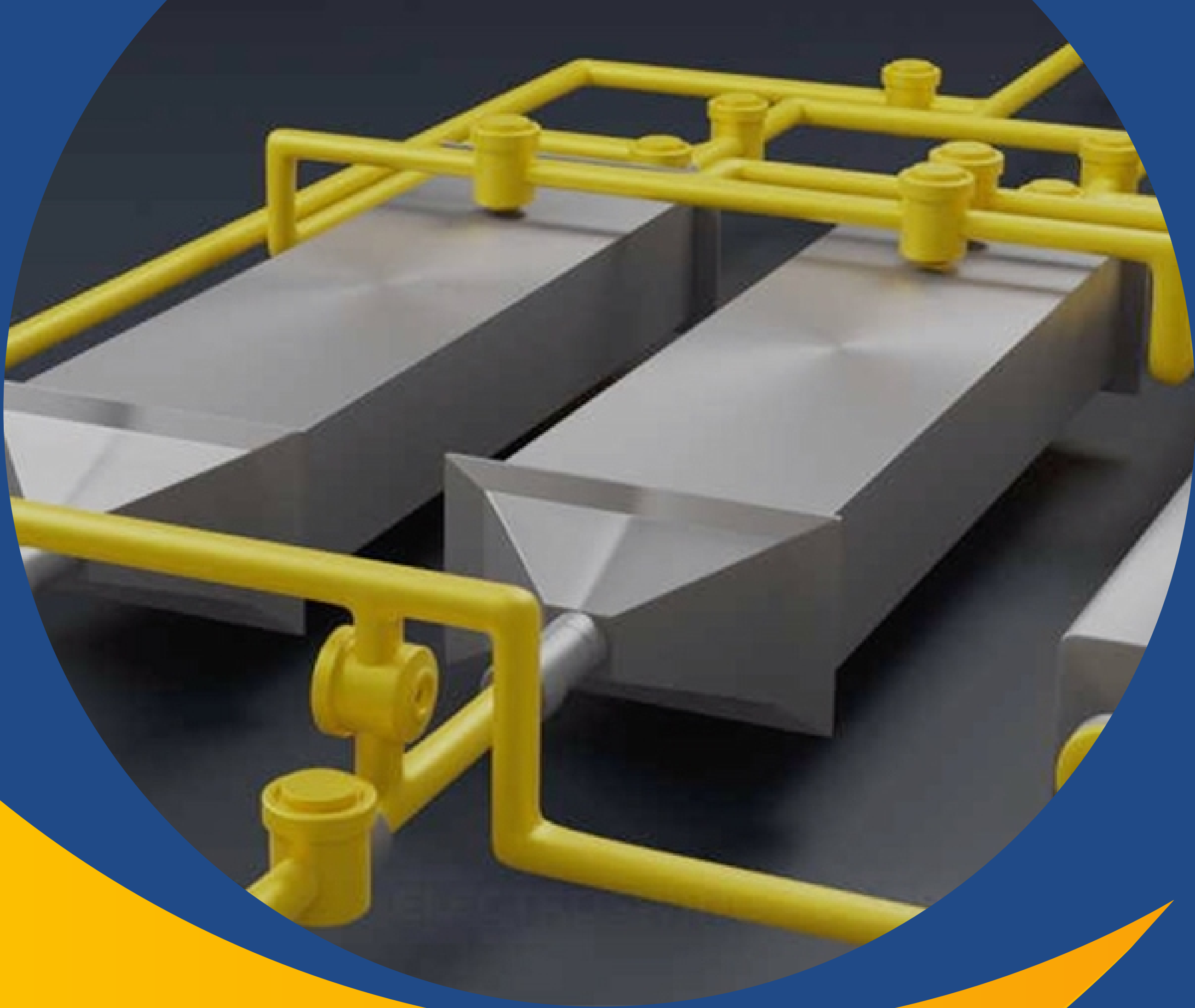

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ENERGY FUTURE

CARBON CAPTURE, UTILIZATION, AND SEQUESTRATION

MIDSTREAM APPLICATIONS ABSTRACT

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Carbon CUS

INTRODUCTION

Carbon capture, utilization, and sequestration (CCUS) is not new to the midstream oil and gas industry. Since the 1970s carbon dioxide (CO2) has been removed from natural gas streams and reinjected into aging reservoirs through enhanced oil recovery (EOR). The methods and technologies used to separate the CO2 from the natural gas stream and deliver it to a wellhead for injection are tried and proven.

The application of these methods and technologies will remain key pieces within the future of the evolving Environmental & Social Governance (ESG) business trend. Key topics of focus in the ESG trend are on identifying business activities resulting in greenhouse gas emissions, particularly those of carbon dioxide and methane which make up about 90% of total greenhouse gasses emitted [1].

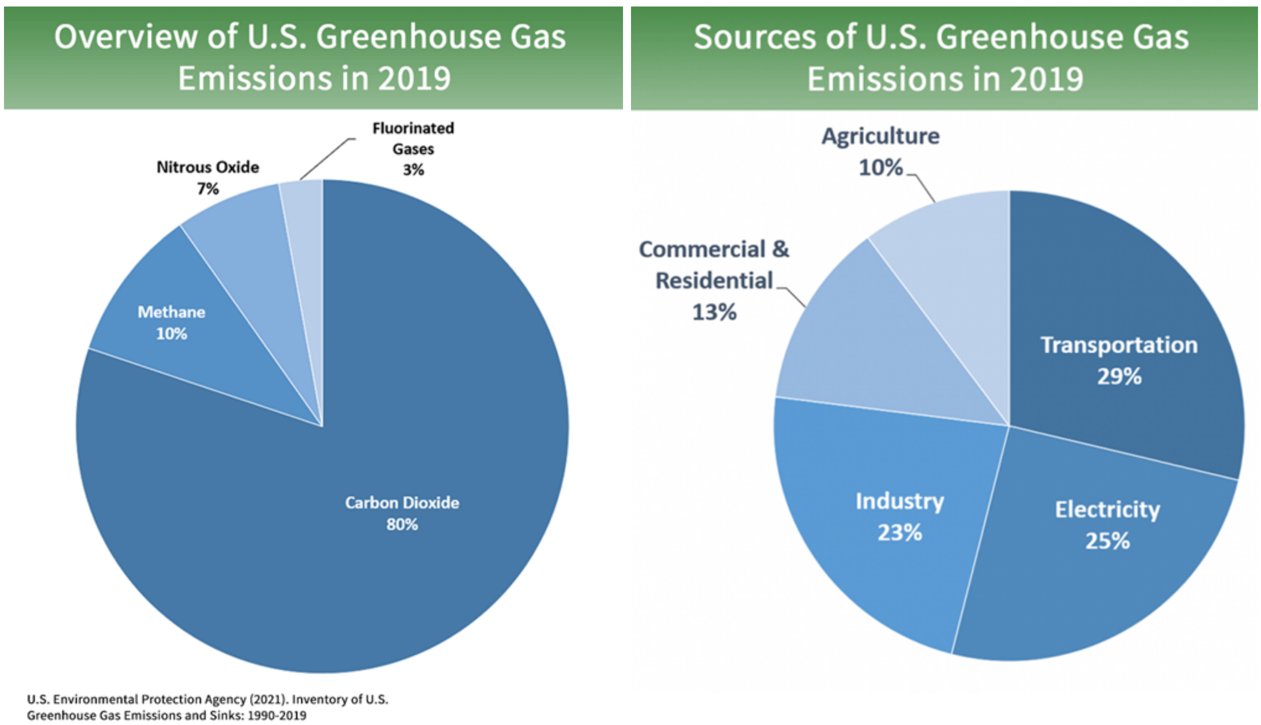


Figure 1. US EPA GHG Emissions Breakdown

An analysis of reported greenhouse gas emissions data by composition and by sector as identified by the United States Environmental Protection Agency (EPA) with their respective percentage are shown in Figure 1 [1].

The MIDSTREAM ROLE IN CCUS

The majority of CO_2 emissions originate from the combustion of fossil fuels in industrial heating, power generation, and transportation. The Blue hydrogen movement seeks to utilize Steam Methane Reforming (SMR) for generation of hydrogen, but the process produces significant carbon dioxide quantities.

To qualify as "Blue", the CO_2 must be captured and utilized or sequestered. The following abstract contains discussions on the capture, utilization, and sequestration of primarily carbon dioxide but may be applicable to other greenhouse gases.

1 CAPTURE

Capture within the CCUS cycle refers to the redirection of carbon dioxide or other greenhouse gases at the point of emission. A block flow diagram shown in Figure 2 outlines the basic steps of the CCUS cycle.

This block flow diagram represents the highly visible sources which most people recognize as contributing to GHG emissions. Alternatively, the midstream industry has reliably been removing carbon dioxide from natural gas streams seen as a contaminant.

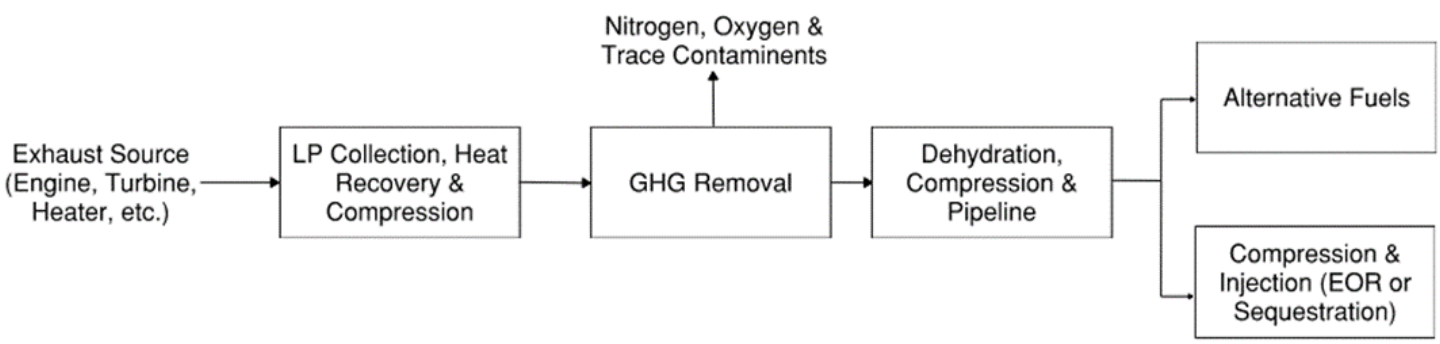


Figure 2. CCUS Cycle BFD (Combustion Sources)

Typically, these are achieved with amine plants removing the CO2 to pipeline quality than venting the stripper overhead directly to atmosphere as a highly concentrated CO2 stream.

A block flow diagram for the CCUS cycle in that application is simpler and shown in Figure 3.

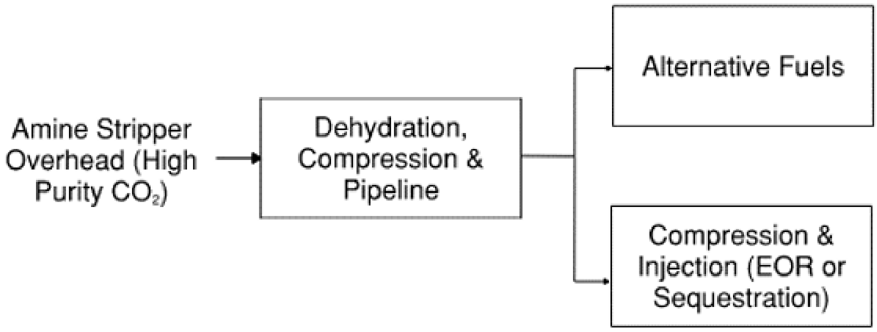


Figure 3. CCUS Cycle BFD (Natural Gas Treating).

The highly visible gas streams are typically low-pressure exhausts from turbines, reciprocating engines, heaters and/or process vents. If the CO2 is the result of combustion, the gas stream is typically high temperature (600oF-900oF turbine outlet) and low pressure (< 20 inH2O). Exhaust temperatures after a heat recovery steam generator might be closer to 300oF.

A typical gas turbine exhaust composition is shown in Table 1 [3]. GE Gas Turbine Exhaust Composition. Most engines, turbines, and heaters operate with excess air to ensure complete combustion of the fuel and reduce combustion temperatures. The exhaust streams are primarily a mix of nitrogen, carbon dioxide, oxygen, with smaller amounts of carbon monoxide and nitrous oxides.

Table 1. GE Gas Turbine Exhaust Composition

Major Species	Typical Concentration (% Volume)	Source
Nitrogen (N_2)	66 - 72	Inlet Air
Oxygen (O_2)	12 - 18	Inlet Air
Carbon Dioxide (CO_2)	1 - 5	Oxidation of Fuel Carbon
Water Vapor (H_2O)	1 - 5	Oxidation of Fuel Hydrogen
Minor Species Pollutants	**Typical Concentration (PPMV)**	**Source**
Nitric Oxide (NO)	20 - 220	Oxidation of Atmosphere Nitrogen
Nitrogen Dioxide (NO_2)	2 - 20	Oxidation of Fuel-Bound Organic Nitrogen
Carbon Monoxide (CO)	5 - 330	Incomplete Oxidation of Fuel Carbon
Sulfur Dioxide (SO_2)	Trace - 100	Oxidation of Fuel-Bound Organic Sulfur
Sulfur Trioxide (SO_3)	Trace - 4	Oxidation of Fuel-Bound Organic Sulfur
Unburned Hydrocarbons (UHC)	5 - 300	Incomplete Oxidation of Fuel or Intermediates
Particulate Matter Smoke	Trace - 25	Inlet Ingestion, Fuel Ash, Hot-Gas-Path Attrition, Incomplete Oxidation of Fuel or Intermediates

An alternative approach being investigated is Direct Air Capture (DAC) of CO2 straight out of the atmosphere. Due to the relatively low concentration of CO2 in the atmosphere, approximately 400 ppm, large volumes of air must be processed to extract impactful amounts of carbon dioxide.

Compare this concentration to that of a gas turbine exhaust which has a CO2 concentration of about 40,000 ppm, but with both cases the majority of the stream being processed is nitrogen and excess oxygen (90% of the stream).

THE TECHNOLOGY

The technology proposed uses large air handlers moving air across a grid with a thin film of solvent. A potential block flow diagram for the Direct Air Capture method is shown in Figure 4.

The DAC technologies currently in development use caustic solutions to bind the carbon dioxide in a carbonate anion.

The highly publicized joint development company 1PointFive, between Occidental and Rusheen Capital Management, will install a DAC facility using technology from Climate Engineering in the Permian in the near future to capture atmospheric carbon dioxide and inject it for EOR. The facility will have a nameplate capacity of one million metric tons CO2 per year [4].

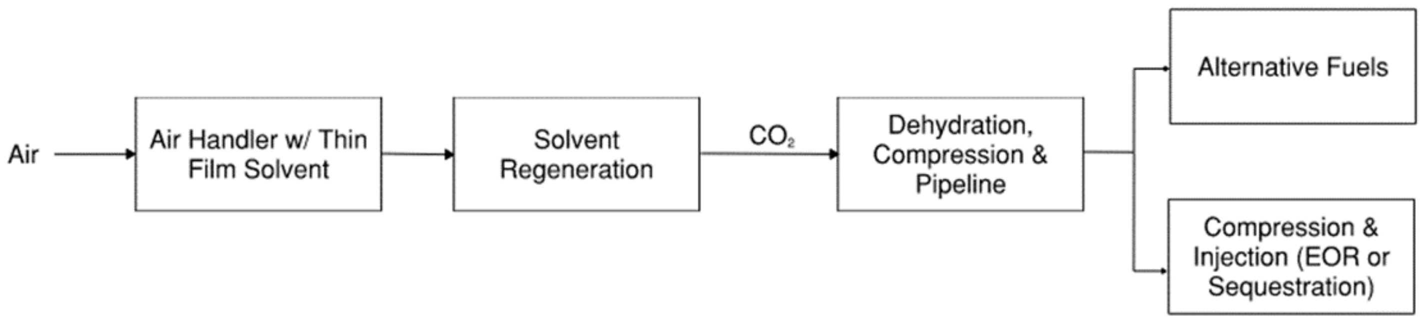


Figure 4. CCUS Cycle BFD (Direct Air Capture)

The caustic solution provides an aggressive means of capturing the CO2 at atmospheric pressure, unfortunately it will also be highly reactive with any other acid components in the atmosphere.

The regeneration of the solvent which requires heating and concentrating the CO2 presents the biggest challenges in scaling up designs so far. Published data on the process is high level and not widely shared.

TECHNOLOGY
Continued

Challenges in collecting and processing the exhaust streams are primarily a challenge due to the low pressures. Collection systems will require low flowing pressure losses to minimize the effect on the upstream combustion process.

The systems will start with modifying the outlet ducting (square, rectangle, or round) to direct the exhausts to a common manifold. This common manifold would feed a high temper-ature blower which would deliver enough head to then allow the stream to pass through a heat exchanger to cool the stream to approximately 120oF.

The heat could be released to the air, captured for Organic Rankine Cycle (ORC) power generation, or cross exchanged with a heat medium for other process heat.

After cooling, the gas stream would be compressed for treating with a chemical (amine) or physical solvent to remove the desired carbon dioxide. The primary reason for the elevated treating pressure is the associated reduction in equipment size.

The carbon dioxide can then move onto the next step in the CCUS cycle while the remaining exhaust stream can be vented or disposed.

The treating step is not without its challenges which exist around the selection of an appropriate solvent to selectively pick up the greenhouse gasses and allow the others to slip into the vent.

Additionally, the presence of oxygen will introduce the risk of enhanced corrosion and reduced lifetime for some solvents.
Other components and particulate matter from industrial processes could also present challenges in the treating phase and may require additional treating steps.

The materials of construction in the capture and treating phase will need to be corrosion resistant and suitable for high temperatures such as 316 stainless steel or ceramic coatings. Once the process stream is dehydrated the CO2 can be piped in standard carbon steel materials.

2 UTILIZATION

Utilization within the CCUS cycle refers to the transportation and alternative reuse options for the greenhouse gas.

Carbon dioxide pipelines are already a well-established sector regulated under PHMSA and DOT 195 with over 4,500 miles of pipeline in safe operation (5).

The majority of these pipelines are in use for enhanced oil recovery (EOR) within depleted oil fields around the country.

Alternative reuse options that are in development include [6]:

- Hydrogenation of carbon dioxide over a catalyst to methane through Sebatier reaction or heavier fuels (gasoline, diesel, & kerosene) through Fisher-Tropsch reaction.
- Carbon mineralization into carbonates
- Algae based biofuels

Outside of EOR, the utilization options for CO2 are still being studied with no commercial scale plants in operation. The majority of carbon dioxide utilization outside of EOR has not progressed due to technical feasibility or energy/water intensive process requirements which offset any profitability.

3 SEQUESTRATION

Sequestration within the CCUS cycle refers to the long-term disposal of carbon dioxide in underground reservoirs or other solid media.

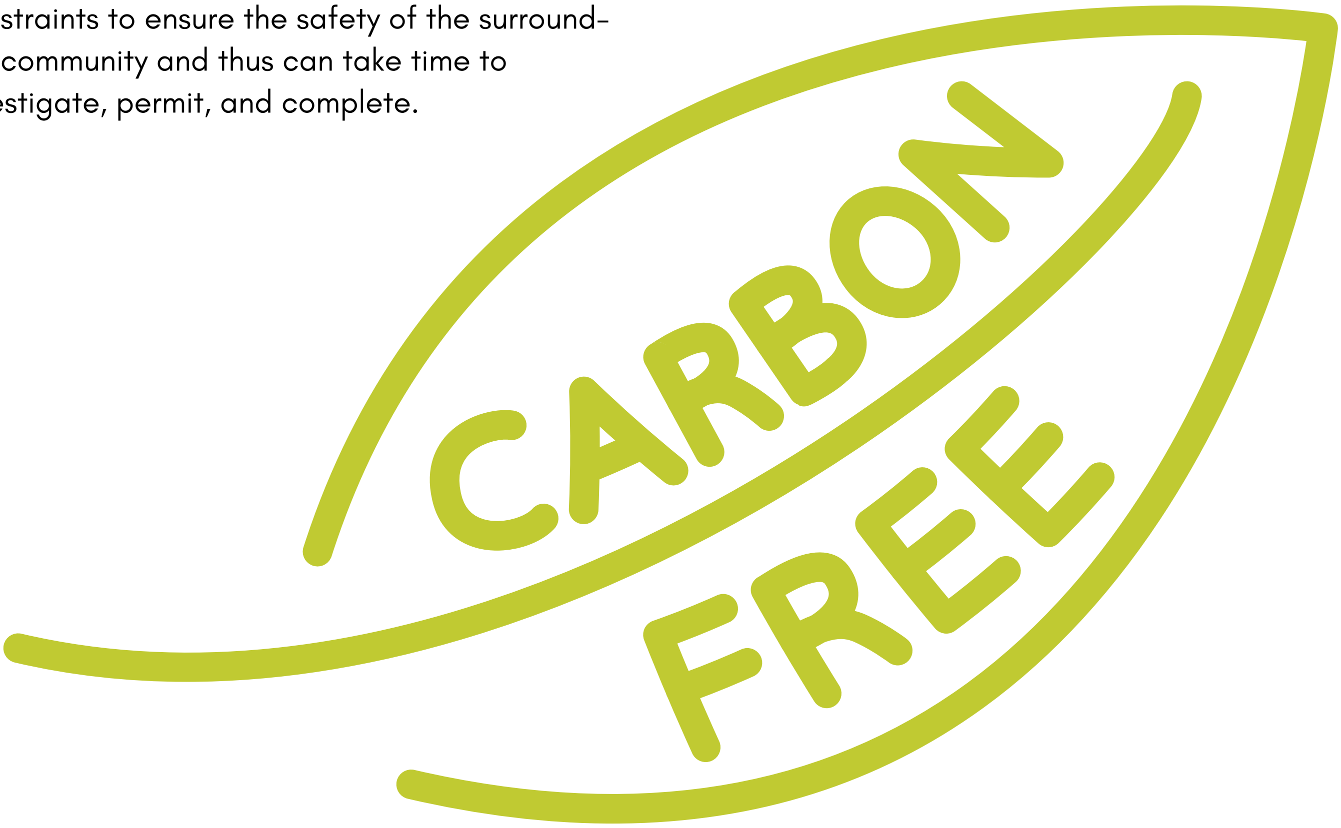
As stated with the utilization step, the majority of carbon dioxide captured in the United States is used for enhanced oil recovery. Sequestration or geologic disposal of a stream (liquid or gas) is a mature practice in the oil and gas industry.

Produced water and hazardous acid gas streams are injected into depleted geologic formations for permanent storage where other disposal methods are not available.

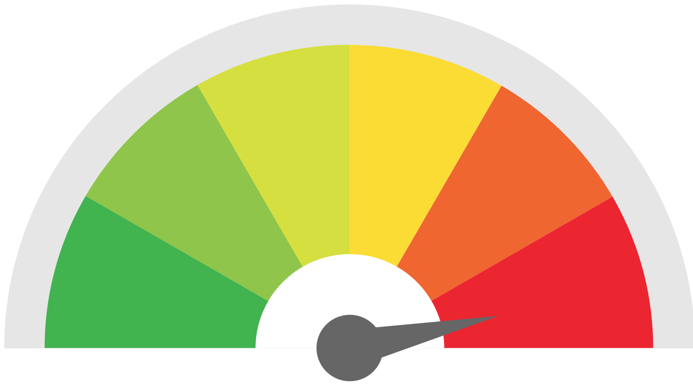
Injection wells require specific geologic constraints to ensure the safety of the surrounding community and thus can take time to investigate, permit, and complete.

The technology and methods used in the midstream industry are already in use safely injecting streams that are 90% or greater carbon dioxide by volume.

An alternative sequestration method is being proposed in Oman [7], to inject the carbon dioxide and water into wells drilled into peridotite ($CaCO_3$ and $MgCO_3$) formations. The natural weathering of the peridotite converts and stores atmospheric carbon dioxide into solid carbonates. A similar approach is being experimented in Iceland where the CO_2 is being injected into volcanic rock formations for mineralization [8].



CCUS PERFORMANCE METRICS



The trends currently suggest that CCUS project success will be heavily dependent on government set carbon tax credits. Therefore, targeting carbon sources with the highest carbon density and lowest energy input will be key to a sustainable investment.

An outline of these two metrics for the three CCUS options discussed in this abstract are contained in Table 2. CCUS Project Metrics.

Table 2. CCUS Project Metrics

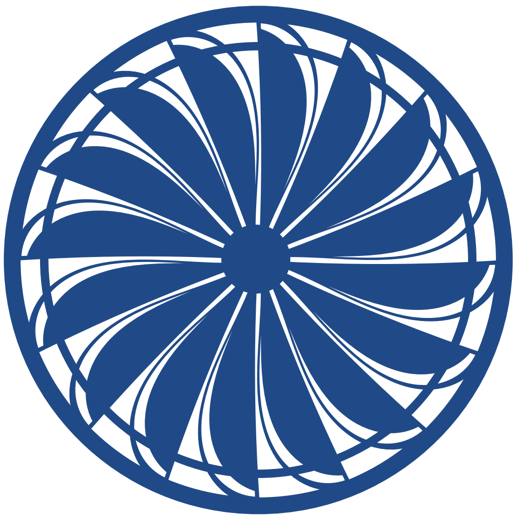
	Metric Tons CO_2 / MMcf Raw Gas	BHP/MMcf CO_2	BHP/Metric Ton CO_2 Utilized or Sequestered
Amine Vent Stream	45.7	285	6.23
Engine/Turbine Exhaust	0.39	485	1,233
Direct Air Capture	0.0103	918	88,953

BHP = Brake Horsepower; MMcf = Million Cubic Feet

This analysis was performed under the following assumptions:

- All options require final compression of purity CO2 stream from 10 psig to 2000 psig for injection at an energy rate of 285 BHP /MMcf CO2.

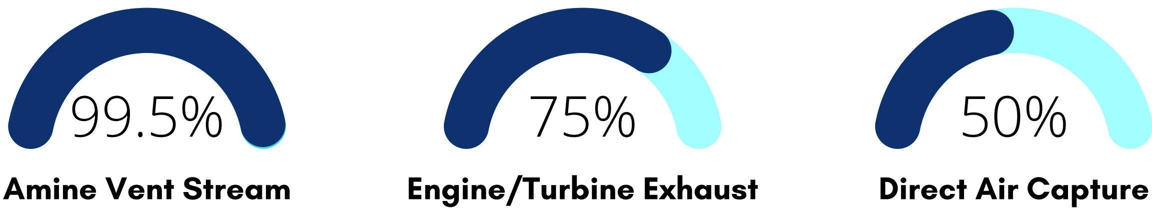
1. The Engine/Turbine Exhaust option needs an additional 200 BHP/MMcf CO2 for the pressurization to an optimal treating pressure as previously discussed.
2. The Direct Air Capture option requires an additional 633 BHP/MMcf CO2 to move the air across a fan with 1 inH2O of pressure increase.



CCUS PERFORMANCE METRICS *Continued*

This analysis was performed under the following assumptions:

- The following capture efficiencies have been applied to the raw gas streams based on the available CO2 concentrations and probable capture technology selections:



- Amine vent stream is a typical high purity stream being vented currently from gas processing facilities.
- Engine/Turbine exhaust volume and compositions are based on two (2) Solar Mars 100 generator packages. This process will require intermediate compression to facilitate treating with a solvent.
- Direct Air Capture assumes treating occurs at atmospheric conditions.

The opportunities around amine vent streams represent the highest carbon density, lowest capital cost, and lowest operating cost compared to capturing exhausts or direct air capture.

Another viable high density carbon source would be the tail gas off a Steam Methane Reformer used in the generation of hydrogen.

CONCLUSION

The midstream industry is readily positioned to take part in the capture, utilization, and sequestration of carbon dioxide from major emission sources.

Challenges as previously outlined are an engineered solution away from being an opportunity.

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