The U.S. Department of Energy (DOE)
Fossil Energy and Carbon Management (FECM)
Award Number: DE-FE0032114

Blue Bison ATR Advanced CCUS System

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REVISED: May 30, 2023

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Final Report
Project Period: October 1, 2021 – February 28, 2023

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Final Report
Covering Period: October 1, 2021 – February 28, 2023
Date of Report: September 19, 2023
Date Submitted: September 19, 2023
Date Resubmitted: N/A

Report Prepared for: DOE NETL

Award Number: DE-FE0032114

Project Title: Blue Bison ATR Advanced CCUS System

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Acknowledgment

"This material is based upon work supported by the Department of Energy under Award Number DE-FE0032114."

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BLUE BISON ATR ADVANCED CCUS SYSTEM

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1. INTRODUCTION

The objective of this project was to design a carbon capture system that could be installed on a 220 MMSCFD blue hydrogen (Blue H_2) facility (Blue H_2 Plant) utilizing auto-thermal reforming (ATR) technology and identify potential sequestration options for the carbon dioxide (CO_2) produced from the Blue H_2 Plant.

This final report describes work conducted for the Department of Energy (DOE) in support of the initial engineering design for a commercial-scale carbon capture and storage system to be installed at a proposed hydrogen production plant. The work was conducted by Tallgrass MLP Operations LLC with support from the University of Wyoming and Technip Energies.

Tallgrass and the Blue Bison Team Members (Blue Bison Team) leveraged their experiences and expanded on existing ATR technology design and engineering to exceed all the DOE success metrics and reach an optimized ATR and carbon capture design while minimizing the levelized cost of hydrogen (LCOH) production and cost of CO_2 capture. The design includes integration of the Blue H_2 Plant, the associated oxygen producing facility, and the carbon capture system to optimize the feedstock requirements and energy efficiency.

In conjunction with the facility design an initial analysis of the subsurface storage potential within the area was also completed. The preliminary study that was conducted showed potential target formations do exist to store the captured CO_2.

The initial engineering and design work conducted throughout the study is a critical step to the overall development of blue hydrogen. The project was able to determine the Levelized Cost of Hydrogen (LCOH) and helped develop an overall Blue H_2 Plant design with increased capital estimate accuracy to assist in progressing commercialization leading to further project development and ultimately project execution.

The carbon capture system would facilitate the development of a replicable world scale Blue H2 Plant that would help achieve the DOE’s target for carbon neutral blue H2 production at less than $1 per kg. Achieving this goal has the potential to make a substantial impact nation-wide, reinforcing national energy security and leadership, as well as providing jobs and revenues for US businesses. Blue H2 at scale will create carbon-neutral fuel, allow businesses to utilize existing assets for blue H2 transportation and/or consumption, and create a diversified clean energy portfolio to better address climate change.

2. PROJECT DESCRIPTION

2.1 Project Management and Planning Tasks and Deliverables

The items described below were completed as part of the deliverables outlined with Task 1.0 – Project Management and Planning.

2.1.1 Project Management Plan (PMP)

Tallgrass managed and directed the project in accordance with a PMP that was updated as needed throughout the project as simulation/modeling efforts progress. The project success was evaluated based on the completion of criteria outlined within the PMP. Specifically, the initial engineering design, TEA, EH&S, risk assessment, CCUS technology description and TRL, host site finalization, H_2 plant description, CO_2 storage and utilization pathways and CCUS integration, and H_2 utilization. Utilizing Tallgrass management processes, the team met all technical, schedule, and budget objectives and requirements. The team conducted a risk management plan to identify perceived risks and then created strategies to mitigate if such risks applied. To keep on target with the schedule, milestone logs and a detailed baseline schedule were utilized. A cost profile was also employed and regularly updated to outline the actual spending of each member to stay within budget requirements.

2.1.2 Technology Maturation Plan

The Technology Maturation Plan (TMP) was developed to describe the current technology readiness level (TRL) of the proposed technology/technologies, relates the proposed project work to maturation of the proposed technology, describes the expected TRL at the end of the project, and describes any known post-project research and development necessary to further mature the technology. The TRL is determined from the Technology readiness assessment (TRA). The TRA is the BASF OASE White carbon capture technology integrated with the critical subsystem as described as the ATR syngas shift conversion and cooling train. It was concluded that the ATR based Topsoe's SynCOR™ technology and CO_2 capture with BASF's OASE® White individually have a TRL of 9. The OASE White technology for the purpose of removing CO_2 from syngas streams has operated over the full range of expected mission conditions on over 113 syngas reference plants/applications. BASF currently markets its gas-treating portfolio under the trade name OASE®, where OASE® white is applied in the removal of acid gases from syngas for carbon capture. As an integrated design, the OASE White with TRL 9 utilized with Topsoe SynCOR to produce Blue H_2 at the size and scale outlined within the current grant, is TRL 7 with the goal to progress to higher TRL levels. To progress from TRL 7 to TRL 9 the project would require the following:

1. Additional engineering for not just the carbon capture system but the entire ATR facility. This would require moving into a FEED study and ultimately detailed engineering.

2. Construction and commissioning of the facility to the size and scale that warranted a commercially viable project.

3. Customers for the hydrogen being produced with firm commitments and definitive sales documents.

2.1.3 Project Management

The Blue Bison Team is comprised of industry leaders in carbon capture and technology, carbon sequestration, infrastructure development, EPC contracting for H_2 plant construction as well as awardees of past DOE funded projects. Tallgrass worked in conjunction with the Blue Bison Team to manage and coordinate the technical, financial, and contractual services of the project, including interactions with industrial collaborators, stakeholders, external suppliers, and any state or federal agencies.

2.1.4 Collaborative Meetings

The key to the success of the project is constant and consistent communication within the team. Monthly, and in some cases weekly, technical meetings with team members were established and conducted to encourage collaboration, share data, assess progress, and resolve questions and unresolved issues. The monthly meetings were held to focus on the overall schedule as well as managing the critical path activities in parallel with the budget. Weekly conference calls and updates were held to focus on the previous week's performance and identify completed tasks, tasks to be completed for the upcoming week, and a 30-day look ahead to keep the team on task and on budget. During the project, the team reported to the DOE per guidelines set forth in Federal Assistance Reporting Instructions, focusing on the status of key milestones outlined within the PMP from a schedule and budget standpoint.

2.2 Initial Engineering Tasks and Deliverables

The initial engineering package describes engineering work conducted for the DOE in the initial engineering design on a commercial-scale carbon capture and storage system to be installed at a proposed hydrogen production plant. The items described below were subtasks completed and included within the initial engineering package as part of Task 2.0 – Initial Engineering.

2.2.1 Design Basis

The Blue Bison Team utilized the design criteria set forth by the DOE and incorporated the site conditions listed below.

Design Basis - Overall Unit

- Plant capacity: 220 MMSCFD (@ 60°F & 14.7 psia) net Blue H_2 product
- Blue H_2 Product
  - Purity: 99.97 (v)%
  - Pressure: 345 psig
  - Temperature: 114°F
- Carbon Index: 97% reduction
- CO_2 Product
  - Purity: 99.0%
  - Pressure: 2200 psig
  - Temperature: 100°F

Design Basis – Site Conditions

- Site Location: Douglas, Wyoming
- Elevation: 4916 ft
- Barometric pressure: 12.3 psia
- Relative humidity: 60% (for process calculation)
- MDMT: -35°F
- Natural gas feedstock
  - Pressure: 365 psig
  - Temperature: 60°F

2.2.2 Process Flow Diagrams (PFD), Piping and Instrument Diagrams (PID), Block Flow Diagram (BFD) and 3D Model.

The Blue Bison Team, developed PFD, PID and a 3D model for the carbon capture system. The Blue Bison Team also developed high-level drawing package outlining the integration of the carbon capture system with the Blue H_2 Plant that were included within the initial engineering package. Below are illustrations of the 3D model (Figure 1) and Block Flow Diagram (Figure 2) from the initial engineering package.

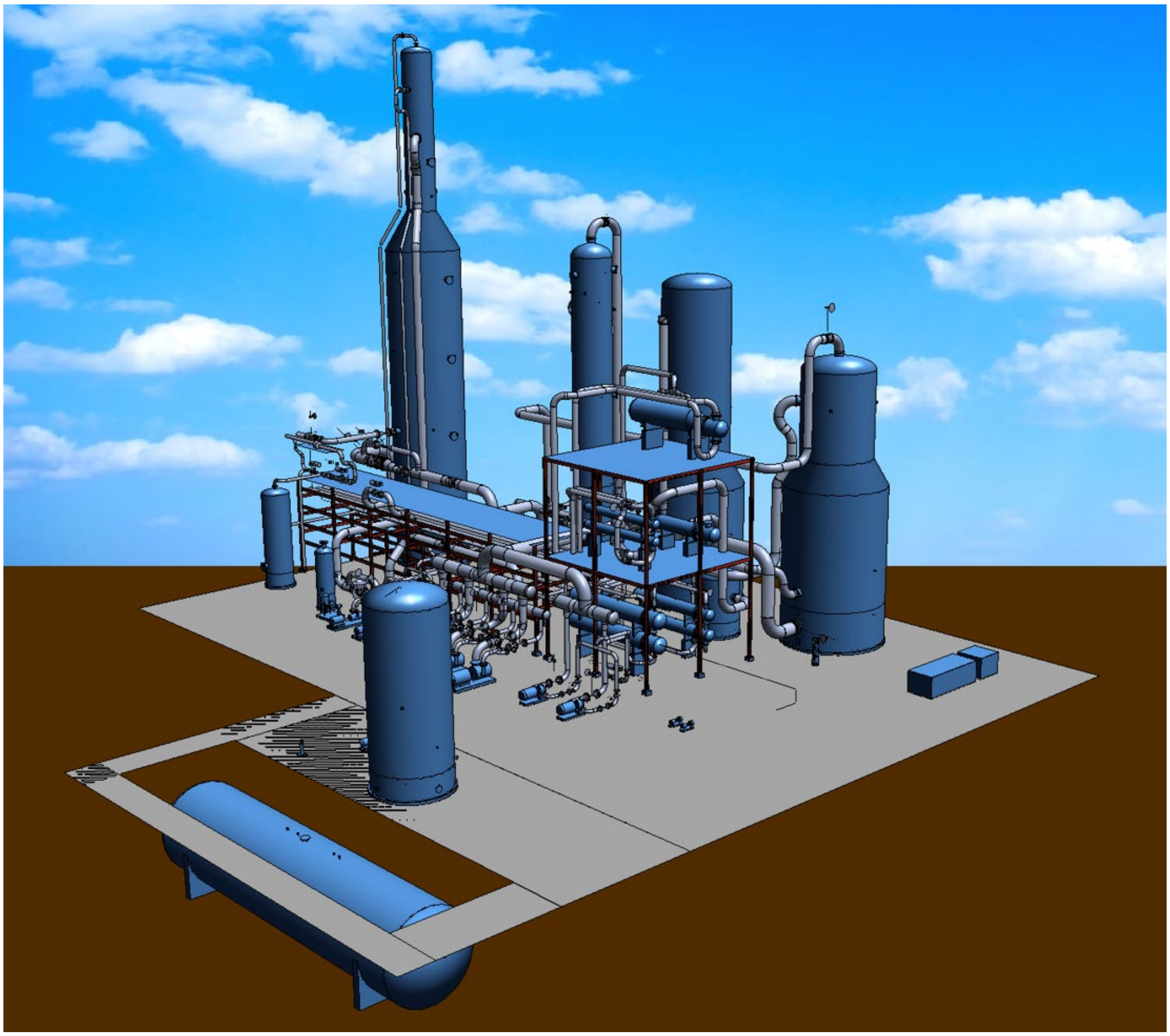

Figure 1: 3D model of BASF's OASE® White carbon capture technology

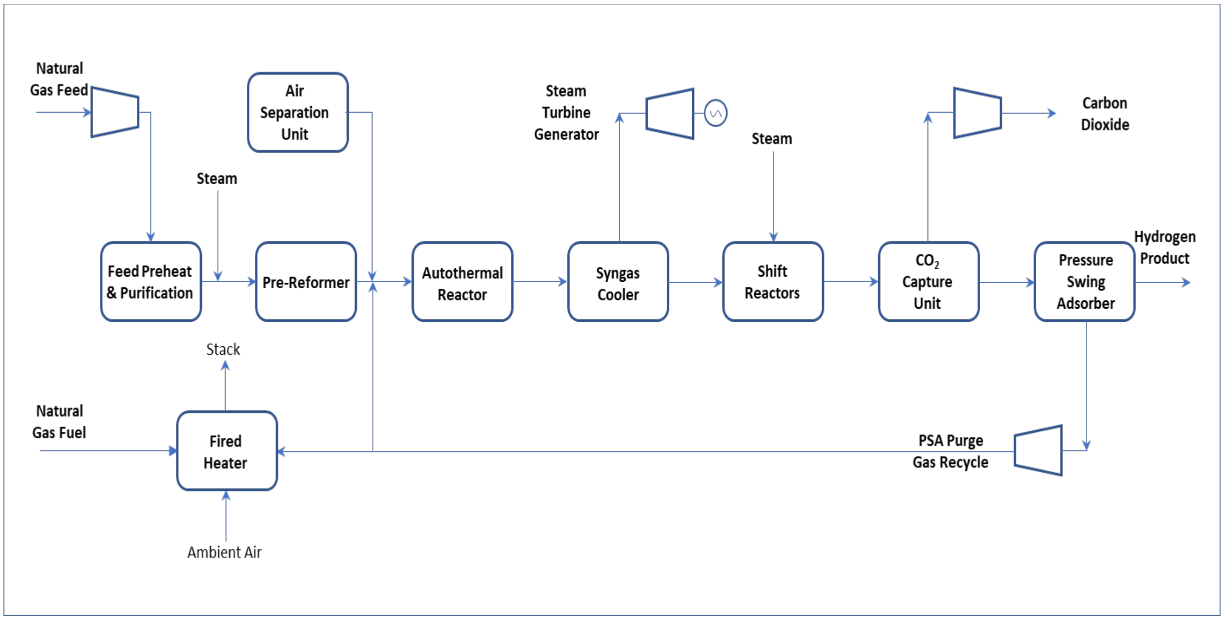

Figure 2: BFD – 220 MMSCFD Blue Bison ATR with Carbon Capture

This section highlights the key characteristics of the process description:

Feed Treatment: The natural gas feed that comes in from battery limit (BL) is mixed with recycled hydrogen. This mixture is then compressed by Feed Compressor K-201 and heated against flue gas in Feed Preheat Coil 1 (E-217) and Feed Preheat Coil 2 (E-214). Once the mixture is a sufficient temperature, it goes through a Hydrotreater (R-201) where any organic sulfur is converted to hydrogen sulfide and olefins, unsaturated hydrocarbons, are saturated to paraffins. The final step of feed treatment is for a Sulfur Absorber to remove all hydrogen sulfide from the mixture by using a zinc oxide catalyst to absorb any sulfur contained in the feed. The following reaction is depicted below:

$$H_2S + ZnO \Rightarrow ZnS + H2O$$

Pre-Reforming: The desulfurized feed is mixed with the process steam to achieve a specific steam to carbon mole ratio. The mixture is then preheated in the Mixed Feed Preheat Coil (E-212) in the Fired Heater (H-201) and is then sent to the Pre-reformer (R-211). In the Pre-reformer, the process gas is converted into a mixture of methane, hydrogen, carbon monoxide, carbon dioxide and steam via an endothermic reforming reaction and an exothermic shift reaction.

Reforming

$CH_4 + H_2O \Leftrightarrow CO + 3H_2$ Endothermic $\Delta H^\circ_{77F} = +195.64$ Btu/mol

Shift

$CO + H_2O \Leftrightarrow CO_2 + H_2$ Exothermic $\Delta H^\circ_{77F} = -38.89$ Btu/mol

Autothermal Reforming: The Pre-reformer effluent is sent through Reheat Coils 1 and 2 in the Fired Heater. It then enters the Autothermal Reformer (ATR) (R-212) with oxygen from the Air Separation Unit (ASU). Within the ATR, a combination of a combustion and an endothermic steam reforming reaction takes place.

High Temperature Shift (HTS) Conversion, Low Temperature Shift (LTS) Conversion and Heat Recovery: The syngas that exits from the ATR consists of a mixture of hydrogen, carbon oxide, unreacted methane, and steam. The syngas is then cooled down by generating steam in the Waste Heat Boiler No. 1 (E-221). Additional process steam is added to the syngas before entering the High Temperature Shift Converter (HTS) (R-221). In the HTS, carbon monoxide and steam partake in an exothermic shift reaction to produce hydrogen and carbon dioxide.

$$CO + H_2O \Leftrightarrow CO_2 + H_2 \quad \text{Exothermic} \qquad \Delta H^{\circ}_{77F} = -38.89 \text{ Btu/mol}$$

The syngas is then cooled through a series of heat exchangers and then sent to the Low Temperature Shift Converter (R-222). In the LTS, a further shift reaction occurs to produce additional hydrogen and carbon dioxide as performed in the HTS. The raw hydrogen is cooled through a series of exchangers. Effluent from the exchangers consist of syngas and process condensate. The process condensate is separated using the Process Condensate Separator No. 1 (V-220) and No. 2 (V-221). This allows the dry syngas to enter the CO_2 Removal Unit for carbon capture and syngas separation. The process condensates from the two condensate separators are mixed and pumped by the Process Condensate Pumps (P-651A/B) to the Process Condensate Stripper (C-651).

Syngas CO_2 Removal and Compression: Syngas from the Process Condensate Separator No. 2 is treated in the CO_2 Removal Unit using amine-based gas treatment technology from BASF to recover CO_2. The feed gas goes through the CO_2 Absorber (C-302). From the absorber, the treated gas enters the Final Gas Separator (V-301), and the CO_2 rich solution enters the Reverse Pump. The Reverse Pump recovers the hydraulic energy before the mixture is sent through the Flash Gas Cooler (E-307) and the Flash Gas Separator (V-305) before being recycled back to the feed gas. The gas is then flashed and absorbed and enters the CO_2 Stripper (C-301) where most of the absorbed CO_2 is stripped off by heat. This regenerated solution is next sent through a CO_2 Product Cooler and Product Separator to remove the saturated amine solution before being sent to the CO_2 Compressor.

Hydrogen Purification: Process gas from the CO_2 Removal unit is sent to the Pressure Swing Adsorber (PSA) unit (X-300) to recover high purity hydrogen. The PSA unit consists of multiple absorbers that follow a cycle of absorption, stepwise depressurization, purging, and stepwise re-pressurization—so that all the other constituents of the gas other than hydrogen are removed in a single process step. The system maximizes hydrogen recovery by effectively utilizing residual hydrogen in an absorber vessel at the end of its cycle to repressurize the other vessels. The hydrogen produced from the PSA Unit will have a purity of 99.97 mol% with a combined CO and CO_2 content of less than 10 ppm_v, with the balance being nitrogen and methane.

Fired Heater Heat Recovery: Fired Heater (H-201) is used to provide heat source for the process. The majority of the firing is provided by the purge gas from the Pressure Swing Adsorber (PSA) unit. Natural gas is used as the makeup fuel.

Steam Generation and Power Generation: A single Steam Drum (V-602) acts as the sole collection vessel for all steam generated in the plant. Steam is generated by heat recovery from Waste Heat Boiler No.1 (E-221) and Waste Heat Boiler No.2 (E-222). Boiler feed water is preheated at BFW Preheater No.1 (E-223) and BFW Preheater No.2 (E-224) against Syngas. Steam from Steam Drum (V-602) is superheated in Steam Superheater (E-213) against Syngas. Continuous blowdown from Steam Drum (V-602) and intermittent blowdown from Waste Heat Boiler No.1 (E-221) and Waste Heat Boiler No.2 (E-222) are routed to Boiler Blowdown Drum (V-603). The liquid from Boiler Blowdown Drum (V-603) is sent out to battery limit. Part of the superheated steam is used as the process steam. The rest of the steam is routed to Turbine (TG-401) for power generation. Steam condensate from Turbine (TG-401) is re-used as BFW for the plant.

Process Condensate Stripping: Condensate from Cold Process Condensate Separator (V-221) is heated in the Process Condensate Feed/Effluent Exchanger (E-651) against the hot stripped condensate. The pre-heated process condensate enters at the top of the Process Condensate Stripper (C-651) and the saturated steam enters at the bottom so the ammonia and methanol levels in the condensate can be reduced to maintain an acceptable impurity level in the steam. The stripped condensate enters the Deaerator (V-602) which is used to remove CO_2 and O_2 in the water. Condensates from the Turbine Unit and various other equipment are also sent to the Deaerator. The deaerated water is then pumped through the BFW Pump, preheated in the BFW Preheaters, and then sent to the Steam Drum.

2.2.3 Utilities

The Blue Bison Team developed utility flow diagrams that determined the inputs into the techno-economic analysis and calculated the sequestered CO_2 cost ($/metric ton) and the levelized cost of Blue H_2. The utility summary was categorized into Product, Feedstock and Other that included the following components:

Product

- Blue H_2 product
- CO_2 product

Feedstocks (process feeds and make-up fuel)

- Natural gas feed
- Natural gas fuel
- Oxygen

Others

- Catalyst and chemicals
- Cooling water
- Demineralized water
- Instrument air
- Makeup water to cooling tower
- Natural gas to flare pilots
- Nitrogen
- Power
- Raw water
- Wastewater

An operating expenditure calculation was performed to calculate the operating cost of the plant at full capacity. A summary of the utility's cost for natural gas, electricity, and water consumptions in one year is provided below (Table 1). The levelized variable costs include costs of all the utilities and consumables such as NG, power, and water. In NETL's methodology, fuel cost contribution to levelized cost of product is itemized separate from the other variable costs.

Utility Name	Units	Unit Price ($)
Natural Gas	MMBtu (HHV)	$3.00
Electricity	MWh	$50.00
Water	1000 gallons	$4.00

Table 1. Utility Unit Price

The team also developed utility packages for specific items required for hydrogen production and CO_2 removal. The packaged units developed are as follows:

- Wastewater Unit for wastewater treatment from the plant.
- Demineralized Water Unit for raw water treatment before sending the water to the plant.
- Cooling Tower Package for cooling water recirculation and water cooling.
- Flare Package for standalone flare system.
- LIN System for Liquid Nitrogen system.
- Startup Package Boiler to provide steam during unit startup.
- Chemical Dosing Unit for boiler water treatment.
- CO_2 Product Dryer to remove water in CO_2 product to desired moisture level.

2.2.4 Heat and Material Balances

The Blue Bison Team developed, through sound engineering and scientific principles, heat and material balances associated with the carbon capture system. The molar composition rates and percentages of each stream were calculated to account for the materials entering and leaving the system. This task was required to confirm that the purity and capture levels outlined within the FOA were met. This deliverable was created using PROII software with accurate and equilibria, physical and thermodynamic property assumptions.

In total, fourteen (14) separate streams were identified: Natural gas feed, natural gas fuel, rich oxygen from air separation unit, auto thermal reactor and effluent to boiler, CO_2 removal unit inlet, CO_2 compressor suction, CO_2 product to battery limit, Blue H_2 Product to battery limit, off gas fuel to fired process heater, off gas recycle to ATR, makeup demineralized water, high pressure steam to turbine, recycle H_2 and stack emissions from heater.

2.2.5 Plot Plan and Equipment Layout Drawings

The Blue Bison Team created a facility plot plan for the Blue H_2 Plant and the carbon capture system and incorporated plot plan into the preferred location at the host site. Below is an overview of the layout completed during the project. The plot plan (Figure 3) was created utilizing equipment layout drawings outlining equipment extents, inputs and outputs, process lines etc.

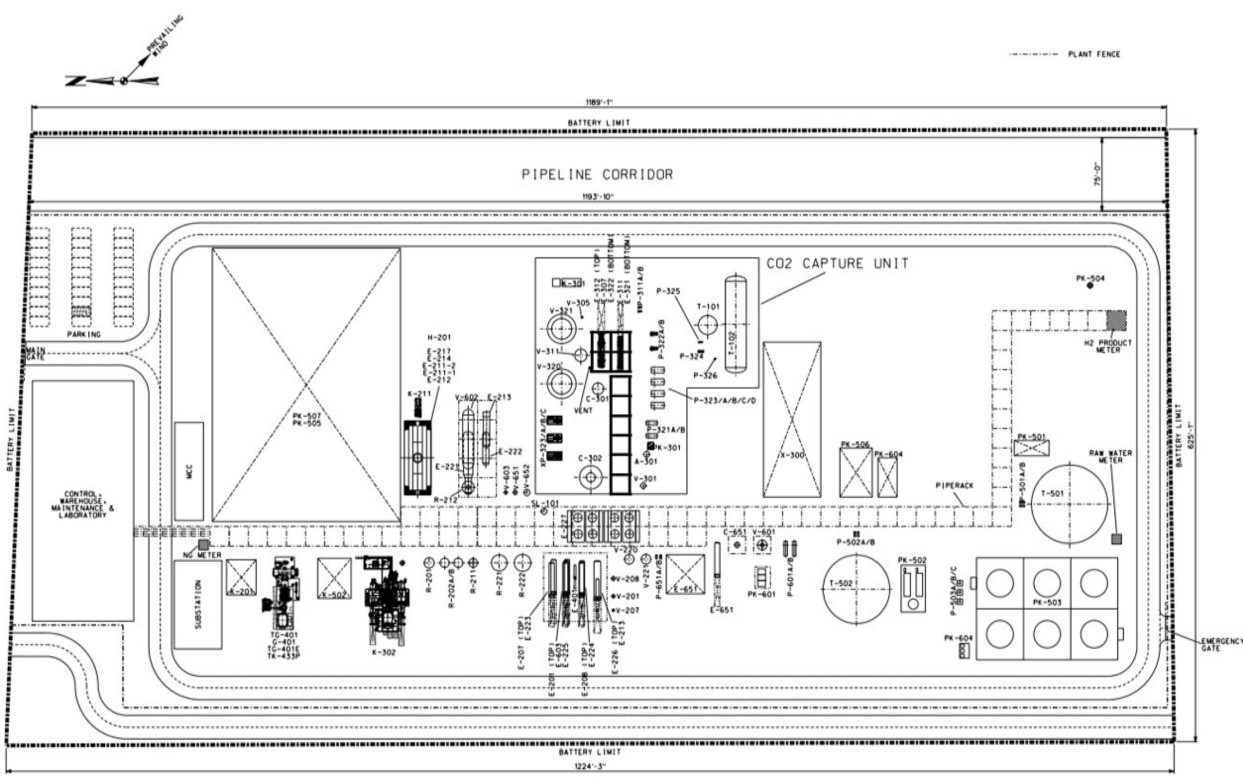

Figure 3: Preliminary Plot Plan

2.2.6 Vendor Quotations

The Blue Bison Team developed the required documentation to obtain vendor quotes for the carbon capture system and critical equipment packages related to the Blue H_2 Plant. Included with this deliverable were technical proposals and commercial proposals (including delivery time, price, and other commercial conditions) for each system and/or equipment packages. This was obtained and created for each long lead item, as well as creating technical and commercial bid tabulations.

2.2.7 Equipment Lists

The Blue Bison Team developed engineered process and utility equipment lists for the Blue H_2 production facility and carbon capture. Detailed equipment list for carbon capture system (Table 2) and carbon capture system layout (Figure 4).

Equipment Title	Equipment Tag
CO_2 Stripper	C-301
CO_2 Absorber	C-302
Final Process Gas Separator	V-301
HP Flash Drum	V-320
LP Flash Drum	V-321
aMDEA Solvent Storage Tank	T-101
aMDEA Solvent Preparation Drum	T-102
Solution Filter	A-301
Overhead Condensate Pump	P-311 A/B
Lean Solution Pump	P-321 A/B
Split Stream Pump	P-322 A/B
Semi-lean Solution Pump	P-323 A/B/C/D
aMDEA Solvent Storage Tank Pump	P-324
aMDEA Solvent Makeup Pump	P-325
Reverse Pump	XP-323 A/B/C
Flash Gas Cooler	E-307
CO_2 Product, Cooler	E-311
Stripper Reboiler	E-312
Solution Heat Exchanger	E-321
Lean Solution Cooler	E-322
Flash Gas Recycle Compressor	K-301

Table 2: Carbon capture system equipment list

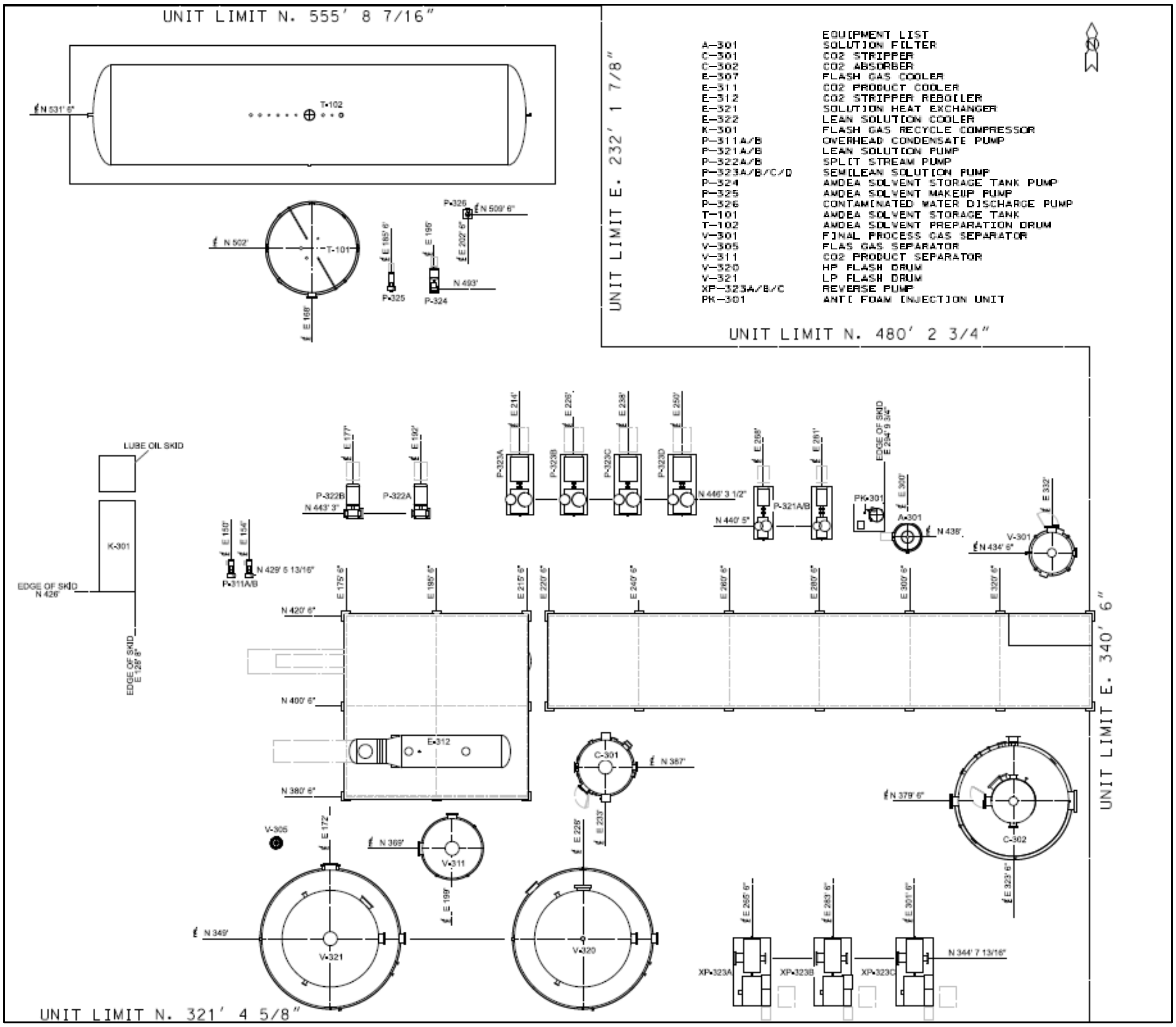

Figure 4: Preliminary Carbon Capture Unit

2.2.8 Sequestration Storage Summary

As a part of the project, a sequestration CO_2 Storage Potential Assessment was conducted by the Center for Economic Geology Research at the University of Wyoming. Through the analysis it was concluded that six (6) formations exist within the study Area of Interest (AOI) that are capable of permanently sequestering CO_2, in quantities, aligned with volumes from this project.

Sequestration Methodology: To assess the potential for CO_2 storage, well logs were gathered from deep hydrocarbon wells within the study area. Well loggers were downloaded from the Rocky Mountain Region Database through S&P Global LogNet. Figure 1 shows the location of available wells used for modeling and resource assessment. Geologic formation tops were picked using the gamma ray and sonic logs. To calculate porosity from the sonic logs, the Raymer-Hunt-Gardner (RHG) method was used (Raymer al., 1980). The matrix time used for sandstones was 56 microseconds. To prevent incorporating non-reservoir units such as dolomites into the calculation, a cut-off of 55 microseconds was used. Porosity was set to zero for sonic log that were 55 microseconds or less.

$$\Phi = \frac{5}{8}\, x\, \frac{DT_{log} - 56}{DT_{log}}$$

A structural model was built using Schlumberger's Petrel software using formation tops picked from the well logs in the study area. The model was built coarse to meet feasibility assessment goals, with x and y cell sizes at 2640 feet by 2640 feet. Upscaled porosity logs generated through the RHG method were geostaticially distributed by Sequential Gaussian Simulations. Due to limited data availability, many of the modeled distributions show "missing formations". It is likely that the formations do exist within these areas, but the project team kept outputs conservative to better utilize the limited dataset. Storage capacities where calculated using the probability capacity.

A detailed map was developed showing the study area in the black boundary for modeling and resource assessment (Figure 5). Geometry of the southern portion of the model was drawn intentionally for the purpose of staying north of the mapped faults. Well locations are black circles on the map. The team also created a table that represents corresponding information for the inventory of legacy wells used in the model construction (Table 3).

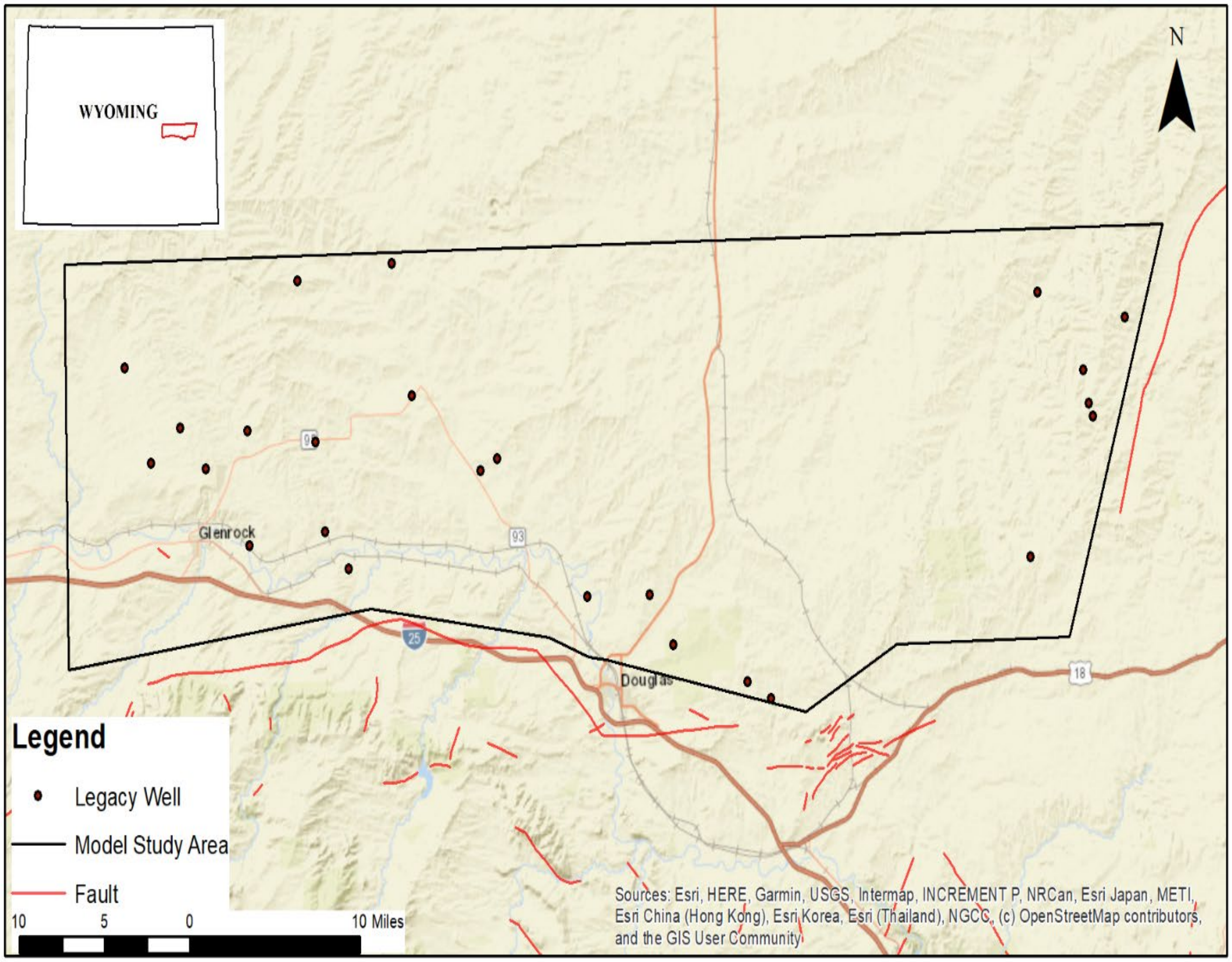

Figure 5: Subsurface study area

Well API	Latitude	Longitude	KB Elevation (Ft)	TD (Ft)
4902720047	43.004076	-104.890438	4586	10071
4902720118	42.92339	-104.82942	5138	10949
4902720133	42.985781	-104.789349	4852	10565
4902720145	42.931422	-104.833829	5122	11048
4902720819	42.953203	-104.839612	4986	10374
4900906412	42.934101	-105.890446	5530	12825
4900920067	42.86514	-105.72357	5030	11800
4900920275	42.857456	-105.81166	5046	8026
4900920639	42.911819	-105.924458	5405	10050
4900920915	42.81868	-105.34802	5129	14900
4900921854	42.92297	-105.73351	5214	14500
4900921874	42.78675	-105.32183	4995	13015
4900921919	42.90902	-105.52221	5160	13735
4900921920	42.749794	-105.209902	5179	13034
4900921947	42.973108	-105.953733	5495	12485
4900922101	42.90772	-105.86131	5446	11113
4900922464	42.819	-105.4202	4856	13353
4900922489	42.9016	-105.54246	5056	13670
4900921829	42.761317	-105.236389	5172	13146
4900922538	43.02613	-105.751942	5656	14562
4900922556	42.84107	-105.69661	5054	10920
4900922655	43.035661	-105.641378	5449	14567
4900922556	42.84107	-105.69661	5054	10920
4900922719	42.931142	-105.812074	5326	12850
4900928283	42.95084	-105.62055	5287	19210
4900929382	42.834732	-104.905781	5363	10450

Table 3 Information for legacy wells in the model construction

Estimates developed by the Department of Energy method developed by Goodman et al., 2011. This is equation is below.

$$\Phi_{Volume} * \rho_{CO_2} * E_{saline} = P\# \, Sum$$

Φ_{Volume} is pore volume that is estimated by the Petrel model. CO_2 density of 0.736 metric tons/m^2 was used for ρ_{CO_2}. E_{saline} represents the salinity coefficient and used 0.074, 0.14, and 0.24 for P10, P50, and P90 respectively. P# Sum is the total amount (metric tons, Mt) in the study area for potential CO_2. There were assumptions captured in the modeling due to data limitations. All units were modeled as being continuous across the study area. The logic for determining petrophysical cut-offs for the reservoir are mentioned above but could overlook zones with lesser storage potential thereby decreasing overall capacity estimates. Similarly, heterogeneous lithologies were grouped which could similarly result in overestimates of storage potential. The models relied on statistically distributing porosity and thickness using Sequential Gaussians Simulations, which produced erosional features due to data scarcity. We adopted a conservative approach to capture and portray the available data to retain these features. It should be noted no core data was available to calibrate calculations for porosity. CO_2 density was chosen as a constant throughout the area and depth, though this would be variable in a commercial project and impact total volumes.

Results: For future assessment of this area focus must be on acquiring and developing a more robust dataset to accurately quantify the southern powder river basin for CO_2 storage. Water data was not gathered or used in this study and formations identified for storage could be producing hydrocarbons but were not verified. Well logs will need to be digitized into a format suitable for modeling and petrophysical evaluation. Seismic acquisition is highly suggested if there is still a lack of coverage over the area after digitization of any additional existing well logs. Faults have been reported in this area and seismic would reduce the risk and uncertainty. Core data will also need to be acquired for well log calibration and for providing data for CO_2 simulations.

2.2.9 Update Blue H_2 Plant Description and Carbon Capture System Integration

The Blue Bison Team updated the plant description and BFD (Figure 6) to detail the integration between the Blue H_2 Plant and the carbon capture system. The Blue Bison Team also evaluated an alternate flow scheme utilizing 100% H_2 firing in the fired heater that pre-heats the natural gas feed and the use of Technip Energies' proprietary TPR® technology. TPR® (Technip Parallel Reformer) is a heat exchanger type reformer which utilizes heat from the autothermal reformer effluent to do additional reforming without increasing the firing duty in the autothermal reformer. The total steam make of the plant will be lower than the based design case because some of the heat from the autothermal reformer was used as the heat source from the TPR®. The potential benefits of TPR® integration to ATR could be smaller ATR size, lower O_2 consumption, smaller ASU, and smaller reheat coils.

Using the integrated technology for the carbon capture system (CCS), Blue Bison is calculated to have roughly a 97.2% carbon capture rate with a detailed air emissions summary found below (Table 4). An output stream of carbon dioxide "product" was identified, and this product is sent to sequestration at a rate of 9,221 lb/mol per hour. Accordingly, this translates to 184.12 MT/hr or 1,532,306 tonnes of CO_2 captured per year. Thus, it is determined that 2.8% of CO_2 is emitted hourly (5.139/184.12), and conversely 97.2% of CO_2 emissions are captured.

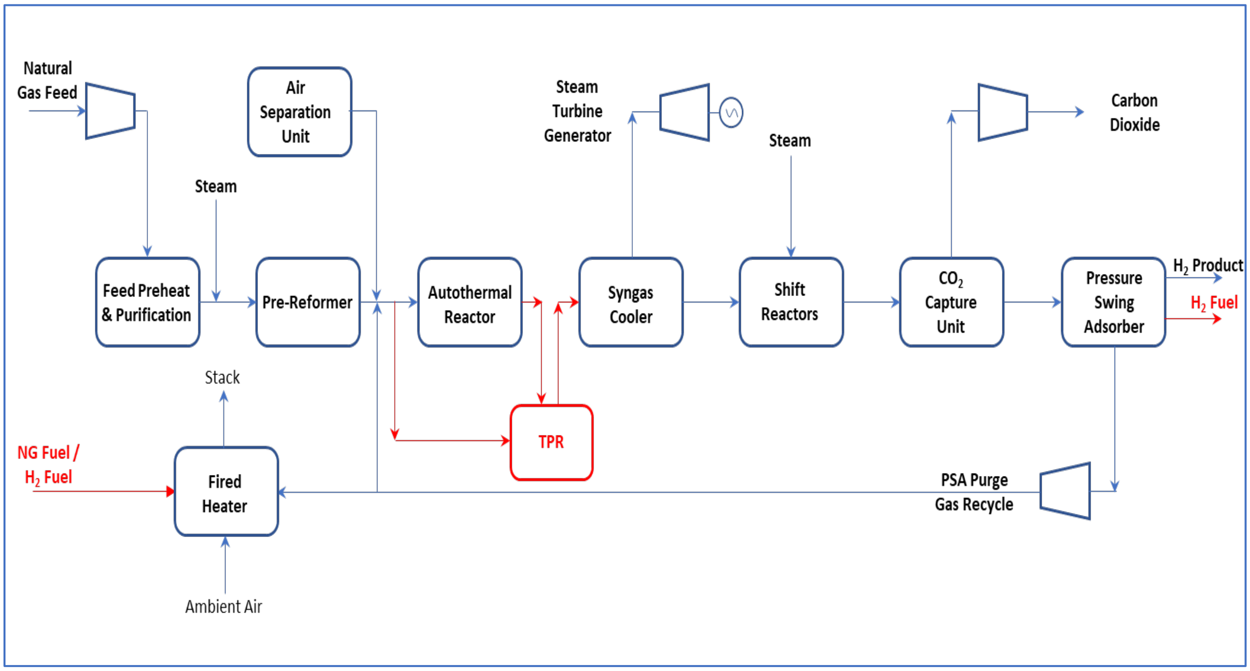

Figure 6: BFD - 220 MMSCFD Blue Bison ATR with Carbon Capture with TPR®

Air Emissions				
Flue Gas Flow	MSCFH	2,186.00		
Molecular weight		26.40		
Temperature (stack)	°F	391.00		
Component	lb/Mmbtu (@ 3% O_2)	lb/hr	kg/hr	
Nox	0.035	7.15	3.24	
Sox	*<1	<0.5	0.23	
VOC	0.0017	0.35	0.16	
Particulates	0.005	1.02	0.46	
*Sox is based on ppmvd (@ 3% O_2)				
Stack Composition				
Stack Composition	Composition %	lbmol/hr	Mol weight	kg/hr
Carbon Dioxide	4.47	257.34	44.01	5,139.00
Nitrogen	67.06	3,862.13	28.01	49,083.00
Oxygen	2.31	132.86	15.99	964.00
Argon	0.91	52.53	39.95	952.00
Water	25.25	1,454.44	18.02	11,892.00
Total Composition %	**100**			
Total Molar Rate		**5759.3**		

Table 4: Air Emissions Table

2.3 Techno-Economic Analysis (TEA)

The Blue Bison Team completed a TEA utilizing components from the deliverables generated from the initial engineering and design documentation. The TEA includes required elements as applicable to the technology:

- General process flow diagram identifying all major process equipment for the power plant including CO2 capture and compression systems, separation vessels, heat exchangers, pumps, compressors, etc.
- Material and energy balances around the complete power plant and around all major pieces of equipment there in, including all heating and cooling duties, and electric power requirements.
- Complete stream tables showing operating pressures, temperatures, compositions, and enthalpies for all streams entering or leaving major process equipment.
- Economic analysis that follows the NETL “Quality Guidelines for Energy System Studies: Cost Estimation Methodology for NETL Assessments of Power Plant Performance.” The code of amounts for the capital cost estimate will follow those used in the Bituminous Baseline Study.
- Estimates for equipment and consumables unique to the process being developed.

2.3.1 Economic Analysis and Final TEA (Inc. Required calculated output from analysis)

The Blue Bison Team developed an economic analysis based on “Quality Guidelines for Energy System Studies: Cost Estimation Methodology for NETL Assessments of Power Plant Performance”.

The code of accounts for the capital cost estimate will follow those used in the “Cost and Performance Baseline for Fossil Energy Plants - Volume 1: Bituminous Coal and Natural Gas to Electricity (Rev 4, 2019),” aka Bituminous Baseline Study (BBS) BBS.

Operating and maintenance cost will be itemized and presented in the format used in the BBS. The levelized cost of hydrogen (LCOH) is the minimum required H2 selling price to achieve a 7.84% after-tax real rate of return on equity over the life of the plant. The LCOH was calculated on a real money basis over a 12-year 45Q horizon and on an extended 25-year horizon. The benefit of Section 45Q sequestration is included to calculate a flat cost of hydrogen of $0.889 per kg over a length of 12 years. Assuming the cost per kilogram of hydrogen from year 1 to year 12 remains $0.889, the required real LCOH after initial 12 years (thus after the 45Q ends) increases to $0.945 per kg. Based on this analysis, the Blue Bison Team was able to conclude that Blue H_2 production is feasible, at a cost of less than $1.00/kg Blue H_2.

2.4 Additional Studies

Additional studies consisting of the workforce readiness plan, process hazard analysis and environmental health and safety were completed. Below is a synopsis of those additional studies:

2.4.1 Workforce Readiness Plan

A document was created to discuss training programs, collaboration with educational facilities, and outline potential certifications and licensing that may be required.

Additionally, the University of Wyoming is developing a Center of Excellence dedicated to advancing research programs around hydrogen industry and the location of the Blue H_2 Plant is within a designated Qualified Opportunity Zone. In addition to helping to inform a new research focus area within the University, this project will coordinate directly with the University of Wyoming to access their experts in CCUS and carbon management CCUS. This collaboration will also include training students using data gathered from the project to advance CCUS and other commercialization goals.

2.4.2 Process Hazard Analysis (PHA)

The Preliminary PHA was conducted for the carbon capture unit utilizing the HAZOP methodology with a team of project, process, instrumentation, and operations engineers and personnel. A HAZOP study was conducted to ensure that the plant design is safe for operations using the initial PID's. The PHA identified process hazards and deviations for the new facility and gave recommendations for safety improvement for both personnel and the environment. The following objectives were set:

- To systematically review the intended operation of the facility, and to analyze potential process safety and environmental hazards; specifically:
- To identify credible causes of incidents which could result in a release of highly hazardous materials.
- The team will also note when a credible cause may lead to significant capital loss or major operational upsets (notes as equipment damage or operational issues only).
- To determine whether existing safeguards are adequate. If not, make recommendations to improve the design and/or operation of the process.

Various nodes on P&ID were defined. Each node is a small portion of the process that includes one unit operation, typically on major process equipment with related piping and instrumentation or a complete system (e.g., compressor including a suction drum, intercoolers). For each node, deviations from normal operation for various process variables (flow, temperature, pressure, level, concentration etc.) were analyzed for possible consequences. Likely causes and consequences for each of the deviations were discussed to identify hazard scenarios without taking credit for any safeguards. Severity and likelihood ratings were applied for each pair of causes and consequences. Based on these ratings, risk levels were identified for each hazard scenario and additional safeguards were incorporated in the design where needed.

Improvements generated from the PHA are incorporated into engineering designs and processes to minimize potential negative effects to human health and the environment. The Blue Bison Team has already incorporated 22 recommendations into the PID's.

2.4.3 Environmental Health and Safety

The purpose of the EH&S Risk Assessment is to assess the environmental friendliness and safety of chemicals used in the processes for the Blue Bison Plant.

Since air emissions are expected to occur at the Plant, engineering controls have been put in place to use catalysts to remove unwanted air contaminants before exit from the stack. Air stack emissions are not anticipated to contain hazardous air pollutants in sufficient quantity to have a negative impact on human health or the environment. Furthermore, permit-required routine emissions testing and reporting will ensure on-going compliance with applicable air pollutant limits. Wastewater discharges from the Blue H_2 Plant are expected to occur during start-up, operation, and during various process blowdown activities. Wastewater is not anticipated to contain hazardous pollutants in sufficient quantity to have a negative effect on human health or the environment but may not be of quality to re-use in the process. Industrial solid waste generated at the site could include containers and disposable components utilized in the Blue H_2 Plant processes. These wastes will be contained in appropriate waste holding containers and disposed of at an authorized facility. Industrial solid waste is not anticipated to contain hazardous pollutants in sufficient quantity to have a negative effect on human health or the environment.

A chemical solvent, activated n-methyl diethanolamine (aMDEA), will be used in conjunction with the BASF's OASE white carbon capture technology. The aqueous amine, aMDEA, is used in the CCS process to absorb CO_2 in the gas stream of the Plant. The aMDEA rich solution can be heated to facilitate the release of pure CO_2 which is then captured and stored. OASE white has potentially negative effects to human health and the environment if handled poorly. The engineering controls call for a closed loop system containing the compound in suitable storage vessels and tanks with secondary containment structures, minimizing the risk of releases, spills, and possible exposure or release to the environment. A comparison of the properties of OASE white and n-methyl diethanolamine is shown below (Table 5).

Property	OASE White	Methyl diethanolamine
Physical and Chemical Properties:		
Form	liquid	liquid
Odor	amine-like	amine-like
Color	colorless to yellow	colorless to yellow
Flammability	not flammable	not readily flammable
Stability and Reactivity:		
Oxidizing properties:	Not fire-propagating	Based on its structural properties is not classified as oxidizing.
Possibility of hazardous reactions:	Shows a strong exothermic reaction with acids.	The progress of reaction is exothermic. Reacts with halogenated compounds, oxidizing agents, acids, acid chlorides.
Incompatible materials:	Acids, acid chlorides, acid anhydrides	Acid chlorides, acid anhydrides, acid forming substances, acids, oxidizing agents, nitrosating agents.
Decomposition products:	Carbon oxides, nitrogen oxides	Carbon oxides, nitrogen oxides, nitrous gases
Thermal decomposition:	No decomposition if stored and handled as prescribed/ indicated.	No decomposition if used as directed.

Table 5: Properties of OASE White and Methyl diethanolamine

During the Feed Treatment Process, the feed goes through a Sulfur Absorber to remove sulfur content from the Hydrotreater to not contaminate the downstream catalysts. In the Sulfur Absorber, sulfur in the feed is absorbed by the catalyst, zinc oxide, which yields the byproducts zinc sulfide and water. Zinc sulfide may react with water to form hydrogen sulfide gas which is toxic at certain concentrations. Engineering controls and design specifications eliminate the potential for water to be in proximity to the Sulfur Absorber catalyst and byproducts.

Measures have been designed to prevent the introduction of contaminants including front-end purification processes. If contaminants are inadvertently introduced into the system, there are engineering controls in place to ensure the elimination of contaminants in the natural gas feed and utilization of DMW for solution preparation and make-up water requirements.

Final disposition of anticipated waste products will be determined by quantities and chemical composition. Accumulated waste will be disposed of in accordance with Federal, State and Local regulations.

All potential contaminants will be contained in proper locations and receptacles designated specifically for storage and containment of the corresponding contaminants. A comparison of the safety and handling guidelines of OASE white and n-methyl diethanolamine is shown below (Table 6).

	OASE White	Methyl diethanolamine (aMDEA)
Precautions:	Wear protective gloves, protective clothing, eye/face protection. Avoid breathing dust/fume/gas/ vapors/spray.	Wear eye/face protection Wash with plenty of water and soap thoroughly after handling.
Accidental release measures:	Personal precautions: Avoid inhalation and contact with eyes. Environmental precautions: Discharge into the environment must be avoided. Methods and materials for containment and cleaning up: For large amounts, pump off product. For residues, pick up with suitable absorbent materials for containment and cleaning up. Clean contaminated floor and objects with water and detergents. Collect waste in suitable containers to incinerate or take to a special waste disposal site.	Personal precautions: Wear appropriate respiratory protection. Use personal protective clothing. Ensure adequate ventilation. Environmental precautions: Do not discharge into drains/surface waters/groundwater. Methods and material for containment and cleaning up: Spills should be contained, solidified, and placed in suitable containers for disposal.
Handling and storage:	Precautions for safe handling: Ensure through ventilation of stores and work areas. Handle in accordance with good industrial hygiene and safety practice. When using do not eat, drink, or smoke. Hands and/or face should be washed before breaks and at the end of a shift. Protection against fire and explosion: Prevent electrostatic charge—sources of ignition should be kept well clear—fire extinguishers should be kept handy. Conditions for safe storage: Segregate from acids and acid forming substances.	Precautions for safe handling: Ensure through ventilation of stores and work areas. Handle in accordance with good industrial hygiene and safety practice. When using do not eat, drink or smoke. Hands and/or face should be washed before breaks and at the end of the shift. Protection against fire and explosion: Prevent electrostatic charge - sources of ignition should be kept well clear - fire extinguishers should be kept handy. Conditions for safe storage: Segregate from acids and acid forming substances.
Exposure control and personal protection:	Personal protective equipment: Respiratory equipment: Wear NIOSH-certified organic vapor respirator if ventilation is inadequate. For emergency, high exposure situations—wear full facepiece respirator. Hand protection: Wear chemical resistant protective gloves. Eye protection: Tightly fitted safety goggles. Body protection: Depends on activity and possible exposure (head protection, apron, boots etc.)	Personal protective equipment: Respiratory protection: Wear a NIOSH-certified organic vapor/particulate respirator. Hand protection: Chemical resistant protective gloves. Eye protection: Tightly fitted safety goggles.

Table 6. Solvent Handling and Safety Guidelines

2.4.4 Compliance with U.S. EH&S Laws

The team is dedicated to operating in compliance with the US Environmental Health and Safety Laws. These laws include the Comprehensive Environmental Response and Liability Act of 1880 (CERCLA), Toxic Substances Control Act (TSCA), Clean Water Act (CWA), Clean Air Act (CAA), NAAQS and SIPs, WDEQ Air Quality Division Standards and Regulations, Superfund Amendments and Reauthorization Act (SARA), and Occupational Safety and Health Act (OSHA).

3. Conclusion

The Blue Bison Team exceeded the success metrics set forth by this FOA, as defined below:

- Development of an initial engineering study for a commercial-scale carbon capture, storage, and utilization system from an industrial plant producing blue hydrogen.
- CO_2 purity of 95%
- Net CO_2 capture efficiency of 90%+
- Total CO_2 captured above 100,000 tonne/year net CO_2
- Blue H_2 purity is 99.97 mol%

Success metrics were achieved utilizing process design assumptions within the FOA for CO_2 capture and compression and Blue H_2 product as defined below:

- Hydrogen product stream: CO + CO_2 is less than 10 ppm
- H_2 delivery pressure of 360 psia
- CO_2 delivery pressure at 2,215 psia
- CO_2 transport and storage costs at or below $10/tonne

Blue H_2 at scale will create low carbon fuel, allow businesses to utilize existing assets for Blue H_2 transportation and/or consumption, and create a diversified clean energy portfolio to better address climate change.

The deliverables developed during the initial engineering and design study are a critical step to the overall development of Blue H_2 but require continued analysis and development to reach full deployment. Some critical next steps for future project development consist of:

- FEED study for further refinement of the plant design and increased accuracy of capital and operating costs
- Continuation of the subsurface analysis through reservoir modeling, seismic interpretation, test wells and Class VI permit application
- Further evaluation for potential customers and development of offtake agreements