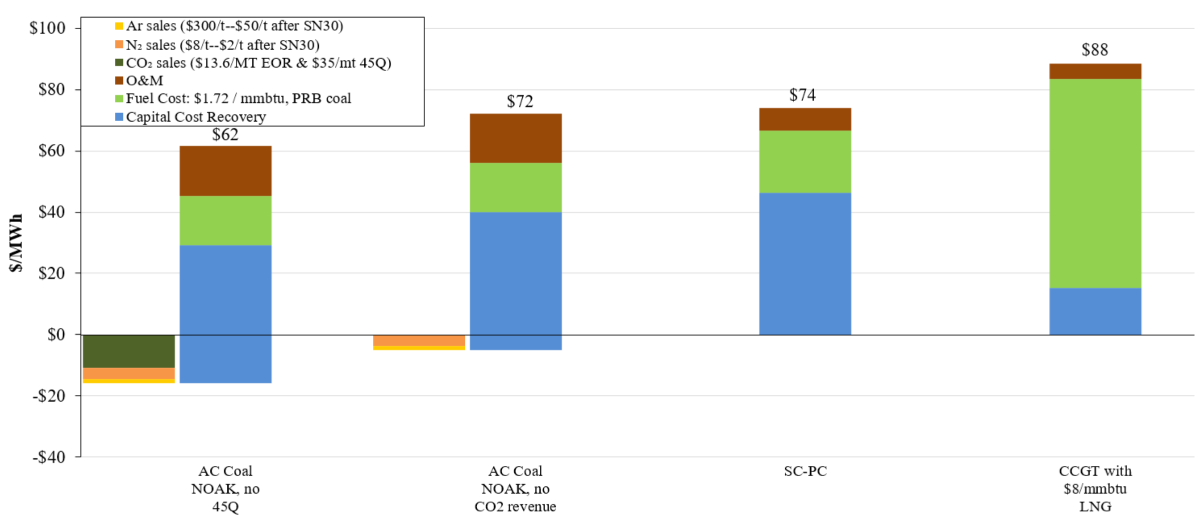
To further detail the competitiveness of Allam Cycle coal, Figure 1 also shows a case with a FOAK plant also claims the 48a tax credit and a two cases with $2.68 / MMBTU Illinois Coal.

Additionally, the US has over 5,000 miles in CO_2 pipelines connecting over 100 CO_2 offtakes, expanding the map of locations to build a CCS plant with minimal infrastructure required. The market for CO_2 for EOR is massive, with total potential demand enough to purchase 25 billion tons of CO_2 as the industry advances.[x] In 2014, 3.5 billion cubic feet of CO_2 were injected for EOR. The natural supply of CO_2 is limited geographically and in total size, with only 2.2 billion metric tons of total natural reserves. This necessitates a supply of CO_2 for the EOR industry to grow, and guarantees a large and growing market for Allam Cycle coal CO_2.

The subsurface geology in the US is attractive for sequestration as well, with a number of pilot projects and one commercial scale injection well operating in Decatur, Illinois. Sequestration will be particularly important on the coasts and the Midwest where EOR is not an option. The DOE has estimated the total storage capacity in the United States ranges between 2.6 trillion and 22 trillion tons of CO2, enough for thousands of CCS plants running for thousands of years.[xi]

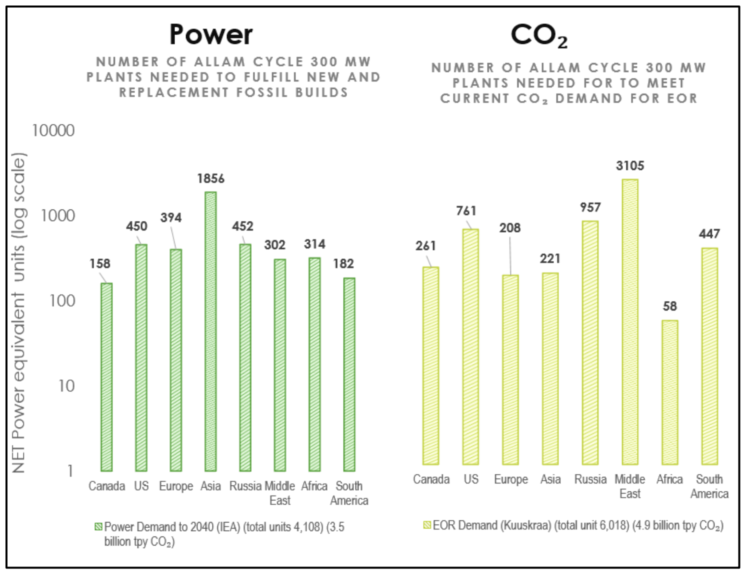
International Market Applicability: The Coal Allam Cycle's biggest international market is in fast growing economies where power demand is quickly increasing, and cheap natural gas is in short supply. This encompasses parts of India and China as well as much of eastern Asia. This region also has the most experience in constructing the coal gasifiers needed for this system. We have modeled further sensitivities for the global market: the nth-of-a-kind Allam Cycle with $0-$13.6 value per MT of CO_2, compared against conventional coal (SC-PC) and a CCGT with $8 / mmbtu imported liquefied natural gas, as shown in Figure 2.[xii] Capital costs are not adjusted internationally. We expect capital cost decreases to be roughly proportional across technologies, and thus not greatly impact relative competitiveness.

Figure 2: Cost of Allam Cycle Coal in Global Market



We expect the initial FOAK Allam Cycle plants to be built in the US, as with 45Q it is the most attractive place for CCS in the world for initial deployment. The deployment of both coal- and gas-based Allam Cycle plants will bring down the cost for the core cycle agnostic of fuel source. This is key: deployment of the natural gas Allam Cycle will have a direct impact on lowering the cost of the Coal Allam Cycle, since the core Allam Cycle is common and nearly identical in each system. Thus we expect to deploy the Allam Cycle at scale globally with nth-of-a-kind costs. As shown above with conservative industrial gas prices, this system will be cheaper than conventional coal with \$13.6 CO_2 and at cost parity with \$0 CO_2. After economics, the zero air pollution profile of this cycle may drive deployments globally, particularly in countries like Korea and China and India where air pollution is a top domestic issue. Allam Cycle may even be deployed without carbon capture initially, venting the CO_2 until an offtake is fully developed, and in the meantime delivering power at the same price with zero other air emissions.

Figure 3: Global Power and CO_2 Demand



Canada and the EU are also attractive international markets given their CO_2 policies, as are Middle Eastern countries like Saudi Arabia and UAE that have large demand for CO_2 for their oilfields, though the potential for Allam Cycle plants may be limited by power demand not CO_2 demand And Middle Eastern coal power is still being built despite massive gas supplies. In UAE, for example, 2.4 GW of coal are currently under construction and UAE is targeting 11.5 GW of new coal by 2050.[xiii]

The basic economic proposition for these countries is similar to the 45Q and EOR LCOE's shown in Figure 1, and so have not been broken down specifically here.

The scale of the global region is broken down in Figure 3 by power demand and CO_2-EOR demand. CO_2 sequestration and utilization are not included, which greatly increases the CO_2 offtake potential and opens up regions without EOR for CCS.

Estimated cost of electricity (and ancillary products): As shown above, the cost of electricity is estimated at \$15-\$43 per MWh with 45Q, across various scenarios. Without CO_2 incentives, the price rises to \$62-\$72 per MWh. Byproduct revenues are modeled as inputs to this power price output. Internal research and industry quotes led to our conservative estimate of \$13.6 / MT CO_2 for EOR, and our range of estimates for Nitrogen at \$2-\$8 per ton, and Argon at \$50-\$300 per ton. Byproduct values are uncertain and site specific. The Nitrogen value is an average value, assuming a combination high purity sales, low purity sales, and venting. For the FOAK each year, 2,190,623 MWH of power, 1,572,210 tons of CO_2, 70,773 tons of Argon, and 4,605,832 tons of Nitrogen will be produced.

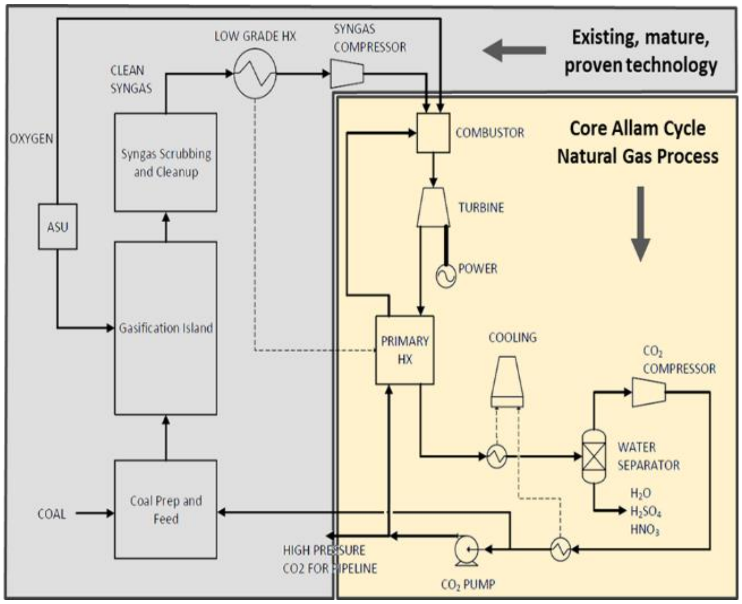
Market advantage of the concept: By producing power that is cheaper and has zero emissions, the Allam Cycle applied to coal as well as gas can become the new standard for power generation worldwide. Never have clean and cheap and dispatchable all coincided. Additionally, the power island has a much smaller footprint compared to conventional fossil fuel power plants given that the supercritical CO_2 working fluid has a very high density heat capacity, hence reduce the size of the power plant equipment, including gas turbine, heat exchanger, compressor and pumps. The compact design heat exchangers currently tested in the NET Power demo plant has much smaller footprint compared to the commercial heat recuperator. The smaller material needs of this equipment reduces construction costs, and most of the equipment in the power cycle can be built as modular, factory assembled skids. As an oxy-fuel cycle, the core cycle equipment, gas turbine, is not dependent on ambient conditions and is nearly identical from plant to plant. This will help to enable an assembly line, modular approach for construction, and also make sure the gas turbine can have a constant power output with site conditions. In general, only the cooling water system and the first stage of the main air compressor in Air Separation Unit experience ambient conditions. Design of the transition points between compressors and pumps will also minimize the impact of the cooling water temperature change. Therefore, the impact of ambient conditions on the Allam Cycle efficiency is much smaller than its impact on CCGT system. Finally, CO_2 is generated at high purity and pressure, reducing the cost of getting the CO_2 pipeline ready, and virtually eliminating the penalty of capturing CO_2 instead of venting it.

PLANT CONCEPT DESCRIPTION AND IMPORTANT TRAITS

The Allam Cycle Coal is a syngas fired power generation cycle invented by 8 Rivers Capital, LLC. Simply stated, Allam Cycle Coal is an integration of commercially available coal gasification technology and the Allam Cycle natural gas (NG), as shown in Figure 4 below. The natural gas version of the cycle is being commercialized by NET Power, beginning with a 50 MWth plant currently operational in La Porte Texas. The Allam Cycle is essentially fuel agnostic. Based on “desk top” studies, engineering design and analysis the Allam Cycle can run on a wide range of fuels including but not limited to NG, coal syngas, tail gas, industrial off-gas, to name a few, by using the syngas combustor developed by 8 Rivers.

Work on the coal syngas-fueled Allam Cycle has advanced in a parallel program to the NG cycle. This program is focused on the coal-specific aspects of the Allam Cycle, building off of the advancement of the core Allam Cycle at the La Porte 50 MWth facility. The Allam Cycle coal program has been supported by several consortiums over the past 5 years. Activities have been centered on addressing key potential challenges specific to the coal syngas Allam Cycle, including corrosion testing, gasifier selection, impurity removal and syngas combustor development. This study contributes to advancing the technology towards a commercial 294 MW_e net output Allam Cycle plant.

Figure 4: Allam Cycle Coal Process Integration with Gasification



The technology has the potential to enable new coal generation globally and domestically, using American technology and American coal. An Allam Cycle coal power system has the potential to produce electricity at a lower cost than new natural gas combined cycle (CCGT), supercritical pulverized coal (CCGT) and integrated gasification combined cycle (IGCC) facilities. The system includes full carbon capture (nearly 100%) and eliminates all other air emissions. The inherent emissions capture of the Allam Cycle provides an additional revenue stream,CO_2 for various uses including enhanced oil recovery and likely "proofs" it against future environmental regulations. Including revenue from CO_2, Ar, N_2 and tax credits, a first of a kind plant power price of $33 / MWH is expected.

An Allam Cycle coal plant will be the cleanest fossil fuel plant ever built with regards to Environmental Health and Safety since there is no vent stack in the system, all the combustion derived species will be captured in the system. The system removes all NOx, SOx, and particulate emissions, while >97% of the CO_2 can be stored permanently. Thus, there would be no air-born hazards or toxicological impacts from the Allam Cycle section of this plant, and to the degree that it displaces generation from neighboring fossil plants, it will actually reduce local air pollution. The "zero carbon" argon generated will be transported by truck or rail to existing industrial gas users, displacing argon that is generated with carbon-emitting power. The same industrial gas offtake will be used for nitrogen, but with a portion of the nitrogen potentially vented, given the large volumes over 4 MMT per year. Conventional black water treatment system and zero liquid discharge system are included in the system design in this study.

Meeting the Design Criteria Outlined in the RFP: Allam Cycle coal is able to meet or exceed all of the 10 design criteria for the coal plant of the future outlined by the RFP, while fulfilling the other objectives laid out through DOE's evaluation points.

<u>Modularity:</u> The proposed Allam Cycle coal plant is designed to produce 294 MWe power. The power island has a much smaller footprint compared to conventional fossil fuel power plants given that the supercritical CO_2 working fluid has a very high density heat capacity. The smaller material needs of this equipment reduces construction costs, and most of the equipment in the power cycle can be built in a modular basis. High pressure sCO_2 cycles have a high power density which leads to small equipment and therefore increased modularity.

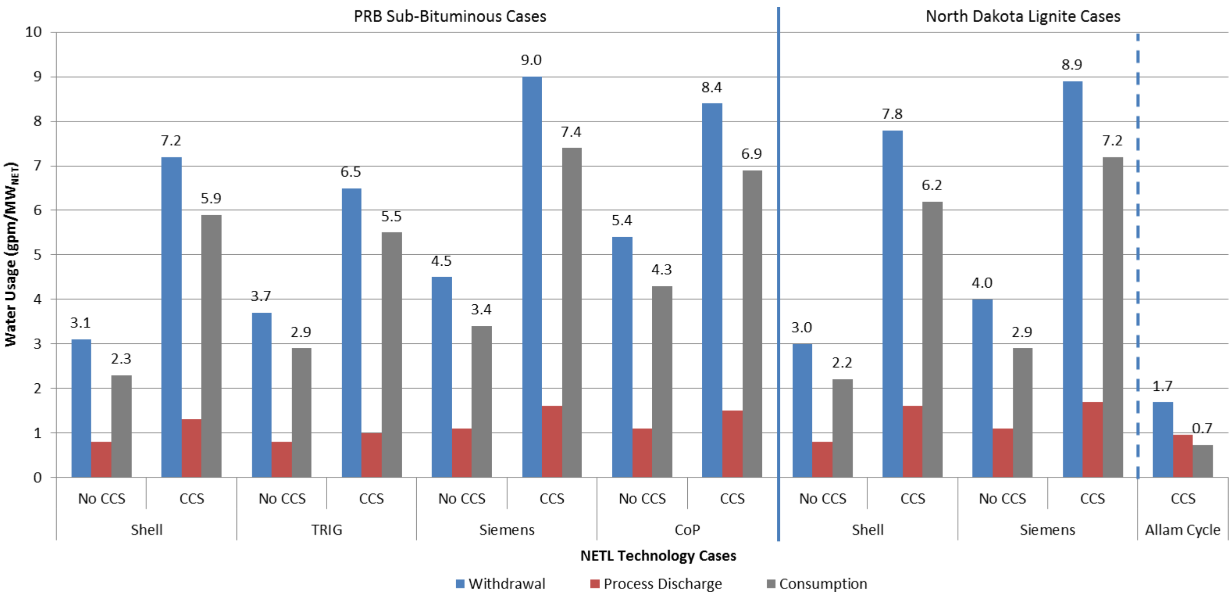
The coal gasification system in the Allam Cycle is much simpler and smaller size compared with conventional coal to chemical plants and IGCC systems, given that water gas shift reactor, pre-combustion CO2 removal units are eliminated in the Allam Cycle.

Near Zero Emissions: Allam Cycle coal inherently captures over 97% of CO_2 at pipeline pressure, without any additional equipment. This is expected at 150 bar, but can go as high as 300 bar, the highest operating pressure in the cycle, without additional CapEx. The oxy-combustion cycle generates nearly pure CO_2 that doesn't require expensive separation from other flue gases. Coal derived nitrogen is the only nitrogen source entering the cycle, so NOx formation is expected to be very low. In this study, a conventional acid gas removal system is included to remove sulfur from syngas down to single digit ppm level, any residual SO_X and NO_X in the flue gas can be removed in the CO_2-water separator without additional equipment to prevent contaminant buildup effect

Ramp Rates: Ramping speeds of the Allam Cycle are projected to at least be in-line with NGCC, with the potential to exceed that performance. The plant is operated in a fashion which maintains metal temperatures, and therefore equipment thermal profiles, remain nearly constant. Therefore, there is no "thermal inertia" during ramping. This will be determined through operation of the La Porte plant over the next year. Greater turndown capabilities than NGCC are expected, all the way down to zero net load to the grid, enabling rapid dispatch and low-load operation. The ability to generate extra power for sale beyond the plant's 294-MWe rating, is also possible for duration in the range of 4 hours. This is done by lowering ASU power usage by using locally stored oxygen, which was generated during times of low power demand and stored in tanks, and the oxygen storage tank is included in the standard ASU design package. For the coal based Allam Cycle, because the syngas combustor can co-fire natural gas and coal syngas without changing the turbine inlet condition, natural gas will be used to meet the required ramping and turndown capacity without interfering with the gasifier operation.

Water Consumption: Allam Cycle coal would provide water savings on the order of 50%+ as compared to a variety of CCS technologies. Figure 5 shows the Coal Allam Cycle using the Siemens gasifier compared against NETL IGCC baselines for various technologies based on lignite feedstock. Based on the DOE NETL report (Cost and Performance Baseline for Fossil Energy Plant Volume 1: Revision 3, 2015), the raw water withdrawal for NGCC without carbon capture is 4.2 gpm/MW_{net}, and the raw water consumption is 3.3 gpm/MW_{net}, thus Allam Cycle coal system reduce the water consumption by over 70% compared to NGCC system even without carbon capture. These major reductions are the result of two primary factors. 1: The elimination of the steam cycle reduces water needed for steam. 2: The semi-closed Allam cycle captures and condenses combustion derived water. The combustion derived water captured in the water separator is acidic with a P.H value of about 3.7, it is neutralized in the sour water treatment system and recycled back to the power system.

Figure 5: Analysis of Water Usage



Reduced Design, Construction and Commissioning Schedules: The smaller footprint of Allam Cycle equipment will reduce material costs, and enhance efforts for modular fabrication. The module core power cycle shared by NET Power and Allam Cycle coal will allow learnings from the design and construction of the initial NET Power Plants, to be constructed in the early 2020s, to be utilized by Allam Cycle coal.

Enhanced Maintenance: Maintenance costs for the Allam Cycle will be low due to the simplicity of the cycle. It requires only one turbine and its oxy-syngas combustor eliminates a portion of the upstream and downstream cleanup required by IGCC, such as a water gas shift reactor, and a downstream NOx removal system. The heat exchangers have excess surface area to allow for a given level of fouling before system performance is impacted. In addition, maintenance access is planned and available for inspection and cleaning as needed when the cycle is not operating.

Coal Upgrading and Other Value Streams: One of the most important traits of the coal Allam Cycle is that it can be integrated with coal to chemical processes efficiently and cost effectively, to co-produce hydrogen, methanol, ammonia and other coal derived chemical products. Syngas produced from gasifier system goes to a water gas shift reactor and then hydrogen is removed from syngas by a PSA unit, high CO rich syngas is fed to the Allam Cycle for power generation, CO_2 captured from the cycle can combine with H_2 for chemical productions. In addition, being primarily fuel gas agnostic, the Allam cycle could be integrated with a wide range of coal derived syngas including; gasification, tail gas, pyrolysis gas, etc. Entrained flow dry feed gasification technology gives added benefits by using a wide variety of coal feedstocks without the need of any major upgrading. The Allam Cycle itself generates significant secondary value streams. In addition to oxygen, the ASU produces Nitrogen and Argon, two valuable industrial gases used for fertilizer and welding that can be sold.

Natural Gas Co-Firing: The Allam Cycle syngas combustor has the ability to co-fire natural gas. Recycled CO_2 is the tuning parameter for the combustor operation with different fuel gas input. Since over 90% of mass in the combustor is recycled CO_2, with different fuel input, the turbine can maintain the same operating conditions in terms of temperature, pressure, flow rate and flue gas composition.

Target Level of Performance: In this project, detailed Aspen modeling was conducted to estimate the Allam Cycle coal plant performance using the commercially available dry feed Siemens entrained flow gasifier system with full water quench design. Both Illinois No.6 bituminous coal and Montana sub-Bituminous coal were used for the process modeling. The coal feedstock information is shown in Table 1. A Greenfield, Midwestern U.S. site condition was used for the analysis. The net efficiency of the Coal Allam Cycle is shown in Table 1A with the gross output and incurred parasitic load displayed above each case. The efficiency for the Coal Allam Cycle system ranges from 43.3% to 44.5% on a LHV basis with a different coal feedstock. The parasitic loads of the entire Allam Cycle coal plant was accounted for in the system efficiency calculation, including ASU, coal preparation, coal drying, coal feeding, gasifier, syngas cleanup, acid gas removal, zero liquid discharge, slag and ash handling, cooling tower, Allam Cycle power island and CO2 purification unit (CPU).

Table 1: Coal feedstock information

Rank	Bituminous	
Seam	Illinois No. 6 (Herrin)	
Source	Old Ben Mine	
Proximate Analysis (weight %)[A]		
	As Received	Dry
Moisture	11.12	0.00
Ash	9.70	10.91
Volatile Matter	34.99	39.37
Fixed Carbon	44.19	49.72
Total	100.00	100.00
Sulfur	2.51	2.82
HHV, kJ/kg (Btu/lb)	27,113 (11,666)	30,506 (13,126)
LHV, kJ/kg (Btu/lb)	26,151 (11,252)	29,544 (12,712)
Ultimate Analysis (weight %)		
	As Received	Dry
Moisture	11.12	0.00
Carbon	63.75	71.72
Hydrogen	4.50	5.06
Nitrogen	1.25	1.41
Chlorine	0.29	0.33
Sulfur	2.51	2.82
Ash	9.70	10.91
Oxygen[B]	6.88	7.75
Total	100.00	100.00

Rank	Sub-Bituminous	
Seam	Montana Rosebud	
Source	Old Ben Mine	
Proximate Analysis (weight %)[A]		
	As Received	Dry
Moisture	25.8	0.00
Ash	8.2	10.91
Volatile Matter	30.3	39.37
Fixed Carbon	35.7	49.72
Total	100.00	100.00
Sulfur	0.73	0.98
HHV, kJ/kg (Btu/lb)	19,923 (8,564)	26,787 (11,516)
LHV, kJ/kg (Btu/lb)	19,150 (8,252)	25,810 (11,096)
Ultimate Analysis (weight %)		
	As Received	Dry
Moisture	25.77	0.00
Carbon	50.07	67.45
Hydrogen	3.38	4.56
Nitrogen	0.71	0.96
Chlorine	0.01	0.01
Sulfur	0.73	0.98
Ash	8.19	10.91
Oxygen[B]	11.14	15.01
Total	100.00	100.00

Table 1A: Allam Cycle Coal Efficiency

Illinois No. 6 Bituminous Coal

Coal thermal input (MW in LHV)	670
Gross output (MW)	475.6
ASU load (MW)	-68.2
Total compression/pumping load in the Allam Cycle (MW)	-94.6
Gasification utility (MW)	-9.9
Cooling tower (MW)	-4.7
Net Power output (MW)	298.2
Net efficiency in LHV (%)	44.5%

Montana PRB Coal

Coal thermal input (MW in LHV)	680
Gross output (MW)	472.2
ASU load (MW)	-70.9
Total compression/pumping load in the Allam Cycle (MW)	-92.6
Gasification utility (MW)	-9.95
Cooling tower (MW)	-4.59
Net Power output (MW)	294.2
Net efficiency in LHV (%)	43.3%

The unique controls system of the Allam Cycle afford it the ability to maintain a near constant temperature profile during load following. Such a mechanism prevents the turbine and primary heat exchangers from experiencing thermal cycling and therefore undue stress. Additionally, the controls system generates modest changes in combustion pressure during partial load operation. The combination of these items permit the Allam Cycle to experience a relatively flat performance profile during variable output. It has been estimated that from 100% to 70% load the reduction in plant efficiency would be less than 4%.

The Allam Cycle utilizes a recirculating, trans-critical CO_2 working fluid in a high-pressure, low-pressure-ratio, highly-recuperated, semi-closed Brayton cycle. The cycle operates with a single turbine that has an inlet pressure of approximately 4,350 psia (300 bar) and a pressure ratio of 10. The ratio of recycled CO_2 mass flow to the combined fuel and O_2 mass flow is in the range of 25:1 to 35:1. To maintain a mass balance within the semi-closed cycle, a portion of the high-purity CO_2 process gas is exported at a point within recompression to a high-pressure CO_2 pipeline (typically at 1,450 psia [100 bar]) for sequestration or utilization. This net export is approximately 5% of the total recycle flow.

The coal-based Allam Cycle, as shown in Figure 4, comprises two primary processes: the gasifier island and the core Allam Cycle power generation process. The gasifier island utilizes proven technologies supplied by several commercial vendors from small (50 tons/day) to large (>2000 tons/day) scale systems that are in operation throughout the world (272 operating gasification plants worldwide, utilizing 686 gasifiers) (Higman, 2016). Thus, this portion of the overall process is commercially available, and for this effort, the team has selected Siemens entrained flow dry feed gasifier for the baseline, but recommend evaluating the R-GAS™ gasifier for the detailed integration analysis in future based on its added benefits. (Please see section Key features of R-GAS™ technology for details)

A 300 MWe scale Allam Cycle plant has not yet been built, but the 50 MWth facility has undergone adequate testing that makes the 300 MWe plant the next development step. Development of the coal-based Allam Cycle will build off of the knowledge gained from lab-, pilot-, and large-scale testing programs already completed or currently under way since the coal-based variant is nearly identical to the natural gas-based Allam Cycle in terms of facility design, process conditions, required equipment, controls, etc. However, switching to a coal-based fuel and integrating with a gasifier island requires several additional developments prior to being ready for commercial demonstration. These additional developments were identified via a detailed feasibility and scoping study completed on the coal-based Allam Cycle by a consortium consisting of 8 Rivers, the Electric Power Research Institute, ALLETE Clean Energy (ALLETE), and Basin Electric Power Cooperative (BEPC) (Forrest et al., 2014). Significant work (Table 2) was conducted to address technical challenges via lab- or pilot-scale testing in preparation for a large-scale program. Each key issue and the associated severity and mitigation are summarized in Table 2.

Based on work to date, the coal-based Allam Cycle is ready for a large demonstration. The technology readiness level (TRL) of the gasifier island is at TRL9, with over 20 years of operating experience and multiple installations, and the core Allam Cycle will soon be at TRL 8 using natural gas as fuel, once the La Porte plant exports power in the coming months. Key technological risks specific to the coal Allam Cycle have been addressed to the degree indicated in Table 2, which puts the overall coal-based system at a TRL5–6, indicating it is ready for a large pilot. The proposed program will mitigate remaining risks to ready the technology for commercial demonstration.

Table 2: Summary of Allam Cycle key issues and suggested mitigations

Development Pathway for the Coal-Based Allam Cycle	Lab- or Small Pilot-Scale Validation
Materials selection. The materials utilized in the core Allam Cycle power island must be able to withstand the additional corrosion risks presented by the introduction of coal-derived impurities that are able to bypass the gasification island and enter the process stream with the syngas fuel.	Three sets of static corrosion tests (1000–2000 hr each) were completed in 2016. Six different materials which can be potentially used in the coal Allam Cycle were tested at 30 bar, 50°– 90°C in the gas mixture, mimicking the chemistry of the flue gas in the coal Allam Cycle (Lu et al., 2016). These tests showed that standard stainless steel materials could survive the expected conditions of the Allam Cycle. A 1500-hr dynamic corrosion test was completed in mid-2017. Six alloy coupons were tested at 30 bar, 50°–750°C, in the gas mixture mimicking the chemistry of the flue gas in the coal Allam Cycle. Analysis of those materials indicated adequate lifetimes for materials in the recuperator. A 1500-hr, 300-bar corrosion test was completed at the end of 2017. The test mimicked the corrosion of the oxidant stream in the coal Allam Cycle at 300 bar, from 50° to 750°. None of the alloys were rejected for use in a sCO2 system under these conditions. It is expected that the alloys will have typical lifetimes for use in these environments and under these conditions.
Impurity management. As a semi-closed supercritical CO_2 Brayton Cycle,	Pre-combustion removal of coal-derived impurities is a well-proven process with commercially available

impurities introduced into the system must be actively controlled in order to prevent their concentration in the process stream which would impact material corrosion rates. For the coal Allam Cycle, impurity management will consist of bulk, pre-combustion removal (prior to introduction into the core Allam Cycle) and post-combustion, maintenance removal to prevent elevated concentrations in the recycled gas stream.	technologies able to achieve the required performance (e.g. Selexol, MDEA [monodiethanolamine], Rectisol, etc.) A parametric laboratory-scale study was conducted in 2017 of the post-combustion DeSNOx process, which consists of a simple water wash column to treat the combusted syngas and recirculated CO2. Under coal Allam Cycle conditions typical of precombustion impurity removal, approximately 99% SO2 removal and 50% NOx removal is expected with the DeSNOx process. Additional process strategies could be considered to increase the NOx removal. However, the combination of Selexol pre-combustion removal and DeSNOx post-combustion cleanup were identified as adequate to maintain the required process conditions.
Syngas combustion. A combustor is required to utilize coal-derived syngas produced by the gasification island. The design of this component represents a modification of the natural gas-fired combustor able to utilize the lower Btu content of coal-derived syngas.	The natural gas development program has informed the design of the syngas-fired unit. Computational fluid dynamics (CFD) modeling of this design was performed as part of a U.S. Department of Energy (DOE)-funded program in 2016, which showed that only slight modifications to combustor geometry were required to match the combustor outlet conditions of the natural gas unit. Pilot-scale testing of the 5-MW$_{th}$ natural gas-fired combustor was completed in 2015. Data from this program were used to design the 50-MW$_{th}$-scale unit at NET Power's pilot facility in La Porte, Texas. In July of 2018, NET Power successfully completed the combustion testing phase of the test program.

Table 2A. Remaining Key Risks Required to Be Mitigated

Remaining Challenges	Risk Mitigation
Materials selection. Selected materials must be shown to provide necessary lifetimes of both piping and equipment.	Materials have been shown to demonstrate sufficient survival at simulated conditions in the lab. However, operation in actual conditions is necessary to inform estimates of lifetime to achieve the necessary assurances and maintenance cost estimates for a full-scale

	commercial demonstration. Furthermore, estimates of lifetimes of equipment utilizing these materials is required in the actual environment.
Syngas combustion. Combustor must be shown to operate with syngas, which has a lower heating value and higher flame speed relative to natural gas. Controllability must also be demonstrated.	Successful testing of a 20-25 MW_{th} syngas combustor will allow rapid scale-up to the 50 MW_{th} "can-type" combustor scale required by the commercial-scale Allam Cycle combustion turbine. Controllability of this system, including start-up, shutdown, and transient operation, also needs to be demonstrated. 8 Rivers is pursuing funding to run a 150 hour 20-25 MWth combustor test.

Brief description of each process block

Syngas Compressor: The syngas fed from the syngas conditioning, metering and filtering skid is compressed to slightly above 330 bar in the gas compressor before entering the combustor. A single motor driven reciprocating compressor shall be provided. The discharge pressure accounts for the all relevant pressure drop between the compressor and the inlet connection to the combustor. The syngas entering the compressor (supplied from syngas skid) is assumed to be of adequate cleanliness such that there is no damage to the compressor.

O_2-CO_2 Pump: The O_2 required for combustion is delivered from ASU at 110 bar and diluted with recycled CO_2 leaving the CO2 compressor. The composition will be around 20% mass O_2 and 80% mass CO_2. The oxidant is compressed to slightly over 300 bar in the pump before entering the combustor The discharge pressure accounts for the all relevant pressure drop between the pump and the inlet connection to the combustor.

Combustor System: The combustor is capable of using a range of fuels without any hardware changes. By adjusting the fuel mix to dilution CO_2 ratios for each fuel, combustor exit temperatures remained 2100°F.

The design allows for the use of a very stable diffusion flame injector. The swirl-stabilized diffusion flame permits a wide range of stable operating conditions from ambient start-up to 300 bar at design point pressures and temperatures. Additionally, the inlet temperature of the oxidizer and diluent is above fuel auto-ignition levels, which contributes to flame stabilization. The flame zone is near the fuel injector and combustion occurs as oxidizer and fuel mix near the front of burner.

Carbon dioxide has a high heat capacity, which means it is a suitable fluid medium for heat transfer. This thermos-physical property makes it ideal to cool the combustor liner walls. However, there are limitations on the amount of heat that the CO_2 can remove from the liner. To satisfy liner material limitations, a ceramic thermal barrier coating will be plasma sprayed to the hot side walls (inside) of the combustion liner.

Main CO_2 Compressor: One 100% centrifugal compressor shall be provided to elevate the re-circulating stream of CO_2 to a pressure of about 60-70 bar. This allows CO_2 to achieve a dense phase after being cooled in a stainless-steel plate-fin cooler to a temperature of about 64F (ambient conditions used in this study) before entering the CO_2 pump.

At this discharge pressure and temperature, the CO_2 density approaches a value of 50 lb/ft3 which is adequate for CO_2 pump suction. There will be no danger of cavitation when the discharge pressure is combined with cooling conditions prevailing during peak ambient temperatures. The discharge pressure accounts for the all relevant pressure drop between the main CO_2 compressor and the inlet connection of the CO_2 pump.

The main CO_2 compressor shall be designed in accordance with the appropriate vendor standards. The compressor set will be provided with inter-coolers (as required)

CO_2 Pump: centrifugal pump shall be provided to increase the pressure of CO_2 to slightly higher than 300 bar before entering the combustor after being heated to close to turbine exhaust temperature in the main heat exchanger. The discharge pressure accounts for the all relevant pressure drop between the compressor and the inlet connection to the combustor.

Heat Exchanger: One high pressure, counter flow heat exchanger train with two sub-sections is provided to cool the turbine exhaust stream while heating the high-pressure CO_2 recycle stream that flows into the combustor, and O_2-CO_2 stream.

Materials for lower temperature section of the heat exchanger and associated piping will withstand slightly acidic and corrosive environments. Appropriate instrumentation for all interconnecting piping indicating inlet and outlet conditions, with respect to temperature and pressure will be provided, with vendor providing appropriate interfaces for the required instrumentation.

All required interconnection between the two heat exchanger sub sections will be included as part of vendor's scope of supply. End connections shall be suitable for welding to adjacent pipes and equipment.

Water Separator: The turbine exhaust stream leaving the heat exchanger is directed to a water separator, which cools process fluid below the dew point to condense and remove any residual combustion-derived water in the process fluid. In the water separator, CO2 process gas at approximately 30 bar and low temperature (60–90°C) comes in direct contact with sub-cooled combustion derived water. The liquid combustion derived water as well as any soluble trace species, such as SOx and NOx, are removed from the gaseous CO_2 stream, the CO_2 process stream leaving the water separator, which is free of liquid water and at ambient temperature, is directed to the main CO_2 compressor.

ASU: The ASU is required to supply 1,506 tpd of oxygen to the gasifier, 27 tpd of oxygen to the oxy-Claus unit and 2,879 tpd of oxygen to the Allam Cycle power block. Cryogenic air separation technology is a well-established process, offered by several technology providers with strong expertise in the cryogenic sector, with plants configured to provide pure oxygen, nitrogen or oxygen plus nitrogen in operation in multiple locations across a range of industries. The total oxygen requirement of 4,412 tpd represents a world-scale facility but is within the capacity range of existing facilities; a plant with five (5), 5,250 tpd oxygen, ASU trains was brought on-line in 2017 at Jamnagar, India.

In the ASU, air is filtered, compressed, cooled and dried before being separated through cryogenic distillation in a cold box to produce the oxygen and nitrogen product streams. A fraction of the nitrogen product stream is used for regeneration of the molecular sieve units which dry and remove carbon dioxide from the air before it enters the cold boxes, and also to produce chilled water used to pre-cool the air. Since the ASU is sized on oxygen production, the use of nitrogen for ancillary duties does not result in an increase in the size of the ASU. As well as producing gaseous oxygen, the ASU has been designed to liquefy oxygen, so that a back-up store of liquid oxygen (LOX) can be provided. This LOX storage provides redundancy in the oxygen supply to the plant in the event of an ASU outage, but also allows the operation of the ASU to flex in order to vary the electrical power available for export, thereby taking advantage of variations in power price or to provide grid support functionality.

Coal Delivery, Storage And Handling: Coal is delivered to the plant by rail. Unit trains consisting of 100 ton each x 100 railcars of bottom-discharge are unloaded via a receiving hopper and series of conveyors to the coal yard. The coal stacker transfers the coal to either the long-term storage pile or to the reclaim area. The coal storage capacity is designed to hold a minimum inventory of 30 days of design consumption to allow for any disruption in coal deliveries.

The coal feeding system, from the coal yard to the gasification island, consists of stacker/reclaim, conveyors, elevated feed hoppers, crushers, magnetic separators, and day silos. The crushers are designed to break down coal to a size not exceeding 35 mm. Coal from the crushers is transferred by enclosed belt conveyors to the day silos which are close to the gasification island.

Magnetic separators are used to remove ‘tramp’ iron from the crushed coal. Sampling systems are installed to analyze both the as-received coal and the as-fired coal to ensure the reliable and efficient operation of the plant.

Coal Feed System: Raw coal is delivered to the Coal Silo. This coal gets transferred to the coal Pulverizer by the weight belt conveyor. The raw coal enters the Pulverizer where it is pulverized and dried. The feed is ground to the desired particle size distribution and dried to about 5 wt% moisture for Illinois # 6 coal (6% for Sub bituminous PRB coal).

The dried coal is drawn from the coal feedstock bins and fed through a pressurization lock hopper system to high pressure discharge feeder using coal lock hoppers which operate in cycles to pressurize the solids in a batch process. There are four main steps in each Coal Lock Hopper cycle: Draining, Depressurization, Filling, and Pressurization. The coal is fed from high pressure feeder in a dense phase mode, with carbon dioxide or nitrogen as transport gas.

Gasifier Island: For this study a dry feed, entrained flow, slagging, single stage, down-flow gasifier was chosen, producing syngas at high pressures and temperatures. Dry feeding helps achieve high conversion rates, lower oxygen consumption and higher efficiencies as compared to slurry fed systems. For a baseline case Siemens entrained flow fully quench gasifier was chosen. The gasifier uses a cooling screen/liner design to control the reactor vessel wall temperature. The gasifier temperature is controlled above the slag fluid temperature to assure the creation of a protective slag layer on the inside of the cooling screen. The gasifier unit also contains a built in quench section below the reaction section where both the hot raw syngas and liquid slag are discharged. The raw gas and slag are cooled by injection of recycled gray water. High-temperature reactions inside the Gasifier convert the carbonaceous components in the coal feed to raw syngas, having primary constituents of CO, H2, CO2, and H2O. The sulfur in the coal feed converts primarily to H_2S and the remainder to COS. Chlorine and fluorine in the coal feed converts to HCl and HF, respectively. Small amounts of HCN and NH3 are also produced in the Gasifier.

Slag Collection and Handling: The solids are removed as both slag and ash. Liquid slag is solidified in a water bath and removed via a lock hopper system. The slag from lock hopper is transferred to the slag conveyor belt, where it separates from the water and the slag gets carried away to storage or waste land. Fine ash carried over with the syngas is captured in venturi and syngas scrubber.

Syngas Scrubber/Black Water Treatment: The raw syngas exiting the gasifier enters the scrubber for removal of chlorides and any fine ash. The quench scrubber washes the syngas in a countercurrent flow, which removes essentially all traces of entrained ash particles. The bottoms from the scrubber are sent to the black water treatment system for processing, where the suspended solids are removed from black water and gray water is return back to gasifier as quench media. The small blow down from black water treatment unit goes to waste water treatment facility.

Mercury Removal: Mercury removal from the syngas stream is achieved using packed beds of solid sorbent. Typically, activated carbon is used for this application, but proprietary adsorbents consisting of a mixture of metal sulphides are also available from some suppliers. The sorbents are not regenerated; spent sorbent is replaced and sent for disposal when the bed becomes saturated, typically on a 2-yearly interval.

COS Hydrolysis: Many acid gas removal processes have a low selectivity in the removal of carbonyl sulphide (COS). The use of COS hydrolysis pretreatment in the feed to the AGR process converts the COS to more easily capturable H_2S. The COS hydrolysis reaction is equal molar with a slightly exothermic heat of reaction, as shown in the following reaction:

$$COS + H_2O \leftrightarrow CO_2 + H_2S$$

COS hydrolysis is achieved in a fixed-bed catalytic reactor, with activated alumina catalysts typically being employed. Since the reaction is exothermic, higher conversion is achieved at lower temperatures. However, at lower temperatures the reaction kinetics are slower. Although the reaction is exothermic, since the concentration of COS in the syngas is low, the heat of reaction is dissipated among the large amount of non-reacting components and the reaction is essentially isothermal. The product gas typically contains less than 4 ppmv of COS

Acid Gas Removal: Acid gas removal (i.e. H2S removal) is achieved using a chemical or physical solvent. The syngas is contacted counter-currently in an absorber column against lean solvent, where near-complete H2S removal (typically together with partial CO2 removal) is achieved, with ‘sweetened’ syngas discharged from the top of the column and routed to the Allam Cycle power block. The rich solvent from the bottom of the absorber is transferred to the tripper column, where heat and depressurization are utilized to regenerate the solvent and produce a stream of sour gas that is routed to the Claus unit.

A range of solvents may be employed in the AGR unit. These include a range of amine-based formulations (for example, based on methyl diethanolamine (MDEA)), along with proprietary solvent processes such as Selexol, Rectisol and Sulfinol. For the purpose of this study it has been assumed that the Sulfinol process is employed. For the Allam Cycle, CO2 removal from syngas is not required, a simple and low cost amine based sulfur removal can be applied.

Claus Sulphur Recovery Unit: The H_2S-rich acid gas from the AGR is treated in the Claus SRU, where H_2S is converted into elemental sulphur using low pressure oxygen from the ASU via the following reactions:

$$H_2S + 3/2\ O_2 \leftrightarrow H_2O + SO_2$$

$$2H_2S + SO_2 \leftrightarrow 2H_2O + 3S$$

The second reaction, the Claus reaction, is equilibrium limited. The overall reaction is:

$$3H_2S + 3/2\ O_2 \leftrightarrow 3H_2O + 3S$$

One-third of the H_2S is burned in the furnace with oxygen to provide sufficient SO_2 to react with the rest of the H_2S. Since these reactions are highly exothermic, a waste heat boiler recovers this heat to generate HP steam. Sulphur is condensed in a condenser that raises LP steam. The tail gas from the first condenser then goes to a series of 2 or 3 catalytic conversion stages where the remaining sulphur is recovered via the Claus reaction. Each catalytic stage consists of gas preheat, a catalytic reactor, and a sulphur condenser.

Liquid Sulphur flows to the Sulphur pit, from where it is routed to storage prior to being exported by rail or road as either heated molten Sulphur or as solid Sulphur blocks. The tail gas from the SRU is quenched with process water, compressed and recycled back to the inlet of AGR absorber. This configuration results in essentially zero Sulphur emissions from the SRU.

Key Features of R-GAS™ Gasifier: In this study, R-GAS™ gasifier was also investigated as the future gasifier option to further improve the performance and reduce the cost. R-GAS gasifier is an oxygen-blown, dry-feed, plug-flow entrained reactor, baselined for this application with a full quench configuration which requires no syngas filtering or fine ash letdown system. R-GAS™ gasifier will be sized for 2,068 tonnes/day of dry pulverized Illinois # 6 coal (for sub-bituminous PRB coal the R-GAS™ gasifier will be sized for 2,442 tonnes/day of dry pulverized coal)**.** Key differentiators of R-GAS™ technology are:

a) Low void fraction coal transport minimizes introduction of inert gas to increase effective gas content and enable coal flow splitting to multiple injector elements
b) Multi-element injection to rapidly mix the coal with oxygen, creating a plug flow that eliminates large scale recirculation zones, increases reaction temperatures and kinetics, decreases required residence time to achieve high conversion and cold gas efficiency (exceeding that of competing technologies), while decreasing vessel size
c) R-GAS™ technology contains no refractory and pilot testing of the water cooled reactor liner suggest a service life of at least 10 years. Similarly, several injector configurations have been tested in the pilot plant, with no indications of wear on the surfaces exposed to the high temperature reactions and verifying life predictions of at least 2 years. The gasifier vessel and balance of plant will be designed for 30 year life.
d) Rapid spray quench design that provides flexibility to deliver dry or saturated syngas. Use of gray water for quench helps to reduce fresh water consumption
e) Simple mechanical arrangement that minimizes disassembly and reassembly time during maintenance

f) Expected maintenance will be one week for inspection and cleaning per year, providing a single train availability of 98%.
g) The simple mechanical arrangement in which the liner and the injector can be easily assembled and removed from the gasifier vessel from above means that the turnaround time to replace an injector is expected to be less than two days, providing spare hardware is available, and less than one week to replace a liner.
h) The 4% per minute ramp rate can be accomplished through storage capability of syngas in buffer drums
i) GTI's R-GAS™ technology has been demonstrated at pilot scale for both dry and wet collection of coarse slag. The dry approach eliminates black water systems and thus minimizes water usage.

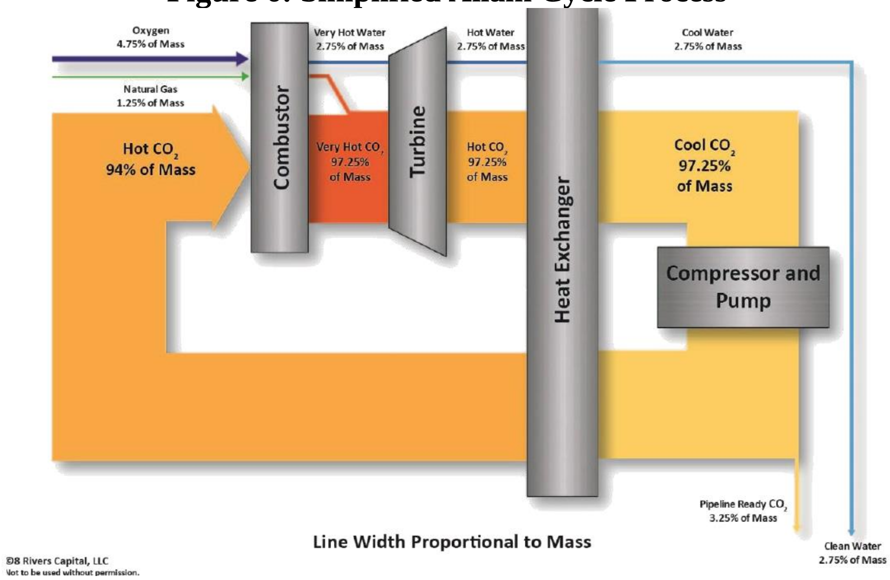
Cost Comparison: The total plant cost of a typical "Entrained flow Gasifier & Accessories" section like Siemens for a baseline case is estimated to be $ 152,863,000 USD. R-GAS™ gas gasification technologies gives overall 17.5% savings on total plant cost for "Gasifier & Accessories section". Utilizing its advanced rapid-mixing feed injection components and a unique plug-flow pattern of the gasification zone, GTI's R-GAS™ technology features a compact gasifier of much smaller dimensions comparing to other traditional pressurized gasifiers (such as the ones by Shell, GE, Siemens, etc.). Oxygen / coal / utilities consumption is lower than other gasification technologies. R-GAS™ is the state-of-the-art technology, variety of feedstock can be gasified and technology has been vigorously developed over the years.

Extent and manner of use of other fuels in conjunction with coal: The Allam Cycle is basically gaseous fuel agnostic, and can run on a wide range of fuel gas. The combustor is designed to use the most readily available fuel source. As the fuel differs from this, through use of a different coal feedstock, or just simply from variations in the coal, the fuel entering the cycle can be modified through the use of diluent CO_2 or NG. In this manner, key combustion control parameters, such as the Wobbe Index, can be controlled. This allows for variability in the fuel without impact on the operation of the cycle.

Description of any thermal or energy storage that is integrated and used: The Allam Cycle has unique ability to actually provide energy storage services by storing electricity as chemicals, through the Air Separating Unit (ASU) and the gasifier. During low power demand, the plant can be turned down to zero net load while running the ASU and gasifier at full capacity, storing liquid oxygen and syngas for later use. At times of high power demand, the Allam Cycle uses this stored oxygen and syngas or pipeline natural gas to lower the parasitic load a few hours at a time, extra power for sale beyond the 294-MW rating. Potential syngas storage capacity can be included which will enable flexibility for the gasifier during load following. If tanks were add to store 4 hours of oxygen, the plant would have a 284 MWH storage system, solely for the cost of the tanks. The exact sizing of this storage system will be dependent on the specific site and power grid node and pricing. Additional tanks could extend the hours of storage to >10 hours.

Power system working fluid and process conditions: The Allam Cycle utilizes a recirculating, trans-critical CO_2 working fluid in a high-pressure, low-pressure-ratio, highly-recuperated, semi-closed Brayton cycle. The cycle integrates with the exhaust from a single turbine that has an inlet pressure of approximately 4,350 psia (300 bar) and a pressure ratio of 10. All heat from combustion is recuperated in the cycle, eliminating the need for a bottoming cycle such as a steam Rankine cycle use in conventional combined cycle (CCGT) systems. The cycle is also direct-fired, meaning the combustion turbine is directly integrated into the supercritical CO_2 power cycle. Since CO_2 is used as the primary process fluid in the cycle, combustion-generated CO_2 within the semi-closed cycle is simply cleaned, dried and pressurized along with this primary process CO_2, and exported as high-pressure CO_2 export product, typically at 1,450 psia (100 bar), for sequestration or utilization. This net export CO_2 is approximately 3.25% of the total CO_2 process flow for the natural gas cycle, and 5% of the CO_2 for the coal cycle.

Figure 6: Simplified Allam Cycle Process



Features that minimize water consumption: As discussed above, the Allam Cycle coal would provide water savings on the order of 50-60% as compared to baselines for both IGCC and NGCC without carbon capture. Figure 5 showed the Allam Cycle compared against NETL baselines for the Siemens gasifier with lignite feedstock. These major reductions are the result of two primary factors. 1: The elimination of the steam cycle reduces water needed for steam. 2: The semi-closed Allam cycle captures and condenses combustion derived water.

Techniques to reduce design, construction and commissioning schedules from conventional norms including: A range of approaches may be adopted to accelerate project implementation and bring forward entry into service. These include:

<u>Completing as much detailed engineering as possible ahead of the Final Investment Decision -</u> The authorization of some detailed engineering scope ahead of FID allows an acceleration of the EPC program, facilitating earlier placement of orders for main equipment items as soon as the design parameters have been fixed. While the detailed engineering is performed ‘at risk’, the fee associated with the early engineering is modest in the context of the overall project.

<u>Early order placement for long lead items -</u> From the above early engineering, it is possible to bring forward the placement of equipment orders. However, it is likely that the delivery of long-lead items will still lie on the critical path of the project. To further accelerate the program, it is possible to place orders for the longest lead items at risk ahead of FID. A significantly greater value will be committed at risk ahead of FID through this approach, so it should only be adopted when entry into service is extremely time critical.

<u>Standardization of design / procurement of ‘off the shelf’ where possible:</u> Adopting standard design can reduce the timescale for engineering design and potentially reduce the delivery

timescale and equipment costs from suppliers. While the plant design may not be fully optimized, reduced performance may be accepted if this is outweighed by schedule and EPC cost benefits. For the 2nd and subsequent plants, adopting a ‘cookie cutter’ design, replicating the first plant, can significantly reduce engineering and procurement time and costs, with lessons learnt in the commissioning of the first plant also reducing commissioning schedules for subsequent facilities.

Multiple parallel units rather than one large unit: Adopting multiple parallel trains does add to overall complexity, piping runs, number of instruments, valves, etc. However, it does reduce the size of individual equipment items and packages. This has the benefits of potentially widening the number of potential suppliers, accelerating construction/fabrication, making transportation from fabricator to site easier and quicker and facilitating more modularization/off-site construction (see below). A cost benefit analysis would need to be completed based on site specific operating conditions for design optimization.

Modularization/Off-site Construction: Minimizing site work can accelerate construction programs by reducing the potential for scheduling conflicts and weather-related delay, especially where the site is in a challenging location. Packages and sub-assemblies can be fabricated off-site, in parallel in multiple fabrication yards in potentially more benign environmental conditions and closer to suppliers and skilled labor.

Use of a dynamic simulator for operator training: Conventionally, operator training will commence on the plant during the commissioning phase. However, by developing a dynamic plant simulator, this can be used as a training package for the plant operations team at an earlier stage, ahead of the plant being commissioned. This facilitates an earlier entry into service and reduces the potential for plant trips during early operation since the operators will already be fully up to speed.

Smart scheduling of construction activities to minimize the potential for weather disruption**:** Where a plant is located at a site with a challenging climate (e.g. severe winters or tropical storm risk in summer) then key construction activities can be scheduled for those periods of the year when the weather is most benign. For example, major crane operations should be scheduled for those seasons when high winds are least likely to cause disruption and delay.

Gain-share contracting strategies: With a conventional EPC or EPCm contract, there may be no advantage for the contractor to complete the EPC program and hand over the plant ahead of the agreed contractual date. However, by adopting a gain-share approach, there is a financial incentive to encourage early completion and the contractor is more likely to focus on schedule acceleration.

Global procurement strategy: By broadening the range of potential suppliers, shorter delivery times may be achievable for critical long-lead equipment items. Also, splitting orders between suppliers facilitates parallel rather than sequential fabrication, again reducing delivery schedules.

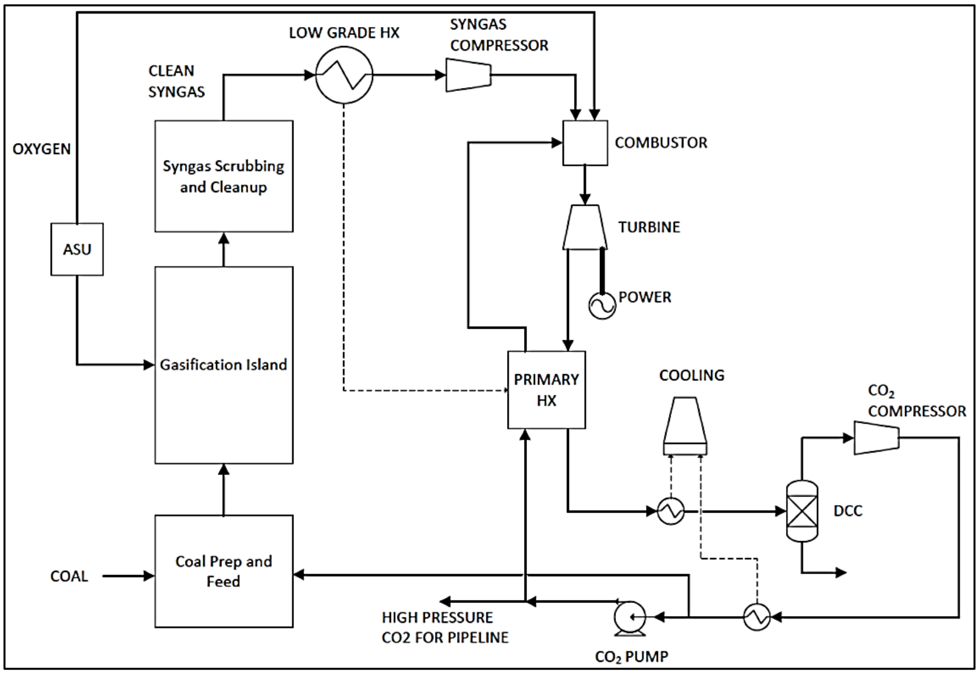
Rigorous Factory Acceptance Tests: Devoting adequate time and effort to the completion of Factory Acceptance Tests increases surety that equipment will be fit for purpose, with any problems identified and rectified prior to the equipment being delivered to site. This will minimize on-site commissioning problems and reduce the commissioning schedule

TECHNOLOGY DEVELOPMENT PATHWAYS

Current State Of the Art

The three key areas of the plant concept are the core Allam Cycle, the gasification island, and the integration of coal into the Allam Cycle, as shown in Figure 7 below.

Figure 7 – Process Schematic of the Coal Syngas Fueled Allam Cycle



NET Power is developing the state of the art in the Allam Cycle with the 50MWth plant in La Porte Texas.

To develop coal-specific Allam Cycle technology, 8 Rivers has led a 5-year R&D program conducted with the NDIC, EERC and local industry in North Dakota. These efforts have helped progress work on economics, corrosion, impurities, gasifier selection, and syngas combustor design. The key remaining challenge is the actual construction and operation of a 5-25 MWth scale syngas combustor, the only component not planned to be demonstrated by the NET Power development program.

The five critical tracks of this effort, along with the status of the work, are described below:

1. **Pre-FEED Study:** perform a site-specific techno-economic study
    - *Status:* A feasibility study of the Allam Cycle using North Dakota lignite was completed with gasifier vendor involvement. Both an entrained flow gasifier and fluidized bed gasifier demonstrated good economics across a wide range of fuel types. A detailed feasibility study shows the Allam Cycle coal system provides significant cost advantages and full carbon capture as compared to IGCC/SCPC[xiv].
        - Coal FIRST RFP application submitted to fund the next step, a Pre-FEED study.
2. **Corrosion Testing:** Evaluate the impact of coal-derived impurities on materials under actual flow conditions.

- *Status:* Two sets of 1500hrs dynamic corrosion tests were completed at the pressure of 30bar and 300bar, at the temperature from 750C to ambient temperature[xv]. Current materials have shown a high resistance to impurity levels achieved by simple pre-combustion sulfur removal, but high sulfur levels needed for 8 Rivers' proprietary downstream removal process requires advanced materials or coated materials. A detailed materials study is ongoing.

3. **Gasifier Selection:** Evaluate what commercially available systems provide optimal cost and performance for the Allam Cycle
   - *Status:* From an initial gasifier down-selection study, both an entrained flow gasifier and fluidized bed gasifier demonstrated good economics across a wide range of fuel types [xvi]
   - Work conducted for this RFP with Gas Technology Institute, a team member, will further advance down-selection of gasifier technologies for best performance based on the criteria established for this study.
4. **Impurity Removal:** Evaluate both pre- and post-combustion impurity removal process to optimize system cost and performance.
   - *Status:* commercially available single stage acid gas removal technologies can be applied post gasification / pre-combustion for sulfur removal in the Allam Cycle coal system.
   - 8 Rivers' proprietary process demonstrated removal of >99% of SO_X. Both SO_X and NOx concentrations in the clean CO_2 stream are below pipeline specifications for CO_2.[xvii] However the upstream Allam Cycle system will require advanced or coated materials to handle higher concentrations of sulfur in the process stream.
5. **Syngas Combustor Development:** Conduct design and testing of a low-BTU combustion system.
   - *Status:* Preliminary design and computational fluid dynamic (CFD) modeling work was completed in 2016 with support from the DOE[xviii]. 8 Rivers has developed the necessary test program to fully demonstrate the combustor, and is currently seeking funding to execute a 20-25 MWth test program.

Overcoming Challenges

The 50 MWth NET Power facility in La Porte Texas has overcome significant hurdles to the development of the Allam Cycle. This plant was designed based on an initial pre-front end engineering design study for a full scale 300-MWe natural gas Allam Cycle plant. The design was then scaled down as far as possible to reduce costs without requiring any major equipment changes. Thus, the demonstration plant will validate the full operating characteristics of a commercial-scale Allam Cycle system, and includes all of the key equipment of a commercial plant with the exception of an onsite air separating unit (O_2 is piped to site from a nearby ASU). While the facility is designed for 50MWth of fuel supply, the CO_2 turbine supplied by Toshiba is actually closer to ~200 MWth scale, allowing for minimal scale up to the 550 MWth scale required for a commercial facility. The combustor can tested in La Porte is the same scale combustor can that will be used in a commercial plant, except that the 550 MWth plant will have approximately 12 combustor cans. In July of 2018, NET Power successfully completed the combustion testing phase of the test program.

NET Power is supporting multiple 300 MWe facilities that are under development for commissioning in the early 2020s. These commercial natural gas facilities will overcome any remaining scale-up challenges for the coal system by demonstrating the full-scale cycle and the 550 MWth turbine, same as will be used by the coal Allam Cycle.

All the other items of equipment for the core Allam Cycle, listed below, can be obtained from several commercial vendors.

Table 3: NET Power Equipment Description
Fuel compressor delivering gas to the combustor at the elevated turbine inlet pressure, an order of magnitude higher than conventional, air-breathing combustion turbines
ASU with O_2 compression. O_2 is pre-mixed with a portion of the recycle CO_2 before being compressed and delivered to the combustor as oxidant. Industrial quality oxygen at 99.5% purity is specified to minimize the introduction of inerts. This requires, in addition to the normal O_2-N_2 separation, an added O_2-Ar separation, at incrementally higher capital and auxiliary power cost. Achieving this level of purity is well within the capability and experience of existing ASU providers.
Recycle CO_2 compressors/pumps, with inlet cooler, intercoolers, and pumps
Wet or dry cooling towers to provide cooling to the CO_2 compressors/pumps
Heat-recovery system to collect and provide miscellaneous thermal resources, including ASU compressor heat, to the working fluid
Suitable recuperative heat exchangers to pre-heat the CO_2 recycle flow and cool the turbine exhaust
Electrical generator and switchgear
Balance of plant.

For the coal-specific modifications to the Allam Cycle, the key remaining component hurdle is demonstration of the combustor operating on syngas, which can be overcome by constructing and operating the combustor. Design work and planning for this combustor testing has already been done under a 2016 DOE grant. The ideal test would utilize syngas from a natural gas steam methane reformer, which would allow for “tuning” of the syngas with various ratios of CO and H_2 to simulate multiple gasified coal sources.

8 Rivers is currently pursuing funding for this 20-25 MWth, 150 hour syngas combustor test.Successful funding and completing of the syngas combustor test is the key remaining hurdle that will allow for commercialization of a 300 MW Coal Allam Cycle plant in the mid-2020s.

Key Technical Risks

After the syngas combustor is demonstrated, the primary key technical risk remaining will be the operation of a full-scale NET Power’s 300 MW commercial unit. That technical risk wouldn’t be specifically borne by a Coal Allam Cycle project, as NET Power's natural gas Allam Cycle projects will be built first. With the 50 MWth demonstration in La Porte, this scale up risk has been limited.

Assessed Technology Gaps and R&D Needed

As described above, the primary key component gap for commercialization is demonstration of the 8 Rivers syngas combustor. The needed gasification technologies are fully commercial, and all the other Allam Cycle components have been and are being fully demonstrated and de-risked by NET Power.

However, further R&D could still help to reduce the cost of the system. R&D to lower the cost of coal gasification or air separation could further improve the cost profile and efficiency of the system. Improvements in heat exchanger technology, CO_2 pumps and compressors, high temperature turbine materials and corrosion resistant materials which would facilitate the post-combustion removal of H_2S (i.e. elimination of the AGR equipment) are four other areas where R&D could lead to efficiency improvements and capital cost reductions.

Pathway To Overcome Technical Risks

NET Power's deployment and operation of 300 MW Allam Cycle plants is the key pathway to eliminating Allam Cycle technical risk. Multiple commercial projects are under consideration, with the first plant anticipated to supply power in the early 2020s. The progress at the 50 MWth demonstration plant will allow for successful scale up.

8 Rivers aims to fund the syngas combustor test by the end of 2019, which will allow for completion of the test in 2021. This will de-risk the syngas combustor. Combined with the successful operation of the 50 MWth natural gas combustor, the syngas combustor technology will be sufficiently demonstrated and understood for scaling to a 300 MWe coal plant.

8 Rivers does not anticipate the need for an Allam Cycle Coal pilot facility, as the combination of the syngas combustor test, NET Power's 50 MWth facility and ensuing commercial-scale facilities will serve as the needed demonstration of the Coal Allam Cycle technology.

With the progress of the above efforts, the key remaining hurdles for the technology are the pre-FEED study and syngas combustor development, both of which can be completed in time for the 2022 timeframe for a full 294 MWe FEED study.

TECHNOLOGY ORIGINAL EQUIPMENT MANUFACTURERS

Identify and succinctly describe the proposed technology OEMs, including list of equipment and those equipment requiring R&D.

This section of the report seeks to identify and discuss the potential Original Equipment Manufacturers for the primary equipment packages of the coal-fired Allam Cycle process. OEMs will be engaged in the pre-FEED stage of the project to progress the project's technical and commercial development.

Our OEM identification process aimed to select only those OEMs that we believe could reasonably deliver the equipment packages required for this project. To achieve this, we prioritised companies with a strong presence in the United States, and those with demonstrable commercial experience in providing solutions for coal-fired power stations, gasification plants and related industrial facilities with similar capacities to those relevant to this project.

Based on the team's experience in the associated technology markets, the NET Power demonstration project and a desk-top survey, we have identified the potential technology OEM providers as below:

Coal Delivery, Handling and Reclaim

Bruks Siwertell: design, produce and deliver systems for loading, unloading, conveying, storing, and stacking and reclaiming dry bulk materials. With a main office in Alpharetta, GA, they specialise in high capacity, enclosed screw-type coal unloaders with discharge rates in excess of 3,000 t/hr, and have delivered thousands of projects worldwide.

Doosan Heavy Industries & Construction: deliver integrated EPC solutions for the power plants and water treatment plants. They have a number of US offices and they provide bulk handling systems to domestic and overseas coal-fired thermal power plants, steel mills, cement plants and other industrial plants. Doosan have a number of EPC contracts in the Asian power markets, including power stations in Vietnam, India and Korea.

Heilig B.V.: are based in the Netherlands and design, develop, and deliver machinery for handling bulk goods and conveying and processing recyclable waste streams. They have a number of demonstrated coal handling projects in screening/crushing, conveying, washing and drying and many demonstrated projects for the handling and treatment of ash. They offer bulk handling installations with capacities of up to 6,000 t/hr.

Metso: offer equipment and services for the sustainable processing and flow of natural resources in the mining, aggregates, recycling and process industries. They have a strong presence in the United States. They offer solutions from the mining of raw materials to the production of feedstock, and their range of bulk handling equipment includes stockyard equipment, conveyors and railcar unloading. Their coal stack and reclaim rates are up to 6,000 t/hr.

Air Separation Unit

Air Liquide: is a global provider of gases, technologies and services for Industry and Health with extensive experience in the supply of ASUs. They have a range of standard and large cryogenic air separation units with capacities up to 6,000 tons/day.

Air Products: are based in the United States and provide gases, chemicals and services for Industry. They offer an air separation solution which can be integrated with the customer's gasification process. Air Products has produced over 1200 air separation plants and currently owns and operates over 300 air separation plants.

Linde Engineering: is an EPC provider of customised industrial plants from design and construction through to operation and support. In 2018, Linde merged with **Praxair**, a provider of industrial gases, plant systems and services. They have produced over 3,000 ASUs, with capacities up to 5,500 tons/day.

Mercury Removal

Calgon Carbon: are a producer of activated carbon and manufacture it in granular, powdered, pelletized, catalytic, and impregnated forms for vapour and liquid purification solutions. They offer activated carbon solutions for mercury removal, primarily focussed around their Fluepac powdered products.

Honeywell UOP: offer a broad platform of regenerable and non-regenerable adsorbents capable of removing mercury. UOP offer GB copper-based adsorbents and HgSIV™ molecular sieve regenerative adsorbents for fixed-bed solutions for mercury removal.
Johnson Matthey: produces mercury removal adsorbents for the gas processing industry. Their PURASPEC fixed bed absorbents are suited for a range of applications within the Gas Processing, Refineries and Petrochemical markets, including mercury removal.

COS Hydrolysis
Axens Solutions: provide their COSWEET™ technology, a combined absorption catalytic conversion process for COS removal, which allows gas sweetening with either total or selective COS removal. Their gas processing business has over 2,500 industrial units under licence.
Haldor Topsoe: provide a range of high-performance catalysts and proprietary technology for the chemical and refining industries. Haldor Topsoe delivered the plant methanation section design for the Huineng SNG plant in inner Mongolia, and for the Qinghua SNG plant in China. They offer CKA-3, a COS hydrolysis catalyst, and can provide project development services.
Johnson Matthey: have more than 25 years' experience in purification solutions for the gas processing industry. Their PURASPEC™ adsorbents and processes are suitable for COS hydrolysis and a range of gas processing requirements. PURASPEC performance is proven within the industry with hundreds of installations worldwide.

Acid Gas Removal
Air Liquide: have designed numerous acid gas removal plants around the world across a range of industry sectors, and can provide systems with capacities up to 1.5 million Nm^3/h.
Axens Solutions**:** provides solutions for the production and purification of major petrochemical intermediates as well as for gas treatment and conversion options. They offer their SPREX® process for the removal of bulk acid gas from highly sour gas. SPREX® is a joint development between IFP Energies nouvelles, TOTAL and Axens Solutions.
BASF: are a provider of chemicals to industry, and also provide a range of chemical process plant / services. They have contributed to around 400 gas treatment plants across the world.
Dow Chemical Company: supply speciality solvents to gas processing plants across the world, and provide acid gas removal products, services and technologies to the gas industry.

Claus Unit (Sulphur Recovery Unit – SRU)
Air Liquide: offer several Claus Unit technologies, including traditional SRUs, emission-free SRUs and an OxyClaus™ add-on technology, to convert hydrogen sulphur into sulphur. Recovery rates are up to 100% and capacities up to 1,000 tpd per train. They have references for more than 170 conventional SRUs and more than 40 for OxyClaus™ units.
Worley: has more than 60 years of experience in the development and application of sulphur removal technology and has two global sulphur technology centres of excellence in Monrovia (California) and London. They have designed, licensed and built, some of the world's largest Claus plants and have developed oxygen-enriched Claus technology.
Linde Engineering: offer three variants of their standard SRU, "straight-through", "split-flow" or "direct-oxidisation", with a number of modified SRU variants and add-on processes which can be specified to suit project sulphur recovery requirements. Linde have designed and constructed more than 70 sulphur recovery plants based on the modified Claus and CBA (Cold Bed Adsorption) processes.

McDermott: offer a complete package of EPC services from conceptual design through commissioning. They have designed and built Claus SRUs, amine units, sour water stripping units, Oxygen Injection™ units, liquid sulphur degassing units, tail gas treating units and thermal incineration units around the world. They delivered a 260 tpd sulphur recovery unit at Valero St. Charles Diesel Processing Facility in Louisiana, USA, alongside several other gas processing packages.

Gasification Island

Air Products: is a provider of turn-key sale-of-gas gasification facilities for solids (coal and biomass) and liquids (refinery residues). In 2018, they acquired Shell's Coal Gasification Technology / Patents, a proven coal gasification technology in place at nearly 200 gasification systems delivering syngas around the world.

East China University of Science and Technology (ECUST): provides a range of gasification systems, including the Opposed Multi-Burner (OMB) system, which operates with dry-feed and coal-water slurry feed, and the SE dry-feed gasification system (developed in collaboration with Sinopec). As of 2017, there were more than 60 gasifiers in industrial operation, with single gasifier capacity between 750 and 4,000 tpd.

Gas Technology Institute (GTI): are a research, development and training organisation addressing energy and environmental challenges. GTI is established as an Illinois not-for-profit corporation. GTI have been actively involved in gasification research and development (R&D) for over 60 years, and have extensive experience in the design, construction, and operation of gasification systems, including seven trademarked processes. The R-Gas coal gasification technology provided by GTI requires further research and development to bring it to commercial demonstration.

Siemens Gasifiers: The Siemens gasifier is a dry-feed, pressurized, entrained-flow reactor, which can be supplied with either a refractory lining for low ash feedstocks or with a cooling screen in the gasification section of the gasifier. The cooling screen consists of a gas-tight membrane wall structure that is studded and refractory-lined with a thin layer of silicon carbide for protection. The molten slag formed in the gasifier chamber cools and solidifies as it contacts the cooling screen, forming a compact slag layer, protecting it from further damage by the flowing slag. Once a slag layer is formed over the cooling screen, subsequent hot slag flows down the reactor chamber into the quench section of the gasifier where it solidifies upon contact with water from a ring of quench nozzles and is removed through a lock hopper.

Zero Liquid Discharge (ZLD)

Aquatech: is a provider of water purification technology for industrial and infrastructure markets with a focus on desalination, water recycle and reuse, and zero liquid discharge (ZLD). They have more than 160 ZLD installations, including stand-alone thermal / evaporative processes, membrane processes or hybrid systems.

Condorchem Envitech: provides primary water, wastewater and air emissions treatment solutions for a wide range of industrial activities. They specialise in vacuum evaporators and crystallisers for the effective implementation of their zero discharge systems.

SAMCO Technologies: provides custom water, wastewater, process separation, and filtration solutions to a diverse range of industries. They provided a ZLD system with deionisation to a chlor-alkali company in Nekoosa, Wisconsin.

SUEZ: offers complete thermal and non-thermal ZLD solutions to manage tough-to-treat wastewaters. Their evaporators, brine concentrators and crystallisers claim to recover more than 95% of a plant's wastewater. Their ZLD solutions are in operation at the Stanton Energy Centre, Florida.

Existing OEM Relationships

The members of the 8 Rivers consortium were primary contributors to the development of the commercial-scale natural gas NET Power project, which was developed in conjunction with key OEM providers including Toshiba, Heatric and other project development partners related to the Allam Cycle. The team therefore have a proven, effective working relationship which is demonstrated by the successful development and delivery of the NET Power project.
In the NET Power project, the key OEM providers provided development and supply of the following equipment packages:

- Toshiba
  - Allam Cycle CO_2 combustor & turbine
- Heatric
  - Allam Cycle CO_2 heat exchanger

Both this concept study plant design and the NET Power project design use the same key Allam Cycle equipment packages, and therefore we will have the opportunity to engage the same OEM providers for these packages to ensure learnings from the demonstration plant are carried into this project.

Beyond the NET Power project, Gas Technology Institute has engaged with a wide range of equipment OEMs in their development of the R-Gas coal gasification technology, and will be able to bring these relationships into the next phase of the project.

In addition, WSP have experience working with Linde (through their BOC subsidiary in the UK) as the ASU technology provider to a proposed oxy-combustion coal-fired CCS power project in the UK.

New OEM Relationships

For the remainder of key equipment packages and identified OEMs, the consortium partners do not have existing OEM relationships. These OEMs will be engaged in the pre-FEED stage of the project to determine the most appropriate technology developers to contribute to the project.

Based on public domain information held on OEM websites, literature and presentation material, the 8 Rivers consortium has had adequate access to information on the equipment referenced in the proposed design. This concept study has not opened communications with the OEMs, this will be carried out in the next phase of the project.

REFERENCES

i https://www.eia.gov/outlooks/aeo/

ii https://www.eia.gov/coal/markets/#tabs-prices-2

iii https://www.albertastrongandfree.ca/wp-content/uploads/2019/03/Getting-Alberta-Back-to-Work_UCP2019Platform.pdf

iv https://www.eex.com/en/market-data/environmental-markets/spot-market/european-emission-allowances#!/2019/05/23

vhttps://icapcarbonaction.com/en/?option=com_etsmap&task=export&format=pdf&layout=list&systems[]=47

[vi] Lu et al. Oxy-Lignite Syngas Fueled Semi-Closed Brayton Cycle Process Evaluation (2014) Total Plant Cost and O&M costs were estimated for lignite system in conjunction with EPRI; AACE Class 5 estimate. Cost data for other technologies is taken from NETL baseline reports (Vol. 3, 2011)

vii NETL baseline reports (Vol. 3, 2011)

[x] An In-Depth Look at Next Generation CO_2-EOR Technology. NETL. Matthew Wallace, Vello Kuuskraa, and Phil DiPietro. September 23, 2013.

[xi] Carbon Capture and Sequestration (CCS) in the United States, CRS Report. https://fas.org/sgp/crs/misc/R44902.pdf

xii https://www.meti.go.jp/english/statistics/sho/slng/index.html

[xiii] https://www.eia.gov/todayinenergy/detail.php?id=36172

xiv Forrest, B., Lu, X., McGroddy, M., Fetvedt, J., et al. Oxy-Lignite Syngas Fueled Semi-Closed Brayton Cycle Process Evaluation. Lignite Research Council, BNI Coal, Minnesota Power, and Dakota Gasification Company.

[xv] Lu, Xijia, McGroddy, Mike, Forrest, Brock, Freed, David, Kay, John, Laumb, Jason, Stanislowski, Joshua, Hurley, John, "DYNAMIC CORROSION TESTS IN A CO2-RICH ENVIRONMENT", Presented at Materials & Technology Conference 2018 (MS&T18), Oct. 17th, 2018

[xvi] "Oxy-Lignite Syngas Fueled Semi-Closed Brayton Cycle Process Evaluation," 2014.

[xvii] "Testing of a Novel Post Combustion Acid Gas Removal Process…", X. Lu, X, et al., Proceedings of ASME Turbo Expo 2017, GT2017, June 26-30, 2017, Charlotte, NC, USA.

[xviii] *Coal Syngas Combustor Development for High-Pressure, Oxy-Fuel SCO2 Cycle Applications,* US Dept. of Energy – NETL, Award Number FE0023985, October 2014