Subtask 5.2 – Transportation and Infrastructure Assessment
Topical Report

March 1, 2017 through May 30, 2019

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Report Issued: July 31, 2018

Report Number: DOE/ FE0029445-3
U.S. DOE Cooperative Agreement Number: DE-FE0029445
CARBONSAFE ILLINOIS EAST SUB-BASIN

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Executive Summary

The CarbonSAFE Illinois – East Sub-Basin project is conducting a pre-feasibility assessment for commercial-scale CO_2 geological storage complexes. The project aims to identify sites capable of storing more than 50 million tons of industrially-sourced CO_2. To support the business development assessment of the economic viability of potential sites in the East Sub-Basin and explore conditions under which a carbon capture and storage (CCS) project therein might be revenue positive, this document provides a screening level estimate of capital and operating costs for CO_2 compression and dehydration surface equipment for the planned Quasar Syngas facility in Terre Haute, IN. Although preliminary, this estimate is based upon a significant amount of Trimeric in-house project experience and data extracted from projects of a similar nature that are applicable to this CarbonSAFE project.

Summary

This Topical Report provides a high-level summary of the Trimeric evaluation of CO_2 compression and dehydration capital and operating costs for the ISGS East Basin CarbonSAFE Phase I project, which will utilize CO_2 produced as a byproduct from the Quasar Syngas ammonia production facility for injection. Assumed CO_2 conditions from the facility are assumed as follows:

- Flowrate: 1.6 million tonnes per year (MTPY)
- Pressure: 1 psig
- Temperature: 120 °F
- Purity: 99.6 mol. % CO_2 (balance water)

Trimeric completed the following tasks as part of this analysis:

1. Created a simulation to model the processes required to compress and dehydrate CO_2 evolved from a Rectisol® CO_2 capture system to typical pipeline pressure of 2,200 psig
2. Estimated purchased equipment costs for CO_2 compression using the power requirements estimated in step 1 and a budgetary quotation provided by MAN Turbo for this facility in February 2017 for an integrally geared centrifugal compressor at similar inlet and outlet conditions
3. Estimated purchased equipment costs for CO_2 dehydration using in-house cost data from prior CO_2 dehydration projects
4. Estimated fixed capital investment for CO_2 compression and dehydration equipment using typical Lang factors used to scale up purchased equipment costs to estimate total facility costs on past projects
5. Estimated fixed and variable annual operating costs using rules of thumb published in literature and used in prior projects

Results associated with these five tasks are summarized below.

Process Simulation

Trimeric assumed the following inlet conditions and outlet product requirements listed in Table 1 below:

Table 1 – CO_2 Inlet and Outlet Conditions

Property	Units	Inlet	Outlet
Flowrate	MMscfd (MTPY)	83 (1.6)	
Temperature	°F	≤ 120	≤ 120
Pressure	psig	1	2,000
Concentration	mol. %	99.6%	

A budgetary quotation was received from MAN Turbo for the Quasar Syngas application assuming an inlet pressure of 20 psig as opposed to 1 psig; MAN Turbo recommended a six-stage integrally geared centrifugal compressor for this application. Trimeric created an independent process simulation in VMGSim, assuming 86% polytropic efficiency and 97% mechanical efficiency for each stage, and used this simulation to verify the power requirement of 14 MW (14,000 kW) estimated by MAN Turbo.

Discharge pressures and power requirements per stage are summarized in Table 2 below; note that the Stage 1 suction pressure is 20 psig (34.7 psia). Assuming 86% polytropic efficiency and 97% mechanical efficiency across all stages, the required compressor power is 13,943 kW. Assuming 10% overdesign, the estimated nameplate capacity of the machine is 15,300 kW.

Table 2 – Discharge Pressure and Power Requirements for Compressor by Stage

Stage	Discharge Pressure (psia)	Power Required (kW)
Stage 1	68	2,540
Stage 2	134	2,628
Stage 3	264	2,500
Stage 4	520	2,365
Stage 5	1,024	2,739
Stage 6	2,017	1,172
Total Power Required		13,943
Estimated Nameplate Capacity		**15,300**

In order to estimate the power requirements to compress the CO_2 from 1 psig to 2,000 psig, Trimeric modified the process simulation to add an additional stage of compression to compress the CO_2 from 1 psig to 20 psig. The power requirements for this stage, assuming 86% polytropic efficiency and 97% mechanical efficiency, are 3,486 kW. This increases the total power requirements to 17,429 kW; assuming 10% overdesign, the estimated nameplate capacity for this machine would be 19,200 kW.

Compression Purchased Equipment Costs

The MAN Turbo quotation for the six-stage machine that compresses CO_2 from 20 psig to 2,000 psig was approximately $9.3 MM USD, or $670/kW of power required. Assuming a nameplate capacity of 19,200 kW with the increased power requirements to compress CO_2 from 1 psig to 2,000 psig, Trimeric estimates that that purchased equipment costs for the larger compressor would be $12.9 MM USD.

Trimeric used this single estimate for purchased equipment costs because the original MAN Turbo quotation was specific to this site and application, and only required an adjustment to the power requirements for the lower suction pressure of 1 psig.

However, Trimeric validated the standalone purchased equipment cost estimate for compression equipment using a combination of publicly available references and in-house data from commercial projects. Table 3 summarizes the data from the following cost sources that Trimeric reviewed for the purposes of validating the estimate:

- Source 1: Two vendor quotations for in-line centrifugal compressors for full-scale CO_2 compression applications
- Source 2: Two DOE/NETL CO_2 Capture Cost and Performance Baseline studies for CO_2 centrifugal compression from amine post-combustion capture technologies, and an internal techno-economic analysis for an amine post-combustion capture application that was adapted from the published DOE/NETL Baseline studies
- Source 3: Two vendor quotations for centrifugal compressors (one integrally geared and one in-line) for full-scale CO_2 compression applications

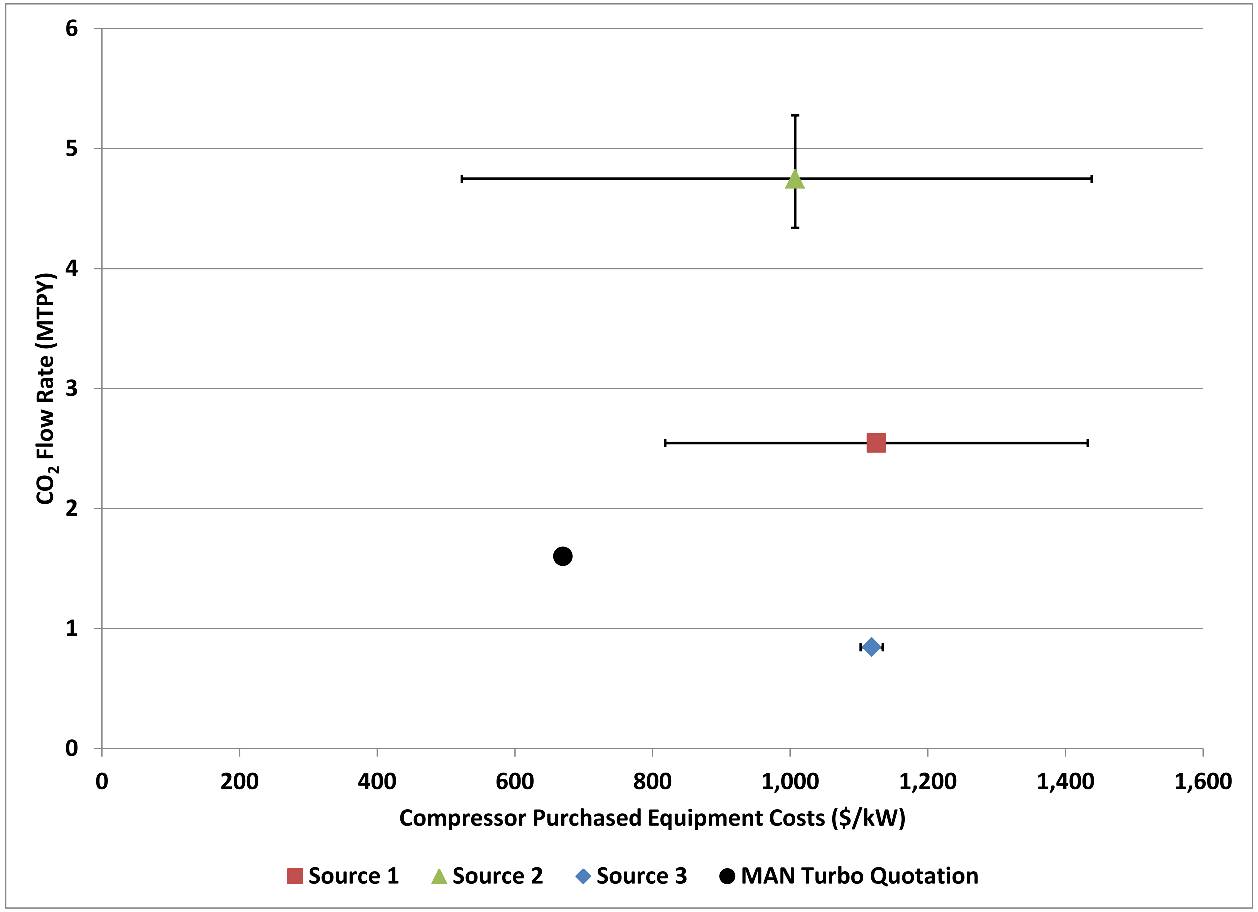
Table 3 – Normalized Purchased Equipment Cost Data for High Capacity CO_2 Compressors

		CO_2 Capacity (MTPY)			PEC ($/kW)		
	Number of Data Points	Low	High	Average	Low	High	Average
Source 1	2	2.55	2.55	2.55	795	1,392	1,094
Source 2	3	4.34	5.28	4.74	535	1,470	1,030
Source 3	2			0.84	1,102	1,135	1,119
MAN Turbo Quotation				*1.6*			*670*

Table 3 provides a range of CO_2 capacities, and normalized purchased equipment costs in dollars per kilowatt of power required; all costs are reported in December 2017 dollars. These three sources are all within the same approximate range with each other on an average $/kW purchased equipment cost basis, despite their differences in CO_2 design flow rate. Please note that the MAN Turbo quotation specific to this application is on the low end of these ranges.

The relationship between CO_2 capacity and normalized purchased equipment costs is illustrated in Figure 1 below. The horizontal bars illustrate the minimum and maximum normalized purchased equipment cost for each data set, while the vertical bar for Source 2 displays the minimum and maximum CO_2 capacity for that data set. The symbols illustrate the average CO_2 throughput and average normalized purchased equipment cost for each data set.

Figure 1 – Relationship of Large CO_2 Compressor Capacity and Normalized Purchased Equipment Costs



Other factors that influence purchased equipment costs such as materials of construction are not considered within this high-level analysis.

Dehydration Purchased Equipment Costs

Trimeric developed a cost curve for CO_2 dehydration using cost information from past capital projects as a function of CO_2 throughput. These projects all used triethylene glycol dehydration systems, which are very common in this application and will be assumed as the initial baseline technology for this application. Using this internally developed cost curve, Trimeric estimated that the purchased equipment costs to dehydrate 1.6 MTPY (83 MMscfd) would be $1.8 MM. When combined with costs for compression, the total estimated purchased equipment cost for CO_2 compression and dehydration is $14.7 MM.

Fixed Capital Investment

The purchased equipment costs for the compression and dehydration unit operations are multiplied by a factor of 3 to estimate the Fixed Capital Investment (FCI) or total facility costs. In addition to the purchased equipment costs, this factor accounts for other costs including equipment installation, instrumentation and controls, piping, electrical, engineering, construction expenses, contractors' fees, and process and project contingencies. A multiplier of 3 times the purchased equipment costs is typically used to estimate the FCI for a mix of vendor-provided skid-mounted equipment, on-site assembly, and field fabrication of interconnecting piping; for packaged vendor equipment, this factor can be as low as 2. For the purposes of this factored estimate, Trimeric selected a factor of 3 to estimate the FCI at $44.0 MM.

Variable and Fixed Operating Costs

Operating cost information is summarized in Table 4 below. Operating costs are separated into two categories: variable costs and fixed costs.

A capacity utilization factor of 95% is assumed for the variable costs, which for the purposes of this study are assumed to be power requirements for compression, and dehydration operating costs (natural gas for the reboiler and glycol makeup). The capacity utilization factor takes into account both the on-stream factor, which is the total percentage of time the facility is operating, and the capacity factor, which is the average percentage of the production rate compared with the design production rate. The annual electricity cost is estimated based on an assumed electricity cost of $0.0712/kWh, which is the average price of electricity for industrial consumers for Indiana in March 2018 as published by the United States Energy Information Administration.

The fixed costs include an estimate of the number of operators required to run the facility and an estimate of the supervisor labor (assumed to be 20% of the operating labor costs). Trimeric assumed a team of four operators supported by one supervisor can provide essentially 24-hr per day coverage. Trimeric used the average hourly wage for Chemical Plant and System Operators for Indiana in May 2017 according to the U.S. Bureau of Labor Statistics. This value was $ 27.49 / hr for May 2017. Using a guideline in the American Institute of Chemical Engineers (AIChE) course entitled "Practical Project Evaluation", Trimeric estimated direct labor costs using the following equation:

$$\left(\frac{8\ hours}{shift}\right) * \left(\frac{21\ shifts}{week}\right) * \left(\frac{52\ weeks}{year}\right) * (1.20\ for\ overtime) * \left(\frac{\$\ 27.49}{hour}\right) + \left(\frac{40\ hours}{week}\right) * \left(\frac{3\ weeks\ vacation}{operator - year}\right) * (4\ operators) * \left(\frac{\$\ 27.49}{hour}\right) = \$301{,}000$$

Maintenance expenses are estimated at $53.62/kW-yr ($40/hp-yr) based on past experience with large CO_2 compressor facilities. The plant operating overhead is assumed to be 75% of the operating and supervisor cost (typical factor). The fixed costs do not include the capacity utilization factor. Total operating costs are estimated to be $12.7 MM annually, with a majority of these costs attributable to electricity requirements for compression.

Table 4 – Summary of Estimated Annual Operating Costs

Variable Costs		
Capacity Utilization Factor	%	95
Electricity Usage	kW	17,429
Electricity Cost	$/kW-hr	0.0712
Annual Electricity Cost	$/yr	10,327,000
Annual Dehydration Costs	$/yr	855,000
Total Variable Operating Costs	*$/yr*	*11,182,000*
Fixed Costs		
Operating Labor	FTE	4
Cost of Labor	$/hr	27.49
Operating Labor Cost	$/yr	301,000
Supervisor Labor	% of op labor	20
Supervisor Labor Cost		60,000
Compressor Maintenance Cost Factor	$/kW-yr	53.62
Annual Compressor Maintenance Cost	$/yr	935,000
Plant Operating Overhead	% of total labor	75
Plant Operating Overhead Cost	$/yr	271,000
Total Fixed Operating Costs	*$/yr*	*1,567,000*
Total Operating Costs	***$/yr***	***12,749,000***

Summary

This memo provides a screening level estimate of capital and operating costs for CO_2 compression and dehydration for the ISGS East Basin CarbonSAFE Phase I project. Purchased equipment costs were estimated at $14.7 MM. Fixed Capital Investment or total facility costs were estimated at $44.0 MM. Annual operating costs were estimated at $12.7 MM.

These estimates, while preliminary, are grounded with a good deal of actual Trimeric in-house project experience and data. They would likely serve as a good starting point that could be refined in a more detailed evaluation as the project moves forward.