

Front-End Engineering Design Study for a Carbon Capture Plant Retrofit to a Natural Gas-Fired Gas Turbine Combined Cycle Power Plant

primary project goal

Bechtel National, Inc. has performed a comprehensive front-end engineering design (FEED) study for a carbon capture and compression plant retrofit to an existing natural gas-fired combined cycle (NGCC) power plant located in Texas. The capture plant is based on conventional technology comprising a non-proprietary aqueous solvent, monoethanolamine (MEA), an absorber-stripper cycle, and multi-stage centrifugal compressors.

technical goals

- Developed a project design basis to provide general project requirements that apply to the specific plant site, ambient conditions, fuel feedstock and flue gas characteristics, environmental requirements, and modularization design requirements.
- Developed process engineering documents for constructing the carbon capture system, including block flow diagrams, heat and mass balance diagrams, process flow diagrams for major components, piping and instrumentation diagrams, and a water balance diagram.
- Conducted a preliminary hazard and operability (HAZOP) study and produced a report to document the results.
- Developed civil, structural, mechanical, electrical, and control systems engineering design packages.
- Developed a layout and design package that includes process plant arrangement drawings and piping and instrumentation diagrams.
- Summarized expected emissions and waste streams.
- Reviewed various contracting and purchasing options for procuring a new process system and performed a constructability review to identify construction access, lay-down areas, and sequencing of construction work.
- Developed an overall project capital cost estimate within a $\pm 15\%$ accuracy.
- Prepared a final FEED study package that is available for public use.

technical content

Bechtel executed a FEED study on retrofitting an existing NGCC power plant with an amine-based post-combustion carbon capture plant. The prospective end use for the captured carbon dioxide (CO₂) is enhanced oil recovery (EOR). Bechtel has developed a technology readiness level (TRL) 9 carbon capture, utilization, and storage (CCUS) concept for retrofitting an existing NGCC with mature and field-proven technology and equipment. Figure 1 illustrates a simplified process flow diagram of a conventional absorber-stripper scrubbing system with a non-proprietary solvent such as MEA.

program area:

Point Source Carbon Capture

ending scale:

FEED

application:

Post-Combustion Power Generation PSC

key technology:

Solvents

project focus:

Amine-Based Solvent Technology Retrofit to NGCC Plant

participant:

Bechtel National, Inc.

project number:

FE0031848

predecessor projects:

N/A

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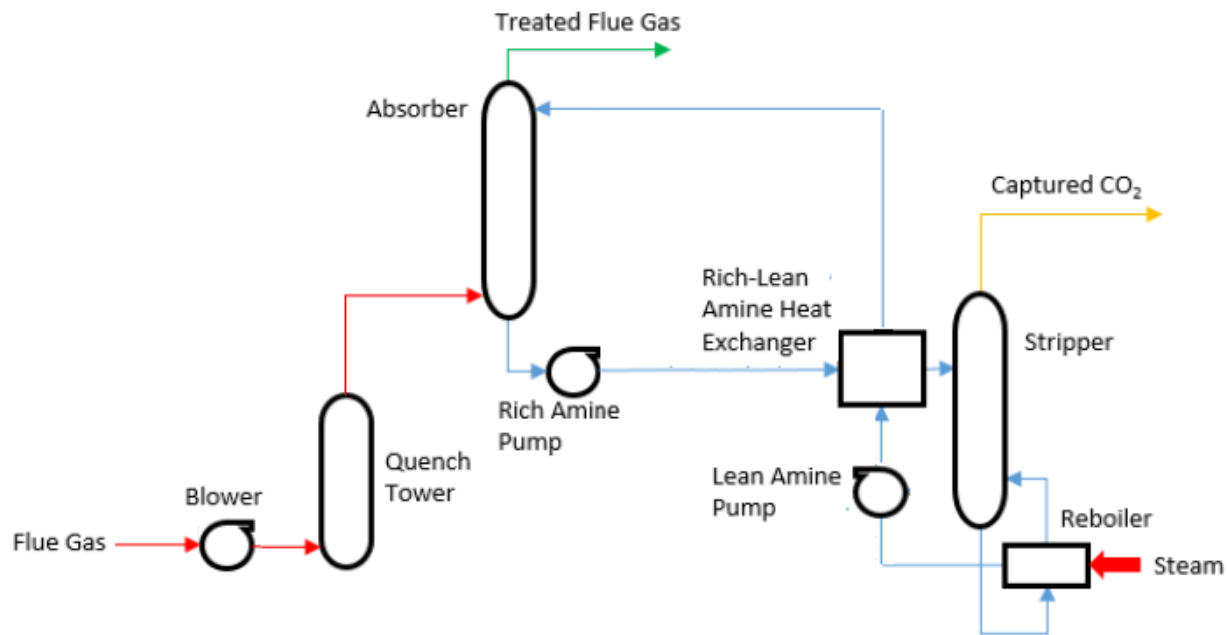


Figure 1: Generic simplified flowsheet for amine-based CO₂ capture from flue gas.

Bechtel has applied an “open access” and “open technology” methodology to the process and physical design of the facilities and the solvent used in the technology. An “open access” technology approach denotes that the owner/operators of a post-combustion carbon capture plant are in full control of the technology used in the plant. The post-combustion carbon capture hardware can be procured by competitive tendering against a non-proprietary specification, similar to conventional power plants. This allows the owner/operators to specify the post-combustion carbon capture plant hardware and solvent selection based on the latest published technology and operating experience. “Open access” technology utilizes a generic, non-proprietary solvent that is readily purchased on the open market from chemical manufacturers at a relatively low cost. These features facilitate lower capital and operating expenses and avoid royalty payments and technical restrictions associated with the use of proprietary system designs and solvent selection.

The host site selected for the FEED study is the Sherman Generating Station, a 2x2x1 NGCC located in Sherman, Texas. The 758-megawatt-electric (MWe) power plant built by Bechtel is powered by two Siemens F class gas turbines. The selection of the site has several advantages, including:

- The NGCC plant was built by Bechtel; therefore, key project personnel have access to all design documents and are familiar with the facility.
- The plant includes F class gas turbines, a state-of-the-art technology.
- The location of the host plant is near oil-bearing formations favorable for EOR operation.

Lessons learned and experience gained from earlier FEED and FEED verification studies performed by Bechtel were used as a basis for this FEED study. Bechtel prepared a FEED verification in 2015 under the direction of Shell for a proposed carbon capture retrofit to gas turbine Unit 13 at the Peterhead Power Station in Scotland. In 2009, Bechtel performed a FEED study for a CO₂ capture and compression facility designed to capture 85% of the CO₂ emissions from a 420-MWe gas-fired power plant in Norway. Both a proprietary solvent and MEA were used as bases of design. The plants involved in both FEED studies employ Siemens gas turbines, similar to the gas turbines in the Sherman facility; thus, much of the engineering work has already been completed by Bechtel for flue gas conditions very similar to the host site in Texas. Bechtel's FEED report is based on these past design reports.

The major deliverable of this completed FEED study is a design package that includes the following topic areas: flue gas blower and quench, CO₂ absorption, semi-lean amine system, CO₂ stripping and heat integration, CO₂ compression and drying, CO₂ pumping and dense phase transfer, amine reclaiming, and amine storage. It was found in this case study that the baseline CO₂ capture cost is \$114.50/tCO₂ (when including both annualized capital and annual operations/maintenance), that the energy penalty on the powerplant is 67.3 MW, that the average forgone electricity

revenue is equivalent to \$13/tCO₂ captured, and that a pilot testing program should be used to resolve design uncertainties (such as amine degradation rates).

TABLE 1: SOLVENT PROCESS PARAMETERS

Pure Solvent	Units	Design Value
Molecular Weight	mol ⁻¹	61.08
Normal Boiling Point	°C	170
Normal Freezing Point	°C	10.3
Vapor Pressure @ 15°C	bar	<1
Manufacturing Cost for Solvent	\$/kg	1 – 2
Working Solution		
Concentration	kg/kg	35
Specific Gravity (15°C/15°C)	—	1.02
Specific Heat Capacity @ STP	kJ/kg-K	3.6
Viscosity @ STP	cP	4
Absorption		
Pressure	bar	1.089
Temperature	°C	53.5
Equilibrium CO ₂ Loading	mol/mol	0.4 – 0.49
Heat of Absorption	kJ/mol CO ₂	TBD
Solution Viscosity	cP	2.56
Desorption		
Pressure	bar	2.31
Temperature	°C	130.8
Equilibrium CO ₂ Loading	mol/mol	0.22 – 0.25
Heat of Desorption	kJ/mol CO ₂	TBD
Module Design		
Flue Gas Flowrate	kg/hr	2.53 x 10 ⁶
CO ₂ Recovery, Purity, and Pressure	% / % / bar	80-90 / 99.0+ / 200
Absorber Pressure Drop	bar	0.076
Estimated Absorber/Stripper Cost of Manufacturing and Installation	$\frac{\$}{\text{kg/hr}}$	TBD

Definitions:

STP – Standard temperature and pressure (15°C, 1 atmosphere [atm]).

Pure Solvent – Chemical agent(s), working alone or as a component of a working solution, responsible for enhanced CO₂ absorption (e.g., MEA in an aqueous solution).

Manufacturing Cost for Solvent – “Current” is market price of chemical, if applicable; “Target” is estimated manufacturing cost for new solvents, or the estimated cost of bulk manufacturing for existing solvents.

Working Solution – The solute-free (i.e., CO₂-free) liquid solution used as the working solvent in the absorption/desorption process (e.g., the liquid mixture of MEA and water).

Absorption – The conditions of interest for absorption are those that prevail at maximum solvent loading, which typically occurs at the bottom of the absorption column. These may be assumed to be 1 atm total flue gas pressure (corresponding to a CO₂ partial pressure of 0.038 bar) and 40°C; however, measured data at other conditions are preferable to estimated data.

Desorption – The conditions of interest for desorption are those that prevail at minimum solvent loading, which typically occurs at the bottom of the desorption column. Operating pressure and temperature for the desorber/stripper are process-dependent (e.g., an MEA-based absorption system has a typical CO₂ partial pressure of 1.8 bar and a reboiler temperature of 120°C). Measured data at other conditions are preferable to estimated data.

Pressure – The pressure of CO₂ in equilibrium with the solution. If the vapor phase is pure CO₂, this is the total pressure; if it is a mixture of gases, this is the partial pressure of CO₂. Note that for a typical natural gas fired combined cycle power plant, the total pressure of the flue gas is about 1 atm and the concentration of CO₂ is about 3.82 %. Therefore, the partial pressure of CO₂ is roughly 0.0382 atm or 0.0387 bar.

Concentration – Mass fraction of pure solvent in working solution.

Loading – The basis for CO₂ loadings is moles of pure solvent.

Estimated Cost – Basis is kg/hr of CO₂ in CO₂-rich product gas; assuming targets are met.

Flue Gas Assumptions – Unless noted, flue gas pressure, temperature, and composition leaving the heat recovery steam generator (HRSG) unit (wet basis) should be assumed as:

Pressure	Temperature	Composition						
				vol%			ppmv	
psia	°F	CO ₂	H ₂ O	N ₂	O ₂	Ar	SO _x	NO _x
14.5	194	3.82	7.74	74.78	12.81	0.85	-	2

Parameter Descriptions:

Flue Gas Pretreatment Requirements – Flue gas is cooled to approximately 50°C before entering absorber towers through a fogging system that reduces temperature and saturates flue gas with water.

Solvent Makeup Requirements – Detailed in the FEED report.

Chemical/Physical Solvent Mechanism – The chemical/physical solvent mechanism is primarily controlled by the solubility and alkalinity characteristics of the amine. MEA is fully water soluble and exhibits high alkalinity. MEA's low molecular weight permits higher solution capacity and its low boiling point allows higher recovery during reclamation of contaminated solution. Carbon dioxide solubility in MEA solutions is relatively high. Regeneration of MEA solutions is accomplished at reasonable temperatures with moderate heat input. Further discussion is included in the FEED report.

Solvent Contaminant Resistance – Detailed in the FEED report.

Solvent Foaming Tendency – Detailed in the FEED report.

Waste Streams Generated – MEA and ammonia emissions from the absorber are reasonable and are defined in the FEED report. Liquid and solid wastes from solvent maintenance and reclaiming is defined in the FEED report.

Process Design Concept – The process overview under normal operation consists of the following systems:

- Flue gas diversion—The flue gas is directed from the existing stack to the plant.
- Flue gas cooling—The flue gas as supplied is too hot to process efficiently in the absorber and is cooled to its saturation temperature before entering the absorber.
- CO₂ absorption—Parallel absorbers use an amine solution to remove the CO₂ from the flue gas.
- Heat integration—Heat is recovered from internal streams to enhance plant energy efficiency.
- CO₂ stripping—The amine is regenerated for reuse by liberating the CO₂ from the amine solution.
- CO₂ compression and drying—The CO₂ is compressed, dried, further compressed, and liquefied to meet the CO₂ specifications.
- Amine reclamation—Heat stable salts (HSS) and degradation/oxidation products are removed from the amine solution.
- Amine storage—Fresh amine and lean amine are stored and injected into the absorption system to maintain the amine solution concentration.

Proposed Module Design – Detailed in the FEED report.

TABLE 2: POWER PLANT CARBON CAPTURE ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Carbon Captured	\$/tonne CO ₂	114.50	114.50
Cost of Carbon Avoided	\$/tonne CO ₂	136.50	136.50
Capital Expenditures	\$/MWhr	32.43	32.43
Operating Expenditures	\$/MWhr	11.50	11.50
Cost of Electricity	\$/MWhr	63.93	63.93 ¹

Definitions:

Cost of Carbon Captured – Projected cost of capture per mass of CO₂ captured under expected operating conditions

Cost of Carbon Avoided – Projected cost of capture per mass of CO₂ avoided under expected operating conditions

Capital Expenditures – Projected capital expenditures in dollars per unit of energy produced

Operating Expenditures – Projected operating expenditures in dollars per unit of energy produced

Cost of Electricity – Projected cost of electricity per unit of energy produced under expected operating conditions

Calculations Basis – Data are based on Panda Power’s Sherman Natural Gas-Fired Combined Cycle Power Plant located in Texas.

Scale of Validation of Technology Used in TEA:

- This study used the ProMax® process simulation software to develop the mass and energy balances for the design energy case. The Carbon Capture Simulation Initiative (CCSI) Toolset (by the National Energy Technology Laboratory [NETL]) was also applied to compare results using the ASPEN Plus simulation package. Results from the two modelling tools were evaluated to identify uncertainties. Because of those modelling uncertainties, pilot plant testing was recommended before proceeding to full-scale plant design.
- Costs were based on actual costs from quotes for full-scale facility and costs for construction.
- MEA has been extensively piloted at the National Carbon Capture Center (NCCC) in Alabama and at Test Center Mongstad in Norway.

Qualifying Information or Assumptions:

- Capital cost estimate based on worldwide sourcing.
- Costs are specific to the Sherman, Texas, site.
- Estimate includes builders risk insurance and general liability.
- Operating hours per year: 5,000.
- Level of operation: 420 MW equivalent.
- Average value of reduced electricity sales to the Electric Reliability Council of Texas (ERCOT): \$25/MWhr.
- Electricity sales reduction: 67.3 MW.

technology advantages

- Use of generic solvent avoids restrictions and costs associated with proprietary solvents.
- An “open access” and “open technology” approach can accelerate CCUS deployment and reduce the costs of CCUS by facilitating efficient know-how exchange and competition within the fleet of plants that may be built over the next five to 10 years.

¹ Assumed cost of electricity is \$20.00 per MWh without carbon capture.

- “Open access” and “open technology” full-scale plants can facilitate the progression of post-combustion capture systems currently at TRL 9 to achieve a commercial readiness index of 6 within 10 years or less.
- Bechtel has extensive experience in carbon capture studies, plus detailed design, construction, and operation of NGCC power plants and CO₂ capture plants, including involvement in several previous FEED studies on CO₂ capture retrofits to NGCC plants.

R&D challenges

- Steam extraction complexity.
- Confirmation of carbon capture simulation software accuracy for generic amine solutions at high solvent strengths.

status

The project team has developed final engineering documents that include block flow diagrams, process flow diagrams, heat and mass balances, water balance diagrams, piping and instrument diagrams, and summary equipment specifications. Engineering design packages were prepared for civil, structural, mechanical, electrical, automation, and environmental systems.

available reports/technical papers/presentations

“Front-End Engineering Design (FEED) Study for a Carbon Capture Plant Retrofit to a Natural Gas-Fired Turbine Combined Cycle Power Plant (2x2x1 Duct-Fired 758-MWe Facility with F Class Turbines),” DOE Kick-off Meeting, November 15, 2019. [https://www.netl.doe.gov/projects/plp-download.aspx?id=10905&filename=Front-End+Engineering+Design+\(FEED\)+Study+for+a+Carbon+Capture+Plant+Retrofit+to+a+Natural+Gas-Fired+Gas+Turbine+Combined+Cycle+Power+Plant.pdf](https://www.netl.doe.gov/projects/plp-download.aspx?id=10905&filename=Front-End+Engineering+Design+(FEED)+Study+for+a+Carbon+Capture+Plant+Retrofit+to+a+Natural+Gas-Fired+Gas+Turbine+Combined+Cycle+Power+Plant.pdf).

“Front-End Engineering Design (FEED) Study for a Carbon Capture Plant Retrofit to a Natural Gas-Fired Turbine Combined Cycle Power Plant (2x2x1 Duct-Fired 758-MWe Facility with F Class Turbines),” NETL Project Review Meeting – CCUS Integrated Projects, August 18, 2020. https://netl.doe.gov/sites/default/files/netl-file/20CCUS_Elliott.pdf.

“Front-End Engineering Design (FEED) Study for a Carbon Capture Plant Retrofit to a Natural Gas-Fired Turbine Combined Cycle Power Plant (2x2x1 Duct-Fired 758-MWe Facility with F Class Turbines),” Final Project Presentation, June 17, 2021. [https://www.netl.doe.gov/projects/plp-download.aspx?id=10904&filename=Front-end+Engineering+Design+\(FEED\)+Study+for+a+Carbon+Capture+Plant+Retrofit+to+a+Natural+Gas-fired+Gas+Turbine+Combined+Cycle+Power+Plant+.pdf](https://www.netl.doe.gov/projects/plp-download.aspx?id=10904&filename=Front-end+Engineering+Design+(FEED)+Study+for+a+Carbon+Capture+Plant+Retrofit+to+a+Natural+Gas-fired+Gas+Turbine+Combined+Cycle+Power+Plant+.pdf).