Carbon Capture, Utilization and Sequestration (CCUS) Value Chain

Limiting global temperature increases to 1.5 °C by 2050 will require an additional 5,635 MTPA (million metric tonnes per annum) of carbon capture capacity to meet the climate target set by the Intergovernmental Panel on Climate Change (IPCC). As of 2021, 39 MTPA of deployed carbon capture capacity exists worldwide, with 43 MTPA of full-scale projects currently in various stages of development. The striking difference in available vs. required carbon capture capacity shows the market is ripe for new CCUS projects.

These projects in development are concentrated mostly in the U.S., Northern Europe, and China, and are driven by carbon price incentives. The facilities are strategically located in industrial belts based on carbon sources and proximity to suitable reservoirs or formations. Nevertheless, CCUS economics can be challenging, making it necessary to understand the different segments of the CCUS value chain to bring projects to fruition.

Figure 1.0 depicts a case study for post-combustion carbon capture from a coal power plant. The process involves capture of 1.4 MTPA of CO_2 from flue gas from a 240-MW turbine. The supercritical-state fluid is transported via an 82-mile pipeline and injected into a well at an Enhanced Oil Recovery (EOR) project.

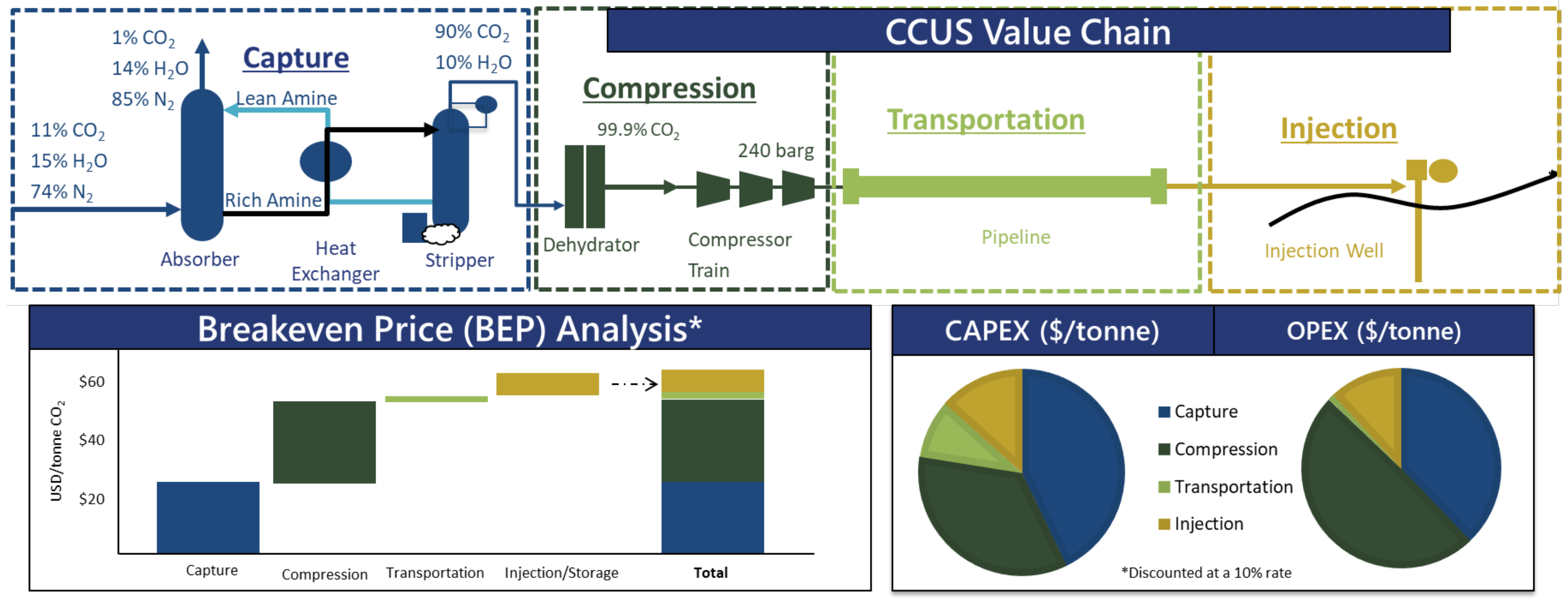

Figure 1.0: CCUS Value Chain and Project Economics

The economics also are shown on Figure 1.0. A vertically integrated project connects the value chain segments — capture, compression, transportation and injection — and results in a breakeven price of $65 per tonne of CO_2. That is a 10% rate of return on the investment. The equivalent price of CO_2 reflects the benefits in incremental oil recovery in EOR projects and related carbon capture tax credits. The capital expenditures (CAPEX) and operating expenditures (OPEX) in the value chain indicate that capture and compression, respectively, are the main contributors to the costs.

Academic and industrial jargon have inconsistent terms to describe the capture configuration, and show the location of CO_2 capture and the technology used to separate and generate the pure CO_2 stream. Although configuration and technology are interrelated, Figure 2.0 depicts the processes and equipment organized by capture and separation configurations and their typically associated technologies.

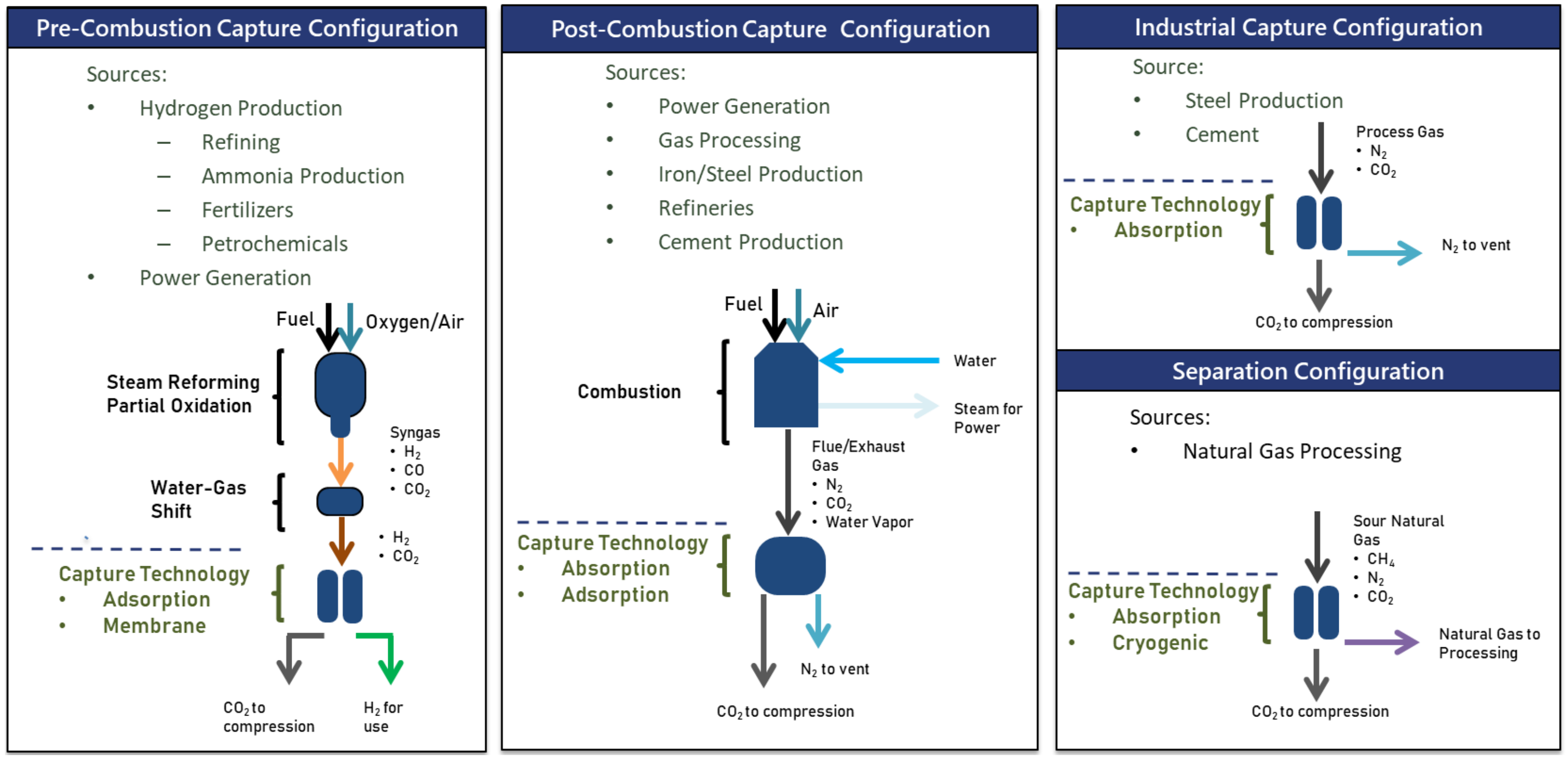

Figure 2.0: CO2 Capture: Configurations and Typical Associated Technology

The capture configurations are as follows:

- **Pre-combustion** is normally utilized during hydrogen-generation processes that include steam reforming or partial oxidation. Because of the high volumes of hydrogen generated, pre-combustion capture can be tied to refining, ammonia and fertilizer production and petrochemical manufacturing.
- **Post-combustion** makes use of a capture unit located after the combustion process. It separates CO_2 from a flue gas stream, as in the earlier example.
- **Industrial processes** generate CO_2 through the manufacturing chemistry. Steel and cement production emit significant amounts of CO_2 as a direct result of process chemical reactions.
- **Separation capture** removes CO_2 from reservoir gas streams.
  The most common configurations in use today are pre-combustion and separation, mostly because of hydrogen manufacturing in ammonia and fertilizer production and gas processing when reservoir CO_2 concentrations are high.

The major capture technologies are as follows:

- **Absorption** is the most commercially mature carbon capture technology and consists of a liquid solvent, usually amine-based, which selectively absorbs CO_2 out of a gas stream in an absorber column. Recent advancements in absorption have focused on optimizing the solvent or process configuration.
- **Adsorption** is commonly used in conjunction with the pre-combustion configuration and uses a solid sorbent instead of a liquid solvent. CO_2 is adsorbed onto the sorbent packing in a column until saturation, where the sorbent is regenerated by manipulating the column temperature (Temperature Swing Adsorption (TSA) or pressure (Pressure Swing Adsorption (PSA). The latest advancements in adsorption have focused on improving the sorbent material and shape of the packing.
- In **membrane separation**, a thin membrane selectively lets certain gas species (the permeate) across, while the remainder of the gas cannot cross the membrane (retentate). Membrane separation is promising based on startups and pilot plants with small-scale success, but has not yet been proven to scale-up.
- Finally, **cryogenic separation** is a physical process that manipulates stream temperature to remove CO_2. Cryogenic separation has only been attempted at a pilot scale. With no upscaling or technical advancements, the technology remains non-commercial.

Depending on the distance of capture-to-market location and volumetric requirements, CO_2 can be transported in

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different physical states. In the gas phase, CO_2 has lower density, and higher capacities that require larger pipeline diameters. For instance, Kinder Morgan transports CO_2 in gas phase from basins in Colorado to the Permian requiring relatively large-diameter pipelines. Supercritical and dense phase CO_2 exhibit higher densities closer to those of liquids so more CO_2 can be transported with a smaller diameter pipeline. However, high pressures are required to achieve supercritical or dense phase CO_2, thereby requiring additional compression and greater pipe-wall thickness. Further compression to injection pressures can require significant energy: the back end of a high-pressure compressor can reach 3,500 psi. Design considerations influence initial CAPEX requirements, and include a number of compressor stages and a dehydration package. The energy requirements to operate the compressors dictate OPEX, which is typically higher for low CAPEX. As always, tradeoffs must be studied to arrive at an optimal cost for the compression segment of the value chain.

As of 2018, only 5,000 miles of CO_2 pipelines existed worldwide and we anticipate the CO_2 midstream market will increase rapidly in the near future to accommodate the requirements of large-scale CCUS. Repurposing of existing oil and gas pipelines rather than constructing new CO_2 pipelines is a possibility to reduce cost. When comparing CO_2 pipelines to oil and gas pipelines, key differences stand out. CO_2 forms carbonic acid in the presence of water, which is highly corrosive to steel. Therefore, it is necessary to dehydrate the CO_2 stream to high purity using a TEG (tri-ethylene glycol) system before it enters the pipeline. Internal corrosion protection is used depending on the pipeline design life and CO_2 purity. It is also important to maintain operating conditions within a certain pressure and temperature to prevent phase transition.

Injection of CO_2 began commercially in 1972 and is considered technically mature. CO_2 requires corrosion-resistant materials in various well components. For example, piping, valves and wellheads may require Stainless Steel 316 for corrosion resistance. Tubing requires Glass Reinforced Epoxy (GRE)-lined carbon steel, Internally Plastic Coated (IPC) carbon steel or another Corrosion Resistant Alloy (CRA). Additionally, a supercritical pump may be required to pressurize the CO_2 to injection pressure, or miscibility pressure if EOR is considered.

In addition to being utilized for EOR, CO_2 can be stored for long-term sequestration in depleted oil and gas reservoirs or deep saline formations. Most long-term storage projects today inject CO_2 into saline formations, but many planned projects in the near future will store CO_2 in depleted oil and gas fields. The depleted fields must be evaluated for CO_2 storage capacity considering pressure requirements, potential leakage pathways, reservoir integrity and the optimal configuration of injection wells. Finally, storage requires a robust monitoring, reporting and verification (MRV) plan per 40 CFR 98.440 from the U.S. EPA.

For storage capacity certification, the SPE approved the CO_2 Storage Resources Management System (SRMS) in 2017.

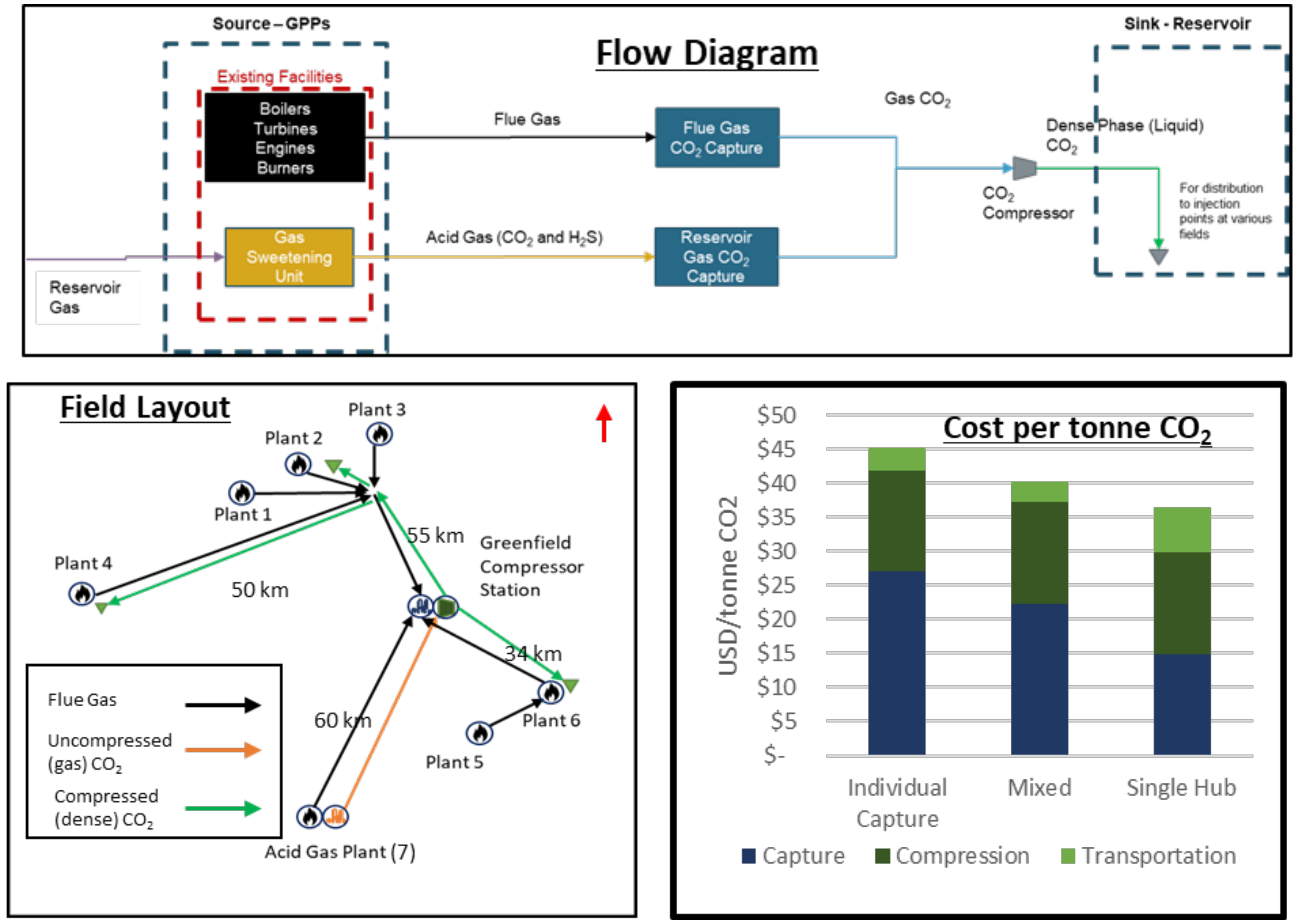
Besides optimizing each value chain segment, we reviewed potential capture concepts for multiple natural gas processing plants located in a region shown in Figure 3.0 on opposite page.

The development includes seven (7) plants that process more than 10 Bscfd of natural gas, with one processing acid gas with a significantly higher H_2S and CO_2 content. The compressed CO_2 is then distributed back to the fields for EOR. In the development, one extreme is an individual capture case for each gas processing facility with its own carbon capture plant getting CO_2 from the flue gas generated from onsite power as well as an individual compressor station. At the other extreme is a single hub wherein all CO_2 from the flue gas is captured at one central location, with the exception of the acid gas plant, which transports a pure stream of gas-phase CO_2 to the central compressor station. A single hub is significantly cheaper at \$36/tonne CO_2 compared to \$44/tonne CO_2 for the individual capture. Within that range, the company considered numerous cases of mixed hubs for a phased approach to reduce the initial capital expenditure.

This case study proves that taking advantage of economy of scale and phasing development are effective ways to make a CCUS project economical. It also shows the importance of applying the hub concept to capture, compress and transport CO_2 to various locations for EOR. This conclusion applies equally to regional collaborative CO_2 storage hubs.

Figure 4.0 summarizes breakeven price reduction avenues we have discussed in both case studies.

Figure 3.0: Regional Development



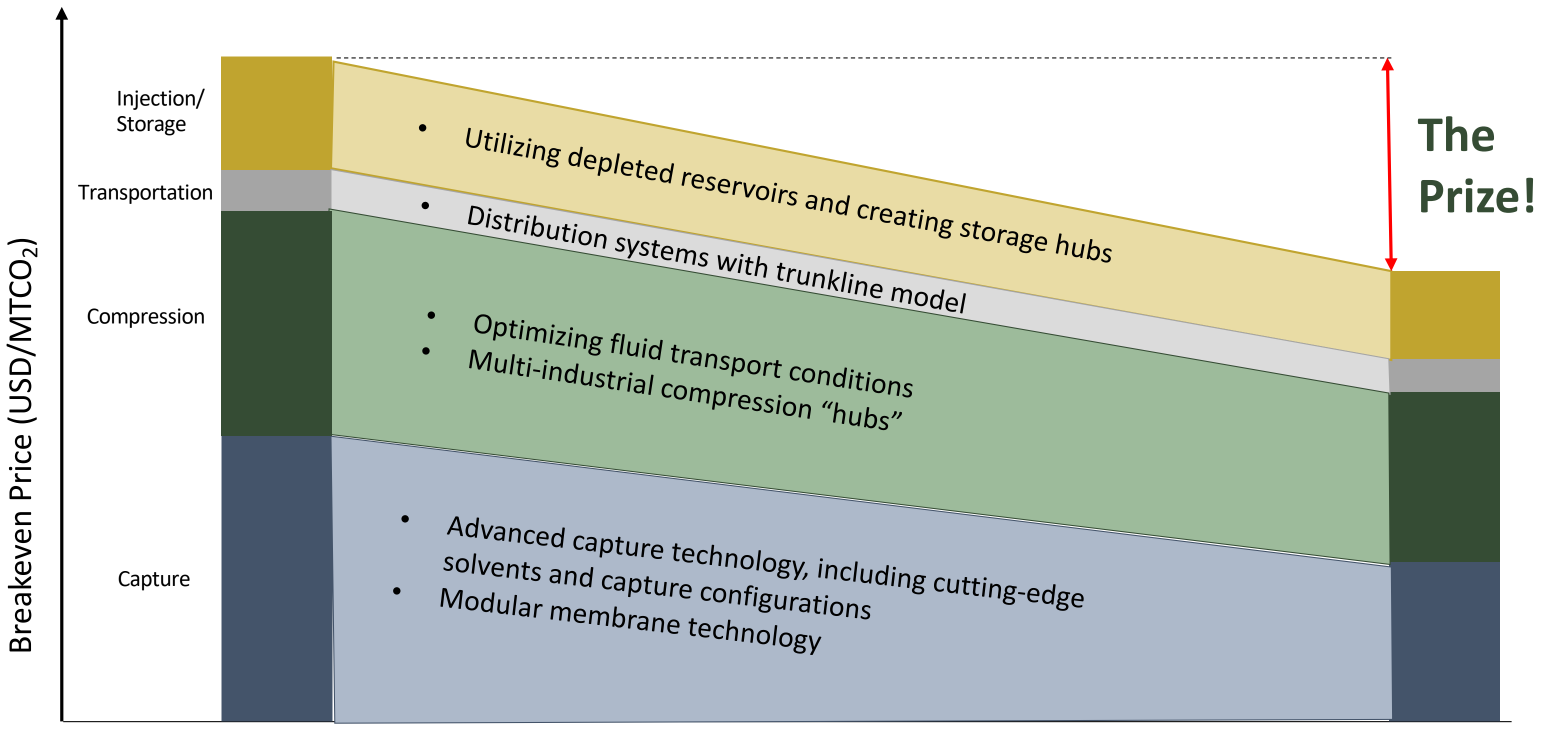


Figure 4.0: Breakeven Price Reduction

Restating the opportunities to reduce the breakeven price are as follows:

- For injection and storage, identify and select formations to create strategic storage hubs with optimal injection plans to reduce costs.
- For transportation, the biggest way to reduce costs is to optimize pipeline lengths or operating conditions, or to use a trunkline model. Alberta Carbon Pipeline has done the latter with an operating facility that gathers carbon from a couple of different facilities and transports it in one pipeline (trunkline) downstream for injection.
- For compression, opportunities to reduce costs are evident in hubs, commercial and public/private partnerships and optimization of fluid transport conditions.

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- In capture, the biggest opportunity to reduce costs per tonne of carbon is in the technology, which includes optimizing the solvent or configuration or using a technology that hasn't necessarily been proven at a commercial scale, but has been relatively successful on a pilot scale.

In addition to cost reduction opportunities, policy continues to increase the price of carbon to improve revenue. Policy instruments like carbon taxes and tax credits, e.g. 45Q, allow tax offset opportunities to maximize profits from a primary revenue stream, such as the sale of oil or power. Emission trading systems (ETS) allow companies to trade emission allowances, typically in units of tonnes of CO_2, which provide a revenue source directly generated from storing carbon. The number and magnitude of these policy instruments have steadily increased and are expected to increase more rapidly in the future.

In conclusion, the two main components to increase commerciality are reducing costs and increasing revenue. Innovative solutions are formed using appropriate contracting and commercial models generated via a deep comprehension of CCUS value chain components, technology, designs, project configurations and risks and coupling them with carbon-credit incentives.

Ryder Scott is focused on technologies for capture, compression and transportation. This is useful to clients that want to understand a new technology marketed by a startup and how to contextualize that in a larger CCUS market. The firm's geologists, geophysicists and reservoir engineers are highly competent when assessing formations and utilizing carbon for EOR or long-term storage. Ryder Scott monetization strategies focus on incremental oil recovery from EOR, tax credits and emission-allowance benefits from long-term storage. Ryder Scott also offers verification and validation of emissions to help navigate the complex regulatory standards in reporting.

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