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
Report Title: Technology Gap Analysis, Public Version

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)

Company Point of Contact: Adam Goff. 8 Rivers Capital.
Telephone: +1 919-667-1800
Fax: 919.287.4798
Email: adam.goff@8Rivers.com

Date of Submission: January 10th, 2020
Date of Revision: February 18th, 2020

Contents

CONCEPT BACKGROUND

8 Rivers is pursuing this Pre-FEED study for a 714 MWt (HHV) near zero emissions coal fired power plant located adjacent to Peabody's North Antelope Rochelle Mine (NARM). The power plant will receive coal directly from the mine and use that coal to generate syngas which will then be utilized in a syngas fueled Allam-Fetvedt Cycle power plant. The power plant will export about 287 MWe of power to the local network, yielding an efficiency of 40.2% (HHV). This will be via a dedicated switchyard or alternatively via the NARM switchyard subject to available capacity.

Because of the inherent low emissions nature of the Allam-Fetvedt Cycle the overall plant will have over 93% carbon capture. The various gases produced in the process will either be re-used within the process or will be sold for commercial use. Water will be cleaned and re-used within the process, with the facility operated on a zero liquid discharge basis.

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 1 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 in development by 8 Rivers[i].

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 290 MW_e net output Allam Cycle plant. This study will be used by 8 Rivers, the technology and project developer, to support the development of a near zero emissions project with a goal to commission the commercial facility within 5 years.

The technology has the potential to enable new coal generation globally and domestically, using American technology and American coal. An

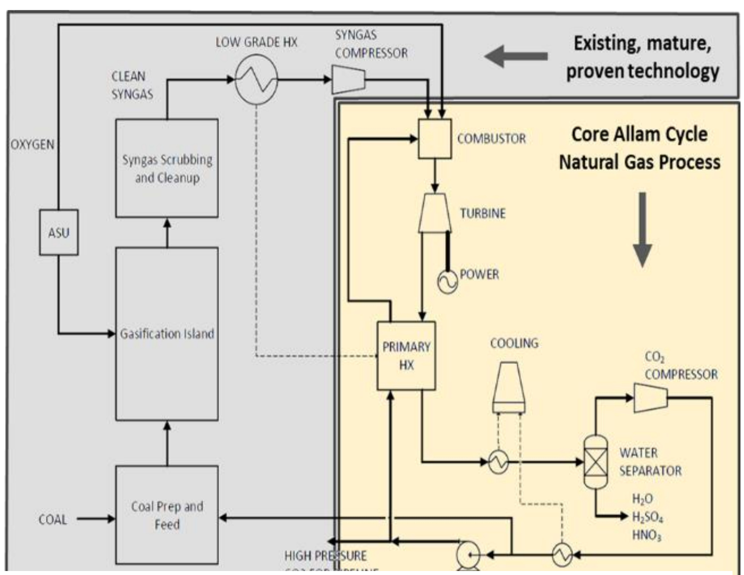

Figure 1 - Allam Cycle Coal Process Integration

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 (SCPC) and integrated gasification combined cycle (IGCC) facilities. The system includes over 93% carbon capture 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 nearly all NOx, SOx, and particulate emissions, while >93% of the CO_2 can be captured and 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.

Plant production/facility capacity

The proposed Allam Cycle coal plant is designed to have 550MWt in LHV cleaned syngas fed into the Allam Cycle power island. Table 1 shows the plant's net and gross capacity with the Wyoming subbituminous coal chosen for the Pre-FEED study. The system efficiency and auxiliary load with selected site and Wyoming coal was updated with vendors' input in the Pre-FEED study.

Coal thermal input (MW in LHV)	676
Gross generator output (MW)	468.15
ASU load (MW)	-72.19
Total compression/pumping load in the Allam Cycle (MW)	-86.29
Gasification utility (MW)	-5.23
Cooling tower (MW)	-4.35
Miscellaneous BOP (MW)	-6.2
Net power output (MW)	286.7
Net efficiency (% LHV)	42.40%

Table 1 - Allam Cycle Efficiency With Wyoming subbituminous coal

In addition, the Allam Cycle coal plant produces CO_2, Argon, and Nitrogen for sale. At the 85% Capacity Factor modeled in the Conceptual design, the plant will produce 1.57 million tons of CO2 per year, 4.6 million tons of Nitrogen, and 71,000 tons of Argon.

Plant location consistent with the NETL QGESS

For the Pre-FEED study, 8 Rivers has selected to site the plant at Peabody's North Antelope Rochelle Mine (NARM), and to use Peabody's coal from that mine. Peabody submitted a Letter of Support to the original Coal FIRST application, and has provided all the necessary site and coal information for the Pre-FEED. Due to the large native power demand and the proximity to multiple CO_2 offtakes, this is a favorable location for siting an actual power plant.
When available, we have used NARM specific parameters. Otherwise, we have used NETL QGESS design parameters.

Parameter	Value
Location	Greenfield, Teckla, WY
Topography	Rolling
Transportation	Rail or highway
Ash/Slag Disposal	Off Site
Water	Ground water
Elevation, (ft)	4830
Barometric Pressure, MPa	0.101
Average Ambient Dry Bulb Temperature, °C	9
Average Ambient Wet Bulb Temperature, °C	5.2
Design Ambient Relative Humidity, %	61%
Cooling Water Temperature, °C	10
Air composition based on NETL QGESS, mass %	
N_2	72.429
O_2	25.352
Ar	1.761
H_2O	0.382
CO_2	0.076
Total	100.00

Table 2 - NARM Site Parameters

Business case from Conceptual Design

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 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 the same or 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 >93% carbon capture 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 Pre-FEED, we assume the use of the Wyoming subbituminous Coal from the NARM. The composition of the fuel is confidential and has been removed from the public report.

Table 3 - Analysis of Peabody North Antelope Rochelle Mine 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.[ii] To adjust this projection for Wyoming subbituminous coal we assume that the mine mouth price remains at $.70 / MMBTU for Wyoming subbituminous 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 for a generic project using Wyoming coal. For the specific NARM site at the mine mouth, we expect the cost provided by Peabody to be closer to the $.70 / MMBTU mine mouth coal price, to be updated in the levelized cost analysis in the Cost Results Report. The cost of Wyoming subbituminous coal is in the process of being provided by Peabody for the Cost Results Report. We also show a case at $2.68/MMBTU delivered cost, which uses the same methodology for Illinois Basin coal's 2019 price point.[iii]

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 2, with current value of CO_2, Allam Cycle coal can bid into the dispatch order at $0 / MWH, 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 be $15 / MWH, which would still be low enough to be the first fossil source in the dispatch stack.

CO2 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)[iv], the cap and trade system in Europe (\$29 / MT)[v], or the Korean emission trading system (\$20 / MT).[vi] 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.

Note on Cost Modeling Methodology and NETL QGESS

As discussed with DOE, 8 Rivers plans to update our LCOE modeling to better match the NETL QGESS reports provided. However, 8 Rivers is waiting until the updated data from the Pre-FEED is available to revise the economic modeling, which will occur in the Cost Results Report. As such, the LCOE charts referenced herein all match the work from Conceptual Design, and will be updated later.

Domestic Market Applicability

As shown in Figure 2, 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, 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

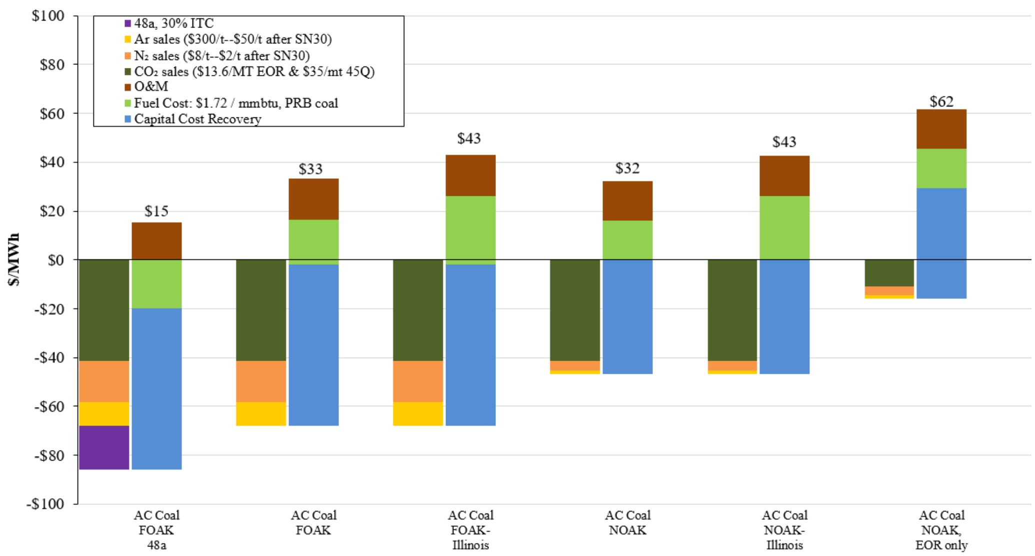

Figure 2 - Levelized Cost Comparison In The US Market

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.

The Allam-Fetvedt Cycle is modeled with a 36 month construction time compared to 31 months for CCGT. It's assumed to have a $4,328 / KW overnight capital cost, compared to $911 / KW for the H class CCGT. Total FOAK capital cost is $4,821 / KW. The FOAK has $105.7 / KW fixed O&M cost, and $1.8 / MWH variable O&M cost. Total NOAK capital cost is $3,286 / KW. Natural gas is priced at $2.90 / MMBTU and PRB coal at $1.72 / MMBTU.[vii] Cost data for other technologies is taken from NETL baselines 2011 Vol 3.[viii] 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 3) 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 3 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 2 also shows a case with a FOAK plant also claims the 48a tax credit and a two cases with $2.68 / MMBTU Illinois Coal. 48a is a 30% ITC available to power plants that use 75% coal feedstock and achieve 70% carbon capture with 40% HHV efficiency, a benchmark that Allam Cycle coal meets in all scenarios. It requires 400 MW total nameplate capacity. This Allam Cycle Coal design exports about 290 MW of electricity, but its nameplate capacity will be above 470 MW as shown later in Table 1A, and thus qualifies for 48a. For the purposes of 48a, IRS has defined nameplate capacity as "aggregate of the numbers (in megawatts) stamped on the nameplate of each generator to be used in the project."[ix] It can be claimed alongside 45Q, is already in statute, and has over $1 billion in credits currently claimable.[x] This 48a credit the higher CO_2 revenue per MWH of coal makes the Coal Allam Cycle competitive against the natural gas Allam Cycle being commercialized by NET Power. NET Power's LCOE is higher than the coal Allam Cycle with 48a.

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.[xi] 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.[xii]

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.[xiii] Capital costs are not adjusted internationally. We expect capital cost decreases to be roughly proportional across technologies, and thus not greatly impact relative competitiveness.

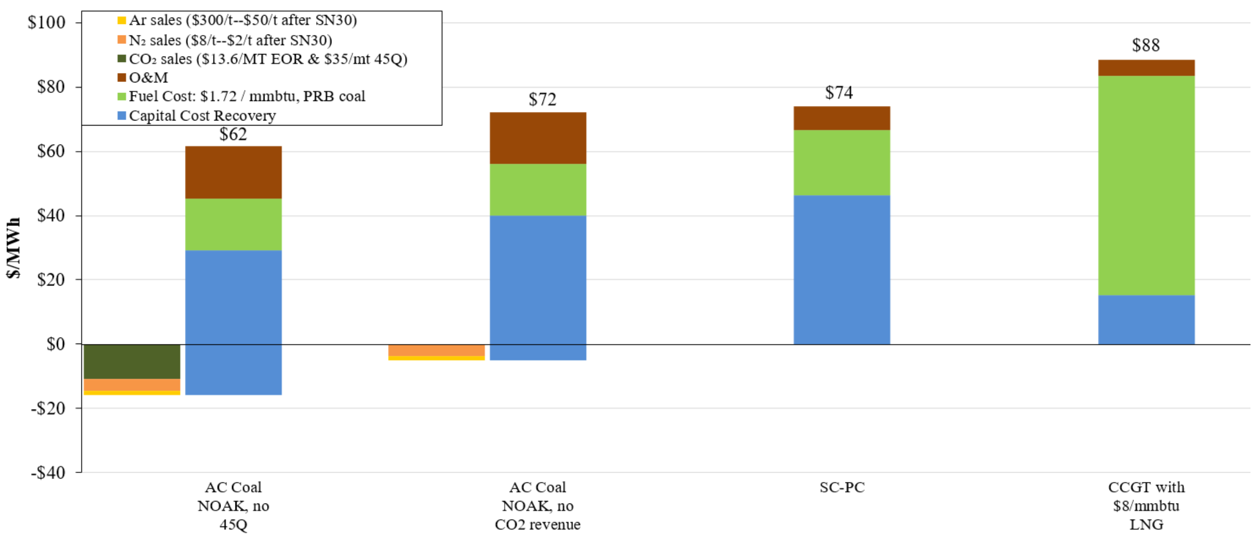

Figure 3 - Cost of Allam Cycle Coal in Global Market

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.

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.[xiv]

The basic economic proposition for these countries is similar to the 45Q and EOR LCOE's shown in Figure 2, and so have not been broken down specifically here.

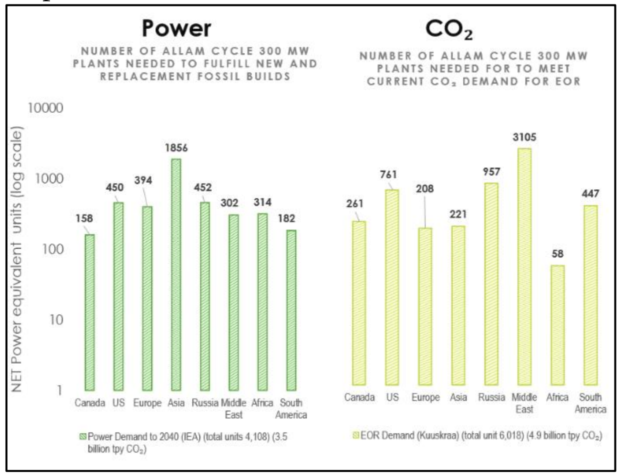

Figure 4 - Global Power and CO2 Demand

The scale of the global region is broken down in Figure 4 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.

TECHNOLOGY GAP ANALYSIS

Current State Of The Art

As a new power cycle, the Allam Cycle is itself a state-of-the-art technology system that largely relies on fully proven components. With two key exceptions. First, the sCO2 combustor, which is an oxy-combustion system, done in the presence of a large mass of pre-heated CO_2, to reach the pressures and temperatures require to drive the turbine. The La Porte plant demonstrated the first such combustor. The test was on a 50 MWt combustor, which Toshiba considers their commercial size, as they plan to use 10-12 combustors aligned radially around a larger turbine. In July of 2018, NET Power successfully completed the combustion testing phase of the test program. At that time, major equipment had been operated between 500 and 900 hours, and over 170 hours of testing with fuel in the system was completed, with individual test runs lasting over 24 hours. Findings from this program will be applied to the syngas combustor.

The sCO_2 turbine is the other exception. It is driven by CO_2 rather than steam or air, and experience pressures similar to a steam turbine simultaneously with the temperature profile of a gas turbine. Toshiba's turbine in La Porte was in a 200 MWt pressure shell, leading to 2.5x-3x scale up to full scale. Due to size limitations on the blades, the demonstration turbine had partial arc admission of approximately 90°. This resulted in parts of the turbine being closer to a 200 MWt design with the corresponding difference in scale-up to a full design.

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 3) 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 3.

Based on work to date, the coal-based Allam Cycle is ready for full scale 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 is at TRL 7. Commercial scale projects are being actively pursued. Key technological risks specific to the coal Allam Cycle have been addressed to the degree indicated in Table 3, 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.

We believe that after this Pre-FEED, and with the potential for syngas combustor development under the Critical Components FOA, Allam Cycle Coal will be immediately ready for a FEED study followed by financing and construction of a first of a kind full scale plant. As such, we are planning to apply for the Coal FIRST FEED announced in the recent NOI for release on May 2020, so long as Allam Cycle Coal is not specifically prohibiting from submitting an application.

Overcoming shortcomings, limitations, and challenges

Our approach to overcoming the remaining challenges are shown in Table . This table is specific to the challenges facing the Coal Allam Cycle. The other main challenges to the Allam Cycle, particularly the scale up to the first 300 MWe unit with a >500 MWt sCO2 turbine, will be overcome by the first deployments of the Gas Allam Cycle by NET Power, with the first plant targeting commissioning in 2022, and so are listed in a separate table. The Allam Cycle risks and mitigations will benefit from being retired commercially before the implementation of the syngas fired version. There risks and potential mitigation are presented in Table 4, along with their potential impact on the Coal Allam cycle.

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 to mimic the coal Allam Cycle conditions. 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 MWth syngas combustor will allow rapid scale-up to the ca. 50 MWth "can-type" combustor, or larger scale silo combustors 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. If this is funded as part of the Critical Components FOA, we anticipate a 2 year test duration finishing in 2022.
Combustor/turbine. Issues specific to the combustion turbine process.	Areas of technical risk initially identified include seal buffering and leakage, high Reynolds Number gas path and cooling flow behaviour, combustion testing and development plus corrosion behaviour. This list is not all-inclusive but indicative of developing trends. Should the design go forward a full "SIRA" risk assessment would be performed at the start of the project. This assessment would be used to plan design tasks intended to retire or mitigate identified risks.

Table 4- Remaining Key Risks Required to Be Mitigated

Allam Cycle risks and mitigations.	Lab- or Small Pilot-Scale Validation
Materials selection. The base natural gas fired Allam Cycle materials must withstand the potentially corrosive environment within all areas of the plant. In addition, the materials	Corrosion testing is being performed within the La Porte demonstration and testing facility. 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

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.	chemistry of the flue gas in the coal Allam Cycle (Jason D. Laumb 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 (Lu et al., 2018).
Impurity management. As a semi-closed supercritical CO_2 Brayton Cycle, 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.	Pre-combustion removal of coal-derived impurities is a well-proven process with commercially available technologies able to achieve the required performance (e.g. Selexol, MDEA [monodiethanolamine], Rectisol, etc.) Acid gas removal vendors confirmed MDEA process can remove H2S from syngas down to less than 10ppmv, which meets the requirement for the combustor and turbine operation. All SOx and NOx produced in the combustor are removed in the downstream water separator naturally in the forms of H_2SO_4 and HNO_3, via "lead chamber process" reactions. A parametric laboratory-scale study was conducted in 2017 of the lead chamber process reactions under the Allam Cycle coal system conditions, which consists of a simple water wash column to treat the combusted syngas and recirculated CO2. The lab testing shows that any trace SOx and NOx in the combustion flue gas can be completely removed in the water separator (Lu et al., 2017). Therefore, MDEA process is selected for the pre-combustion sulfur removal technology in this pre-FEED study.
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	The natural gas development program has informed the design of the syngas-fired unit. In addition, knowledge gained in operating the facility during the combustion tests is of benefit to the syngas combustion designers in understanding operation of the process and the impact on combustor operations. Computational fluid dynamics (CFD) modeling of this design was performed as part of a

combustor able to utilize the lower Btu content of coal-derived syngas. The risks of the natural gas turbine were mitigated with successful operation during testing and fired turbine operations.	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-MWth natural gas-fired combustor was completed in 2015. Data from this program were used to design the 50-MWth-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. At that time, major equipment had been operated between 500 and 900 hours, and over 170 hours of testing with fuel in the system was completed, with individual test runs lasting over 24 hours. Findings from this program will be applied to the syngas combustor. Shock tube testing of syngas combustion at the conditions required in the Allam Cycle was conducted in 2017 and was used to further validate modeling parameters, especially for the calibration of the supercritical CO_2 oxy-syngas combustion reaction kinetics. Successful operation of the NG combustor in the integrated facility is directly applicable to the syngas combustor. Cycle operability and interaction with the combustor was determined and explored. Knowing what the cycle and support equipment are capable of will have benefits for syngas.

Table 5- Summary of Allam Cycle key issues and suggested mitigations

Perceived technology gaps and R&D needed for commercialization by 2030

The only remaining technology gap after the Coal FIRST Pre-FEED and given the in-progress commercialization of the natural gas Allam Cycle is the syngas combustor. The turbine is the same turbine that will be used in the natural gas version of the cycle. The turbine inlet temperature, pressure, and volumetric flow is that same between the two different fuels. Due to the highly recycled nature of the process, the majority of the fluid entering the turbine is CO_2. There is a slight difference in water content due to the C:H ratio differences between natural gas and coal derived syngas. Siemens has extensive experience in thermal barrier coatings development for syngas environments with elevated water contents. This C:H ratio difference manifests itself as a difference in average molecular weight of the process stream. This difference has a negligible impact on the operation of the turbine[xv].

Fuel Selection	NG	Slurry-Feed	Dry-Feed
Average Process Fluid MW	41.8	42.5	43.0
Condition/Design MW	–	1.017	1.029

Table 6- Comparison of Turbine Inlet Streams[xvi]

Successful testing of a 50 MWth combustor run at a 20 MWth syngas load will allow rapid scale-up to the 50 MWth "can-type" combustor scale required by the commercial-scale Allam Cycle combustion turbine, or scale-up to a silo style combustor. Controllability of this system, including start-up, shutdown, and transient operation, also needs to be demonstrated. Confidence is high based on the successful completion of the natural gas combustion testing. 8 Rivers is pursuing funding to run a 100-200 hour 20 MWth combustor test. If this is funded as part of the Critical Components FOA, we anticipate a 2 year test duration. At the end of this syngas combustor test, the syngas combustor/turbine system will be at a TRL level 6.

Development pathway description for the plant concept, including need for pilot plant.

The commercialization timeline for Allam Cycle coal has been removed from the public report. A pilot of the syngas combustor is required, but no further pilot plant is needed, because of the learning from the 50 MWt Allam Cycle plant in La Porte and the impending commercial scale gas Allam Cycle plants. The US is a favorable location for these carbon capture project, due to the 45Q tax credit ($50 / MT of capture) and the 48a tax credit (30% investment tax credit for coal with CO_2 capture), which can offset the costs of initial deployments, as shown in the Business Case. To qualify for 45Q, a plant must commence construction before January 1st of 2024. To meet this deadline, the syngas combustor test must be completed, as is currently scheduled for Q4 2021, and a FEED must be completed, as is scheduled for 2022 through the Coal FIRST FEED FOA in May of 2020. Before the first coal Allam Cycle plant, a 300 MW Allam Cycle natural gas plant is expected to be commissioned in 2022, the learnings from which will be applied to future coal plants. This natural gas deployment will have proven out all of the technology elements, in particular the turbine, except for the coal gasifier which is already commercial, and the syngas combustor which is planned to be fully de-risked at the La Porte site through the Coal FIRST Critical Components program.

Figure 5- Development pathway

CONFIDENTIAL LIMITED RIGHTS DATA

KEY TECHNOLOGY EQUIPMENT MANUFACTURERS

Coal Delivery, Handling and Reclaim

Bruks Siwertell

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

Doosan delivers 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.

Heilig B.V. is 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

Metso offers 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.

Coal Drying and Pulverizing

Williams Patent Crusher

Williams Patent Crusher is a manufacturer of size reduction equipment to meet the unique needs of a variety of specialized industries. Their products feature customized systems heavy-duty size reduction products, including shredders, crushers, grinders and pulverizers. Williams Fluid Bed Roller Mill design can have infinite turn down while maintaining product size. They offer roller mill system capable of handling ~1500 TPD each. They have wide range clients and also have experience with coal driven power plants.

Carrier Vibrating Equipment, Inc

Carrier Vibrating Equipment offers more than 60 years experience developing customized solutions for material processing. They offer full range of drying and cooling equipment for foundry and processing applications. From fluid bed dryers and coolers to sand coolers to tornesh dryers, they can customize a solution for virtually any material. They have a number of demonstrated coal handling projects in conveying, washing and drying . Carrier has developed a number of thermal coal dryer systems for several types of coal and process applications. Some of these include:-Anthracite coal for additives in the steel making industry; metallurgical grade bituminous coals used in making coke; bituminous coals used in direct steel making processes such as the "Corex" process; beneficiation of PRB coals, beneficiation of lignite coals and lignite coals prior to gasification or liquefaction. They offer fluidized coal dryers with capacities up to 250 TPH in a single unit, depending on the thermal load.

Schwing Bioset

Schwing Bioset have been helping wastewater treatment plants, mines and power generation customers by engineering material handling solutions. They offers coal drying technologies for a variety of coals.

Air Separation Unit

Air Liquide

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

Air Products is 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

Linde 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.

Hangyang

Hangyang is a China based global provider of gases, technologies and services for Industry with extensive experience in the supply of ASUs. They have a range of standard and large cryogenic air separation units with capacities up to 140,000Nm3/hr oxygen production capacity.

Mercury Removal

Calgon Carbon

Calgon is 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

Honeywell offers 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

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

Axens Solutions provides 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

Haldor Topsoe provides 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

Johnson Matthey has 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

Air Liquide has 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 Nm3/h.

Axens Solutions

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

BASF is 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

Dow supplies speciality solvents to gas processing plants across the world, and provide acid gas removal products, services and technologies to the gas industry.

UOP

UOP provides process solution, equipment, product and service in refining and chemical industries. For acid gas removal products, they supply both MDEA solvent process and Selexol process.

Claus Unit (Sulphur Recovery Unit – SRU)

Air Liquide

Air Liquide offera 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

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

Linde offers 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

McDermott offers 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.

Tail Gas Treatment for Sulfur Recovery

Merichem Company

They have lhe LO-CAT® process which is wet scrubbing, liquid redox system that uses a chelated iron solution to convert H2S to innocuous, elemental sulfur. The LO-CAT technology’s sulfur removal capacity niche ranges between 0.5 to 25 TPD. When the ratio of CO2 to H2S is greater than 3 and/or the volumetric sour gas flowrate varies on a frequent basis, LO-CAT technology can be a valid option to remove up to 40 tons/day of sulfur from sour gas streams.With over 200 licenses globally, the LO-CAT technology is in use within several markets and industrial segments LO-CAT systems are extremely versatile and the plants can process any type of gas stream. The process provides licensees the flexibility of maintaining very high H2S removal efficiencies at 2(in excess of 99.9%)at 100% turndown, regardless of the H2S concentration, flowrate and sulfur loading.

Pietro Fiorentini

Pietro Florentini s a service provider in the field of oil and gas clean up. They license H2S removal technology based on reduction-oxidation reaction- that converts H2S present in sour gas to elemental sulphur through reaction with aqueous ferric ions. Process forms solid sulphur particles that are easily filtered from the solution.

Gasification Island

Air Products

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)

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)

GTI is 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.

Zero Liquid Discharge (ZLD)

Aquatech

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

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

SAMCO 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

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, with exception of the turbine OEM, 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.

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.

Currently, 8 Rivers is working with Siemens on the development of a syngas turbine system for the coal based Allam Cycle application. Siemens has extensive experience in gas turbine design, development, testing and operation as well as corresponding expertise in high pressure steam turbines. These two skills can me merged together to create the necessary hybrid technology needed to develop the Allam Cycle turbomachinery and combustion system. Further details of Siemens turbomachinery work are later in this report.

List of commercial equipment

All the equipment in the coal gasifier island mentioned above are commercial available. In the Allam Cycle power island, except for the full scale combustor and turbine system, all other equipment are commercial available, including:

SYNGAS COMPRESSOR

The syngas fed from the syngas conditioning, metering and filtering skid is compressed to slightly above 390 bar in the gas compressor before entering the combustor. One 100% 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 of adequate cleanliness to ensure that there is no damage to the compressor.

O_2-CO_2 PUMP

The O_2 required for combustion is delivered from the ASU at 110 bar and mixed with recycled CO_2 leaving the 100% motor driven CO_2. compressor. The target composition will be around 20% mass O_2 and 80% mass CO_2. The mixture is compressed to slightly over 300 bar in the 100% O_2/CO_2 pump before entering the combustor. The discharge pressure accounts for all relevant pressure drops between the pump and the inlet connection to the combustor.

CO_2 COMPRESSION

One 100% 1st stage centrifugal CO_2 compressor shall be provided to elevate the re-circulating stream of CO_2 to a pressure of circa 65 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 101ºF. before entering the 2^{nd} stage CO_2 centrifugal compressor.

At this point the flow splits with circa 10% of the flow going to the CO_2 Purification Unit and the balance of the flow to the second 100% centrifugal compressor which elevates the pressure to give 110 bar at the O_2/CO_2 pump inlet.

The discharge pressure accounts for the all relevant pressure drop between the inlet to the 1^{st} stage CO_2 compressor and the inlet connection of the O_2/CO_2 pump inlet..

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

CO_2 PUMP

A single 100% centrifugal pump shall be provided to increase the pressure of CO_2 to slightly higher than 390 bar before it enters the combustor after being heated to close to turbine exhaust temperature in the main heat exchanger. The discharge pressure accounts for the relevant pressure drop between the compressor and the inlet connection to the combustor.

HEAT EXCHANGER

One high pressure, counter flow heat exchanger train is provided to cool the turbine exhaust stream while heating the high-pressure CO_2 recycle and O_2-CO_2 streams that flow into the combustor.

Materials for the lower temperature section of the heat exchanger and associated piping are designed to withstand the 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 CO2 stream, the CO2 process stream leaving the water separator, which is free of liquid water and at ambient temperature, is directed to the main CO2 compressor.

CO2 Purification Unit (CPU)

A cryogenic process is applied to purify the export CO_2 to over 99.99% purity to meet the pipeline standard. Water and oxygen in the purified CO_2 stream are less than 10ppmv. CPU in the Allam Cycle is simpler and less energy intensive compared to the conventional CPU design because the CO_2 stream entering CPU unit is already at high pressure (60-70bar). CO_2 is liquefied through expansion by exploring the J-T effect, and separated from gaseous species in a distillation column. The purified liquid CO_2 is pumped to 152bar for pipeline transportation. The off gas which contains CO_2, O_2 and Argon is sent to the vent stack. The overall CO2 capture rate in CPU is around 93-95%, and can be tuned by the distillation column design.

List of equipment requiring R&D

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.
All components for Allam Cycle Coal are commercially available today except for the turbine, which will soon be available via the natural gas Allam Cycle, and the syngas combustor, which will require further funding to develop.

>500 MWth sCO_2 turbine

Though one has not been built yet today, this sCO2 turbine will be commercially available in time for Allam Cycle Coal deployment. NET Power has announced plans to deploy multiple plants at this scale, with the first targeted for 2022, indicating that this turbine will soon be available[xvii]. Learnings from Toshiba's 200 MWt pressure shell turbine deployed in La Porte Texas will allow for this successful scale up. Multiple turbine OEMs are expected to supply this turbine. In this pre-FEED study, Siemens will provide the turbine design based on the Allam Cycle coal system conditions.

50 MWt syngas combustor

Pilot-scale testing of the 5-MWth natural gas-fired combustor was completed in 2015. Data from this program were used to design the 50-MWth-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. At that time, major equipment had been operated between 500 and 900 hours, and over 170 hours of testing with fuel in the system was completed, with individual test runs lasting over 24 hours. Findings from this program will be applied to the syngas combustor.

Demonstration of the syngas combustor is the only key piece of equipment that needs further demonstration beyond the NET Power effort.

Successful testing of a 50 MWt commercial scale syngas combustor at will allow rapid commercial deployment of the ca. 50 MWth "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 100-200 hour 20 MWth combustor test. If this is funded as part of the Critical Components FOA, we anticipate a 2 year test duration.

In the current Pre-FEED study, Siemens is responsible for the syngas combustor/turbine development. The Siemens design has proceeded on a multi-track approach which breaks down the study into several key topics, which are confidential and have been redacted from the public report.

A&E Firm Prior Work With OEMs

WSP already has experience of working with Siemens both as a turbine generator OEM and also in other areas such as control systems, large electric motors and power distribution equipment.

REFERENCES

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

[ii] https://www.eia.gov/outlooks/aeo/

[iii] https://www.eia.gov/coal/markets/#tabs-prices-2

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

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

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

[vii] 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)

[viii] NETL baseline reports (Vol. 3, 2011)

[ix] https://www.irs.gov/pub/irs-drop/n-12-51.pdf

[x] https://www.law.cornell.edu/uscode/text/26/48A

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

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

[xiii] https://www.meti.go.jp/english/statistics/sho/slng/index.html

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

[xv] H. P. Bloch and C. Soares, "Turboexpander Protection and Upgrading," in *Turboexpanders and Process Applications*, Boston, Gulf Professional Publishing, 2001, p. 432

[xvi] Lu, X., Forrest, B., Martin, S., Fetvedt, J., McGroddy, M., and Freed, D., *Integration and Optimization of Coal Gasification Systems with a Near-Zero Emissions Supercritical Carbon Dioxide Power Cycle*, Proceedings of ASME Turbo Expo 2016: Turbine Technical Conference and Exposition, GT2016-58066, June 13-17, 2016, Seoul, South Korea

[xvii] https://www.powermag.com/300-mw-natural-gas-allam-cycle-power-plant-targeted-for-2022/

Jason D. Laumb; "SUPERCRITICAL CO2 CYCLES FOR POWER PRODUCTION", Presented at the 8th International Freiberg Conference on IGCC & XtL Technologies Cologne, Germany 12–16 June, 2016. https://tu-freiberg.de/sites/default/files/media/professur-fuer-energieverfahrenstechnik-und-thermische-rueckstandsbehandlung-16460/publikationen/2016_16-2.pdf

Lu, Xijia, McGroddy, Mike, Forrest, Brock, Freed, David, Kay, John, Laumb, Jason, Stanislowski, Joshua, Hurley, John;" DYNAMIC CORROSION TESTS IN A CO2-RICH ENVIRONMENT"; Materials & Technology Conference 2018 (MS&T18);DOI: 10.7449/2018mst/2018/mst_2018_1035_1042

Lu, X., Martin, S., McGroddy, M., Swanson, M., Stanislowski, J., Laumb, J., "TESTING OF A novel Post combustion acid removal process for THE direct-fired, oxy-combustion ALLAM CYCLE power generation system", GT2017-65217, Proceedings of ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition, GT2017, June 26-30, 2017, Charlotte, NC, USA