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Concept Area of Interest: Inherently Capture
Report Title: Design Basis, Public Report

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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.

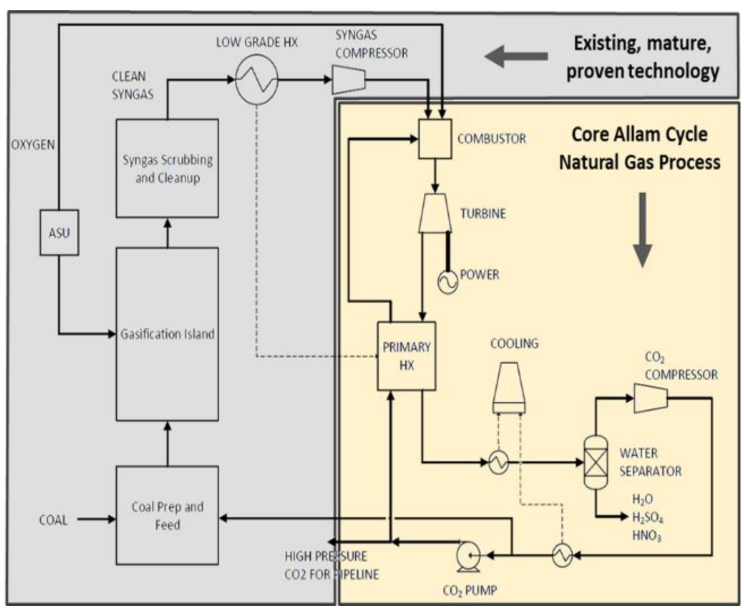

Figure 1 - Allam Cycle Coal Process Integration

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 nearly all NOx, SOx, and particulate emissions, while >93% of the CO_2 can be captured and stored permanently. Thus, there would be no airborne 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 agreed to provide 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 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.[ii] 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.[iii] The cost of Wyoming subbituminous coal will be provided by Peabody for the pre-FEED study.

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 $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 after this design basis 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 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.

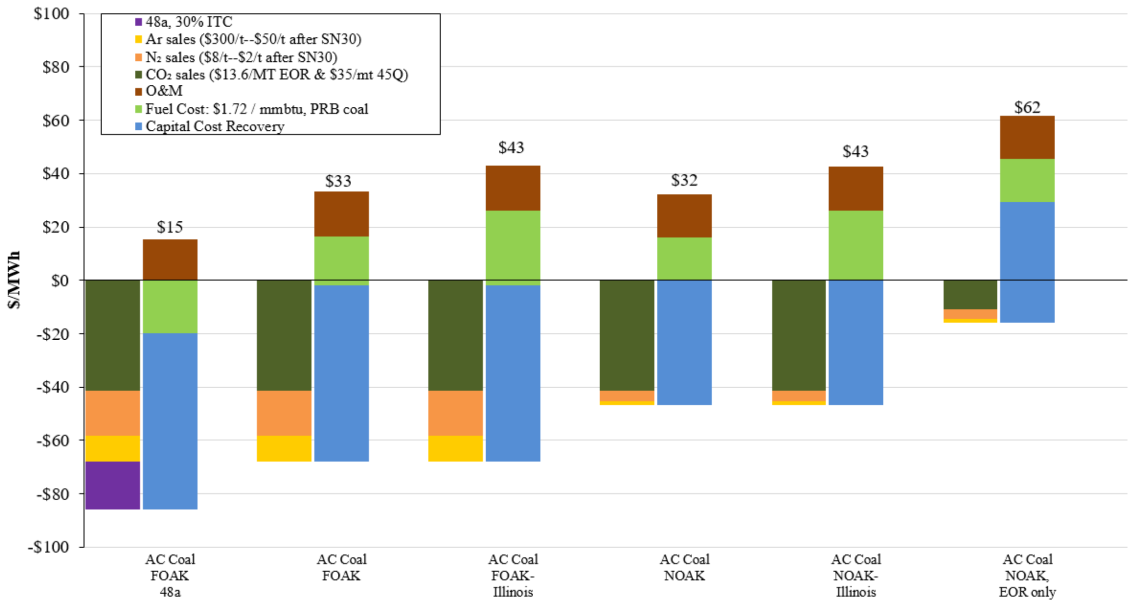

Figure 2 - Levelized Cost Comparison In The US Market

The Allam 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 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 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.

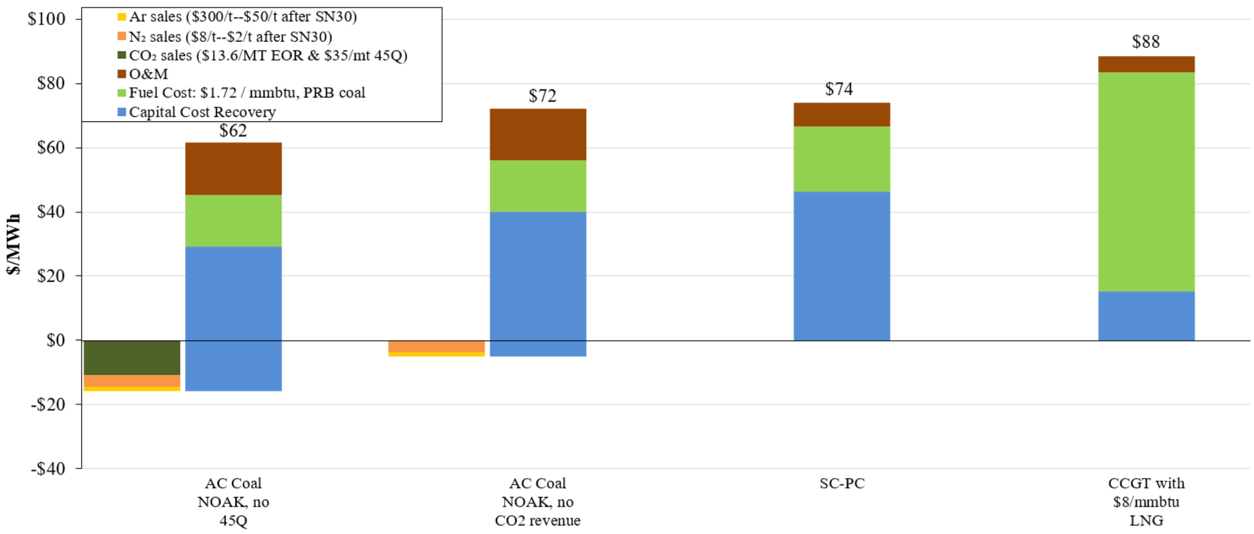

Figure 3 - Cost of Allam Cycle Coal in Global Market

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]

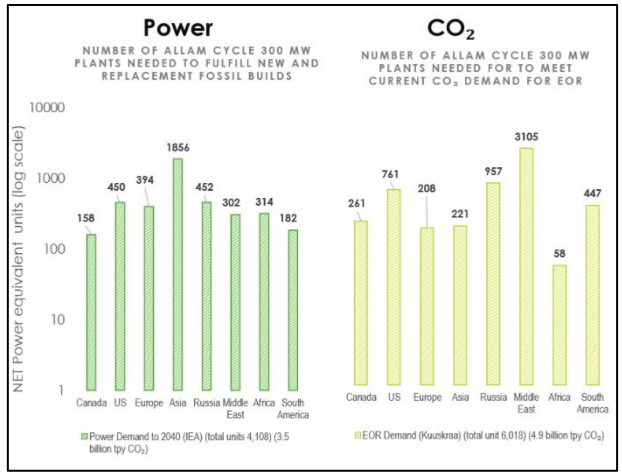

Figure 4 - Global Power and CO2 Demand

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.

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.

PROCESS DESCRIPTION

Proposed Plant Concept Based on Conceptual Design

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 standard thermal power plant equipment, commercially available coal gasification technology and the Allam Cycle natural gas system, as shown in Figure 5 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.

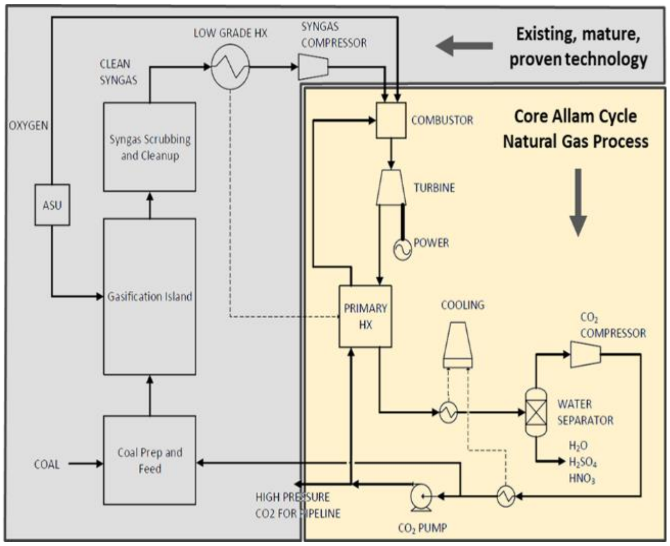

Figure 5 - Allam Cycle Coal Process Integration with Gasification

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 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's power cycle is unique and innovative. It is a 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.

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 >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.

RFP Design Criteria

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.

Modularity

The proposed Allam Cycle coal plant is designed to have 550MWt clean syngas fed into the power island and produce around 285-290 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 93% 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. In addition, mercury and heavy metal are removed from syngas in the gasifier island, zero liquid discharge is included in the plant design to ensure zero emissions.

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 validated through operation of the La Porte plant. Greater turndown capabilities than NGCC are expected, all the way down to zero net load (or negative) to the grid, enabling rapid dispatch and low-load operation. The ability to generate extra power for sale beyond the plant's 290-MWe rating, is also possible for duration above 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. In addition, a syngas storage system is considered in the plant design to facilitate the plant ramping process and mitigate the impact of any unexpected instability of the syngas supply on the turbine operation.

Water Consumption

Allam Cycle coal would provide water savings on the order of 50%+ as compared to a variety of CCS technologies. Figure 6 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 the Allam Cycle coal system reduces 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.

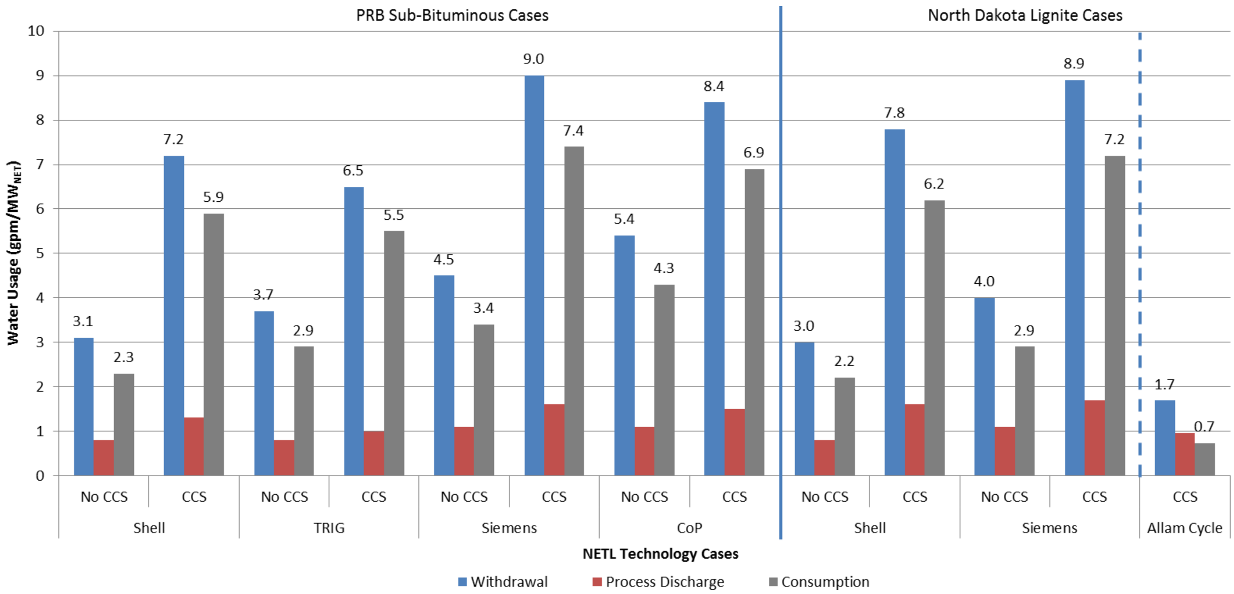

Figure 6 - Analysis of Water Usage

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.

Sparing Philosophy

The sparing philosophy is as follows. The plant is currently being planned as 1x100% for simplicity of operation, increased modularity, decreased piping complexity, and other factors, with exceptions where equipment capacity requires an additional train. Redundancy will be provided to rotating equipment only. This will be re-examined as discussions with vendors proceed to ensure the final choice is optimized.

The plant design consists of the following major subsystems:

- One ASU (1 x 100%).
- Two trains of coal milling and pulverizer systems (2 x 50%).
- One fluidized bed coal dryer system (1 x 100%).
- One train of gasification, including gasifier, cyclone and syngas scrubber (1 x 100%).

- One black water system and ZLD(1 x 100%).
- One COS Hydrolysis Reactor (1 x 100%).
- One Hg removal unit (1 x 100%).
- One AGR unit (1 x 100%).
- One tail gas clean up for sulfur recovery unit (1 x 100%).
- One syngas combustor (1 x 100%)
- One syngas compressor (1 x 100%)
- One CO2 compressor(1 x 100%)
- One turbine (1 x 100%).

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. Sulfur removal and recovery unit in the gasifier island can turn sulfur in the coal into either elementary sulfur or sulfuric acid, as the by-products 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 pre-FEED project, detailed Aspen modeling will be conducted to estimate the Allam Cycle coal plant performance using Sinopec-ECUST (SE) entrained flow gasifier system with full water quench design. Wyoming subbituminous coal is used for the process modeling. North Antelope Rochelle Mine (NARM) site in Wyoming was selected for the pre-FEED design. The net efficiency of the Coal Allam Cycle was shown previously in Table 1 with the gross output and incurred parasitic load displayed. The efficiency for the Coal Allam Cycle system Montana PRB Coal was 43.3% on a LHV basis in the feasibility study. 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). Since the coal used in the pre-FEED study has a similar quality compared with Montana PRB coal used in the concept design, and the same entrained flow gasifier system was selected in pre-FEED study, the system performance in the pre-FEED is similar to the estimate in the concept design, the detailed plant efficiency will be generated from the Aspen modeling with vendors' data inputs, including expected efficiencies at partial load.

It should be noted that the Allam Cycle plant has an ability to handle partial load which is unique. Since there is not an emissions profile associated with the plant, there is no increase in NOx, CO, or particulate emissions with turning down the plant. The plant is capable of operating anywhere from peak efficiency (full load) to a negative efficiency (plant is not exporting electricity and powering auxiliary loads from the grid). During periods of partial load, it may be possible to store liquid oxygen and syngas for use later during periods of high electrical demand as a form of chemical energy storage. In addition, there are other potential revenue streams coming from the plant. All of this changes decisions around operating at partial loads since it moves from a generating efficiency decision to one of maximizing the economics of the entire plant as a whole.

Emissions control summary

In the gasifier system, conventional water quench, cyclone and water scrubber are applied in the SE gasifier system for slag, fine particulates and soluble acid gas removal, such as Chlorine and ammonia. An ammonia removal unit is place to trace NH3 removal. An activated carbon bed unit is applied for mercury and heavy metal removal. A conventional acid gas removal system is included to remove sulfur from syngas down to less than 10ppm level. Coal derived nitrogen is the only nitrogen source entering the cycle, so NOx formation is expected to be very low. 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. 8 Rivers has successfully tested trace SOx/NOx removal in the CO2-water separator at EERC.

The Allam Cycle is an "Inherent CO_2 Capture" technology, due to its use of Oxy-combustion. It is designed to capture all of the produced CO_2, with expected capture rates above 97% after accounting for potential turbo-machinery leakage. CO_2 in the design is captured at 150 BAR.

System Description

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 7, 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 SE gasifier system in the pre-FEED study.

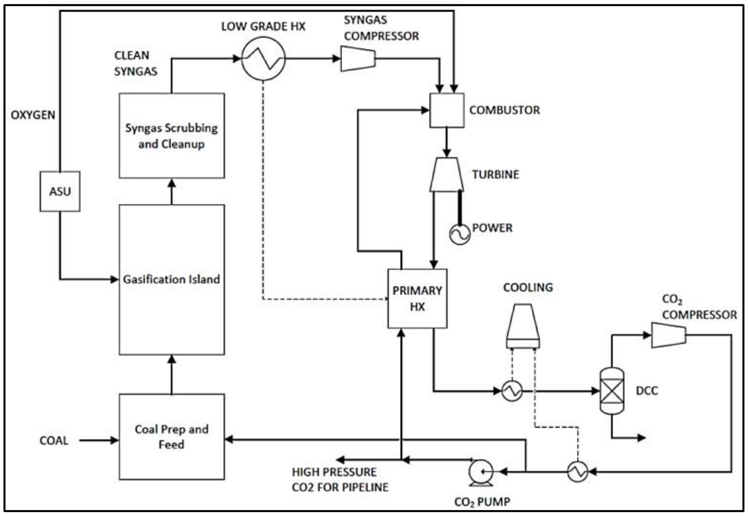

Figure 7 - Process Schematic of the Coal Syngas Fueled Allam Cycle

Advanced technology aspects

As a new power cycle, the Allam Cycle itself can be considered an "advanced technology aspect," as has been described above in the system description. In particular the combustor is advanced, as oxy-combustion is 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. It did so at full commercial scale on natural gas, 50 MWt, as 10-12 combustors can be aligned radially around a larger turbine.

The sCO_2 turbine is the other advanced aspect. 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.

In this pre-FEED study, Siemens is selected as the syngas combustor and turbine provider. All the technical information related to the Allam Cycle will be provided to Siemens for the turbine design.

Further information on the advanced aspects of the Allam Cycle and validation already performed are in Tables 3 and 4 in the next section.

The remainder of the components, from an air separation unit to CO_2 pumps and compressors to heat exchangers are available and should not be considered advanced technology aspects.

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 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 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.

List of components that are not commercially available

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, 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. [xv] 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. Siemens has extensive syngas combustion experience including co-fired syngas/natural gas.
- 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 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.

Table 3 - 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, impurities introduced into the system must be actively controlled in order to prevent their concentration in the	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.) A parametric laboratory-scale study was conducted in 2017 of the post-combustion DeSNOx process, which consists of

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.	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-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.

Table 4 - 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 MWth syngas combustor will allow rapid scale-up to 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 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.

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, adiabatic flame temperatures were maintained at the desired 3600°F and 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.

Turbine-Expander: Conceptual geometry of the turbine expander was developed. The current preliminary concept is a single-flow design and has 10 stages of which the first three are cooled. Inlet annulus diameter is estimated to be 700 mm with a blade radial height of approximately 140 mm based on a preliminary analysis. The design is expected to be a hybrid of state of the art steam turbine pressures combined with D or E-Class gas turbine inlet temperatures. Initial analysis indicates the cooled rows would incorporate convectively cooled internal cavities. The high Reynolds numbers that are a consequence of the high molecular weight gas composition would require development of new cooling correlations. Siemens would make use of the Siemens Energy Center facility located on the campus of the University of Central Florida to perform these experiments. Rig hardware procured under a previous DOE contract and donated to the university by DOE would be used to maximize cost-effectiveness.

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: A centrifugal pump shall be provided to increase the pressure of the $CO_2$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 will be delivered to the plant by trucks or conveyor. Raw coal with particle size up to 3 inch will be delivered from the mine to the site. The coal will be stored in Coal Silo to get sufficient operating capacity.

Coal Feed System: Raw coal ~3,111 tpd (with 27% moisture) 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 8% 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 as transport gas. Total of ~2,500 tpd of dry pulverized coal (8% moisture) is fed to SE gasifier.

Gasifier Island: For this study, a SE entrained flow gasifier was chosen, producing syngas at high pressures and temperatures. SE entrained-flow gasification technology of pulverized coal consists of the units of coal grinding and drying, pulverized coal pressurization and conveying, gasification, scrubbing, slag removal, gray water treatment and gasification utilities, etc. The process flow diagram is as follows:

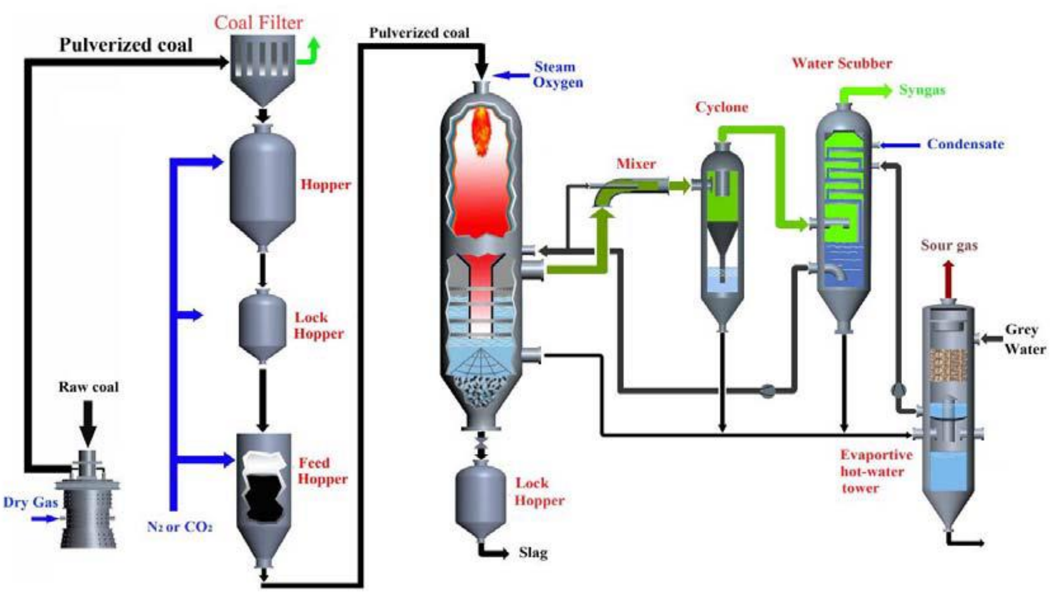

Figure 8 - Gasifier Island Process Flow Diagram

The raw coal, after grinding and drying in coal grinding and drying unit, is spirally sent to a pulverized coal hopper when it meets the requirement for feeding into gasifier as pulverized coal, then it flows to the lock hopper by gravity, subsequently. The pulverized coal in the lock hopper is pressurized firstly to some value that is the same with that of the feed hopper by carbon dioxide or nitrogen, and then is discharged to the feed hopper. After that, the pulverized coal is pneumatically conveyed to the gasifier throughout the coal burner positioned at the top of gasifier. The pure oxygen from ASU and MP steam from gasification BL are also introduced to the coal burner. Gasification reaction takes place at pressure of 4.0 MPa(G), generating crude syngas with main compositions of H2, CO, and CO2. The syngas at high temperature (1400 ~ 1600 ºC) after reaction together with molten slag descends downward with a quenching pipe into the quenching chamber. A large portion of slag after being cooled will fall into the bottom of quenching chamber. The crude syngas, after subjecting to quenching and scrubbing by multi-layer bubble breaking plate in the quenching chamber, leaves the gasifier to mixer, mixed with black water from the bottom of scrubber. The mixture of water/crude syngas after leaving mixer goes into cyclone separator to separate liquid and solid. A majority of fine ash in crude syngas enters liquid and is continuously discharged from the bottom of cyclone separator to evaporative hot-water tower at black water treatment unit.

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 crude syngas after separating liquid phase and fine slag goes into a water scrubber, where it is further scrubbed by gray water and condensate from shift reaction section to remove fine solid particles. The scrubbed crude syngas with ash content less than 1mg/Nm3, leaves the scrubber and enter into downstream shift reaction section.
The reaction chamber of gasifier is lined with membrane water wall, in which the operation temperature of saturated hot water is 271 ºC and operation pressure 5.5 MPa(G). The steam/water mixture leaving water-wall structure will generate saturated steam of 5.5 MPa (G) after steam drum separation. The steam drum saturated water after being pressurized by membrane circulating hot water pump returns to water wall circulation.
In slag water treatment unit, the black water generated in quenching and scrubbing/dedusting units, experiences flash evaporation in the lower part of evaporative hot-water tower, while the heat contained in the flash gas is recovered by the cycled grey water in the upper part of evaporative hot-water tower.

Mercury Removal: Mercury removal from the syngas stream is achieved using down flow 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 2-3 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.

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.

Zero Liquid Discharge (ZLD) Unit

The focus of ZLD is to economically process wastewater and produce clean water that is suitable for reuse. Various vendors offers thermal and non-thermal ZLD solutions to manage tough-to-treat wastewaters stream generated from gasification Island. ZLD unit consists of evaporators, brine concentrators, and crystallizers that can help to recover more than 95% of plant's wastewater while producing the remaining brine as a product or solid.

Description of any thermal or energy storage

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 290-MW rating. Potential syngas storage capacity can be included which will enable flexibility for the gasifier during load following. If tanks were added 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

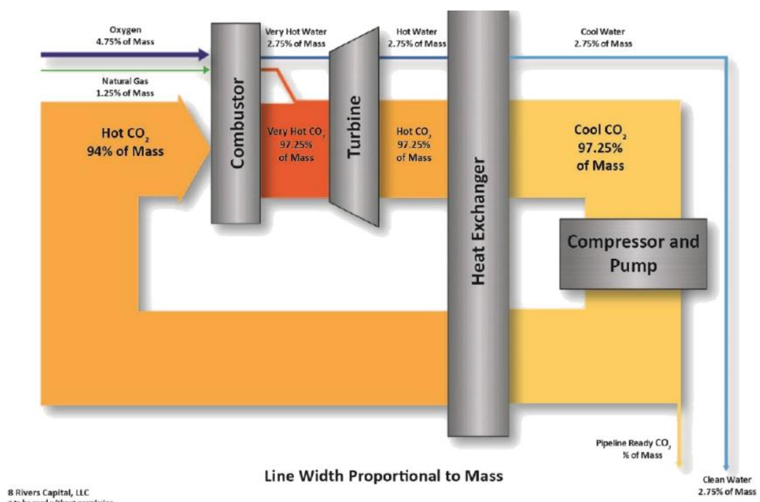

Figure 9 - Simplified Allam Cycle Process

natural gas cycle, and 5% of the CO_2 for the coal cycle.

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 6 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

A range of approaches may be adopted to accelerate project implementation and bring forward entry into service. These include:

Completing as much detailed engineering as possible ahead of the Final Investment Decision

The authorization of some detailed engineering scope ahead of FID allows an acceleration of the EPC program by facilitating earlier placement of orders for long-lead equipment items and special material procurement 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.

Early order placement for long lead items

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, such as the syngas value, based on Siemens’ experience in the previous IGCC project. 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.

Standardization of design / procurement of ‘off the shelf’ where possible

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. The benefits of multiple stream operation, particularly implementation of an N+1 redundancy philosophy, also carries through to the operational phase in terms of increased overall plant availability.

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. Modular 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. They are then delivered to site and installed directly to prepared civil foundations with consequent time savings.

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. Provided the Plant Model is sufficiently accurate it can also be used to verify changes to the Integrated Plant Control System (IPCS) prior to the systems coming on-line.

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 EPC m 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. It should be noted that acceleration must not be detrimental to safety and/or quality.

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 in parallel rather than sequential fabrication, again reduces 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

DESIGN BASIS

Site Characteristics and Ambient Conditions:

The design will be tailored to the North Antelope Rochelle Mine (NARM) site. The NARM site characteristics are shown below.

Table 5 - NARM Site 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 Temp, °C	9
Average Ambient Wet Bulb Temp, °C	5.2
Design Ambient Relative Humidity, %	61%
Cooling Water Temperature, °C	10
Air composition based on NETL QGESS, mass %[xvi]	
N_2	72.429
O_2	25.352
Ar	1.761
H_2O	0.382
CO_2	0.076
Total	100.00

Table 6 - NETL QGESS Make-Up Water Quality[xvi]

Parameter	Ground Water (Range)	POTW Water (Range)	Makeup Water (Design Basis)
pH	6.6–7.9	7.1–8.0	7.4
Specific Conductance, µS/cm	1,096–1,484	1,150–1,629	1312
Turbidity, NTU		<50	<50
Total Dissolved Solids, ppm			906
M-Alkalinity as $CaCO_3$, ppm[a]	200–325	184–596	278
Sodium as Na, ppm	102–150	172–336	168
Chloride as Cl, ppm	73–100	205–275	157
Sulfate as SO	100–292	73–122	153
Calcium as Ca, ppm	106–160	71–117	106
Magnesium as Mg, ppm	39–75	19–33	40
Potassium as K, ppm	15–41	11–21	18
Silica as SiO	5–12	21–26	16
Nitrate as N, ppm	0.1–0.8	18–34	12
Total Phosphate as PO	0.1–0.2	1.3–6.1	1.6
Strontium as Sr, ppm	2.48–2.97	0.319–0.415	1.5
Fluoride as F, ppm	0.5–1.21	0.5–0.9	0.8
Boron as B, ppm	0.7–0.77		0.37
Iron as Fe, ppm	0.099–0.629	0.1	0.249
Barium as Ba, ppm	0.011–0.52	0.092–0.248	0.169
Aluminum as Al, ppm	0.068–0.1	0.1–0.107	0.098
Selenium as Se, ppm	0.02–0.15	0.0008	0.043
Lead as Pb, ppm	0.002–0.1		0.026
Arsenic as As, ppm	0.005–0.08		0.023
Copper as Cu, ppm	0.004–0.03	0.012–0.055	0.018
Nickel as Ni, ppm	0.02–0.05		0.018
Manganese as Mn, ppm	0.007–0.015	0.005–0.016	0.009
Zinc as Zn, ppm	0.005–0.024		0.009
Chromium as Cr, ppm	0.01–0.02		0.008
Cadmium as Cd, ppm	0.002–0.02		0.006
Silver as Ag, ppm	0.002–0.02		0.006
Mercury as Hg, ppm	0.0002–0.001		3E-04

Fuel type and composition:

The system will be designed on the PRB Coal from the NARM. The composition of the fuel is confidential and has been removed from the public report.

Table 7 - Analysis of Peabody North Antelope Rochelle Mine Coal

Flexible plant performance targets

The flexibility of Allam Cycle Coal is projected to at least be in-line with NGCC, with the potential to exceed that performance. Flexible performance targets to match and exceed are:

- The current ramp rate assumes that we are targeting an ability to provide 30 MW - 45 MW of load increase or decrease each minute during warm operation.
- Cold Start Up to reach full load in less than 4 hours assuming that pre-heating systems have been adequately sized to operate during the ramping period. This is subject to confirmation in detailed design.
- Turn Down: Zero net load to the grid, enabling low-load operation and rapid dispatch.
- Energy Storage: Approximately 1200 MWH of storage capacity is included as part of the default ASU design with respect to oxygen buffering. This can be increased with additional capacity possible with syngas storage or additional O2 tanks for more duration.
- Peaking: Peak from 290MW up to approximately 325 MW using stored oxygen and assuming an ASU turndown of 50%.

Water requirements

Allam Cycle coal is projected to require 1.7 gallons per minute (gpm) for every $MW_{net,}$, and consume .7 gpm for every MW_{net}. Figure 11 below shows the Coal Allam Cycle using the Siemens gasifier compared against NETL IGCC baselines for various technologies based on lignite feedstock. 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 the Allam Cycle coal system reduces the water consumption by over 70% compared to an NGCC system.[xvii] 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.

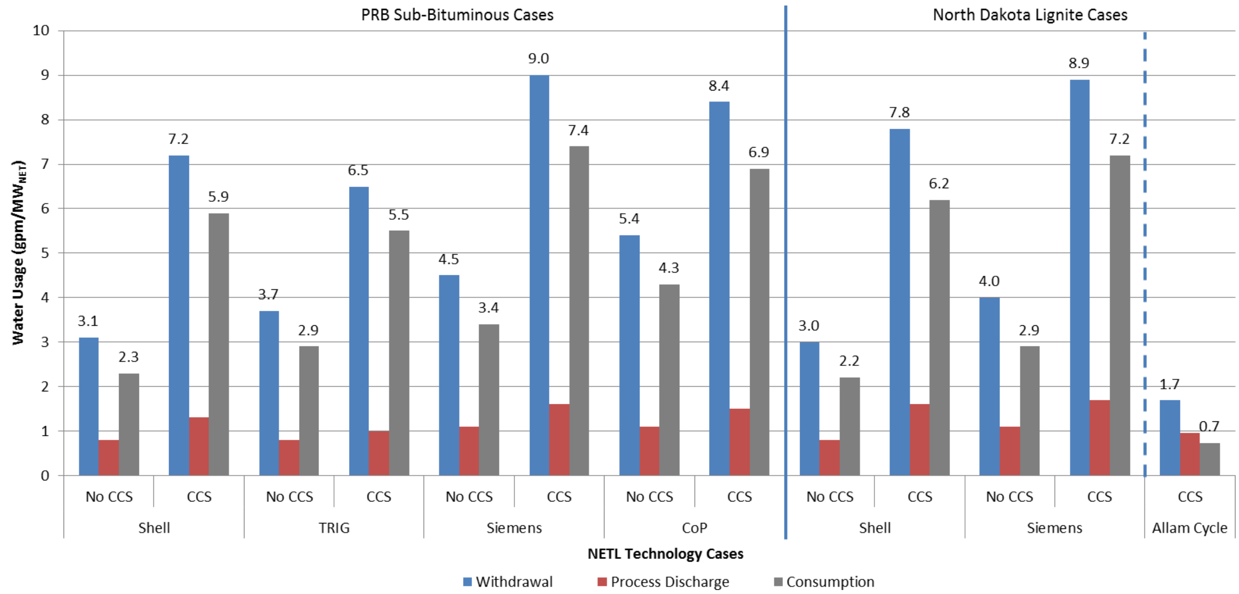

Figure 10 - Analysis of Water Usage

System size basis

The proposed Allam Cycle coal plant is designed to have cleaned syngas fed into the Allam Cycle power island. The table below 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 8 - Allam Cycle Efficiency With PRB Coal updated during Pre-FEED

Environmental targets

Allam Cycle Coal is a near zero emissions coal facility, with the associated environmental targets from the system shown below:

- >93% CO_2 capture at 150 bar
- Zero liquid discharge: Recovery of >95% of plant's wastewater and production of the remaining brine as a product or a solid.
- Since there is no vent stack, we have nothing to emit to the air. All the combustion

derived species are captured either in gas phase or liquid phase.

- >99% SOx removal
- >99% NOx removal. Coal derived nitrogen is the only nitrogen source entering the cycle, so NOx formation in the first place is low
- Mercury and heavy metal are removed from syngas in the gasifier island

Major equipment performance assumptions

Vendors are still in the process of supplying the necessary information to supply the major equipment performance assumptions, and so those assumptions will be provided later on in this pre-FEED process.

Projected plant capacity factor

Due to the by-product revenues from CO_2, Argon, and Nitrogen, this Allam Cycle Coal plant is expected to be dispatched right after solar and wind, given its near zero marginal cost of production given those revenues. Its projected capacity factor in Wyoming is thus expected to be limited solely by its availability, rather than by market conditions. We conservatively project a capacity factor of 85%, with the potential for higher availability and capacity factors to further boost the economics of the facility.

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