• Value Chain Introduction and Terminology
• Market Overview
• Technology and Costs
  – Capture
  – Compression and Transportation
  – Injection and Storage
• Case Study: Vertically-Integrated CCS
• Case Study: Regional CCS
• Historical Carbon Capture Performance and Issues
## VALUE CHAIN TO COMMERCIALITY

### Surface
- Carbon production, capture, transportation, and injection facilities:
  - Capture Configuration and Technology
  - Compression & Transportation design
  - Injection well design for handling CO₂

### Sub-Surface
- Capacity, containment, and injectivity for CO₂ 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 CO₂ reserves and EOR projects (SPE-SRMS)

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*CCS & CCUS is interchangeably used wherein CCS is Carbon Capture and Storage/Sequestration and CCUS – Carbon Capture, Use/Utilization, and Storage/Sequestration*
Specifications: Post-combustion carbon capture from a coal power plant; Capturing 1.4 MTPA from 240 MW boiler; 82 mile pipeline, 12” diameter, \( \text{CO}_2 \) transported in supercritical state; Injection for EOR

- \( \text{CO}_2 \) injected for EOR – much of the \( \text{CO}_2 \) will remain in the reservoir as a result
- Economics driven by:
  - Oil price: At what price does incremental oil recovery generated by miscible \( \text{CO}_2 \) injection justify cost to build/operate facility?
  - 45Q Tax Credit: Generates tax offset varying depending on end-use of \( \text{CO}_2 \)
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

Planned CCS projects vs carbon pricing (as of January 2021)
DE-MYSTIFYING CARBON CAPTURE

Capture **Configuration** location of CO₂ capture in the stream flow and general type of equipment
Capture **Technology** process technology used to separate CO₂ from other components to generate a pure CO₂ 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**
CO₂ captured after combustion occurs from coal-fired power plant

**Technology:**
Absorption Absorber Column Stripper Column
Absorber and stripper used as component of absorption technology

**Currently Deployed CCS Projects**

Source: Power Engineering
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

**Industrial Capture**
- Source:
  - Steel Production
    - Cement
  - Process Gas
    - N₂
    - CO₂

**Direct Air Capture**
- Sources:
  - Atmospheric Air

**Separation**
- Sources:
  - Natural Gas Processing
  - Sour Natural Gas
    - CH₄
    - N₂
    - CO₂

- Capture Technology
  - Absorption
  - Cryogenic

- CO₂ to compression
- N₂ to vent
- Natural Gas to Processing
APPLYING CAPTURE TECHNOLOGIES

**Absorption**
- Most deployed technology

**Absorber**
- Solvent
- Flue Gas
- CO₂

**Stripper**
- Solvent with CO₂

Latest advancements have focused on:
- Optimizing solvent or process
- Refrigerated Ammonia solvent
- CaO looping

**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 CO₂
- Not commercially mature – low temperatures require high amounts of energy

**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 H₂O to produce more H₂ and CO₂
3. Vacuum Swing Adsorption separates CO₂ and H₂
4. CO₂ 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

**SMR** reforms natural gas to produce syngas (carbon monoxide and hydrogen gas)

**Water-gas shift reactor** used CO and H₂O to produce more H₂ and CO₂

**Vacuum Swing Adsorption** separates CO₂ and H₂

**CO₂ gas** is dehydrated and compressed

**Syngas**
- H₂

**H₂O**

**CO₂**
Depending on the technical and commercial requirements of project, CO\textsubscript{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\textsubscript{2} transportation is performed at 10 – 15 MPa and 15 – 30 °C to maintain dense phase.

Example: Abu Dhabi CCS Phase 1

**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\textsubscript{2} Pipeline
Dehydration is required to minimize corrosion and can be accomplished using:
- Cryogenic dehydration
- TEG (Tri-ethylene glycol) dehydration

For liquid CO₂ transportation compression is required to shift CO₂ into dense phase
- Centrifugal good for high volume
- Reciprocating good for high pressures
**TRANSPORTATION VIA PIPELINES**

CO₂ Pipelines differ in some critical considerations compared to oil & gas pipelines:

- **Corrosion Protection**: Because CO₂ forms carbonic acid in the presence of water, it is necessary to ensure high CO₂ 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 CO₂ phase transition.

**Pipeline Growth in the Industry**

- As of 2018, over 5000 miles CO₂ pipelines exist worldwide (Compared to 4000 mi in 2013, 1500 mi in 2007)
INJECTION OF CO₂

CO₂ has been injected commercially for EOR since 1972 and is well-developed. Injection of CO₂ requires corrosion-resistant materials and operational practices to prevent corrosion and CO₂ 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 CO₂ 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.

**Operational and Safety Practices Diagram:**

- **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 severe 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

- **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

- **Long String Casing**:
  - Cathodic protection used for casing string (impressed or passive)

- **Acid Resistant Cement**:
  - CO₂ 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

- **Surface casing**

- **Intermediate casing**

- **Perforations**
Captured CO₂ can be used for EOR or stored long-term depending on the project requirements and goals

- CO₂ 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, CO₂ composition, and hydrocarbon characteristics.
- Incremental oil recovery as a % of OOIP can range greatly depending on well placement and reservoir conditions.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Requirements</th>
</tr>
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<tbody>
<tr>
<td>Depth, ft</td>
<td>&lt; 9,800 and &gt; 2,000</td>
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<tr>
<td>Temperature, °F</td>
<td>&lt; 250, but not critical</td>
</tr>
<tr>
<td>Pressure, psia</td>
<td>&gt; 1,200 to 1,500</td>
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<tr>
<td>Permeability, md</td>
<td>&gt; 1 to 5</td>
</tr>
<tr>
<td>Oil gravity, °API</td>
<td>&gt; 27 to 30</td>
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<tr>
<td>Viscosity, cp</td>
<td>≤ 10 to 12</td>
</tr>
<tr>
<td>Residual oil saturation after waterflood, fraction of pore space</td>
<td>&gt; 0.25 to 0.30</td>
</tr>
</tbody>
</table>

Criteria for Screening Reservoirs for CO₂ EOR Suitability

- Projecting incremental recovery includes:
  - Dimensionless recovery curves (example shown to the right)
  - Analysis of historical performance under CO₂ flooding
  - Analysis of analog reservoir performance if there is no CO₂ history for the field.
LONG-TERM STORAGE/SEQUESTRATION

- Associated with the term **CCS**: Carbon Capture and Storage
- **CO₂** can be stored in saline aquifers or depleted gas reservoirs:
  - Saline aquifers can be characterized as Primary, where bulk **CO₂** is injected and limited by aquifer pressure, or Secondary, where water is displaced with **CO₂** and can be disposed or processed and monetized.
  - Depleted gas reservoirs can store a comparable volume of bulk **CO₂** 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.

- Determining reservoir **CO₂** 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.

![SPE-SRMS (Storage Resource Management System)](source: SPE)

![Reservoir Simulation with relative CO₂ Concentration](source: Ryder Scott)
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, CO₂ transported in supercritical state; Injection for EOR

**Break-even Price (BEP) Analysis***

- **CAPEX ($/tonne)**
  - Capture: $20
  - Compression: $40
  - Transportation: $60
  - Injection/Storage: $60
  - Total: $180

- **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 CO₂ from flue gas from on-site power generation – One plant additionally provided CO₂ from reservoir gas.
- We looked at nine different concepts – varying the capture and compression configuration of the plants and estimated CAPEX, OPEX, and $/tonne CO₂ captured for all concepts

Technical Features
- 5.28 MTPA CO₂ 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 CO₂ from 6 barg to 240 barg using 92,600 HP of compression
- Flue gas, gas CO₂, and dense-phase CO₂ pipeline lengths differed based on the concept evaluated

Conclusions
- Based on our analysis, we concluded that capturing CO₂ 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 CO₂ captured?

- Utilizing depleted reservoirs and carbon storage
- Trunkline model
- Optimizing fluid transport conditions
- Multi-industrial compression “hubs”
- Advanced capture technology, including cutting-edge solvents and capture configurations
- Modular membrane technology
Approaches to price of carbon

### Carbon Tax (CO₂/tonne)

- **Carbon Tax By Entity**
  - Sweden: $137.24
  - Switzerland
  - Finland: $72.83
  - Norway: $69.33
  - France
  - Ireland: $52.39
  - Netherlands: $39.35
  - Canada federal fuel charge
  - Portugal: $31.83
  - Denmark: $28.19
  - UK carbon price support
  - Spain: $24.80
  - South Africa
  - Argentina: $17.62
  - Japan
  - Ukraine: $9.15
  - Canada federal fuel charge
  - Australia
  - Brazil
  - China
  - South Korea
  - Mexico
  - Norway
  - Singapore
  - Sweden
  - Switzerland
  - U.S. Tax Credit expanded in 2018 and again in 2021 to increase the value of utilizing CO₂ for EOR or long-term sequestration

### 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 CO₂ 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

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

Source: WorldBank
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)
CO₂ 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
**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 CO₂

**CO₂ Purpose:** To West Ranch (Hilcorp) oil fields for EOR

**Timing:** Constructed on-time and on-budget

**Cost:** About $1B in total

- 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

*Source: EIA*
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
CO₂ 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 CO₂ 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 CO₂ 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