SUSTAINABLE ENERGY CONSULTING

CARBON CAPTURE, UTILIZATION, & STORAGE (CCUS) VALUE CHAIN

MAY 12, 2022

Risk Assessment   Feasibility Studies   Economic Due Diligence   United Nations Classification Framework

Utilization and Sequestration   Authenticate Greenhouse Gas Assertions   Surface and Sub-Surface Integration

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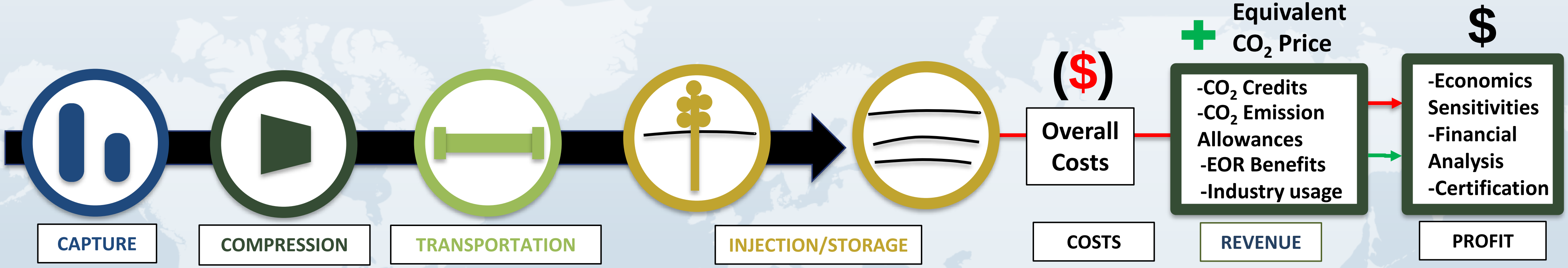
VALUE CHAIN TO COMMERCIALITY



Surface

Carbon production, capture, transportation, and injection facilities:

- Capture Configuration and Technology
- Compression & Transportation design
- Injection well design for handling CO_2

Sub-Surface

- Capacity, containment, and injectivity for CO_2 storage reservoirs.
- Integrated EOR modeling and studies generate optimized development plans.

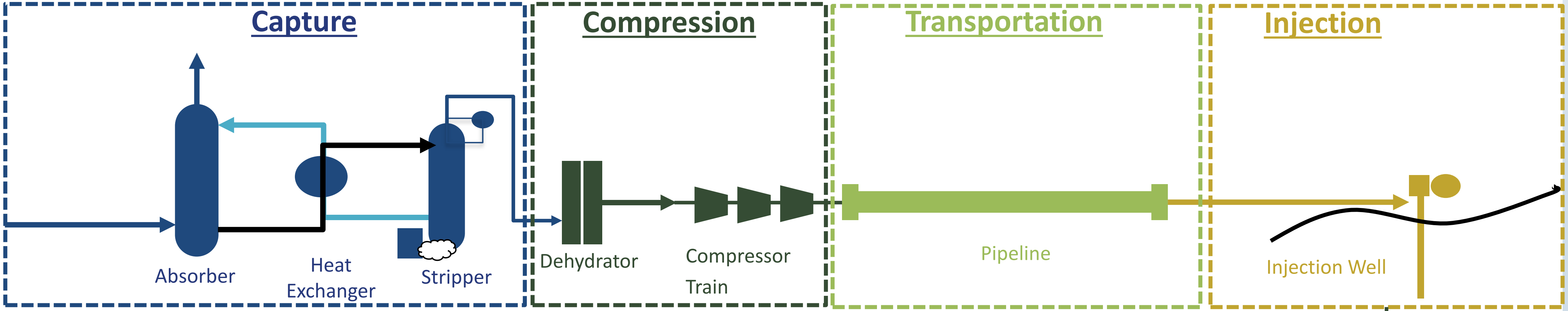
Commercial

- Carbon and climate policies and regulations from capture to point of sale or reservoir to determine the economic benefit such as cost/ revenue sensitivities.
- Certification of CO_2 reserves and EOR projects (SPE-SRMS)

*CCS & CCUS is interchangeably used wherein CCS is Carbon Capture and Storage/Sequestration and CCUS – Carbon Capture, Use/Utilization, and Storage/Sequestration

POWER PLANT CCS PROJECT ECONOMICS

Specifications: Post-combustion carbon capture from a coal power plant; Capturing 1.4 MTPA from 240 MW boiler; 82 mile pipeline, 12” diameter, CO_2 transported in supercritical state; Injection for EOR



- CO_2 injected for EOR – much of the CO_2 will remain in the reservoir as a result
- Economics driven by:
  - Oil price: At what price does incremental oil recovery generated by miscible CO_2 injection justify cost to build/operate facility?
  - 45Q Tax Credit: Generates tax offset varying depending on end-use of CO_2

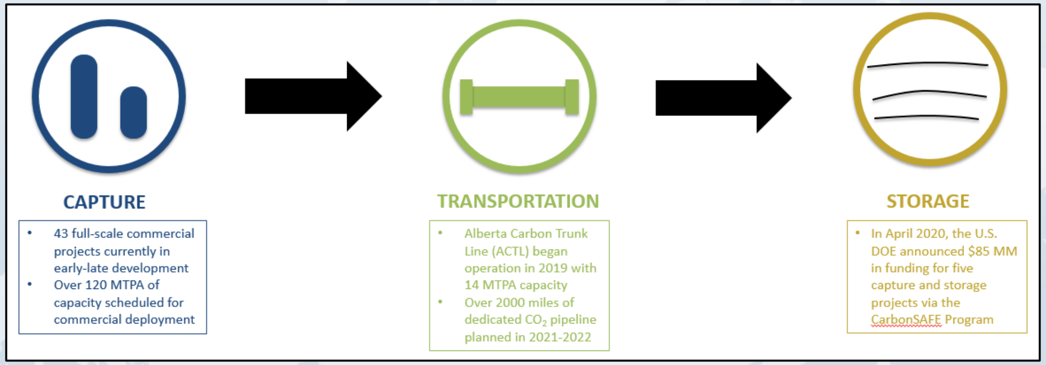
ANALYZING RAPID MARKET GROWTH

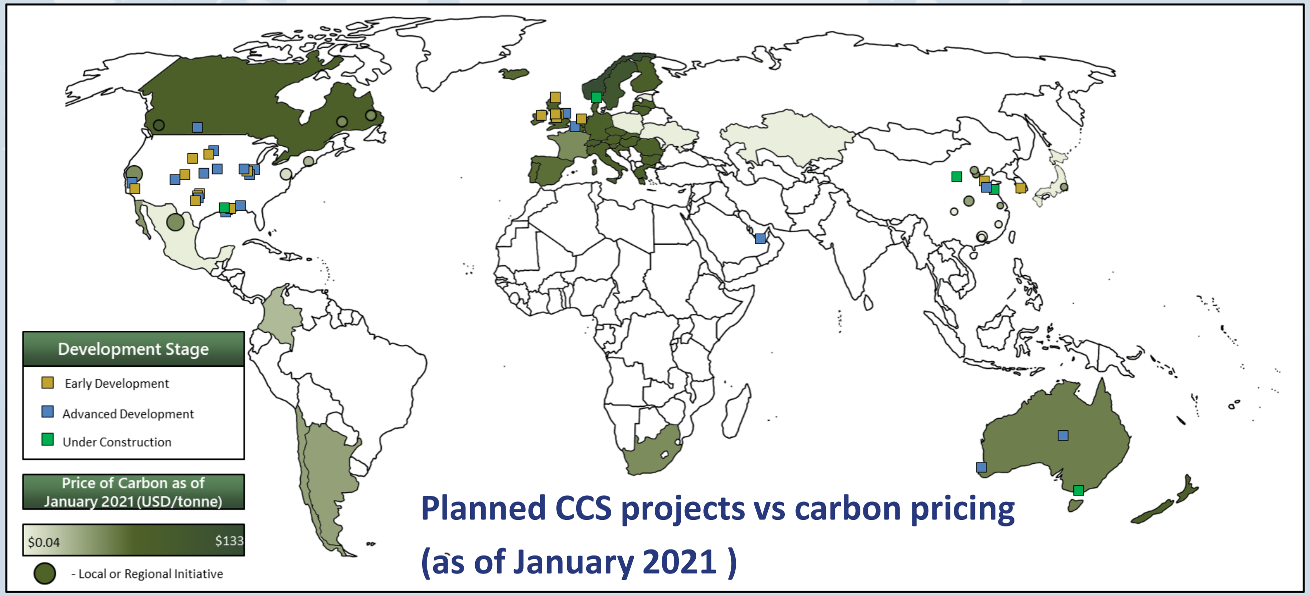
Intergovernmental Panel on Climate Change (IPCC) set a goal of limiting global temperature increase to 1.5 °C in 2015

5,635 MTPA Carbon Capture required by 2050 estimated by Global CCS versus 111 MTPA deployed today

- Majority in U.S., Northern Europe, and China
- Carbon pricing is generally uncertain across projects and is tied to geography
- US Projects in advanced development due to carbon incentive speculation and 45Q
- Projects in Europe generally are in early development

Project Growth Across the Value Chain





Planned CCS projects vs carbon pricing (as of January 2021)

DE-MYSTIFYING CARBON CAPTURE

<u>Capture **Configuration**</u> location of CO_2 capture in the stream flow and general type of equipment

<u>Capture **Technology**</u> process technology used to separate CO_2 from other components to generate a pure CO_2 stream

- Combustion (Post & Pre) configuration dominates while Absorption technology is less risky and most deployed
- Post-combustion capture is almost exclusively used with absorption technology, while pre-combustion capture typically uses adsorption, but can use absorption as well.

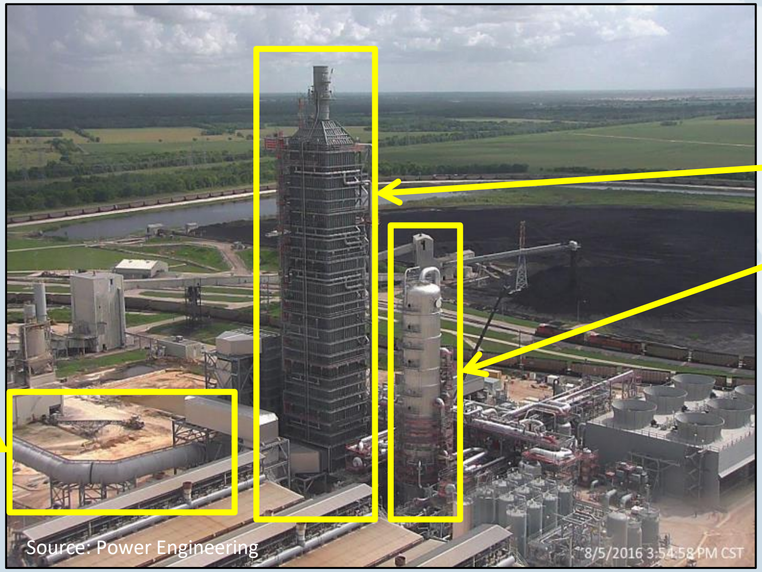
Example: Petra Nova CCS, TX

Configuration:

Post-Combustion

CO_2 captured after combustion occurs from coal-fired power plant

Flue gas stream from power plant exhaust



Technology:

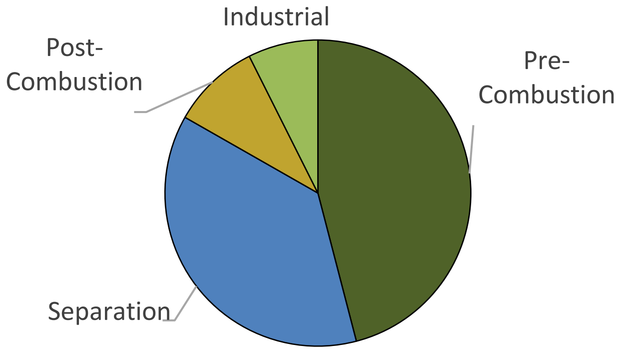
Absorption

Absorber Column

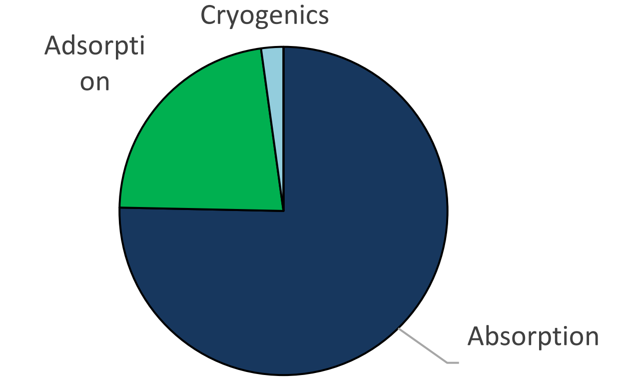
Stripper Column

Absorber and stripper used as component of absorption technology

Capture Configuration



Capture Technology



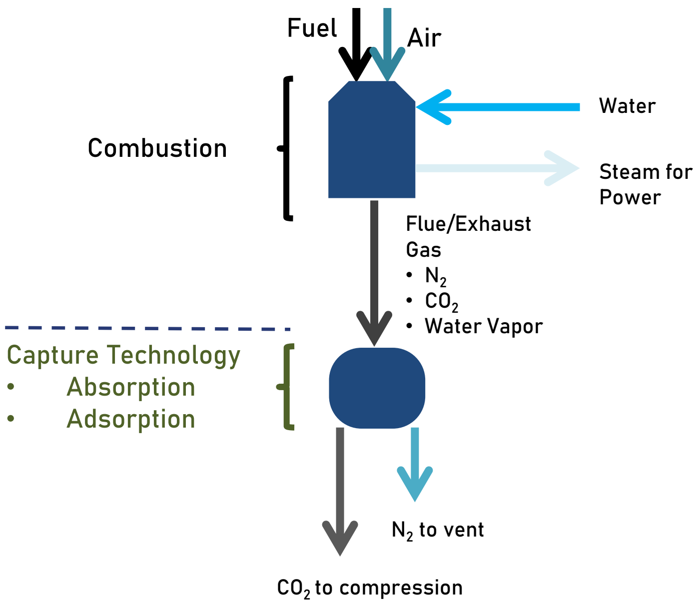
Currently Deployed CCS Projects

ASSESSING CAPTURE CONFIGURATIONS

Post-Combustion Capture

Sources:

- Power Generation
- Gas Processing
- Iron/Steel Production
- Refineries
- Cement Production



Pre-Combustion Capture

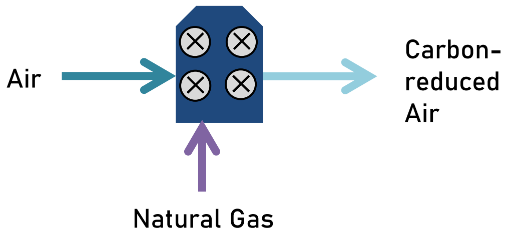
Sources:

- Hydrogen Production
  - Refining
  - Ammonia Production
  - Fertilizers
  - Petrochemicals
- Power Generation

Direct Air Capture

Sources:

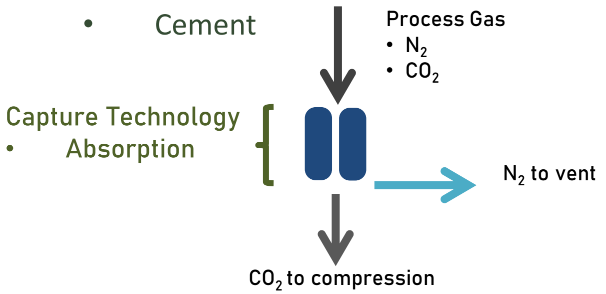
- Atmospheric Air



Industrial Capture

Source:

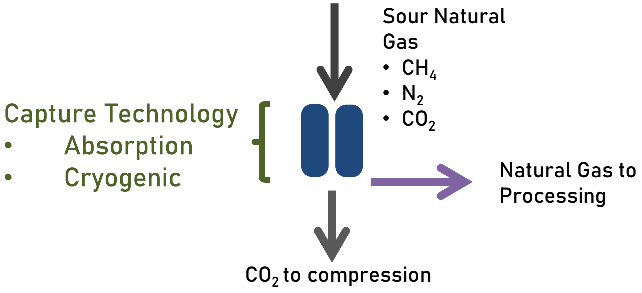
- Steel Production
- Cement



Separation

Sources:

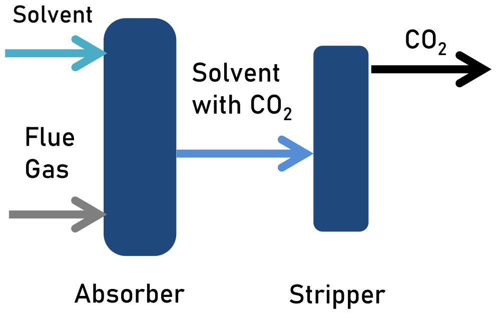
- Natural Gas Processing



APPLYING CAPTURE TECHNOLOGIES

Absorption

Most deployed technology



Latest advancements have focused on:

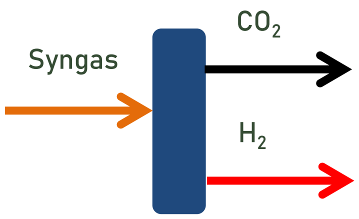
- Optimizing solvent or process
- Refrigerated Ammonia solvent
- CaO looping

Adsorption Example: Vacuum Swing Adsorption at Air Products' Port Arthur SMR

1. SMR reforms natural gas to produce syngas (carbon monoxide and hydrogen gas)
2. Water-gas shift reactor used CO and H_2O to produce more H_2 and CO_2
3. Vacuum Swing Adsorption separates CO_2 and H_2
4. CO_2 gas is dehydrated and compressed

Adsorption

Used in applications where hydrogen or syngas is needed



- Latest advancements have focused on improving the sorbent or catalyst
- Used in fertilizer plants, refineries

Membrane Separation

- Selective membrane only lets certain gas species across
- High pressures required
- Advancements focusing on improving membrane material

Cryogenic Separation

- Physical process reduces temperature to separate CO_2
- Not commercially mature – low temperatures require high amounts of energy

CO_2 FLUID CHARACTERISTICS

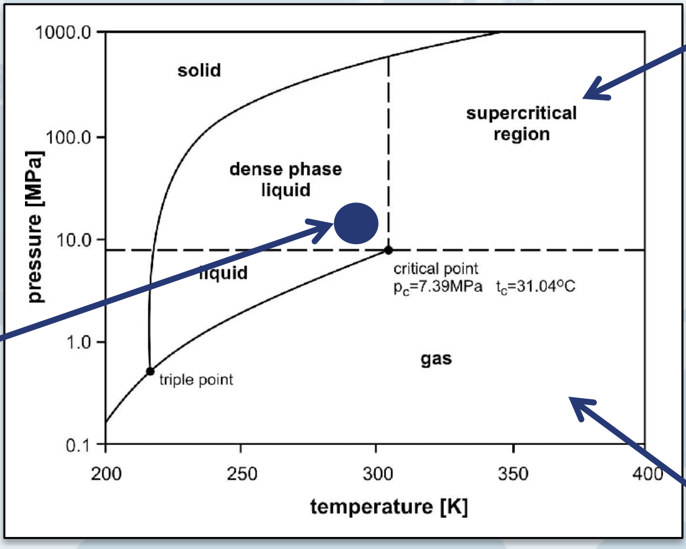
Depending on the technical and commercial requirements of project, CO_2 may be transported in different physical states.

Dense Phase

- The dense phase has a viscosity similar to gas but a density similar to liquids
- Typical CO_2 transportation is performed at 10 – 15 MPa and 15 – 30 °C to maintain dense phase

Example:

Abu Dhabi CCS Phase 1



<u>CO_2 phase diagram</u>

Supercritical Phase

- The supercritical phase is similar to dense phase, but is neither a liquid nor a gas
- Higher pressure drops over the same distance when compared to dense phase

Example:

Hilcorp West Ranch

EOR Pipeline

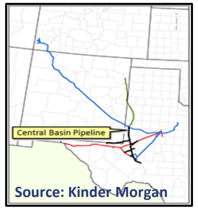
Gas Phase

The low density of gas phase means less capacity is available to transport but does not require high cost of compression to liquid phase

Example:

Kinder Morgan Central

Basin CO_2 Pipeline

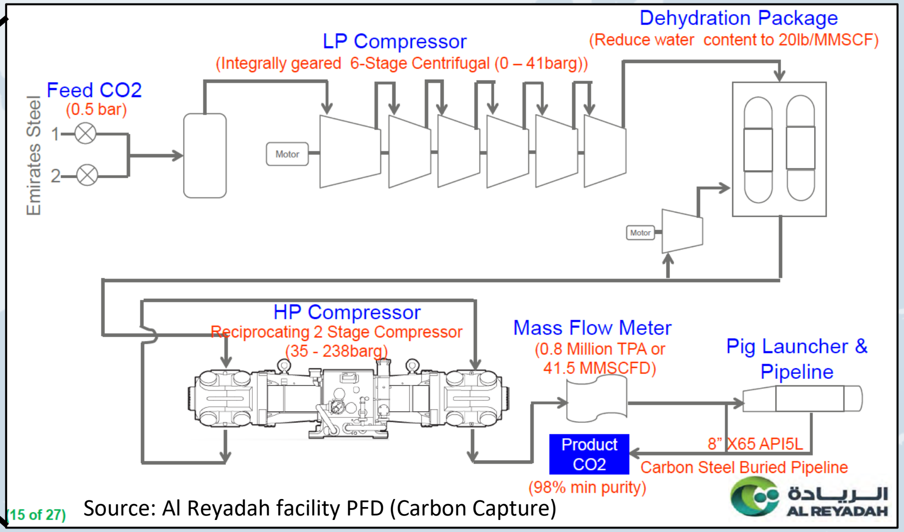


CO_2 COMPRESSION CONSIDERATIONS

- Dehydration is required to minimize corrosion and can be accomplished using:
  - Cryogenic dehydration
  - TEG (Tri-ethylene glycol) dehydration
- For liquid CO_2 transportation compression is required to shift CO_2 into dense phase
  - Centrifugal good for high volume
  - Reciprocating good for high pressures

ADNOC's Al Reyadah Carbon Capture Facility

Al Reyadah PFD showing dehydration and compression



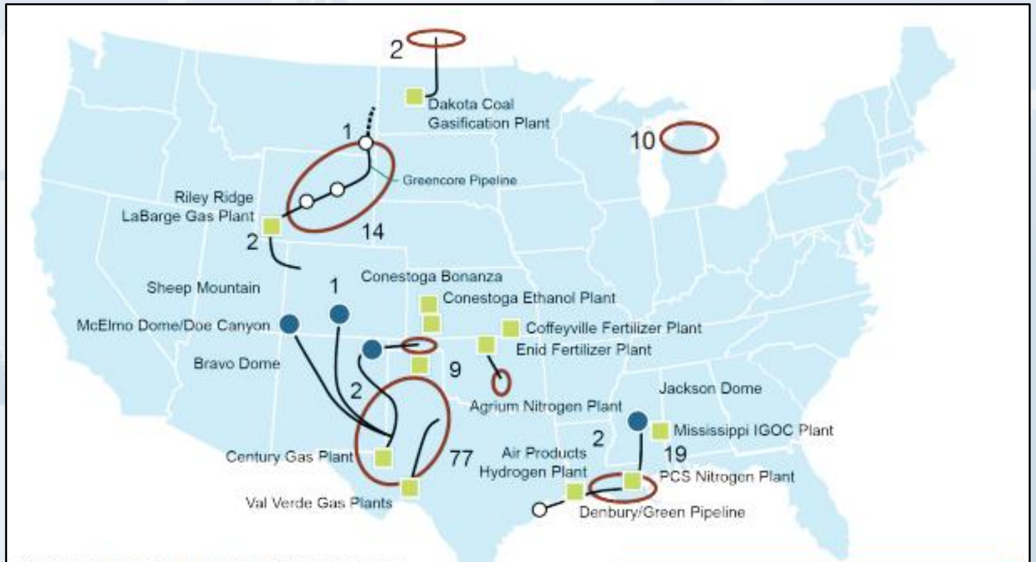
TRANSPORTATION VIA PIPELINES

CO_2 Pipelines differ in some critical considerations compared to oil & gas pipelines:

- Corrosion Protection: Because CO_2 forms carbonic acid in the presence of water, it is necessary to ensure high CO_2 purity through dehydration before entering the pipeline. Internal coating is often required to extend long pipeline operating life.
- Operating conditions: Maintaining operating conditions within certain pressure and temperature ranges is required to prevent CO_2 phase transition

Pipeline Growth in the Industry

- As of 2018, over 5000 miles CO_2 pipelines exist worldwide (Compared to 4000 mi in 2013, 1500 mi in 2007)



139 Number of U.S. CO_2-EOR Projects
- Natural CO_2 Source
- Industrial CO_2 Source
- CO_2 Pipeline
- CO_2 Proposed Pipeline
- CO_2-EOR Region

U.S. regions with large-scale CO_2 pipeline systems currently in operation	Miles of Pipeline
Permian Basin *(W. TX, NM, and S. CO)*	2,320
Rocky Mountains *(N.CO, WY and MT)*	810
Gulf Coast *(MS, LA, and ETX)*	740
Mid-Continent *(OK and KS)*	480
Other *(ND, MI, Canada)*	215

Source: State CO_2-EOR Deployment Work Group

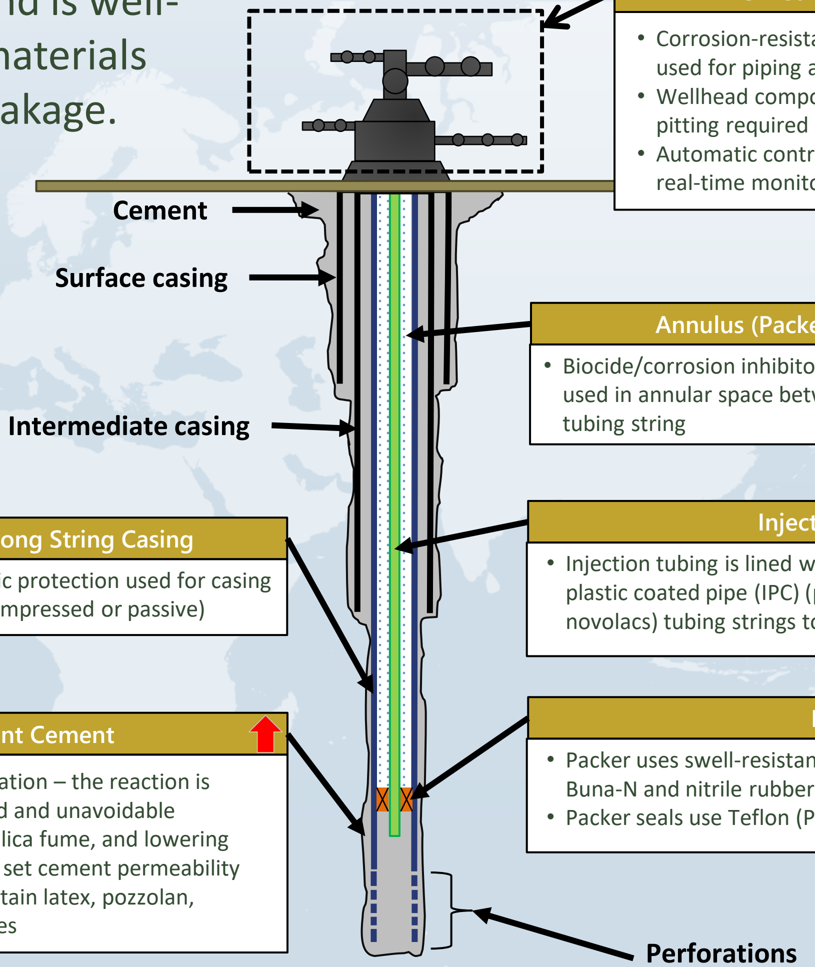
List of Planned and Existing CO_2 Pipelines as of 2016

INJECTION OF CO_2

CO_2 has been injected commercially for EOR since 1972 and is well-developed. Injection of CO_2 requires corrosion-resistant materials and operational practices to prevent corrosion and CO_2 leakage.

Operational and safety practices:

- Corrosion protection of the casing strings is usually done via impressed or passive currents and chemically inhibited (oxygen, biocide, corrosion inhibitor) fluid is used in the casing-tubing annulus.
- Special procedures are used for handling and installing the production tubing to provide gas tight seals between adjacent tubing joints and eliminate coating or liner damage.
- Tubing and casing leak detection methods and repair techniques are required, using both resin and cement squeeze technologies as well as insertion of fiberglass and steel liners.
- Formulation and implementation of criteria unique to siting wells in or near populated areas incorporating: fencing, monitoring and atmospheric dispersion monitoring elements to protect public safety.
- Operator experience with CO_2 injection anticipates normal corrosion and surface facility problems.
- Mechanical integrity testing shows cracks and failure points which is critical for high corrosive, high pressure species.



Christmas Tree/Surface Valving

- Corrosion-resistant materials (316 SS, Monel, CRA) used for piping and metal component trim
- Wellhead components used to be 410 SS but sever pitting required plastic coating and 316 SS is now used
- Automatic control systems regulate flows and provide real-time monitoring capabilities

Annulus (Packer Fluid)

- Biocide/corrosion inhibitor laden fluid is used in annular space between casing and tubing string

Long String Casing

- Cathodic protection used for casing string (impressed or passive)

Injection Tubing

- Injection tubing is lined with fiberglass (GRE) and internally plastic coated pipe (IPC) (phenolics, epoxies, urethanes and novolacs) tubing strings to retard corrosion

Acid Resistant Cement

- CO_2 causes cement degradation – the reaction is thermodynamically favored and unavoidable
- Materials such as fly ash, silica fume, and lowering water content help reduce set cement permeability
- Acid resistant cements contain latex, pozzolan, alumina, and other additives

Packer

- Packer uses swell-resistant elastomer materials such as Buna-N and nitrile rubbers
- Packer seals use Teflon (PTFE) and Nylon for hydraulic seal

ENHANCED OIL RECOVERY (EOR)

Captured CO_2 can be used for EOR or stored long-term depending on the project requirements and goals

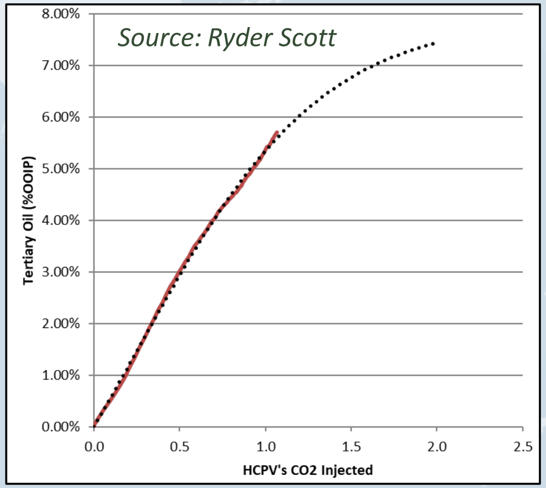
- CO_2 for EOR is associated with the term **CCUS:** Carbon Capture, Utilization, and Storage
- Various screening criteria is used to decide if EOR can be used for incremental oil recovery. Technically (although not practically), all reservoirs can utilize EOR – the driving factor is attainment of Minimum Miscibility Pressure (MMP), which is a function of reservoir depth, permeability, pressure, temperature, CO_2 composition, and hydrocarbon characteristics.
- Incremental oil recovery as a % of OOIP can range greatly depending on well placement and reservoir conditions.

Depth, ft	< 9,800 and >2,000
Temperature, °F	<250, but not critical
Pressure, psia	>1,200 to 1,500
Permeability, md	>1 to 5
Oil gravity, °API	>27 to 30
Viscosity, cp	≤10 to 12
Residual oil saturation after waterflood, fraction of pore space	>0.25 to 0.30

Source: NETL (DOE)

Criteria for Screening Reservoirs for CO_2 EOR Suitability

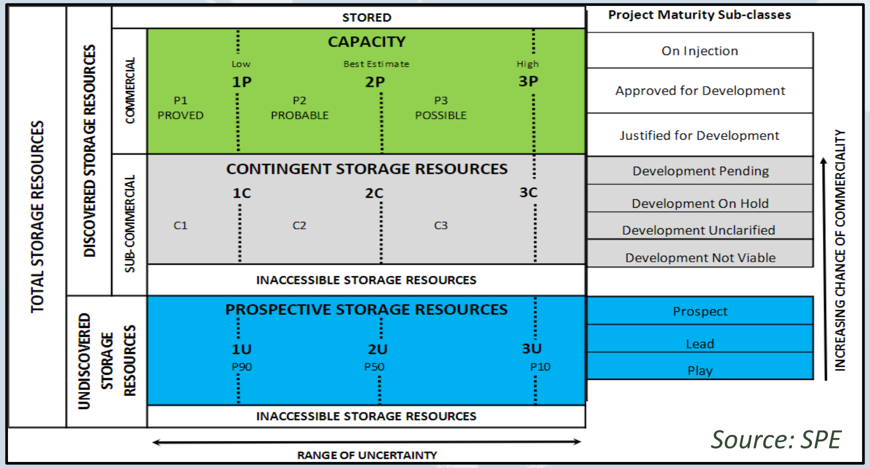
- Projecting incremental recovery includes:
- Dimensionless recovery curves (example shown to the right)
- Analysis of historical performance under CO_2 flooding
- Analysis of analog reservoir performance if there is no CO_2 history for the field.



Dimensionless Recovery Curve showing Tertiary Recovery

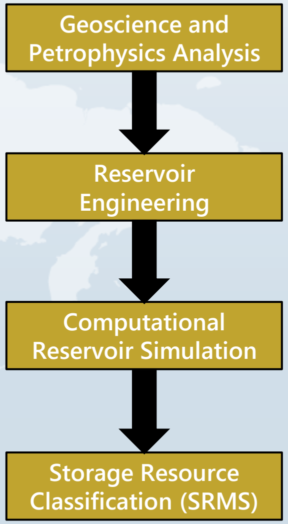
LONG-TERM STORAGE/SEQUESTRATION

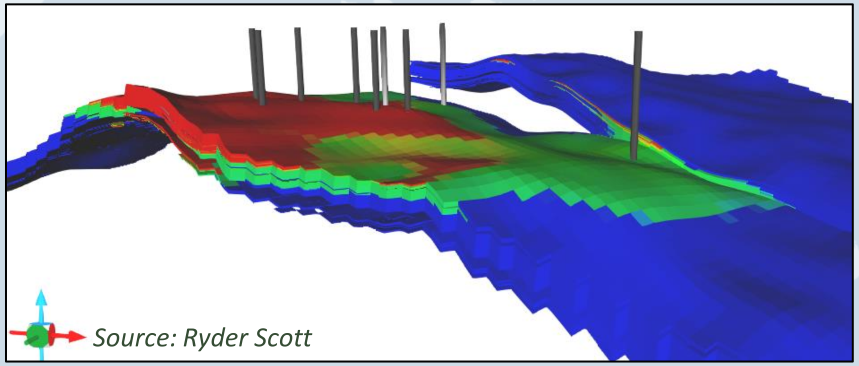
- Associated with the term **CCS**: Carbon Capture and Storage
- CO_2 can be stored in <u>saline aquifers</u> or <u>depleted gas reservoirs</u>:
  - <u>Saline aquifers</u> can be characterized as Primary, where bulk CO_2 is injected and limited by aquifer pressure, or Secondary, where water is displaced with CO_2 and can be disposed or processed and monetized.
  - <u>Depleted gas reservoirs</u> can store a comparable volume of bulk CO_2 to the original in-place gas. Exceeding the original reservoir pressure will risk a formation seal breach. Because the reservoir formerly stored natural gas, there is a lower leakage risk compared to saline aquifers.



SPE-SRMS (Storage Resource Management System)

- Determining reservoir CO_2 storage capacity follows a similar workflow to a reserve assessment.
- Key areas of analysis are leakage pathways (migration points), pressure requirements, trap size, permeability, and well placement
- A typical geoscience approach includes petrophysics, geophysics, the resulting geological interpretation, and geostatic modeling.
- Reservoir engineering follows and includes PVT analysis, SCAL analysis, PTA/RTA for reservoir properties, volumetric analysis, material balance, and computational reservoir simulation.
- The reservoir is characterized quantitatively and assigned storage resource according to SPE-SRMS, which is analogous to SPE-PRMS.

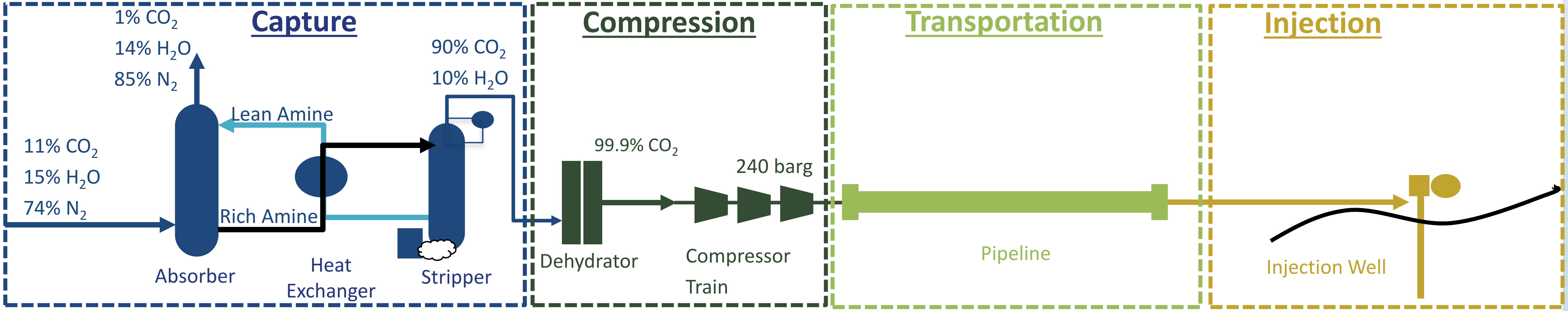




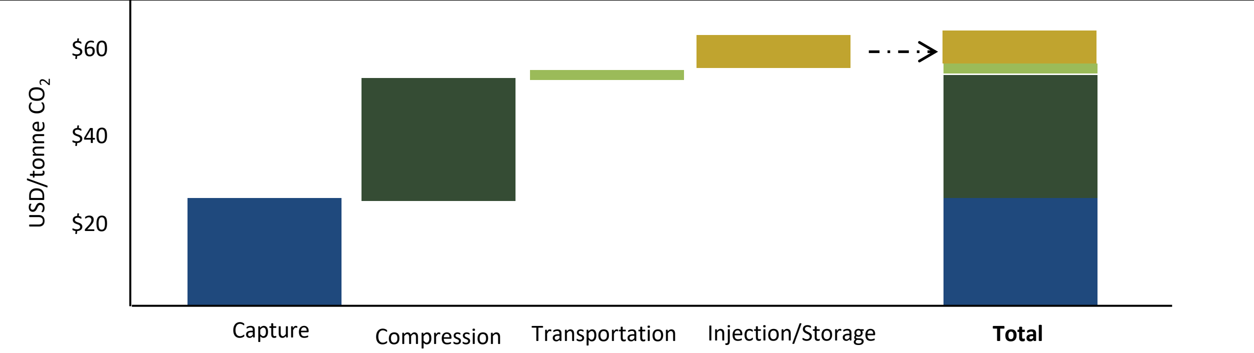
Reservoir Simulation with relative CO_2 Concentration

POWER PLANT CCS PROJECT ECONOMICS REVISITED

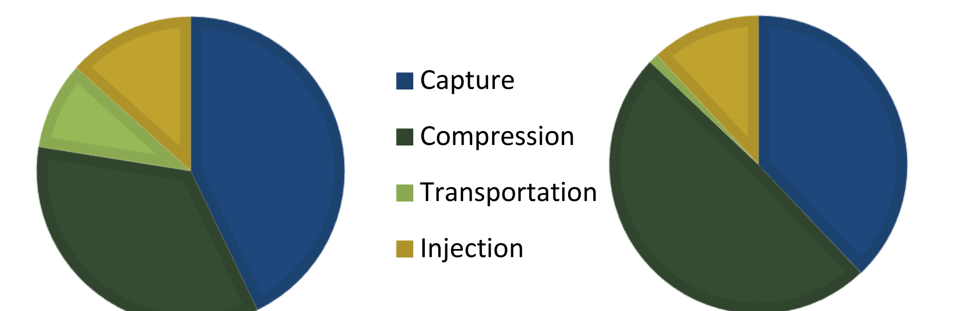
Specifications: Post-combustion carbon capture from a coal power plant; Capturing 1.4 MTPA from 240 MW boiler; 82 mile pipeline, 12" diameter, CO_2 transported in supercritical state; Injection for EOR



Breakeven Price (BEP) Analysis*



CAPEX ($/tonne)	OPEX ($/tonne)



*Discounted at a 10% rate

CASE STUDY: NATURAL GAS PROCESSING CCS CONCEPT COMPARISON

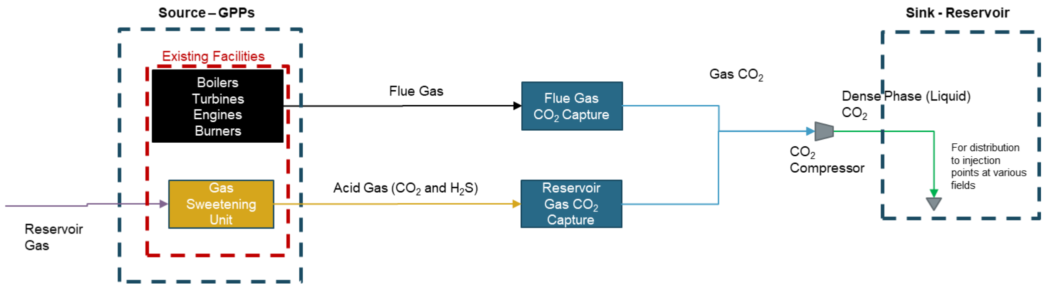
Scope of Work

The client wanted an idea of potential capture concepts and costs for multiple natural gas processing plants located in the same region:

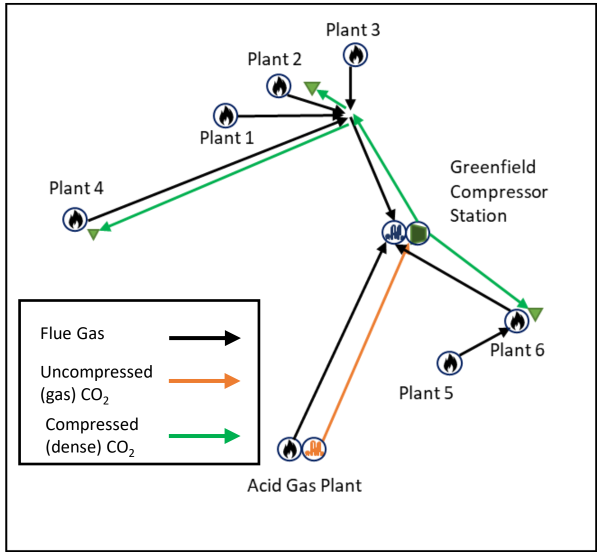
- Seven gas processing plants provided CO_2 from flue gas from on-site power generation – One plant additionally provided CO_2 from reservoir gas.
- We looked at nine different concepts – varying the capture and compression configuration of the plants and estimated CAPEX, OPEX, and \$/tonne CO_2 captured for all concepts

Technical Features

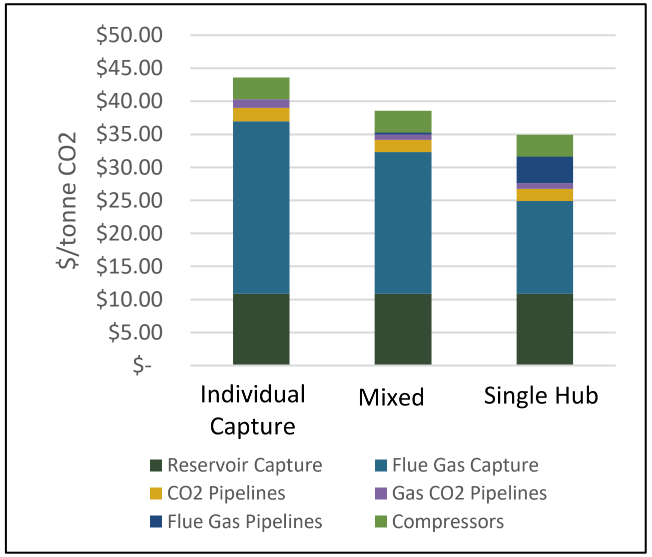
- 5.28 MTPA CO_2 captured
- Over 10 Bscfd of natural gas processed
- Post-combustion absorption considered as commercially mature capture technology
- Greenfield compressor station able to process 432 MMscfd pure CO_2 from 6 barg to 240 barg using 92,600 HP of compression
- Flue gas, gas CO_2, and dense-phase CO_2 pipeline lengths differed based on the concept evaluated



Example Facility and Pipeline Diagram



\$/tonne CO_2

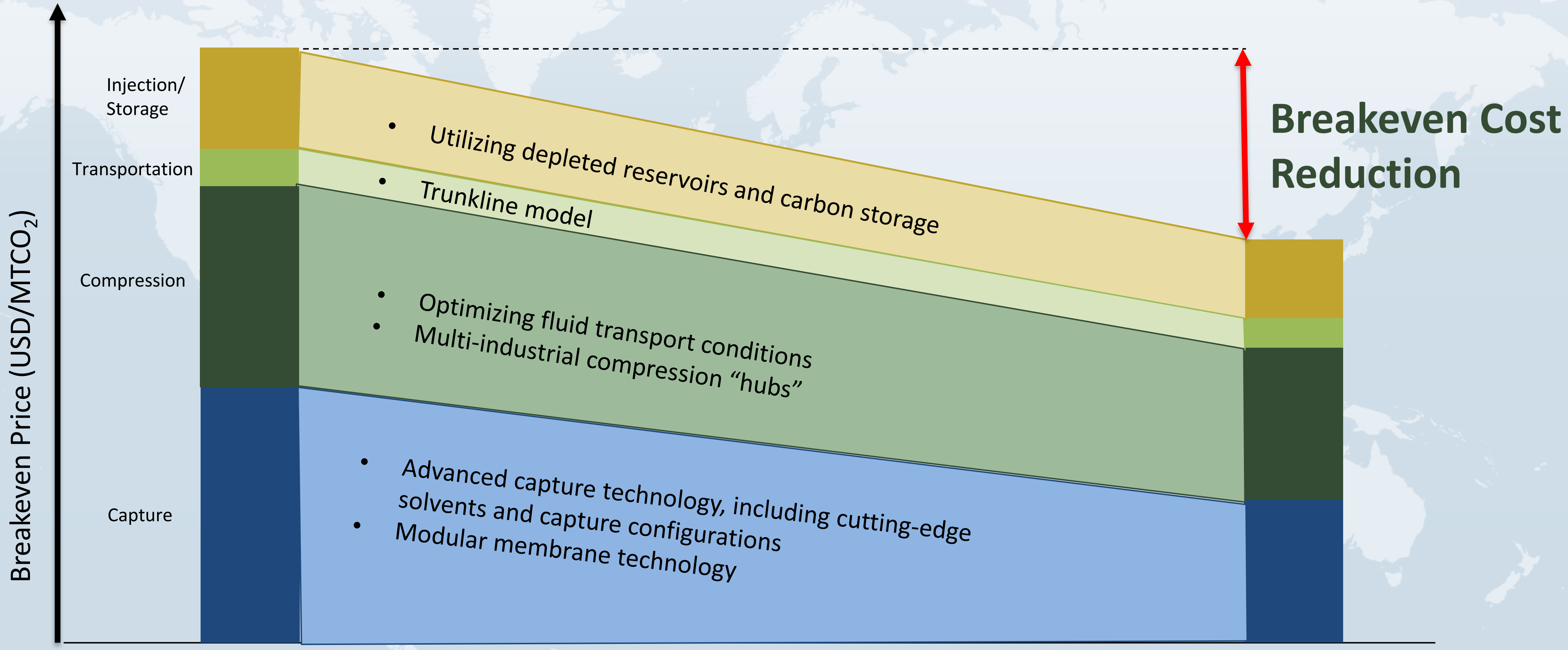


Conclusions

- Based on our analysis, we concluded that capturing CO_2 at a single location instead of individually at each plant would significantly reduce overall project costs

STRATEGIES TO REDUCING BREAKEVEN PRICE

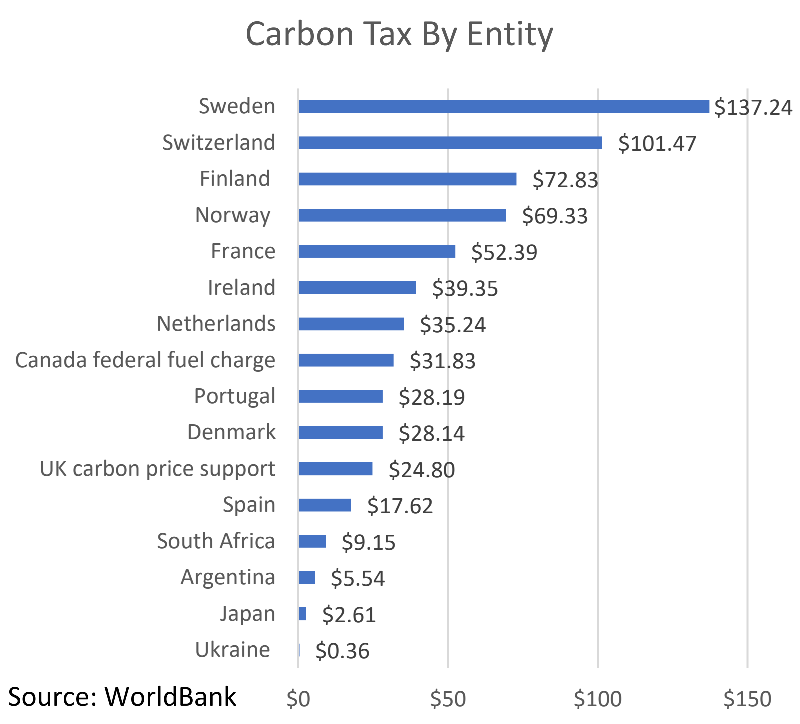
What are some examples of key potential drivers for reducing cost/tonne CO_2 captured?



REVIEWING POLICY CONSIDERATION

Approaches to price of carbon

Carbon Tax (CO_2/tonne)



Source: WorldBank

Carbon Tax Pricing of Various Countries as of December 14, 2021

Emission Trading System (ETS)

- An emissions trading system generally works by the "cap and trade" system. The government establishes a maximum amount of emission allowances (the "cap") and distributes them to different facilities either freely or by auction.
- Facilities are then free to trade excess emission allowances as needed. An under-emitting facility can profit by selling allowances to a facility which is projected to over-emit.

Tax Credit (45Q)

- U.S. Tax Credit expanded in 2018 and again in 2021 to increase the value of utilizing CO_2 for EOR or long-term sequestration
- Facilities must be under construction by January 1, 2032
- *Infrastructure Investment and Jobs Act,* passed November 2021, increases price of carbon from:
  - $50 to $85 per tonne for long-term sequestration
  - $35 to $60 per tonne

HISTORICAL CCUS PERFORMANCE

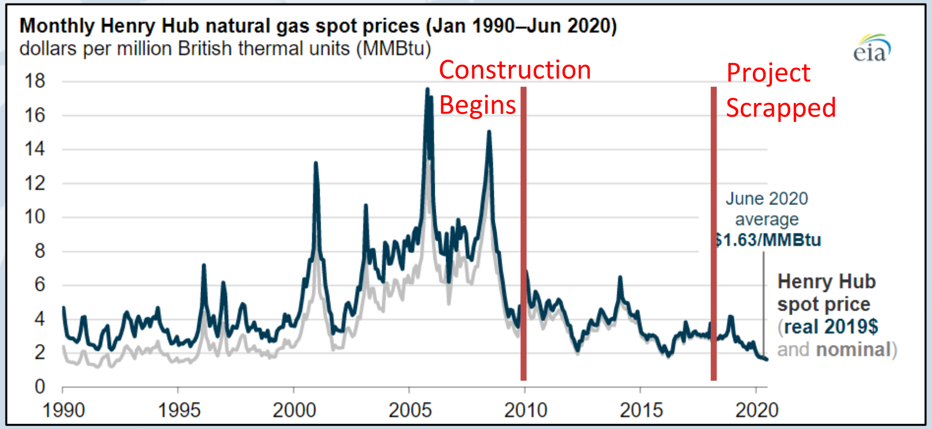
- CCUS is regarded as a critical pathway technology to reducing emissions and atmospheric CO_2 levels.
- Historically, CCUS projects have encountered issues:
  - Kemper
  - Petra Nova
  - Gorgon CCS

KEMPER – PROJECT MANAGEMENT

Major Stakeholder(s): Mississippi Power, Southern Energy
Location: Kemper County, MS
Feedstock: Lignite coal
Capacity: 3.0 – 3.5 MTPA
Capture Technology: Pre-combustion IGCC (KBR)
CO_2 Purpose: Onshore EOR
Timing: Construction began in June 2010, expected completion in May 2014. Scrapped in 2017 after many delays
Cost: $2.2 B projected initially

- Final cost ballooned to $7.5 B before regulators in Mississippi mandated that Kemper switch to natural gas in 2017.
- Project management underestimated the level of technology complexity:
  - Integrated gasification combined cycle (IGCC)
  - Technology issues included chronic coal dust suppression issues, tube leaks in the synthetic gas cooler, insufficient process water capacity, and a too-small nitrogen plant, which required trucks to haul gas to the plant.
- Risk assessment was incomplete - unknown risks included equipment reliability with sustained gasifier operation and economic viability compared to natural gas.
- Changing natural gas market (Economic pressure from natural gas)
- Low-cost gas production

Source: E&E



Source: EIA

PETRA NOVA – MARGINAL ECONOMICS

Major Stakeholder(s): NRG, JX Nippon Oil and Gas Exploration Ltd.

Location: Near Houston, TX

Feedstock: Coal

Capacity: 1.4 MTPA

Capture Technology: Post-combustion amine scrubbing CO_2

CO_2 Purpose: To West Ranch (Hilcorp) oil fields for EOR

Timing: Constructed on-time and on-budget

Cost: About $1B in total

Source: EIA

- NRG's W.A. Parish plant was one of U.S. highest emitters
- Designed production increase as a result of EOR operations is 500 bbl/day, increasing total production to approximately 15,000 bbl/day
  - At $50 barrel, Hilcorp realizes a net loss of oil production
- Shut down May 2020 during pandemic due to poor economics

GORGON CCS – TECHNICAL DIFFICULTIES

Major Stakeholder(s): Chevron (operator), ExxonMobil, Shell, Tokyo Gas, Osaka Gas

Location: Barrow Island, Western Australia

Feedstock: Natural gas

Capacity: 4 MTPA

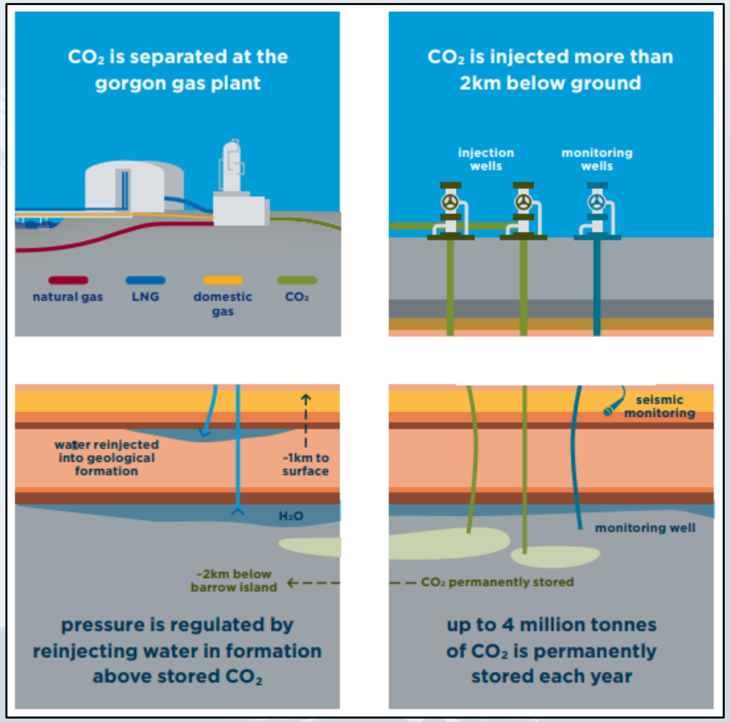
Capture Technology: Natural gas processing

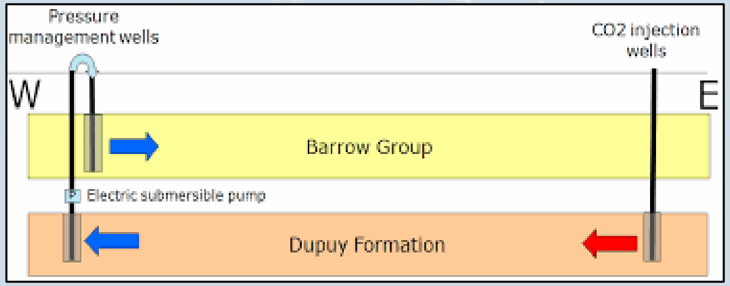
CO_2 Purpose: Long-term sequestration

Timing: Construction began in September 2009, startup of Gorgon in 2016, startup of Gorgon CCS in August 2019 - The delay is reported to have resulted in an additional 7 million tonnes of CO_2 being vented into the atmosphere.

Cost: $2B

- Original project goal was to inject 80% of emissions over first 5 years.
  - Injected 2.26 MT from July 2020 – July 2021 compared to 4 MTPA capacity
  - Total of 5 MT from startup to July 2021
- The project continually ran into problems with its “Pressure Management System”
  - Captured CO_2 injected into the lower Dupuy Formation
  - Water produced from Dupuy formation re-injected into Barrow Formation
- High sand in the process stream (producing wells)
- Chevron may be on the hook for $100 MM in emission offsets





Source: Chevron

THANK YOU

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