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Feasibility Study for Ship Based Transport of Ethane to Europe and Back Hauling of CO_2 to the USA

IEA GREENHOUSE GAS R&D PROGRAMME

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Feasibility Study for Ship Based Transport of Ethane to Europe and Back Hauling of CO_2 to the USA

Overview

This feasibility study was commissioned by the IEA Greenhouse Gas R&D Programme on behalf USDOE. The study was led by Fern Oil Inc. (A Division of Astrup-Fearnleys AS) of the USA.

The study is a first stage assessment of a novel concept of transporting ethane from the USA in dedicated maritime carriers to Europe, which are modified from standard designs to be equipped to carry both ethane and CO_2, so that CO_2 can be transported back (back hauled) to the USA for use in CO2-EOR operations.

Transportation of Ethane to Europe. The Shale gas boom in the United States has also resulted in the production of liquid products like ethane, at competitive prices. In 2016, the USA began exporting ethane first by pipeline to Canada and then by liquefied carrier to Norway in March 2016 and the UK in September 2016[1]. Ethane is used as a key feedstock for plastics production and other industrial uses and is expected to boost UK and Norwegian production of such products as supplies from the North Sea begin to decline.

INEOS a global manufacturer of petrochemicals, speciality chemicals and oil products, secured 15 year contracts for the purchase, distribution and shipping of ethane from the US, underpinning the economics of its petrochemicals assets in Europe for the foreseeable future. INEOS partnered with Evergas, (Danish shipbuilding experts) to build a new class of vessels, the Dragon Class to transport the ethane across the Atlantic. To date 4 such vessels have been built and 4 more will be launched in 2017[2]. The Dragon-class vessels are equipped with autonomous C type bi-lobe tanks, which store 27,500m^3 of gases, such as liquefied natural gas (LNG), ethane, liquefied ethylene gas (LEG), and liquid petroleum gas (LPG)[3].

Adapting Ethane Carriers to Back Haul CO_2. The study has examined from first principles the potential to design new ethane carriers to also carry CO_2. The starting premise was that LNG carriers in Norway have been designed to carry both LNG and CO_2. The Norwegian shipping company IM Skaugen has six 10,000 m^3 ships in their fleet which are rated to 7 bar, -104°C, and are registered for carrying liquefied CO_2 (LCO_2), however, their normal cargo is LPG. It is not clear from the literature if the ships have been used yet for CO_2 transport[4]. The ships are smaller in scale than the Dragon class vessels and not suitable for transporting liquefied gas across the Atlantic.

The study concludes that technically it could be feasible to build new multi fuel vessels like the Dragon class ship that could transport LCO_2 as well as other gases. One of the challenges highlighted in the study is the maximum allowable working pressure of the cargo tank that would be needed to transport LCO_2 is higher than that for LPG service which could cause design issues. However it is accepted that these issues have been resolved for the smaller dual LNG/CO_2 vessels identified above. It is felt that existing carriers may not be suitable for conversion to carry LCO_2 but future new build vessels could consider this design adaptation, if the construction of new vessels are being planned to meet future export demand for liquefied shale gas products.

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[1] https://www.bloomberg.com/news/articles/2016-09-27/first-u-s-shale-gas-arrives-in-u-k-as-ethane-shipment-lands
[2] http://www.ineos.com/big-boats
[3] http://www.ship-technology.com/projects/dragon-class-liquid-gas-transport-vessels/
[4] http://www.sccs.org.uk/images/expertise/misc/SCCS-CO2-EOR-JIP-Shipping.pdf

Market Demand for CO_2 in the USA. The driver for transporting CO_2 to the USA is the projected increase in the demand for CO_2 for EOR in the USA. The study concludes that the single largest constraint to CO2-EOR growth in the USA is the lack of sufficient economically viable sources of CO_2 in the USA itself. Hence the desire to consider off shore supplies for CO_2 to the USA to meet future growth and demand for CO_2 for EOR in the USA. It should be m noted that at the time of the study the price of oil stood around $100 per barrel, since then the price has dropped considerably and this will reduce the growth of domestic CO2-EOR in the USA for several years to come. The projected demand for CO_2 in the USA was 9-26 billion tonnes per annum for conventional CO2-EOR operations. Considering residual oil play demand could increase this demand projection for CO_2 by 75%.

The study did not undertake any economic analyses to consider what a price for exported CO_2 from Europe might look like and whether this fits the cost model for CO_2 for EOR in the USA.

Production of CO_2 for shipping in Europe. Large point source emissions in Europe equated to 1.5Gt CO_2 in 2005, of which 400 emission sources accounted for 75% of those emissions[5]. There is therefore more than sufficient CO_2 to meet the CO2-EOR demand in the USA. However, whilst there are a significant number of point sources of CO_2 in continental Europe that could supply CO_2 there are currently no CCS projects that are operational in Europe that could provide CO_2 for export to the USA. The first project that could come on board is the ROAD project in the Netherlands around 2018-2020, the CO_2 will be used for greenhouses and injection into a gas field[6]. This project has been significantly delayed to date and its actual start date remains uncertain. It is only currently planned to operate for 3 years. After, that the only planned projects are in Norway which will not come on stream until 2022 onwards[7]. There is currently no infrastructure to transport CO_2 in the volumes needed to allow it to be exported. Such an infrastructure is not likely to be built before 2025 at the earliest.

Current market value for CO_2 in the USA is of the order $10-30/t. Such a price will not on its own stimulate the development of CCS projects and pipeline infstaructure in Europe to supply the US market, but it could help facilitate such development in the future.

Conclusions

The report considers a conceptual idea for transporting CO_2 to the USA in modified ethane carriers. The main conclusion that can be drawn are:

1. Whilst ethane is being exported to Europe now the same ships are unlikely to be converted to carrier LCO_2 as well. New ships would need to be built to meet any market demand to back haul CO_2 to the USA.
2. Whilst there is a potential near term demand for CO_2 for EOR in the USA (if oil process recover to $100/barrel), there is unlikely to be large quantities of transportable CO_2 from Europe in the foreseeable future.

In summary, this is an interesting concept and one that should not be dismissed out of hand. But all the pieces of the jigsaw do not slot into place at the current time and may not conceivably do so in the next 5-10 years.

It is also noted that LPG and ethane trades to the Far East from the US Gulf Coast are also now starting and there may be similar considerations on those routes for future investigations of this type.

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[5] IEAGHG Report 2005/02 Building the Costs Curve for Storage in Europe, February 2005

[6] http://road2020.nl/en/

[7] http://bellona.org/news/ccs/2016-09-norway-breaks-vicious-cycle-of-inaction-on-ccs-deployment-with-concrete-plans-for-industry

Feasibility Study of
Ship-Based Transportation of CO_2

Prepared for:
IEA Environmental Projects Ltd on behalf of
The IEA Greenhouse Gas R&D Programme

Contract No IEA/SP/15/0005

The Potential for Dual Fuel Transatlantic and Transpacific LPG/Ethane Carriers for Shipping CO_2 from CO_2 Capture Centres to CO_2 Utilisation Centres

Phase 1 Feasibility Concept Study

Prepared by:
Fearn Oil

In association with:

ABS Consulting

Advanced Resources International, Inc.

University of Wyoming, School of Energy Resources
Carbon Management Institute

April 20, 2016

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Feasibility Study of Ship-Based Transportation of CO_2

Executive Summary

This preliminary examination of the feasibility of using ship-based transportation of CO_2 has been conducted as part of U.S. Department of Energy's (DOE) Quadrennial Energy Review (QER) as directed by the 2014 Presidential Memorandum. The QER, issued in April 2015, focuses on the current and future status of the U.S. energy infrastructure and its ability to promote economic competitiveness, energy security and environmental responsibility, notably mitigation of climate change.

Ship-based transportation of CO_2, as assessed in this preliminary feasibility study, involves the transport of surplus natural gas liquids (NGLs) composed of ethane and liquid petroleum gasses (LPGs) from the U.S. to international markets, with CO_2 transported as "backhaul" to U.S. markets. The landed CO_2 in the U.S. would be used and stored by the domestic CO_2 enhanced oil recovery (CO_2-EOR) industry, Figure EX-1.

Figure EX-1. Hypothetical Voyage: Loading Ethane in Marcus Hook, New Jersey, Discharging Ethane in NW Europe (red line), Loading CO_2 in Rotterdam, Discharging in U.S. Gulf Coast (green line)

Source: ABSC / google maps

An independent appraisal of the feasibility of ship-based transportation of CO_2 conducted by ABS Consulting as part of this assessment concluded that "from a technical standpoint, liquid CO_2 can be carried aboard suitable liquefied gas vessels with approvals, precautions and handling procedures similar to those used for other liquefied gas (LNG, LPGs, etc.) carried as cargo aboard ships." Further discussion of the feasibility and challenge of ship-based transportation of CO_2 is provided below and in the remainder of this report.

1. Ship-Based Transportation of CO_2 and U.S. Energy Security. Our Phase I study of the feasibility and market potential of using ship-based transportation of CO_2 finds that this innovative infrastructure option would significantly support the U.S. energy and climate change goals set forth by DOE in the QER. For example:

- Ship-based transportation of CO_2, shipping CO_2 from countries or areas with challenging CO_2 storage options to the CO_2-EOR market in the U.S., would support American climate change diplomacy goals while enhancing the economic competitiveness and viability of the U.S. CO_2-EOR industry and thus domestic energy security.

- A substantial market exists in the U.S. for reliable, affordable anthropogenic CO_2 supplies (CO_2 emissions) captured from industrial facilities and power plants. The recent recognition and appraisals of residual oil zone (ROZ) resources has expanded the market for CO_2 substantially.

- The U.S. has large, growing volumes of natural gas liquids (ethane and LPG) production that are already being exported, with large additional resource potential that could be exportable. NGLs are by-products of natural gas production and need to be separated from natural gas to enable this product to meet pipeline and market specifications. As such, the natural gas and NGL production industry needs increased export markets to promote a viable domestic industry.

2. Technical and Economic Feasibility of Ship-Based Transportation of CO_2. Based on discussion with CO_2 pipeline operators, U.S. Coast Guard engineering and hazardous materials staff, cryogenic pump makers and LPG vessel operations executives, from a technical standpoint liquid CO_2 can be carried aboard suitable liquefied gas vessels with approvals, precautions and handling procedures similar to those used for other liquefied gases carried as cargo aboard ships.

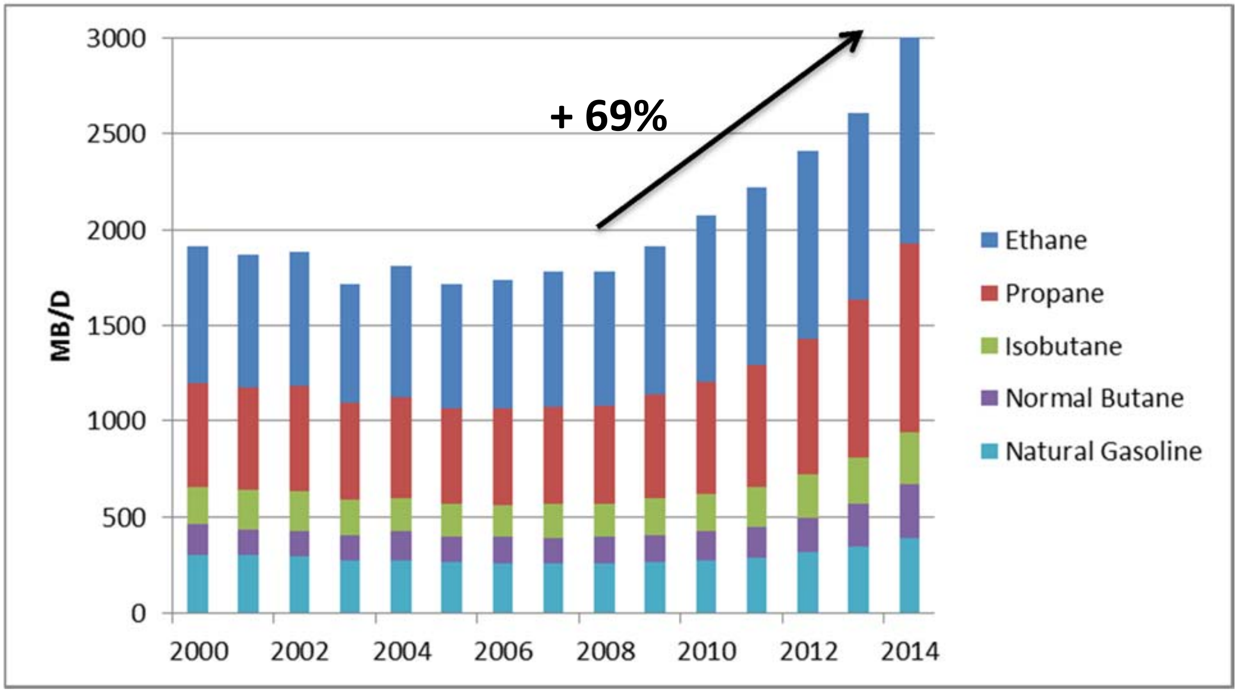
Quoting an email message received from a senior executive of a well-established European liquefied gas carrier with long experience in the transport of cryogenic liquid gases, “Technically, transporting CO_2 is not a big deal. (You) (j)ust have to choose temp/pressure to optimize your supply chain”.

The biggest challenge in utilizing existing liquefied gas carriers for transport of liquefied CO_2 (LCO_2) is the maximum allowable working pressure of the cargo tank, which would be higher than that used for regular LPG service. Although there are existing liquefied gas carriers capable of carrying LCO_2, because of the requirement for increased pressure capability, they are generally smaller and less suited to long-haul trans-Atlantic transport. Suitable vessels for LCO_2 backhaul service would fall into the “handy-size” gas carrier category; vessels with approximately 15,000 cubic meters (m^3) to 30,000 m^3 capacity.

Existing designs of “handy-size” liquefied gas carriers would need to be tailored at the newbuild design stage to make carriage of LCO_2 possible. There may be an opportunity to take advantage of increased numbers of newbuild orders to specify LCO_2 capable ships <u>at a cost which should be only marginally higher than the cost of a standard liquefied gas carrier</u>.

3. Increasing Volumes of Domestic NGL (Ethane, LPGs) Production. The U.S. “shale gas revolution” has enabled domestic natural gas production to fully meet U.S. needs and also support a vibrant LNG export industry. In addition, the “shale gas revolution” has also led to large volumes of natural gas liquids (NGLs) production (ethane plus propane, butane and pentane (LPGs)). This growth in natural gas and by-product NGL production has been so large and so rapid that it has exceeded domestic demand, enabling the U.S. to become a large net exporter of LNG and particularly NGLs, Exhibit EX-2. As shale gas production continues to grow, NGL exports will also need to grow, providing a strong base of export product for ship-based transportation of ethane and other LPGs to global markets. In addition, the U.S. contains a significant technically recoverable resource base that, under favorable demand and price conditions, could provide the foundation for more growth in NGL and LPG supplies for many years to come.

Figure EX-2. Growth of Domestic NGL Supply



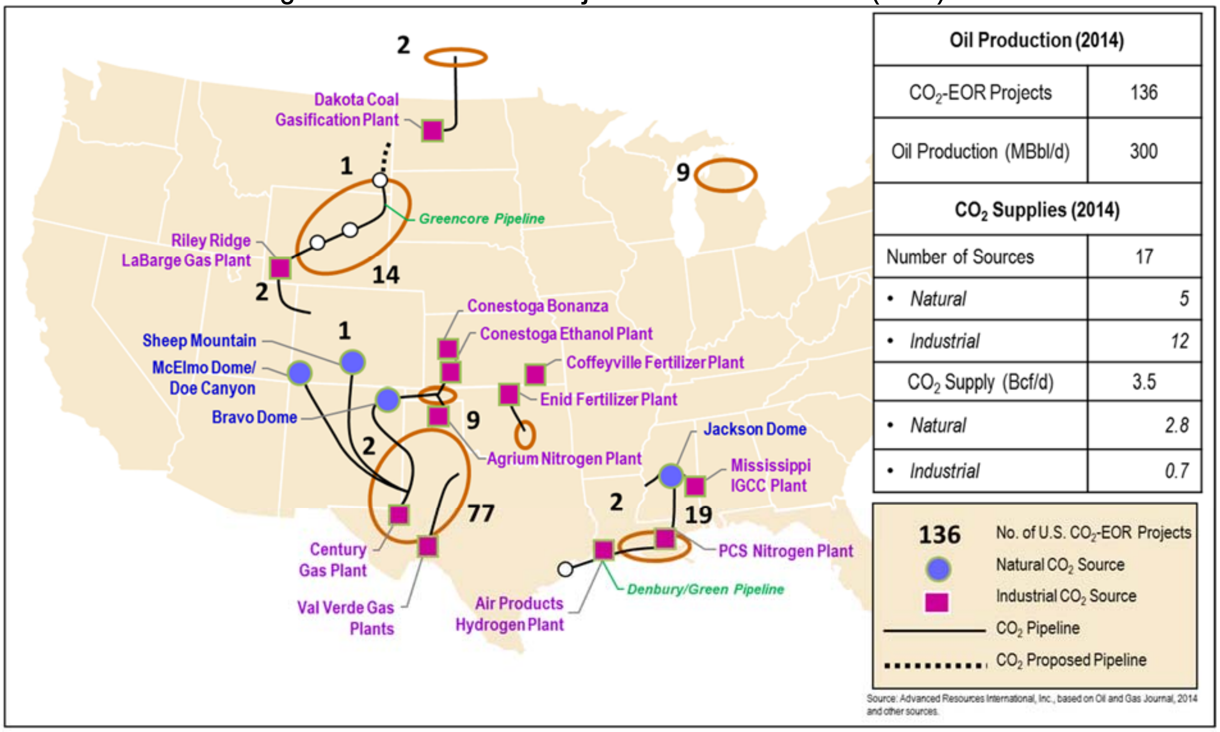
Source: U.S. EIA and ARI, 2015

4. CO_2 Market from the U.S. CO_2-EOR Industry. The U.S. has an active and growing CO_2-EOR industry, built on proven technology and several decades of successful application. Today there are 136 distinct CO_2-EOR projects underway in the U.S., using 3.5 billion cubic feet per day (Bcfd) of purchased CO_2, while facilitating about 300,000 barrels per day of crude oil production from a diversity of geological and geographic settings. Notable is the availability of a major CO_2 transportation network in the Gulf Coast area of the U.S., Figure EX-3.

CO_2-EOR based oil production has grown steadily in the past ten years, supported by the availability of both natural and industrial CO_2 supplies. Recently, the CO_2-EOR industry has established new “footholds” in the Gulf Coast and Mid-Continent drawing on industrial supplies of CO_2. However, the single largest constraint to greater production of domestic oil using CO_2-EOR is still the lack of sufficient, economically viable supplies of CO_2.

The initial target for CO_2-EOR is the 414 billion barrels of oil “left behind” in the main pay zones of existing U.S. oil fields. Of this, 284 billion barrels is technically feasible for CO_2-enhanced oil recovery, creating a demand for 9 to 26 billion metric tons of CO_2.

Figure EX-3. CO_2-EOR Projects and CO_2 Sources (2014)



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In addition to the oil "left behind" after primary and secondary recovery in the main pay portion of an oil reservoir, a large remaining oil target often exists in the lower portion of an oil reservoir (below the reservoir's water-oil contact) called the residual oil zone (ROZ). Advanced Resources has documented the presence of an additional 192 billion barrels of residual oil in-place in the San Andres Formation's ROZ "fairways" in a twelve-county area of the Permian Basin, West Texas. Reservoir modeling by Advanced Resources shows that significant volumes of the oil in-place in the ROZ is technically recoverable using miscible CO_2-EOR, with the "higher quality" portions of this resource offering promise for commercial viability at moderate oil prices.

5. Numerous Precedents Exist for Ship-Based Transportation of CO_2. The transportation and import (as well as export) of liquefied gas into the U.S. is well established with the development of the LNG industry. In addition, the precedent for trans-boundary movement of CO_2 has been established with the transportation of CO_2 from the U.S. (Dakota Gasification Facility) to Canada (Weyburn Oil Field) for use by CO_2-EOR. Additional discussion of this topic, including areas for further investigation, are provided in Chapter 1 and the Appendix to this report.

Proposed Next Steps.

To more rigorously establish the viability of ship-based transportation of CO_2, we propose the following next steps:

1. **Undertake a Detailed Design Study for System Modifications and Additional Examination of Vessel Specification for Transport of LCO_2.** The ABS study finds that the CO_2 backhaul concept is technically feasible with appropriate precautionary measures. Additional study identifying specific vessels, containment system modification requirements, trade routes, actual CO_2 sellers and buyers, load and discharge ports, and infrastructure requirements need to be completed to further establish the technical viability of this CO_2 transportation option.

2. Provide Detailed Examination of the Economic Feasibility of Ship-based Transportation of CO_2. Of particular interest would be: (1) defining the additional shipping distances and offloading time requirements for backhauling LCO_2 to U.S. ports in the Gulf Coast and possibly the West Coast, (2) establishing the capital costs for modifying the vessels and port facilities to handle LCO_2 transport and loading, and (3) estimating the “marginal” and “full” costs of transporting LCO_2 as a backhaul for NGL shipments.

3. Provide Long-Term Market Study of U.S. Ethane and LPG Production and Exports. This market study would define the outlook for future domestic NGL (ethane and LPG) production, the demand for NGLs by the domestic petrochemical industry, and the excess NGL productive capacity needing export markets.

4. Provide a Long-Term Market Study for CO_2 Demand by the CO_2-EOR Industry. Of particular interest would be the size, economic viability and CO_2 demand by the CO_2-EOR industry along the Gulf Coast of the U.S.

5. Further Define the Regulatory and Legal Issues Associated with Ship-Based Transportation of CO_2. While certain precedents exist for importing liquefied gases into the U.S. and for trans-border movement of CO_2, potential legal and regulatory issues that may need to be addressed exist; thus, further examination of these issues, as described in the Appendix, is warranted.

Feasibility Study of Ship-Based Transportation of CO_2

Chapter 1
Overview of Report

Prepared by:

Advanced Resources International, Inc.

Feasibility Study of Ship-Based Transportation of CO_2

Overview of Report

This preliminary examination of the feasibility of using ship-based transportation of CO_2 has been conducted as part of U.S. Department of Energy's (DOE) Quadrennial Energy Review (QER) as directed by the 2014 Presidential Memorandum. The QER, issued in April 2015, focuses on the current and future status of the U.S. energy infrastructure and its ability to promote economic competitiveness, energy security and environmental responsibility, notably mitigation of climate change. One of the major findings of the QER is that innovation at the systems level offers real potential for revolutionary changes to the ways we deliver and use energy. This would, in this case, also apply to the ways in which we facilitate commercially viable approaches for reducing greenhouse gas (GHG) emissions.

Significant parts of the world have the potential for capturing CO_2, from power and other industrial plants, but few opportunities exist globally for productively using or selling this CO_2 for enhanced oil recovery and by-product CO_2 storage. The introduction of tanker ships for transporting CO_2 from source to use would help overcome this barrier to efficient international carbon capture, utilization, and storage (CCUS).

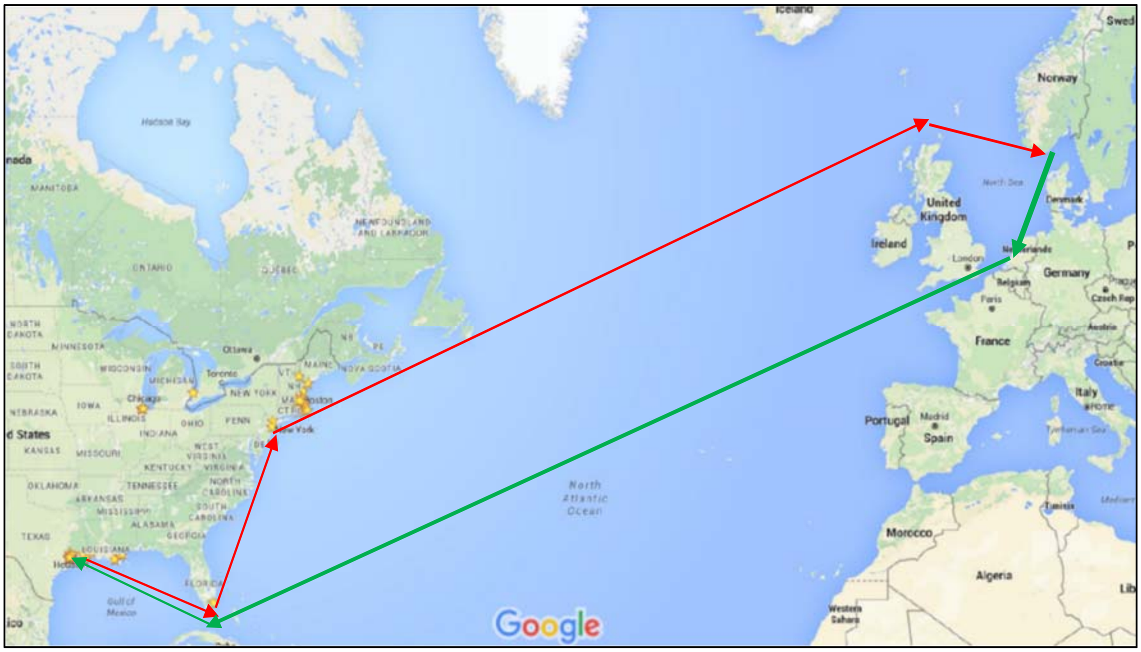
Moreover, the development of liquids-rich shale gas has greatly expanded the production and supply of ethane and LPGs (propane, butane, and pentane) in the U.S., to the point where supply exceeds demand and ethane/LPG exports are now common. Continued growth in liquids-rich shale gas promises a continuation of this situation considerably into the future.

On the other hand, the large stock of mature U.S. oil fields, facing near-term abandonment, desperately need additional supplies of CO_2 for enhanced oil recovery.

One pathway for enhancing the economic viability of this option is to use existing LPG/ethane carriers with modifications (or specifically designed dual-purpose LPG/CO_2 carriers), particularly since, in the return portion of the voyage, an LPG carrier is typically empty.

Ship-based transportation of CO_2, as assessed in this preliminary feasibility study, involves the transport of surplus natural gas liquids (NGLs) composed of ethane and liquid petroleum gasses (LPGs) from the U.S. to international markets, with CO_2 transported as "backhaul" to U.S. markets. The landed CO_2 in the U.S. could be primarily used and stored by the domestic CO_2 enhanced oil recovery (CO_2-EOR) industry, Figure 1-1.

Figure 1-1. Hypothetical Voyage: Loading Ethane in Marcus Hook, New Jersey, Discharging Ethane in NW Europe (red line), Loading CO_2 in Rotterdam, Discharging in U.S. Gulf Coast (green line)



Source: ABSC / google maps

A series of initial studies, by Chiyoda ("Preliminary Feasibility Study on CO_2 Carriers for Ship-Based CCS," October 2011) and by Lloyd's Register ("Feasibility of Danish CCS Scheme Comprised by Capture at Power Plants, Ships Transport and CO_2 EOR," May, 2011), have provided preliminary information establishing the technical viability of this CCUS option. However, numerous issues remain to be defined and assessed, particularly on the technical, commercial and regulatory feasibility of implementing this strategy in the U.S.

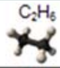
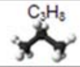
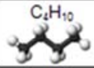
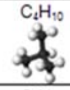
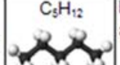
As such, the building blocks for a U.S. strategy of exporting LPGs and importing CO_2 for EOR and associated storage are in place. What is missing is more detailed information for further defining, assessing and implementing such a strategy.

1. Technical and Economic Feasibility of Ship-Based Transportation of CO_2 as a Backhaul for NGL Transport

As part of this preliminary feasibility assessment, an analysis was performed to determine whether carriage of liquid CO_2 is a feasible backhaul option for natural gas liquids (NGLs) and liquefied petroleum gas (LPG) shippers. The objective would be maximize utilization of existing or proposed vessels in liquefied gas service loading cryogenic liquid gases at U.S. Gulf of Mexico or Atlantic coast ports as an alternative to returning to the U.S. in ballast (empty of cargo). The source of the liquid CO_2 (LCO_2) would be CO_2 capture projects in Europe or other locations (such as Asia) to be specifically determined at a future development phase. The study examined the technical, operational and regulatory compliance issues to be considered for liquefied-gas vessels to be used for backhaul cargos of LCO_2.

In the context of this report, to avoid confusion with multiple marine vessel categories and types, the term liquefied gas carrier is used to cover the entire range of vessels with the technical capacity to carry liquid gases, including CO_2. The term natural gas liquids (NGLs) is used throughout this report and covers the spectrum of liquefied gases carried by ship. The term liquefied petroleum gas (LPG) is used in the shipping industry to refer mainly to propane and butane (see Table 1-1 for description of NGLs).

Table 1-1. Common Natural Gas Liquids

NGL Attribute Summary				
Natural Gas Liquid	Chemical Formula	Applications	End Use Products	Primary Sectors
Ethane	C_2H_6 	Ethylene for plastics production; petrochemical feedstock	Plastic bags; plastics; anti-freeze; detergent	Industrial
Propane	C_3H_8 	Residential and commercial heating; cooking fuel; petrochemical feedstock	Home heating; small stoves and barbeques; LPG	Industrial, Residential, Commercial
Butane	C_4H_{10} 	Petrochemical feedstock; blending with propane or gasoline	Synthetic rubber for tires; LPG; lighter fuel	Industrial, Transportation
Isobutane	C_4H_{10} 	Refinery feedstock; petrochemical feedstock	Alkylate for gasoline; aerosols; refrigerant	Industrial
Pentane	C_5H_{12} 	Natural gasoline; blowing agent for polystyrene foam	Gasoline; polystyrene; solvent	Transportation
Pentanes Plus*	Mix of C_5H_{12} and heavier	Blending with vehicle fuel; exported for bitumen production in oil sands	Gasoline; ethanol blends; oil sands production	Transportation

C indicates carbon, H indicates hydrogen; Ethane contains two carbon atoms and six hydrogen atoms
*Pentanes plus is also known as "natural gasoline." Contains pentane and heavier hydrocarbons.

Source: U.S. Energy Information Administration

As a result of improved onshore oil and gas extraction technologies over the last decade, U.S. domestic oil and gas fields produce significant quantities of oil, natural gas and natural gas liquids (NGLs). As a result, NGLs have become available for export as a result of supply exceeding demand in the U.S. (See discussion below and in Chapter 3). Until recently, U.S. export capability has been limited, but major NGL export projects have been developed in the U.S. and are now coming on stream to supply energy products to world markets. NGLs are in demand globally as a feedstock for various industrial and chemical processes.

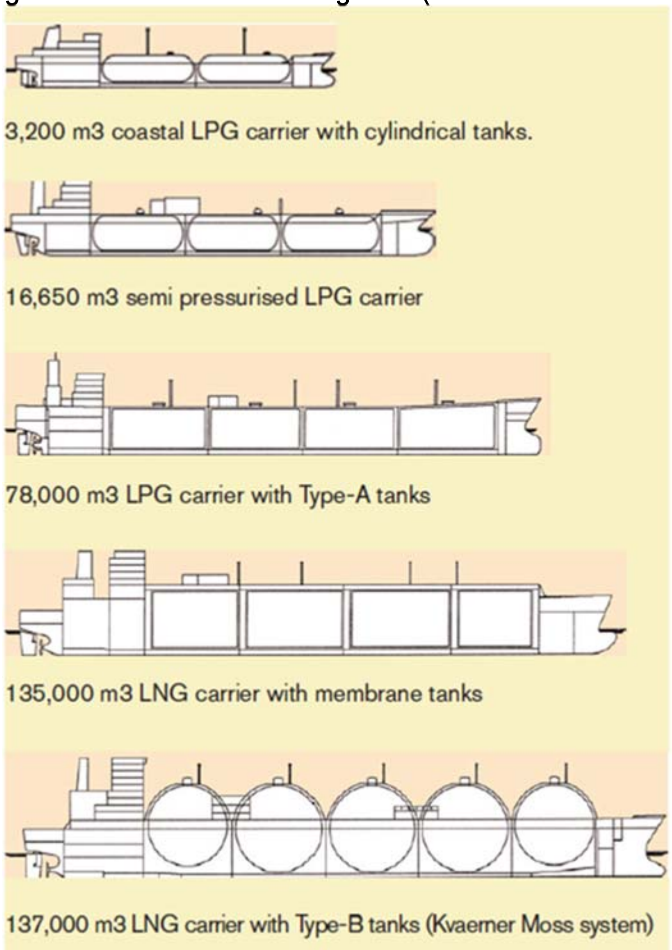
NGL exporting involves the use of specialized ships known as liquefied gas carriers with pressurized cargo tanks and cargo handling systems capable of carrying liquefied gases with temperatures as cold as -160°C (-260°F) throughout a range of pressures. These ships are designed and built according to stringent international design criteria to permit safe transport and handling of cryogenic and pressurized liquid gases. The types of ships that can carry NGLs and LPGs are shown in Figure 1-2.

The biggest challenge in utilizing existing liquefied-gas carriers is the maximum allowable working pressure of the cargo tank, which would be higher than that used for regular LPG service. Although there are existing liquefied gas carriers capable of carrying LCO_2, because of the requirement for increased pressure capability, they are generally smaller and less suited to long-haul trans-Atlantic transport.

Basic vessel technical requirements for carrying LCO_2 are:

- Type 2G or 3G liquefied gas carrier with, or capable of being approved for, a Certificate of Fitness for liquid CO_2
- Type C (pressure vessel) containment system with greater than 7 Bar g design pressure and appropriate safety margin
- Tanks and cargo systems suitable for cryogenic liquid gases colder than -55°C
- Permission from the relevant authorities to carry liquid CO_2
- Sufficient cargo carrying capacity to allow competitive unit freight costs.

Figure 1-2. Gas Carrier Categories (Source: UK P&I Club)



Suitable vessels for LCO_2 backhaul service would fall into the "handy-size" gas carrier category; vessels with approximately 15,000 m^3 to 30,000 m^3 capacity. The notional candidate vessels identified in this report have less than 15,000 m^3 cargo capacity.

Increased U.S. NGL exports are driving requirements for more liquefied gas carriers to lift cargos from Gulf and East coast ports. Existing designs of handy-size liquefied gas carriers are a close fit, but would need to be tailored at the new-build design stage to make carriage of LCO_2 possible. There may be an opportunity to take advantage of increased numbers of handy-size new-build orders to specify LCO_2 capable ships at a cost which should be only marginally higher than the cost of a standard liquefied gas carrier.

Potential time loss and the logistical and operational elements of changing cargo grades and voyage deviations will also significantly affect the feasibility of LCO_2 backhaul on a specific trade route, charter, or contract of affreightment. The potential for net hydrocarbon emissions increases also has to be evaluated in the context of environmentally responsible shipping and CCS project objectives.

A variety of economic and operational factors of moderate complexity and likelihood must be aligned in order for ship-owners to regard LCO_2 backhaul as an attractive market. These include:

- Availability of suitable vessels with the requisite cargo tank design pressure
- Development of needed infrastructure (CO_2 storage and marine transfer facilities)
- Long term commitment of project stakeholders, including shippers and CCS project developers and sponsors
- Sufficient economic inducement for all participants in the value chain.

In general, the CO_2 backhaul concept is technically feasible with appropriate precautionary measures. Favorable shipping and logistics factors provide support and opportunity for development of the concept. Additional study identifying specific vessels, containment system modification requirements, trade routes, actual CO_2 sellers and buyers, load and discharge ports, and infrastructure requirements must be completed for proof of concept.

Based on these criteria for carriage of CO_2 and the initial shipping considerations described above, a number of existing vessels have been identified as being potentially CO_2 capable based on their capacity and permitted cargos. According to information from Clarkson's shipping database, there are approximately thirty pressurized liquefied gas carriers currently in service that could be considered suitable (Table 1-2). These vessels represent part of the potential available pool from which CO_2 backhaul candidates could be chosen. Further study would be needed to identify specific ships that meet the technical requirements to carry CO_2 matched with trading routes that could facilitate CO_2 backhaul cargos and ship owners and charterers with sufficient incentive to accept them.

Note that this is a preliminary screening and that the ships listed above are notional candidates based on capacity and cargo type. Confirmation by the ship owner of LCO_2 technical capability and issuance of a Certificate of Fitness listing LCO_2 as a permitted cargo would be the required next step.

Table 1-2. Candidate Ships Based on Potential LCO_2 Capability Listed by Capacity
(Source: Clarkson's)

Vessel Name	Type	Builder	Built Date	Capacity (cu m)	Tank Temp (C)	Tank Pressure (kgf sq m)	Owner Company
Donau	LPG Carrier	Meyer Werft	01/09/85	30200	-50	7.0	Exmar LPG BVBA
Norgas Napa	Ethylene/LPG	Zhonghua Shipyard	01/10/03	10208	-104	7.0	Teekay LNG Partners
Norgas Shasta	Ethylene/LPG	Zhonghua Shipyard	01/08/03	10208	-104	7.0	Norgas Carriers
Norgas Alameda	Ethylene/LPG	Zhonghua Shipyard	01/05/03	8556	-104	7.0	Norgas Carriers
Norgas Orinda	Ethylene/LPG	Zhonghua Shipyard	01/10/02	8556	-104	7.0	Norgas Carriers
Norgas Petaluma	Ethylene/LPG	Zhonghua Shipyard	01/03/03	8556	-104	7.0	GasMar AS
Norgas Sonoma	Ethylene/LPG	Zhonghua Shipyard	01/01/03	8556	-104	7.0	SGPC
Jemila	LPG Carrier	A.E.S.A.	01/03/83	8040	-48	8.0	Sonatrach Petroleum
Gaz Venezia	LPG Carrier	I.N.M.A.	01/12/95	7434	-48	7.5	Naftomar Shpg & Trad
Mores	Ethylene/LPG	I.N.M.A.	01/02/94	7414	-104	7.5	Lumaship S.r.l.
Virgen del Carmen B	LPG Carrier	I.N.M.A.	01/12/92	7350	-48	7.5	Transgas Shpg. Lines
Coral Palmata	Ethylene/LPG	Cant.Nav.Pesaro	01/06/94	7164	-104	7.0	Anthony Veder
Coral Pavona	Ethylene/LPG	Cant.Nav.Pesaro	01/07/95	7164	-104	7.0	Anthony Veder
Gas Optimal	LPG Carrier	Ast.De Mallorca	01/01/85	7115	-48	8.0	Nautilus Marine
PGC Strident Force	LPG Carrier	Higaki Zosen	01/06/99	6527	-48	7.0	Paradise Gas Carr.
Queen Phenix	Ethylene/LPG	HyundaiHI (Ulsan)	01/10/96	6481	-104	8.0	Daiichi Tanker Co.
Happy Bride	LPG Carrier	Hyundai HI (Ulsan)	01/04/99	6270	-48	7.0	Ultragas Aps
Tanja Kosan	LPG Carrier	Hyundai HI (Ulsan)	01/05/99	6270	-48	7.0	Lauritzen Kosan
Tilda Kosan	LPG Carrier	Hyundai HI (Ulsan)	01/02/99	6270	-48	7.0	Lauritzen Kosan
Syn Atlas	Ethylene/LPG	Cant. Nav. Morini	01/02/93	6073	-104	7.0	Synergas S.r.l.
Tenna Kosan	LPG Carrier	Hyundai HI (Ulsan)	01/09/98	5900	-48	7.6	Lauritzen Kosan
Tessa Kosan	LPG Carrier	Hyundai HI (Ulsan)	01/01/99	5900	-48	7.6	Lauritzen Kosan
Gaschem Weser	LPG Carrier	Malaysia S.Y. & Eng.	01/12/99	5734	-48	9.5	Hartmann Schiff.
Gaschem Hunte	LPG Carrier	Kodja Bahari	01/09/00	5730	-48	9.5	Hartmann Schiff.
Blue Dream	LPG Carrier	Meyer Werft	01/06/81	5647	-48	7.5	Arvina Trade Ltd.
Zuma Rock	LPG Carrier	Meyer Werft	01/01/75	5450	-48	8.3	Petrobulk Shipping
Gaschem Jade	LPG Carrier	J. Pattje	01/10/92	5322	-48	10.5	Hartmann Schiff.
Gaschem Jumme	LPG Carrier	J. Pattje	01/05/93	5322	-48	10.5	Hartmann Schiff.
Melina	LPG Carrier	Lindenau	01/09/84	5253	-48	11.2	Hellenic Petroleum
Habas	LPG Carrier	Usuki Zosensho	01/06/84	5060	-48	7.0	Habas Petrol

Although it is technically feasible to carry LCO_2 in liquefied gas carriers, such as those identified in Table 1-2, it is important to recognize that there are many challenges to be met before CO_2 backhaul can be incorporated into current trading routes.

Existing LCO_2 dedicated vessels are not suited for long haul, cost efficient transport of LCO_2. The LCO_2 capable liquefied gas carriers listed in Table 1-2 may not have sufficient cargo carrying capacity for cost efficient trans-Atlantic voyages.

Absent the current lack of CO_2 supply, active CO_2 trading markets and supporting infrastructure, the most significant challenge is to find existing or on-order ships with cargo tanks that can accommodate the higher pressure required to safely and efficiently carry CO_2.

Further study to include direct surveys of ship owners with vessels operating in LPG service is recommended to identify specific ships meeting these criteria:

- Type 2G or 3G liquefied gas carrier with, or capable of being approved for, a Certificate of Fitness for liquid CO_2
- Type C (pressure vessel) containment system with greater than 7 Bar g design pressure and appropriate safety margin (Note that lower design pressures may be possible if confirmed by operational evaluation)
- Tanks and cargo systems suitable for cryogenic liquid gases
- Permission from the relevant authorities to carry liquid CO_2
- Sufficient cargo carrying capacity to allow competitive unit freight costs.

Existing designs of handy-size liquefied gas carriers are a close fit, but would need to be modified at the newbuild stage with cargo tanks of sufficient design pressure to accommodate carriage of CO_2.

It is possible that new-build vessels designed for LCO_2 as well as NGLs may provide a better marine transport solution as the U.S. NGL export market and the CCS market evolves.

Liquefied gas carriers could be changed to accommodate carriage of CO_2 by increasing the cargo tank design pressure. It is expected that the cost of the required modifications should be only marginally higher than for a standard liquefied gas carrier, but an evaluation of cost in relation to the specific LCO_2 opportunity is recommended.

In order for the concept to work as intended, sufficient monetary inducements to charterers to offset the daily hire rate of the vessel must be offered.

There is also an opportunity cost to be quantified depending on a number of factors:

- Cost to deviate or reposition from the load and discharge ports specified in the charter
- Charterer's willingness to deviate from set voyage routes
- Available backhaul cargos that are more attractive economically, operationally or logistically
- Potential for delayed or missed scheduled loading and related commercial penalties
- Cargo changeover and preparation time costs
- Environmental impacts- hydrocarbon emissions from cargo changeover, carbon emissions offset considerations from potential CO_2 venting.

Current CO_2 marine storage and transfer infrastructure is currently not sufficiently developed to support large scale movement of LCO_2. Collaboration in the form of a joint industry project (JIP) or similar venture between CCS projects, ship owners, LPG shippers, CO_2 end users, regulatory bodies and industry organizations is recommended to develop a coordinated solution incorporating marine transportation of CO_2 that optimizes existing and planned transportation, storage and distribution infrastructure.

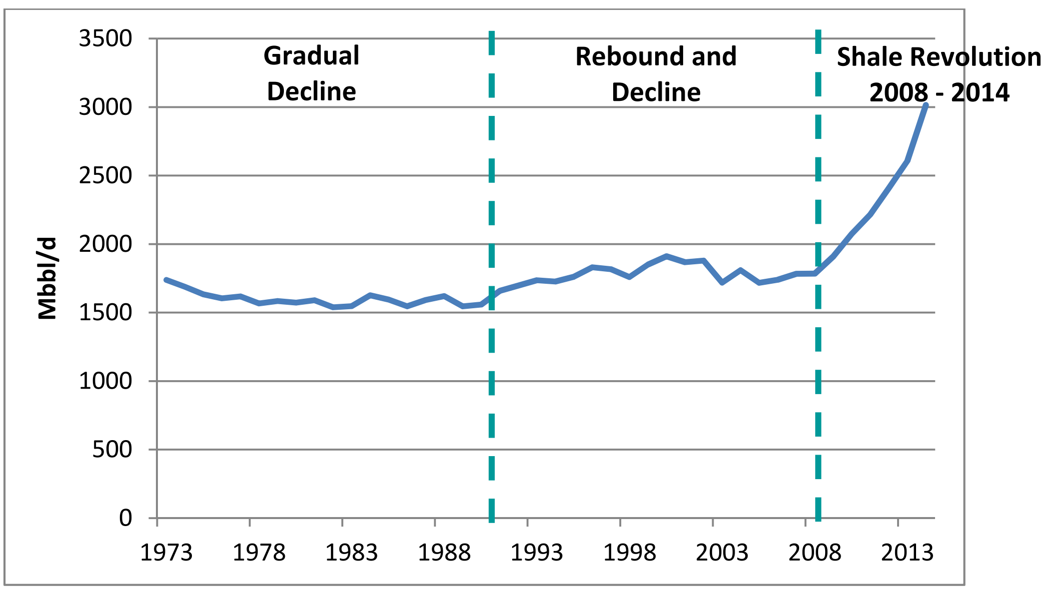
2. Status and Outlook for U.S. Natural Gas Liquids Supply and Demand

After nearly twenty years of decline, domestic NGL production hit a low of 1.6 million barrels per day (MMB/D) in 1990. With expectations of scarcity and higher prices for natural gas, much of the domestic petrochemical industry, particularly along the Mississippi River, relocated to areas with more secure, accessible supplies of NGLs as well as naphtha, an alternative to using NGLs as feedstock in chemical plants.

Subsequently, NGL production rebounded and then stayed relatively flat at 1.8 to 1.9 MMB/D through 2008, but this rebound was met with skepticism by industry as to its sustainability. As such, industry's pessimistic outlook for future NGL production remained entrenched and petrochemical operations continued to relocate overseas, relying primarily on naphtha as the preferred feedstock for ethylene production.

However, since 2008, U.S. production of NGLs (from gas plants) has surged -- from 1.8 million barrels per day in 2008 to 3.0 million barrels per day in 2014, Figure 1-3.

Figure 1-3. Domestic Natural Gas Liquids Production

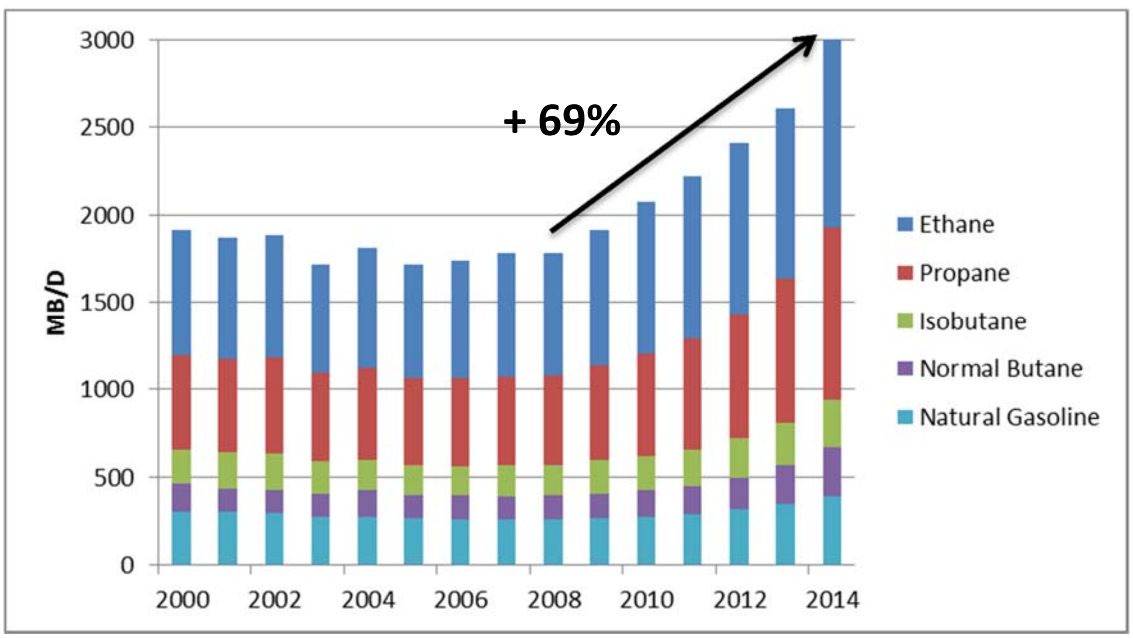


Source: U.S. EIA, 2015

This dramatic change in the domestic NGL supply situation has been brought about by the “shale gas revolution”, particularly the discovery and development of wet, liquids-rich shale gas plays such as the Woodford, SW Marcellus, and Utica. Additionally, liquids-rich associated gas from “tight oil” plays such as the Bakken, Eagle Ford and the stacked formations of the Permian further boosted NGL supply.

Much of the growth in domestic NGL supply has been from increased production of ethane and propane. Ethane production increased by 0.4 MMB/D -- from 0.7 MMB/D in 2008 to 1.1 in 2014 -- despite rejection of an estimated 0.8 MMB/D of technically recoverable ethane in 2014. Meanwhile, propane production increased by 0.5 MMB/D over this same time period, from 0.5 MMB/D to 1.0 MMB/D. In addition, production of iso-butane, normal butane, and pentane (natural gasoline) increased by a combined 0.4 MMB/D, from 0.6 MMB/D to 1.0 MMB/D. Figure 1-4 illustrates the recent growth of NGL production by the five key product streams.

Figure 1-4. Growth of Domestic NGL Supply, by Product



Source: U.S. EIA and ARI, 2015

With the strong growth in domestic NGL production, in 2011 the U.S. became a net exporter of natural gas plant liquids and liquefied refinery gases for the first time since the data for imports/exports of NGLs has been recorded.

Ethane. The primary driver of ethane demand is feedstock for production of ethylene and other chemicals in competition with naphtha. With increasing production of low cost wet (liquids-rich) natural gas, the cost advantage of producing ethylene from ethane has stimulated expansion and new construction of ethane crackers. Additionally, dedicated ethane pipelines, export terminals, and tankers are under development. However, increases in domestic ethane production have greatly exceeded growth in domestic demand. As such, increased ethane exports are needed to remedy the current surplus situation and low price.

Propane. Propane, the most seasonal of the NGL streams, is used in a variety of capacities, from residential heating in the winter, to agricultural use in the fall and petrochemical use year round. With the steady growth of domestic propane production, Figure 1-5, the U.S. began exporting propane in 2011 and exported 0.4 MMB/D of propane in 2014 (0.3 MMB/D, net), Figure 1-65. The exports primarily depart from Gulf Coast terminals located in close proximity to the large NGL processing complex at Mont Belvieu, TX. Additionally, propane is also exported from the Marcus Hook facility on the East Coast. Proposed West Coast propane export terminals in Oregon and Washington are in the early stages of planning.

Figure 1-5. Growth of Domestic Propane Production

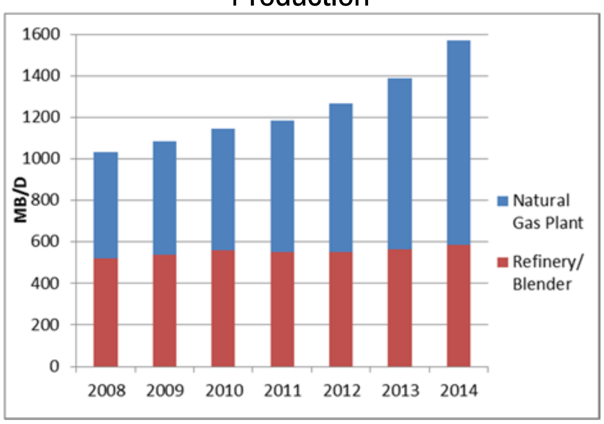
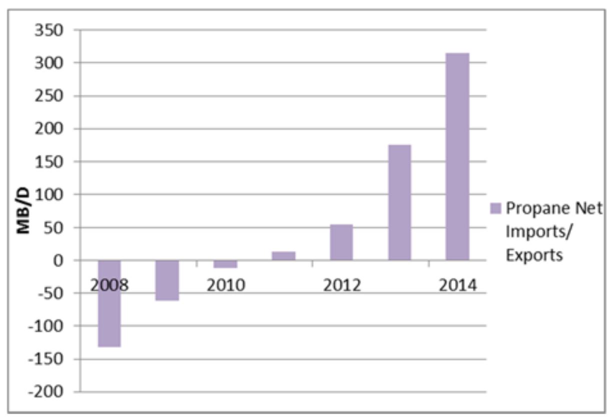


Figure 1-6. Imports and Exports of Propane



Butane and Pentane. Normal butane can be used for gasoline blending and as a petrochemical feedstock, whereas isobutene is primarily used in the production of motor gasoline by refineries. Pentane is primarily used as a blending stock for transportation fuel and as a diluent for heavy oil. These heavier NGL components, iso and normal butane and pentanes plus, are largely consumed domestically. However, in 2014 the U.S. exported a modest volume of butane (55 MB/D, net) and a moderate volume of pentane (152 MB/D, net).

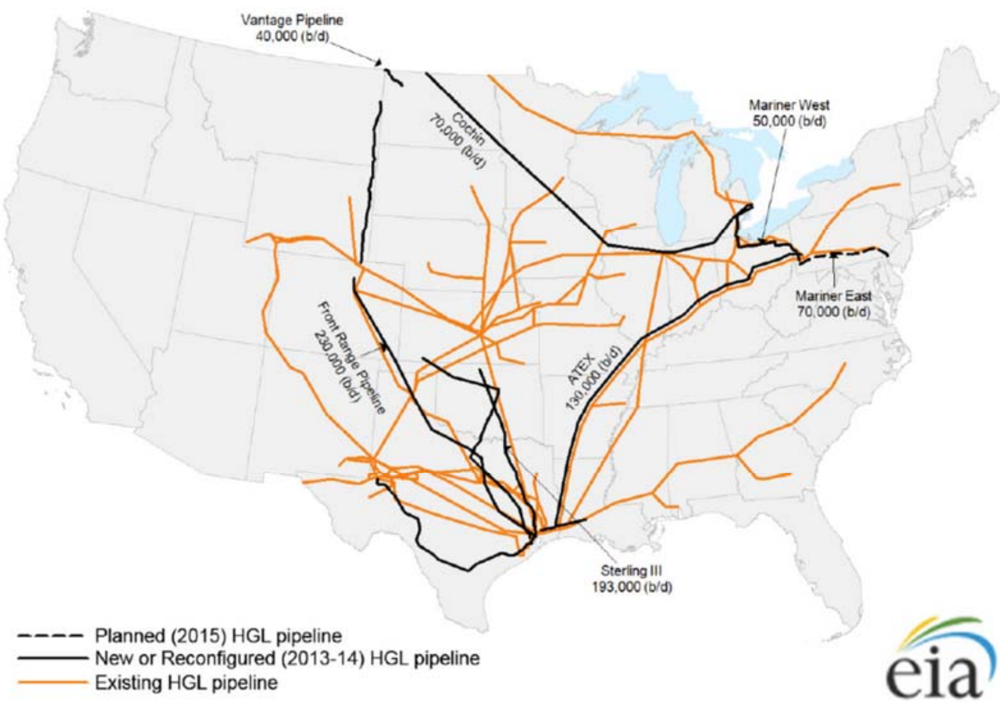
NGL Pricing. NGL prices have collapsed in the last two years due to oversupply and a decline in the price of oil. In the Marcellus, one of the primary regions of NGL supply growth, NGL prices have been hit particularly hard, declining by over 70% in the 18 month period ending in mid-2015.

Ethane, currently with a Mt. Belvieu price of $7.80/B ($0.19 /gal or ~$2.80/MMBtu), is being rejected widely as operators often receive more value by keeping ethane in the gas stream than by processing it. Similarly, propane prices have collapsed as well, with current prices of about $16.80/B ($0.40/gal or $4.40/MMBtu).

Driving the economics of exporting ethane is the price spread between ethane and naphtha, which has favored ethane over the past few years due to the lower cost of ethane and a higher oil price. Overseas, many of the crackers used for the production of propylene/ethylene, the basic building blocks of plastics, use naphtha as a feedstock. Naphtha pricing tracks global oil prices closely, meaning that in the high oil price world of 2012 through the first half of 2014, naphtha was at a disadvantage to ethane as a feedstock. The oil price decline has narrowed the spread between ethane and naphtha, potentially reducing the economic attractiveness of the multiple new “world scale” ethane crackers currently under construction in the U.S. However, the long term fundamentals of a growing ethane supply remain intact, and exports and/or new domestic crackers are needed to balance supply and demand.

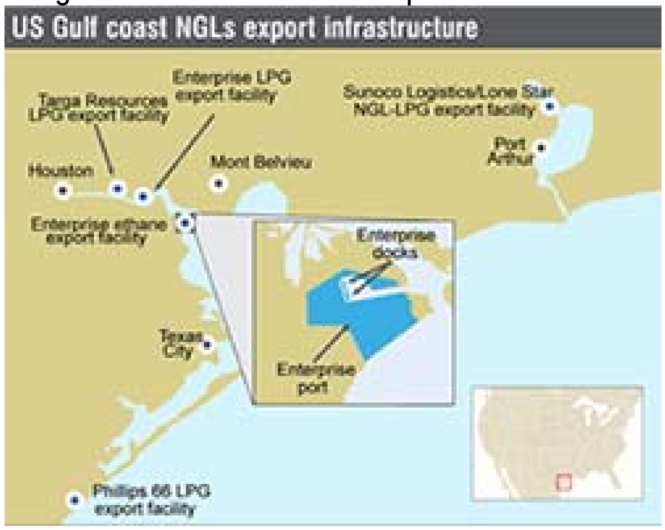
NGL Pipeline System and Exports. To reduce the NGL glut in regions such as the Appalachian Basin, major new NGL pipelines are on line or under construction, such as the Enterprise ATEX ethane pipeline, to transport NGLs to processing and export hubs on the Gulf Coast (Figure 1-7). Ethane shipments to Canada from PADD 2, to be used by Canadian petrochemical facilities, have also commenced on newly built pipelines. The Mariner East project, which Sunoco is currently considering expanding, transports NGLs from the Marcellus Shale to the Marcus Hook export terminal on the East Coast. Companies like Ineos have contracted for the shipment of ethane from Marcus Hook for use at their ethane cracking facilities in Europe.

Figure 1-7. Domestic NGL Pipelines



Much of the domestic NGL storage, processing, and export infrastructure is located on the Texas Gulf Coast (Figure 1-8). In response to increasing domestic NGL supplies and in anticipation of the widening of the Panama Canal in 2016, which will allow for the transit of the largest NGL product ships to and from Asia, many NGL export terminals on the Gulf Coast are undergoing expansions, such as Enterprise's Houston Ship Channel and Targa Resource's Galena Park Marine Terminal. Also, a new LPG export terminal with initial export capacity of 4.4 million barrels per month is currently under construction in Freeport, TX, and is due on-line in the second half of 2016.

Figure 1-8. Gulf Coast NGL Export Infrastructure



Source: Argus Media. 2015

In ARI's proprietary NGL data base, we carry over 100 billion barrels of remaining technically recoverable NGL resource, providing a robust resource base for continued NGL production growth under the right price and demand conditions. Implicitly affirming the sustainability and growth potential of domestic NGL supply are the multitude of new petrochemical facilities being constructed in the U.S. to capitalize on the NGL production resultant from shale gas and "tight oil" development.

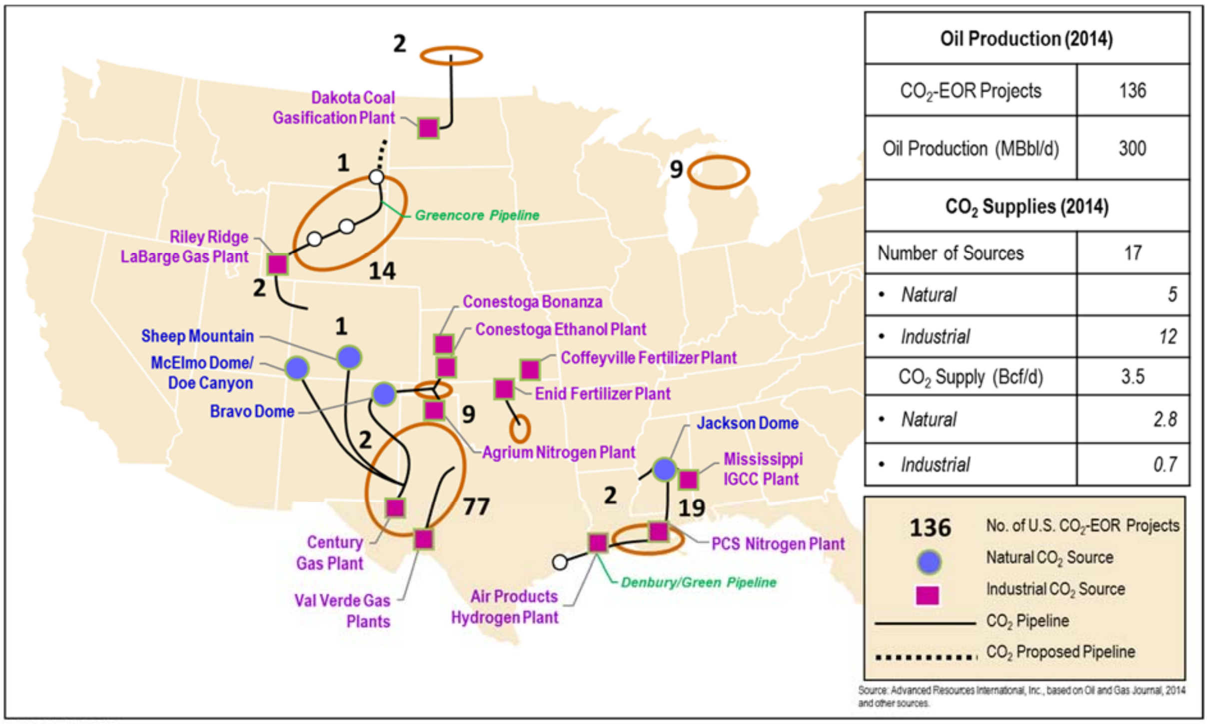
Additional work is required to build upon this preliminary review of the current status of domestic NGL supply, demand and exports to provide a longer outlook for this important hydrocarbon product for years 2015-2025.

3. Market Potential for Ship-Based Transportation of CO_2 for Use by the U.S. EOR Industry

Historical Growth in EOR Production and the Associated Demand for CO_2. The U.S. has an active and growing CO_2 enhanced oil recovery (CO_2-EOR) industry, built on proven technology and several decades of successful application. The first commercial CO_2 flood began in 1972 at the SACROC Unit of the Kelly-Snyder oil field in the Permian Basin of West Texas. This CO_2 flood continues to operate successfully and, with recent investments, currently provides nearly 30,000 barrels per day of crude oil production. In the 1980s, a number of additional field-scale CO_2 floods were launched in major Permian Basin oil fields, such as Seminole, Slaughter and Wasson, establishing the commercial viability of CO_2-EOR.

Today there are 136 distinct CO_2-EOR projects underway in the U.S., facilitating about 300,000 barrels per day of crude oil production from a diversity of geological and geographic settings, Figure 1-9.

Figure 1-9. CO_2-EOR Projects and CO_2 Sources (2014)



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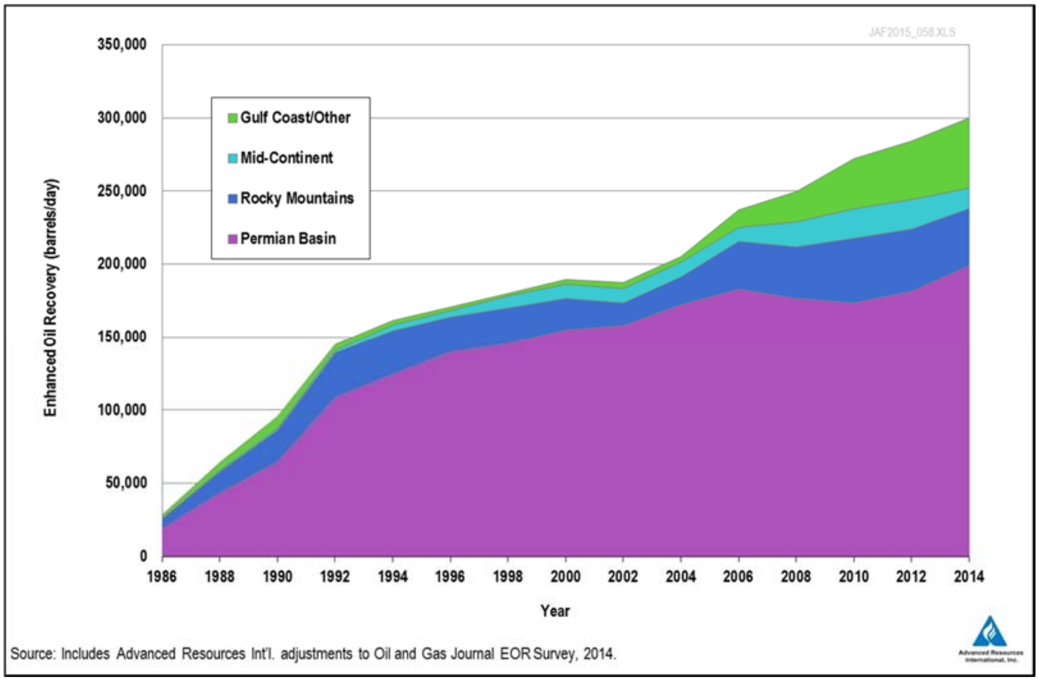
In addition to providing important volumes of domestic oil production, the application of CO_2-EOR in domestic oil fields provides opportunities for secure, long-term storage of CO_2, as well as revenues to the CO_2 capture facilities from the sale and use of industrial CO_2 by the enhanced oil recovery industry.

CO_2-EOR based oil production has grown steadily in the past ten years, supported by the availability of both natural and industrial CO_2 supplies, Figure 1-10. The figure shows that while CO_2-EOR production in the Permian Basin has plateaued, due to limits on readily available CO_2 supplies, it has increased in the Mid-Continent and Gulf Coast, where additional natural and industrial supplies of CO_2 have been developed.

Figure 1-10. Growth of CO_2-EOR Production



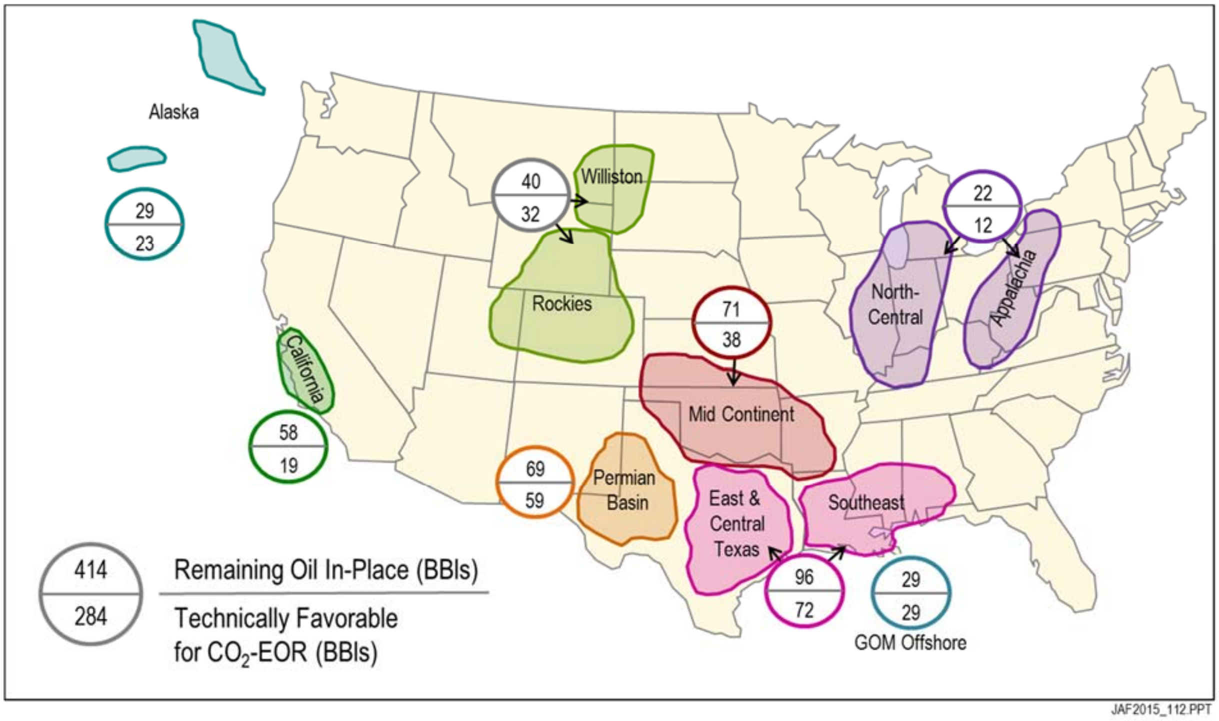
Source: Includes Advanced Resources Int'l. adjustments to Oil and Gas Journal EOR Survey, 2014.

Today, the much higher oil production potential from CO_2-EOR in the various U.S. oil basins is limited by the lack of sufficient supplies of affordable CO_2. In addition, as the existing natural sources of CO_2 for EOR become depleted (such as the McElmo Dome, Colorado and Jackson Dome, Mississippi natural CO_2 deposits), the enhanced oil recovery industry will need to rely increasingly on anthropogenic CO_2 supplies captured from industrial and power plants if it is to achieve its underlying potential. Ship-based imports of CO_2 would help fill the CO_2 supply gap.

Future Growth Potential for CO_2 for EOR. Overall, the U.S. has recovered or proven a little over a third, 210 billion barrels, of its 624 billion barrels of original oil in-place endowment by using primary and secondary methods. As such, 414 billion barrels of oil have been "left behind", providing an attractive target for enhanced (tertiary) oil recovery methods, particularly the use of miscible and immiscible CO_2 injection.

The distribution of the "left behind" oil in-place and the portion of this oil in-place that is technically favorable for CO_2-EOR is shown in Figure 1-11 for eight composite market regions of the country. With over 100 billion barrels of "left behind" oil technically favorable for CO_2-EOR, Figure 1-11 illustrates the importance of the Gulf Coast region (GOM offshore, Southeast and East/Central Texas) as the prime market area for delivery of new supplies of CO_2 for enhanced oil recovery.

Figure 1-11. Regional Distribution of the Target Resource for CO_2-EOR



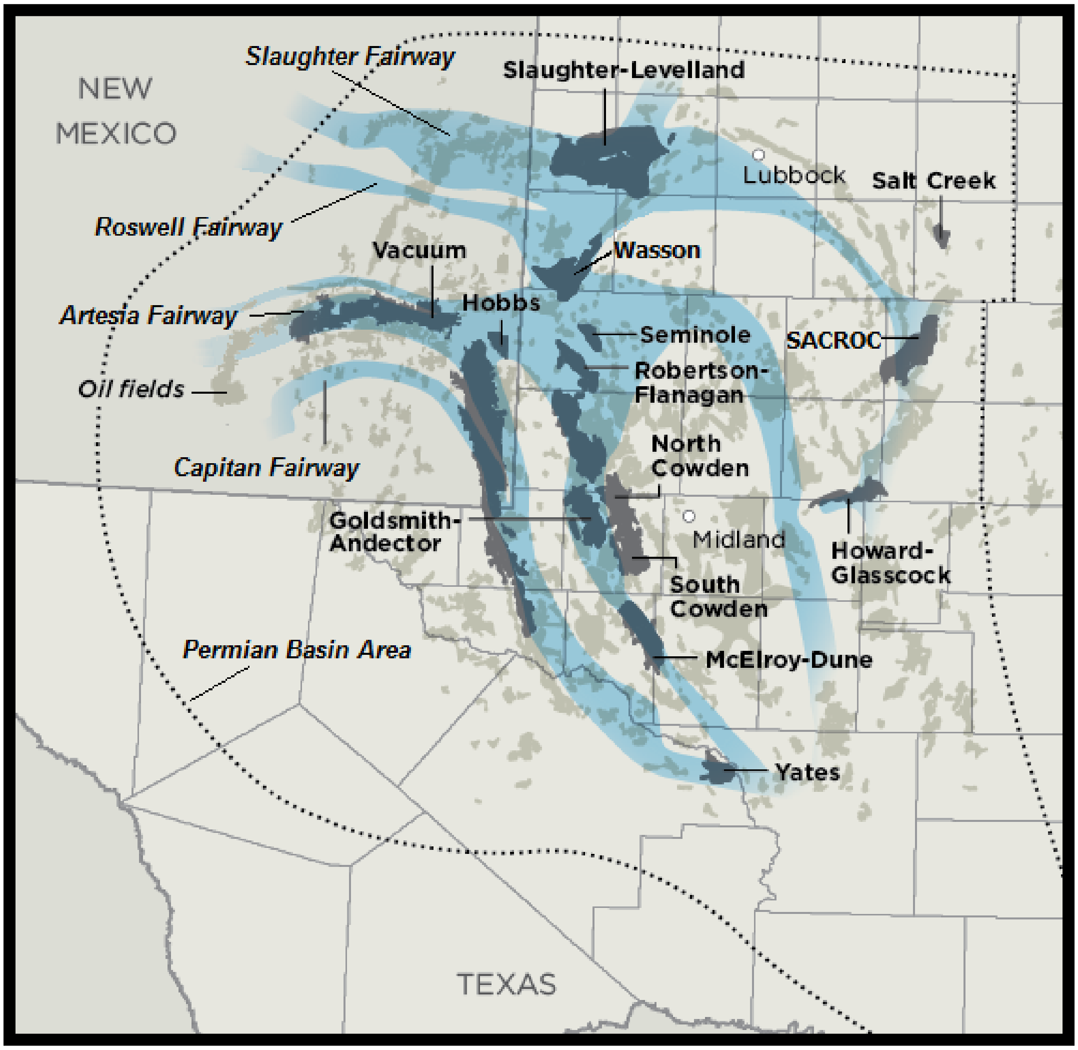
Source: Advanced Resources International, 2015.

In addition to the oil "left behind" after primary and secondary recovery in the main pay portion of an oil reservoir (above the reservoir's water-oil contact), a large remaining oil target often exists in the lower portion of an oil reservoir (below the reservoir's water-oil contact) called the residual oil zone (ROZ).

Advanced Resources has documented the presence of an additional 112 billion barrels of residual oil in-place in the San Andres Formation's ROZ "fairways" in a four-county area of the Permian Basin, West Texas. A significant portion of this ROZ resource, equal to 77 billion barrels of oil in-place, is in "higher quality" reservoir settings (porosity greater than 8% and remaining oil saturation greater than 25%). Reservoir modeling by Advanced Resources shows that 27 billion barrels of the ROZ oil in-place is technically recoverable using miscible CO_2-EOR, with the "higher quality" portions of this resource offering promise for commercial viability.

Recent work by Melzer and Trentham has identified a series of San Andres Formation residual oil zone (ROZ) "fairways" in the Permian Basin that have been created by nature's waterflooding of these oil reservoirs below their main pay zone, Figure 1-12.

Figure 1-12. San Andres ROZ “Fairways of the Permian Basin



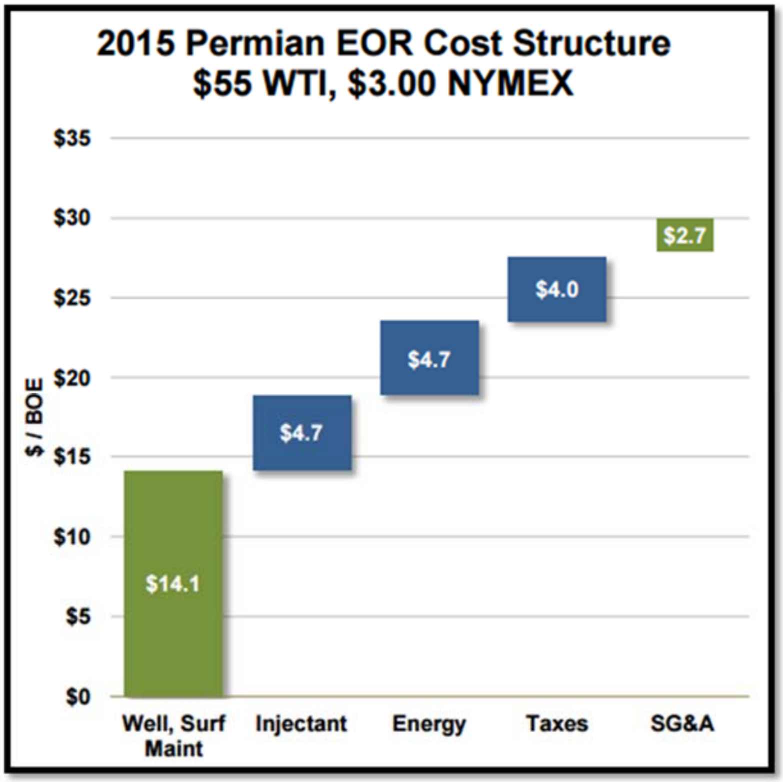
Source: Melzer Consulting, 2014.

In addition to providing potential for additional production of domestic oil, the San Andres ROZ “fairway” resource also offers an additional geologically favorable setting for storing CO_2. More recent work on the San Andres ROZ “fairway” resource of the Permian Basin, involving a detailed log- and core-based assessment by Advanced Resources, the University of Texas Permian Basin and Melzer Consulting identified another 79 billion barrels of residual oil in-place in an eight-county San Andres ROZ “fairway” area south of the original four-county area. While the calculation of technical recoverability of this second large ROZ oil in-place resource has yet to be performed, the eight-county ROZ study did establish that 58 billion barrels of the larger 79 billion barrels of San Andres ROZ “fairway” oil in-place in this eight-county area was in “higher quality” reservoir settings (porosity greater than 8% and remaining oil saturation greater than 25%).

Economic Viability of CO_2-EOR under Low Oil Prices. The recent decline in the price of oil has led some analysts to question the economic viability of CO_2-EOR at a time of lower oil prices. While many of the past studies of the economics of CO_2-EOR have been conducted using oil prices of \$75 to \$90 per barrel, a look at industry’s cost data shows that the application of CO_2-EOR in higher quality oil fields can be economically viable at oil prices of \$50 to \$60 per barrel.

For example, as shown in Figure 1-13, Occidental Petroleum, the most active and largest CO_2-EOR operator in the U.S., with an extensive number of CO_2-EOR projects in the Permian Basin, shows that Permian CO_2-EOR projects can generate significant net operating revenues at a \$55 per barrel (WTI) oil price. Included in the cost structure is an allocation of \$4.70/B for the CO_2 injectant, \$4.00/B for production taxes, \$4.70/B for power and energy and \$16.80 for other CO_2-EOR costs.

Figure 1-13. Typical Costs for a Permian Basin CO_2-EOR Project at Current Oil Prices

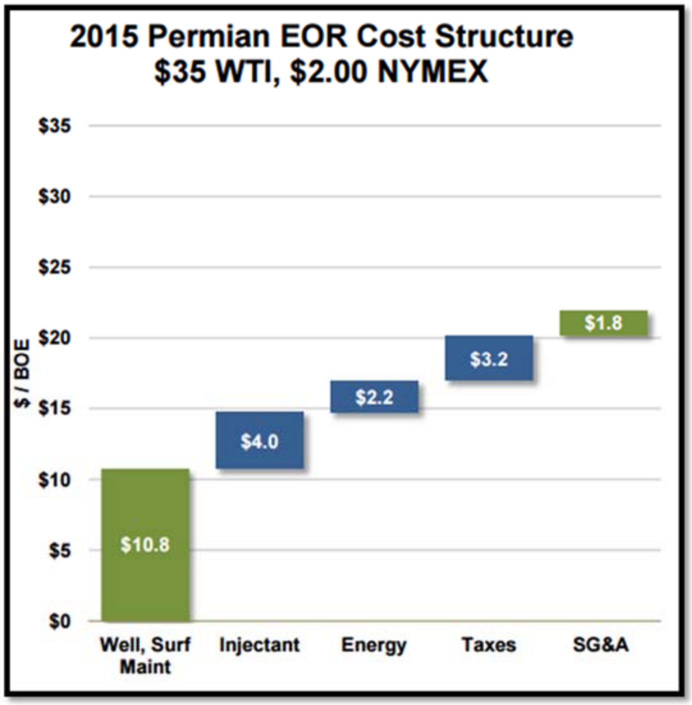


Source: Oxy Petroleum, 2015

Note that the above cost structure does not include the initial capital costs for wells and other facilities or a return on investment. However, a $25/B net operating margin (oil price of $55/B less CO_2 costs of $30/B) provides considerable potential for covering capital investment plus a reasonable return on investment, particularly when a CO_2 flood is initiated in a field setting with already existing, usable water injection and oil production wells.

To further illustrate that CO_2-EOR can be economically viable at lower oil prices, Occidental Petroleum shows that CO_2-EOR can remain cash flow positive with a net operating margin of $13/B even at a much lower oil price of $35 per barrel (West Texas Intermediate, WTI). This is because a number of the costs of conducting a CO_2-EOR project, such as the power/energy and CO_2 supply costs, decline as oil prices decline, as illustrated on Figure 1-14.

Figure 1-14. Typical Costs for a Permian Basin CO_2-EOR Project at Lower Oil Prices



Source: Oxy Petroleum, 2015

Similar economic performance can be demonstrated to be expected for Gulf Coast CO_2-EOR projects.

Our analysis shows that CO_2-EOR is a lower cost, more economically viable option than many of the new sources of North American oil production, such as Canadian oil sands, non-core tight oil plays, exploration for conventional on-shore oil fields and pursuit of moderate-size, deep water Gulf of Mexico offshore oil fields.

Last year, the CO_2-EOR industry purchased and injected a total of 3.5 billion cubic feet per day (Bcfd) (plus recycled CO_2) to produce 300,000 barrels of oil per day of enhanced production. Approximately 80% of the purchased CO_2 volume (2.8 Bcfd) was from naturally occurring CO_2, captured from geologic sources located in Colorado, New Mexico, and Mississippi. However, the volumes of these naturally occurring sources of CO_2 are limited and industry data shows that natural CO_2 supplies are set to decline.

Need for New Sources of CO_2 Supplies. As new CO_2-EOR projects, such as Conroe in East Texas and North Hobbs in the Permian Basin, are launched and CO_2-EOR technology improves, enabling more oil fields to become economically viable for CO_2-EOR, the CO_2 market for EOR will increase considerably. With declining volumes of naturally occurring CO_2, the increased demand will need to be met by CO_2 supplies captured from industrial sources.

The availability of secure, affordable supplies of industrial CO_2 could help launch a new round of growth for CO_2–EOR supported by: (1) ship-bound transport of imported industrial CO_2 directed to high potential domestic oil fields, and (2) the distribution of this CO_2 to oil fields using a series of large-volume CO_2 pipelines, or “trunklines”.

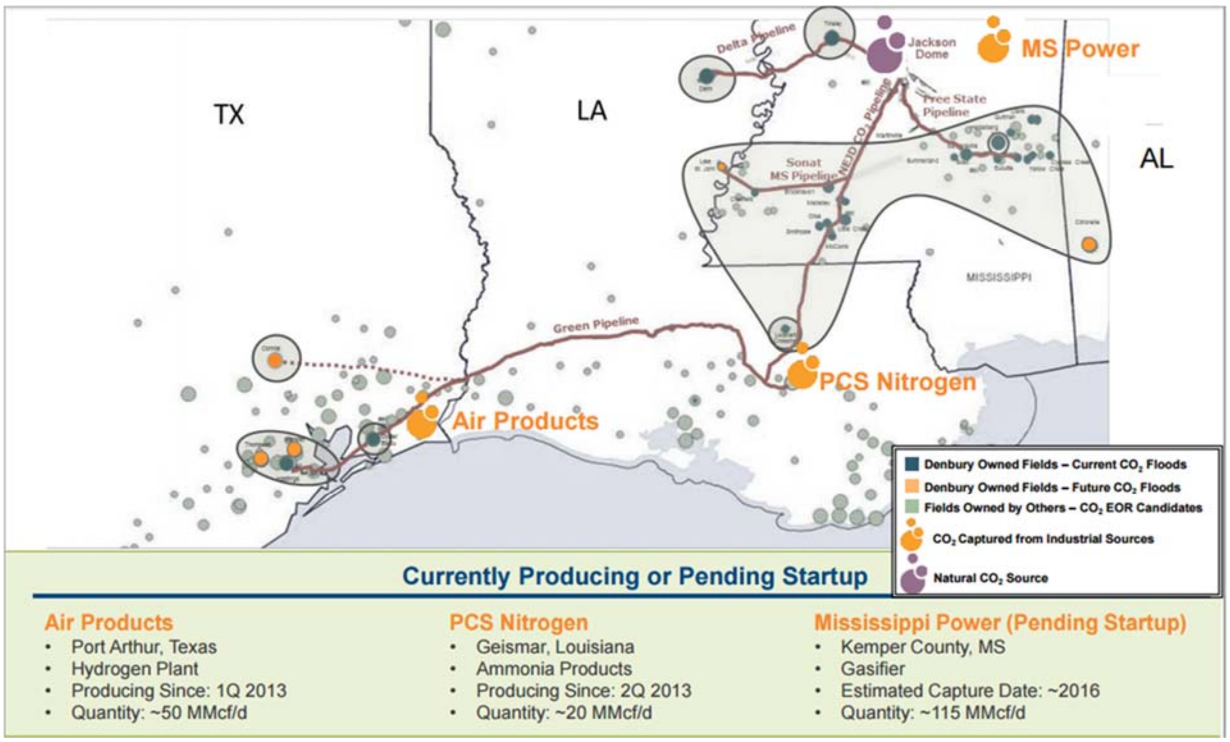
As evidence of the potential for combining captured industrial CO_2 and storage of CO_2 with EOR, all of the active and planned North American CO_2 capture projects at coal-fired power plants will sell their captured CO_2 to oil fields for productive use by enhanced oil recovery with subsequent storage of the purchased CO_2. Moreover, the market for CO_2 by the EOR industry becoming considerably more robust as EOR technology improves. Key technologies -- such as conformance control, targeting unswept portions of oil fields with horizontal wells and adding mobility control to the injected CO_2 -- would make more oil fields economically viable for CO_2-EOR, would more than double the potential oil recovery from CO_2-EOR, and would substantially increase the market demand for CO_2 by the EOR industry.

Finally, a safe, reliable, regionally extensive network of CO_2 transportation pipelines is already in place in more than a dozen U.S. states plus Saskatchewan, Canada. This system is an essential building block for linking the ship-based transportation of CO_2 with its productive use and storage in oil fields with CO_2 enhanced oil recovery. The current CO_2 pipeline system consists of 50 individual CO_2 pipelines with a combined length of 4,765 miles. While the bulk of the existing large-volume CO_2 pipelines connect natural sources of CO_2 (e.g., Bravo Dome, New Mexico) with CO_2-EOR projects in large oil fields (e.g., Wasson, West Texas), numerous additional CO_2 pipeline exist that connect point sources of industrial CO_2 with CO_2-EOR projects in nearby oil fields.

Of the 3.5 billion cubic feet (Bcf) per day (68 million metric tons per year [MMT]) of CO_2 transported, 0.7 Bcf per day (14 MMT per year) is currently from industrial sources, including gas processing plants. With new industrial CO_2 capture facilities coming on line (e.g., Air Products PCS Nitrogen plant in southern Louisiana, Southern Company’s integrated gasification combined cycle (IGCC) plant in Kemper County, Mississippi, etc.) – including over 600 miles of new pipeline – the volume of industrial CO_2 captured and transported is expected to increase substantially.

One example of providing CO_2 from industrial sources to EOR fields is the recently constructed 740 mile Gulf Coast CO_2 pipeline network is owned and operated by Denbury Onshore LLC, Figure 1-15. Two main pipelines comprise the pipeline network, the North East Jackson Dome (NEJD) Pipeline and the Green Pipeline. These two pipelines connect the natural CO_2 source in Jackson Dome, Central Mississippi, as well as new industrial sources to Denbury's CO_2-EOR projects in Mississippi, Louisiana, and East Texas.

Figure 1-15. Southeast Gulf Coast CO_2 Pipeline Infrastructure



Source: Denbury Resources, 2015.

Regulatory Framework for CO_2-EOR. Oil production with CO_2-EOR is a well-established technology in the U.S. Thus, regulatory barriers for producing oil from CO_2-EOR in the U.S. are minimal. For fields currently being developed and produced using CO_2-EOR, it is possible that some may eventually be converted to geologic settings used for permanent geologic storage of CO_2. EPA has promulgated requirements for geologic storage of CO_2, including the establishment of a new class of wells, Class VI. Recent guidance issued by EPA confirms that CO_2-EOR operations can, in fact, result in stored CO_2, and a conversion to Class VI is not a requirement for assuring storage.

EPA has also established greenhouse gas reporting requirements under the Greenhouse Gas Reporting Program (GHGRP) for facilities that inject CO_2 underground for geologic storage and for all other facilities that inject CO_2 underground.

Nonetheless, regulatory barriers remain if credit for the CO_2 stored in the association with CO_2-EOR is sought. For example, under EPA "Clean Power Plan," CO_2 storage with CO_2 -EOR is recognized as a potential compliance mechanism. If CO_2 storage is verified under Subpart RR of the GHGRP, many are concerned that Subpart RR fundamentally conflicts with state-level mineral property and resource conservation law. Most significant concerns under Subpart RR include: (1) processes for and timeliness of EPA approval of monitoring, reporting, and verification (MRV) plans for CO_2-EOR projects, (2) what constitutes "new" activity in a CO_2-EOR project necessitating submittal of a new MRV plan, (3) how federal requirement relate to current state CO_2-EOR/Class II permitting processes, and (4) the extent to which MRV plans are subject to public litigation procedures.

4. Likely Legal and Regulatory Issues Associated with the Maritime Shipment of CO_2 for Use in EOR

The transportation and import (as well as export) of liquefied gas into the U.S. is well established with the development of the LNG industry. In addition, the precedent for trans-boundary movement of CO_2 has been established with the transportation of CO_2 from the U.S. (Dakota Gasification Facility) to Canada (Weyburn Oil Field) for use by CO_2-EOR.

A preliminary "issue spotting" review of potential legal and regulatory issues associated with the maritime transportation of commodity quantities of CO_2 was performed which focused on the transport: (1) between and among the United Gulf Coast, the United States California Coast, northwest Europe, China, Japan and South Korea; and (2) for purposes of use in CO_2-EOR, CO_2-EOR with associated storage, and potentially deep saline sequestration. Likely shipping routes considered included: (1) northwest Europe to the United States; and (2) Far East to Indonesia or California on backhaul of LPG/ethane carriers. This review is included as an Appendix.

Given the technical similarities between liquefied CO_2 and other materials being transported in bulk (e.g., LPG, LNG), analogies may be drawn that provide regulators and policymakers with comfort that the bulk maritime transport of CO_2 is environmentally sound. Nonetheless, the contemplated commercial activities are novel and thus may raise numerous complex, time-consuming, and unanticipated legal and regulatory hurdles, not all of which may be surmountable. Project proponents may have to convince regulators and policymakers in the relevant jurisdictions that these activities can and should proceed.

While this initial review concludes that international and domestic laws and regulations do not explicitly prohibit or constrain CO_2 backhaul in LPG-class carriers, clear answers may nonetheless be required regarding how the contemplated commercial activities may be authorized, permitted, or otherwise allowed.

Thus, while certain precedents exist for importing liquefied gases into the U.S. and for trans-border movement of CO_2, potential legal and regulatory issues that may need to be addressed exist; thus, further examination of these issues is warranted.

Feasibility Study of Ship-Based Transportation of CO_2

Chapter 2

Market Potential for Ship-Based Transportation of CO2 for Use by the U.S. Enhanced Oil Recovery Industry
Phase I Report

Prepared by:
Advanced Resources International, Inc.

Market Potential for Ship-Based Transportation of CO_2 for Use by the U.S. Enhanced Oil Recovery Industry

Phase I Report

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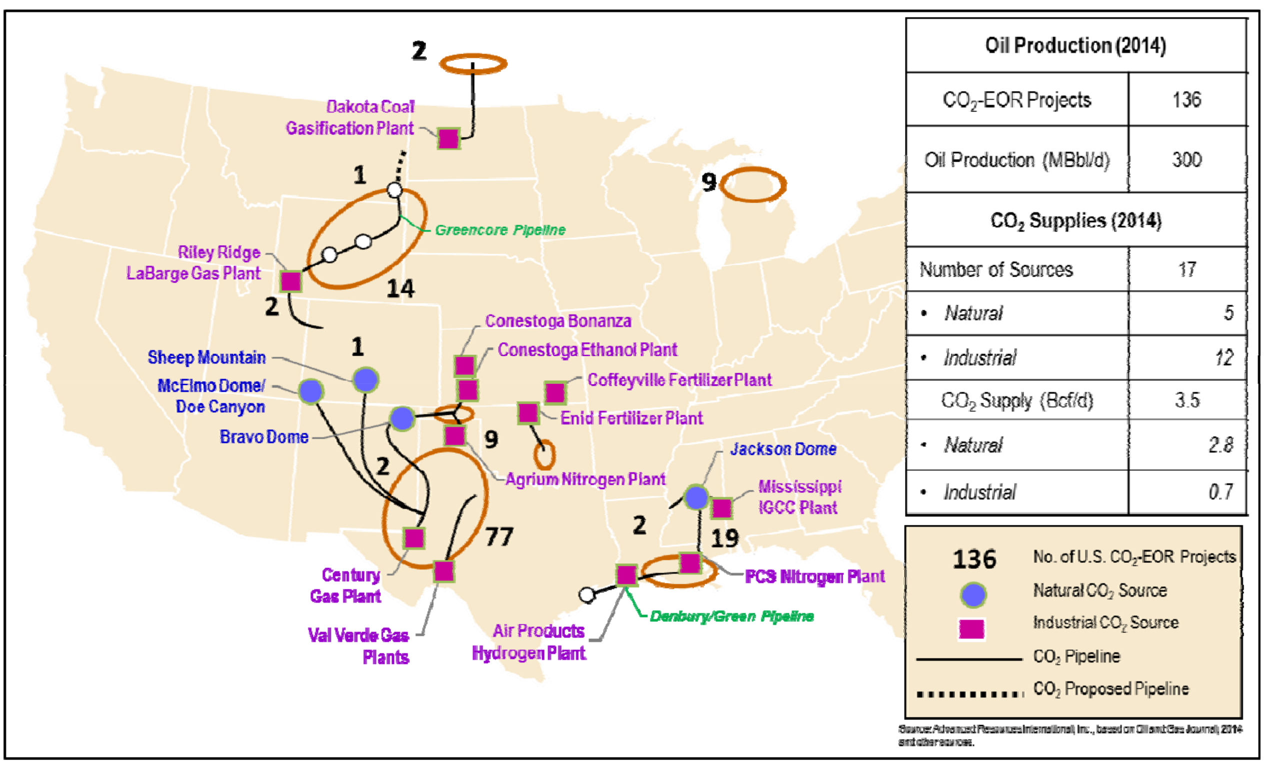
Market Potential for Ship-Based Transportation of CO_2 for Use by the U.S. Enhanced Oil Recovery Industry

Background

The U.S. has an active and growing CO_2 enhanced oil recovery (CO_2-EOR) industry, is built on proven technology and several decades of successful application. The first commercial CO_2 flood began in 1972 at the SACROC Unit of the Kelly-Snyder oil field in the Permian Basin of West Texas. This CO_2 flood continues to operate successfully and, with recent investments, currently provides nearly 30,000 barrels per day of crude oil production. In the 1980s, a number of additional field-scale CO_2 floods were launched in major Permian Basin oil fields, such as Seminole, Slaughter and Wasson, establishing the commercial viability of CO_2-EOR.

Today there are 136 distinct CO_2-EOR projects underway in the U.S., providing about 300,000 barrels per day of crude oil production from a diversity of geological and geographic settings, Figure 1.

Figure 1. CO_2-EOR Projects and CO_2 Sources (2014)



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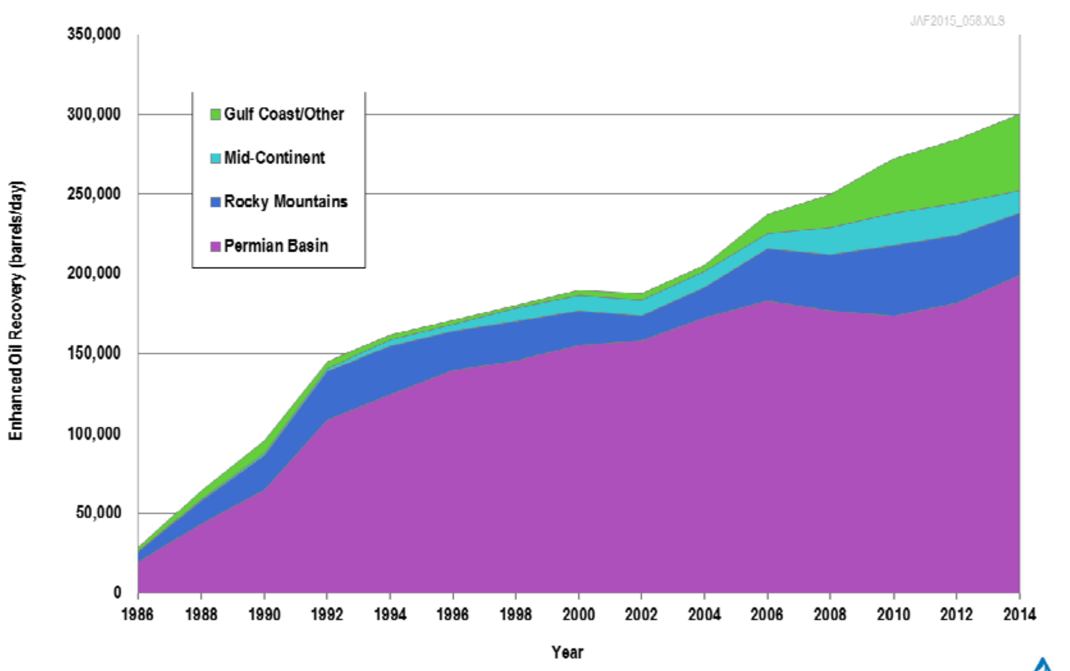
Advanced Resources International, Inc.

Table 1 provides a tabulation of the 127 currently active miscible CO_2-EOR projects including their operator, oil field and pay zone, start date, project area and oil production in 2014. Table 2 provides similar information on the nine currently active immiscible CO_2-EOR projects. (The data in Table 1 are based on the latest (April, 2014) Oil and Gas Journal's survey of enhanced oil recovery, prepared in partnership with Advanced Resources International and Melzer Consulting.)

In addition to providing important volumes of domestic oil production, the application of CO_2-EOR in domestic oil fields provides opportunities for secure, long-term storage of CO_2, as well as revenues to the CO_2 capture facilities from the sale and use of industrial CO_2 by the enhanced oil recovery industry.

CO_2-EOR based oil production has grown steadily in the past ten years, supported by the availability of both natural and industrial CO_2 supplies, Figure 2. The figure shows that while CO_2-EOR production in the Permian Basin has plateaued, due to limits on readily available CO_2 supplies, it has increased in the Mid-Continent and Gulf Coast, where additional natural and industrial supplies of CO_2 have been developed.

Figure 2. Growth of CO_2-EOR Production



Source: Includes Advanced Resources Int'l. adjustments to Oil and Gas Journal EOR Survey, 2014.

Table 1. Currently Active Miscible CO_2-EOR Projects

Miscible CO2-EOR Operations						
Operator	Field	Pay Zone	State	Start Date	Tot. Prod. (bbl/d)	Enh. Prod. (bbl/d)
Anadarko	Patrick Draw Monell		WY	9/1/2003	5,200	5,200
Anadarko	Salt Creek Southern Unit	Frontier, Wall Creek 1	WY	2012	800	800
Anadarko	Salt Creek Southern Unit	Frontier, Wall Creek 2	WY	2012	900	900
Anadarko	Salt Creek Ph 1-8	Wall Creek 2 (Frontier)	WY	1/04	9,000	9,000
Anadarko	Salt Creek Ph 7	Wall Creek 1 (Frontier)	WY	1/10	1,300	1,300
Anadarko	Sussex	Tensleep	WY	12/04	-	-
Anadarko Total					17,200	17,200
Apache	Adair	San Andres	TX	1997	2,300	1,600
Apache	Adair	Wolfcamp	TX	2004	282	200
Apache	Roberts	San Andres	TX	7/4/1905	2,300	-
Apache	Slaughter	San Andres	TX	5/85	600	600
Apache	Slaughter	San Andres	TX	6/89	2,200	2,200
Apache Total					7,682	4,600
Breitburn Energy	Postle - PUMU	Morrow	OK	11/1/1995	912	912
Breitburn Energy	Postle - HMAU	Morrow	OK	11/1/1995	619	619
Breitburn Energy	Poslte - WHMU	Morrow	OK	1/1/1998	2,429	2,429
Breitburn Energy	Postle - HMU	Morrow	OK	8/1/2007	3,110	3,110
Breitburn Energy Total					7,070	7,070
Chaparral Energy	NW Velma Hoxbar	Hoxbar	OK	9/1/2010	266	241
Chaparral Energy	Camrick	Morrow	OK	4/01	1,268	1,210
Chaparral Energy	North Perryton	Upper Morrow	TX	12/07	467	450
Chaparral Energy	Albert Spicer Unit	Upper Morrow	TX	10/2009	87	80
Chaparral Energy	Booker Trosper Unit	Upper Morrow	TX	10/2009	195	195
Chaparral Energy	Gramstorff Unit	Upper Morrow	TX	10/2009	673	673
Chaparral Energy	Farnsworth	Upper Morrow	TX	12/15/2010	1,545	1,442
Chaparral Energy	Burbank	Burbank	OK	6/6/2013	1,361	-
Chaparral Total					5,862	4,291
Chevron	Rangely Weber Sand	Weber SS	CO	10/86	11,000	8,500
Chevron	Mabee	San Andres	TX	1/92	1,810	1,800
Chevron	Slaughter Sundown	San Andres	TX	1/94	3,540	3,500
Chevron	Vacuum	San Andres	NM	7/97	4,000	3,200
Chevron	Dollarhide (Devonian) Unit	Devonian	TX	5/85	1,755	1,755
Chevron	Dollarhide (Clearfork "AB") Unit	Clearfork	TX	11/95	960	960
Chevron	Reinecke	Cisco Canyon Reef	TX	1/98	530	530
Chevron Total					23,595	20,245
ConocoPhillips	South Cowden	San Andres	TX	2/81	160	160
ConocoPhillips	Vacuum	San Andres	NM	2/81	6,000	5,500
ConocoPhillips Total					6,160	5,660
Core Energy	Charlton 6	Silurian - A1/Niagaran	MI	2006	20	20
Core Energy	Charlton 30-31	Silurian - A1/Niagaran	MI	2005	165	165
Core Energy	Dover 33	Silurian - A1/Niagaran	MI	1996	-	-
Core Energy	Dover 35	Silurian - A1/Niagaran	MI	2004	60	60
Core Energy	Dover 36	Silurian - A1/Niagaran	MI	1997	90	90
Core Energy	Chester 5	Silurian - A1/Niagaran	MI	2010	80	80
Core Energy	Charlton 19	Silurian - A1/Niagaran	MI	2014	-	-
Core Energy	Chester 16	Silurian - A1/Niagaran	MI	2014	-	-
Core Energy	Chester 2	Silurian - A1/Niagaran	MI	2009	90	90
Core Energy Total					505	505

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Table 1. Currently Active Miscible CO_2-EOR Projects (Continued)

Miscible CO2-EOR Operations						
Operator	Field	Pay Zone	State	Start Date	Tot. Prod. (bbl/d)	Enh. Prod. (bbl/d)
Denbury Resources	Bell Creek	Muddy	MT	5/13	205	205
Denbury Resources	Little Creek	Lower Tuscaloosa	MS	1985	950	950
Denbury Resources	Lazy Creek	Lower Tuscaloosa	MS	12/01	-	-
Denbury Resources	Grieve	Muddy	WY	3/13	240	240
Denbury Resources	Hastings	Frio	TX	5/10	5,270	5,270
Denbury Resources	West Mallalieu	Lower Tuscaloosa	MS	11/01	2,330	2,330
Denbury Resources	East Mallalieu	Lower Tuscaloosa	MS	12/03	-	-
Denbury Resources	McComb	Lower Tuscaloosa	MS	11/03	1,580	1,580
Denbury Resources	Smithdale	Lower Tuscaloosa	MS	3/05	-	-
Denbury Resources	Brookhaven	Lower Tuscaloosa	MS	1/05	2,500	2,500
Denbury Resources	Martinville	Mooringsport	MS	3/06	500	500
Denbury Resources	Martinville	Rodessa	MS	3/06	-	-
Denbury Resources	Soso	Rodessa 11,180	MS	9/06	2,140	2,140
Denbury Resources	Soso	Bailey 11,701	MS	4/06	-	-
Denbury Resources	Cranfield	Tuscaloosa	MS	07/08	1,460	1,460
Denbury Resources	Lockhart Crossing	Wilcox	LA	12/07	1,140	1,140
Denbury Resources	Delhi	Tuscaloosa, Paluxy	LA	11/1/2009	5,920	5,920
Denbury Resources	Oyster Bayou	Frio	TX	12/1/2010	4,780	4,780
Denbury Resources Total					29,015	29,015
Devon	Beaver Creek	Madison	WY	7/08	3,033	2,810
Devon Energy Total					3,033	2,810
Energen Resources	East Penwell (SA) Unit	San Andres	TX	5/96	1,220	700
Energen Resources Total					1,220	700
ExxonMobil	Means (San Andres)	San Andres	TX	11/83	5,818	5,000
ExxonMobil Total					5,818	5,000
Fasken	Abell (Devonian)	Devonian	TX	4/09	240	200
Fasken	Hanford	San Andres	TX	7/86	400	400
Fasken	Hanford East	San Andres	TX	3/97	45	45
Fasken	Hanford (San Andres)	San Andres ROZ	TX	7/09	280	80
Fasken	River Bend (Devonian)	Devonian	TX	4/09	290	180
Fasken Total					1,255	905
Great Western Drilling	Twofreds	Delawar, Ramsey	TX	1/74	100	100
Great Western Drilling Total					100	100
George R. Brown	Garza	San Andres	TX	11/09	1,500	1,000
George R. Brown Total					1,500	1,000
Hess	Seminole Unit-Main Pay Zone	San Andres	TX	7/83	8,500	8,150
Hess	Seminole Unit-ROZ Phase 1	San Andres	TX	7/96	1,000	1,000
Hess	Seminole Unit-ROZ Phase 2	San Andres	TX	4/04	1,500	1,500
Hess	Seminole Unit-ROZ Stage 1	San Andres	TX	10/07	7,800	7,800
Hess Total					18,800	18,450
Kinder Morgan	SACROC	Canyon	TX	1/72	30,800	28,300
Kinder Morgan	Katz	Strawn	TX	1/1/2011	3,700	3,700
Kinder Morgan	Goldsmith-Landreth	San Andres	TX		1,400	1,350
Kinder Morgan Total					35,900	33,350
Merit Energy	Lost Soldier	Tensleep	WY	5/89	1,375	1,375
Merit Energy	Lost Soldier	Darwin-Madison	WY	5/89	1,061	1,000
Merit Energy	Lost Soldier	Cambrian	WY	6/96	523	500
Merit Energy	Wertz	Tensleep	WY	10/86	921	900
Merit Energy	Wertz	Darwin-Madison	WY	9/00	1,006	1,000
Merit Energy	Northeast Purdy	Springer	OK	9/82	1,800	1,800
Merit Energy	Bradley Unit	Springer	OK	2/97	800	600
Merit Energy Total					7,486	7,175

Table 1. Currently Active Miscible CO_2-EOR Projects (Continued)

Miscible CO2-EOR Operations						
Operator	Field	Pay Zone	State	Start Date	Tot. Prod. (bbl/d)	Enh. Prod. (bbl/d)
Orla Petco	East Ford	Delaware, Ramsey	TX	7/95	50	50
Orla Petco Total					50	50
Occidental	Anton Irish	Clearfork	TX	4/97	5,000	4,000
Occidental	Cedar Lake	San Andres	TX	8/94	3,900	3,000
Occidental	Cogdell	Canyon Reef	TX	10/01	5,700	5,650
Occidental	El Mar	Delaware	TX	4/94	102	94
Occidental	GMK South	San Andres	TX	1982	480	215
Occidental	Levelland (Levelland)	San Andres	TX	9/04	3,071	2,198
Occidental	Devonian Unit (Mid Cross)	Devonian	TX	7/97	297	294
Occidental	Devonian Unit (North Cross)	Devonian	TX	4/72	1,283	1,283
Occidental	North Cowden	Grayburg	TX	2/95	5,090	64
Occidental	North Dollarhide Devonian	Devonian	TX	11/97	1,020	407
Occidental	North Hobbs	San Andres	TX	3/03	6,615	5,315
Occidental	Devonian Unit (South Cross)	Devonian	TX	6/88	4,572	4,440
Occidental	Salt Creek	Canyon	TX	10/93	7,344	6,950
Occidental	Sharon Ridge	Canyon Reef	TX	2/1/1999	1,500	1,350
Occidental	Slaughter (Alex Slaughter Estate)	San Andres	TX	8/00	200	183
Occidental	Slaughter (Central Mallet Unit)	San Andres	TX	1984	2,300	2,100
Occidental	Slaughter (Frazier Unit)	San Andres	TX	12/84	800	700
Occidental	Slaughter (H.T. Boyd)	San Andres	TX	8/01	950	850
Occidental	Slaughter (Igoe Smith)	San Andres	TX	9/05	850	650
Occidental	Slaughter (North West Mallet)	San Andres	TX	2008	1,085	180
Occidental	Slaughter (Slaughter Estate Unit)	San Andres	TX	12/1/1984	3,300	2,900
Occidental	Slaughter (Smith Igoe)	San Andres	TX	8/5/2014	180	100
Occidental	Slaughter (West RKM Unit)	San Andres	TX	2006	1,740	450
Occidental	South Wasson Clearfork	Clearfork	TX	10/84	1,007	-
Occidental	South Welch	San Andres	TX	9/93	800	600
Occidental	T-Star (Slaughter Consolidated)	Abo	TX	7/99	1,950	1,000
Occidental	Wasson (BRU)	San Andres	TX	6/95	4,900	4,300
Occidental	Wasson (Denver Unit)	San Andres	TX	4/83	24,834	24,441
Occidental	Wasson (ODC Unit)	San Andres	TX	11/84	8,023	7,617
Occidental	Wasson (Willard Unit)	San Andres	TX	1/86	6,907	6,567
Occidental	West Welch	San Andres	TX	10/97	-	-
Occidental	Levelland (South East Levelland)	San Andres	TX	4/11/2014	550	250
Occidental	West Seminole San Andres Unit	San Andres	TX	7/1/13	150	-
Occidental Total					106,500	88,148
Resolute Natural Resources	Aneth Unit	Desert Creek	UT	10/98	5,300	2,900
Resolute Natural Resources	McElmo Unit	Desert Creek	UT	1/1/1985	4,000	2,100
Resolute Natural Resources Total					9,300	5,000
Stanberry Oil	Hansford Marmaton	Marmaton	TX	6/80	30	30
Stanberry Total					30	30
Tabula Rasa	East Seminole	Dolomite	TX	10/1/2013	275	25
Tabula Rasa Total					275	25
Trinity	Wellman	Wolfcamp	TX	7/1/1983	1,930	1,930
Trinity Total					1,930	1,930
Whiting Petroleum	North Ward Estes	Yates	TX	5/07	10,194	7,700
Whiting Petroleum Total					10,194	7,700
XTO Energy Inc.	Goldsmith	San Andres	TX	12/96	1,620	1,620
XTO Energy Inc.	Cordona Lake	Devonian	TX	12/85	910	500
XTO Energy Inc.	Wasson (Cornell Unit)	San Andres	TX	7/85	2,000	1,350
XTO Energy Inc.	Wasson (Mahoney)	San Andres	TX	10/85	1,500	1,300
XTO Energy Inc. Total					6,030	4,770
Miscible CO2-EOR Total					306,510	265,729

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Table 2. Currently Active Immiscible CO_2-EOR Projects

Immiscible CO2-EOR Operations						
Operator	Field	Pay Zone	State	Start Date	Tot. Prod. (bbl/d)	Enh. Prod. (bbl/d)
Anadarko	Salt Creek	Wall Creek 1 (Frontier)	WY	10/05	-	-
Anadarko Total					-	-
Denbury Resources	Eucutta	Eutaw	MS	3/06	2,810	2,810
Denbury Resources	Martinville	Wash-Fred 8500	MS	9/06	-	-
Denbury Resources	Tinsley	Woodruff	MS	01/07	9,640	9,640
Denbury Resources	Heidelberg, West	Eutaw	MS	12/08	6,430	6,430
Denbury Resources	East Heidelberg	Eutaw	MS	6/1/2011	-	-
Denbury Resources	East Heidelberg	Christmas	MS	5/12	-	-
Denbury Resources	West Hastings	Frio	MS	12/1/2010		
Denbury Resources Total					18,880	18,880
Kinder Morgan	Yates	San Andres	TX	3/04	20,000	15,000
Kinder Morgan Total					20,000	15,000
Immiscible CO2-EOR Total					38,880	33,880

Today, the much higher oil production potential from CO_2-EOR in the various U.S. oil basins is limited by the lack of sufficient supplies of affordable CO_2. In addition, as the existing natural sources of CO_2 for EOR become depleted (such as the McElmo Dome, Colorado and Jackson Dome, Mississippi natural CO_2 deposits), the enhanced oil recovery industry will need to rely increasingly on anthropogenic CO_2 supplies captured from industrial and power plants if it is to achieve its underlying potential. Ship-based imports of CO_2 would help fill the CO_2 supply gap.

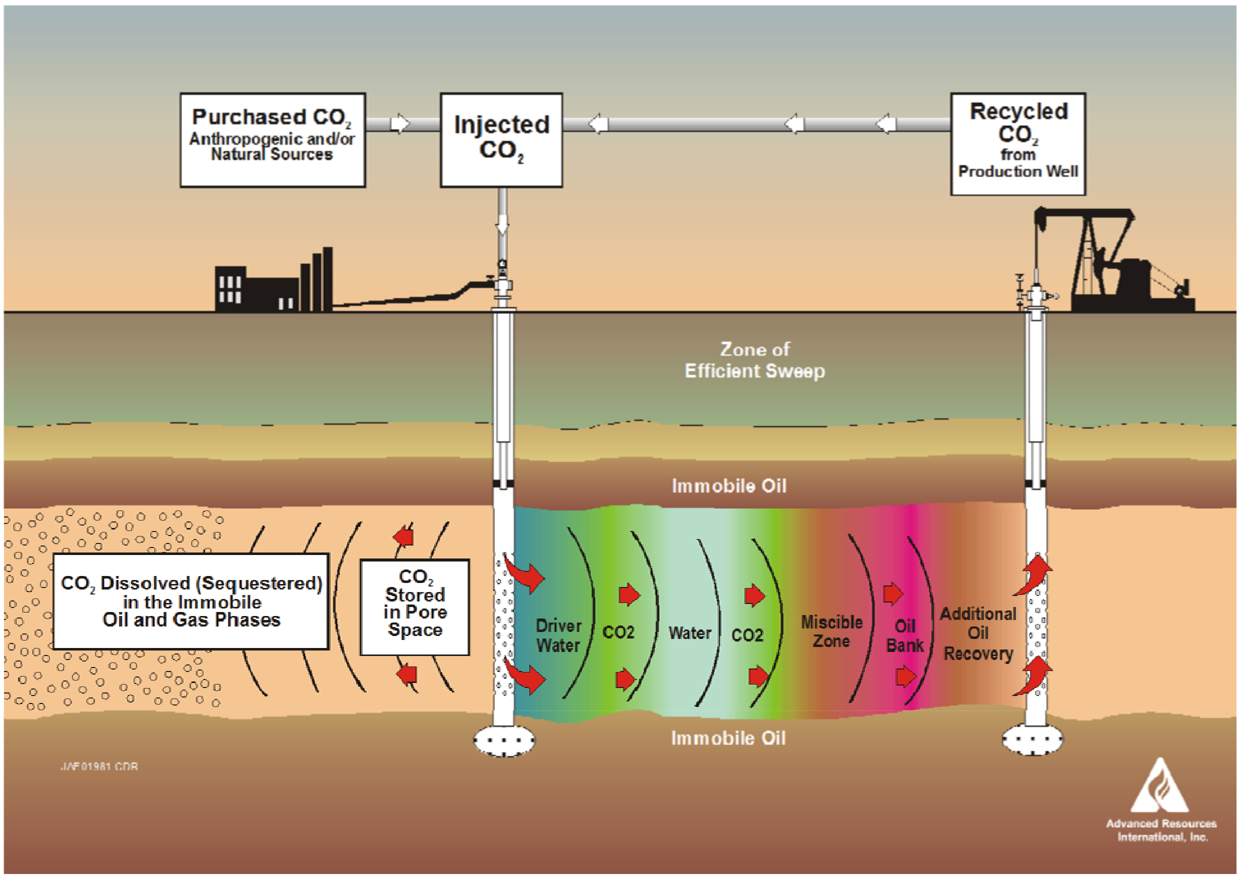
This report addresses six important topics that help define and establish the economic viability, market demand and pipeline infrastructure improvements for ship-based transportation of CO_2 for use by the domestic CO_2-EOR industry:

1. Fundamentals of the CO_2-EOR Process,
2. Size of the CO_2-EOR Target Resource,
3. Economic Viability of CO_2-EOR,
4. Markets for Industrial CO_2 Supplies,
5. CO_2 Pipeline Infrastructure, and
6. Key Regulatory and Environmental Issues.

1. Fundamentals of the CO_2-EOR Process

CO_2-EOR involves using deep wells to inject large volumes of CO_2 at high pressure, with or without alternating volumes of water, to improve (i.e., enhance) oil recovery, Figure 3. Under sufficient pressure, the injected CO_2 becomes miscible with the oil left behind in the reservoir after primary/secondary recovery, reducing the viscosity and the interfacial tension of the oil/CO_2 mixture while promoting its recovery in offset production wells.

Figure 3. The Miscible CO_2-EOR Process



Source: Advanced Resources International, 2015.

For most oil reservoirs, the development of miscibility between the reservoir's oil and the injected CO_2 involves multiple contact between these two fluids. With extraction of the lighter components of the reservoir's oil into the CO_2 phase and the solution of CO_2 into the oil phase, the two fluids to become essentially a single-phase fluid.

A critical value in the miscible CO_2–EOR process is the determination of the minimum miscibility pressure (MMP), the pressure at which sufficient in-situ mass transfer of components between the CO_2 and the reservoir's oil occurs to achieve efficient oil recovery. The addition of an enrichment to the injected CO_2, using hydrocarbon components such as ethane, propane or butane, can lead to lower minimum miscibility pressures (MMP) helping extend the CO_2-EOR process to shallower and higher oil gravity reservoirs.

A CO_2 flood can also be operated at pressures below MMP, where the mechanisms of viscosity reduction, oil swelling and extraction of hydrocarbon components into the CO_2 phase help promote oil recovery. Recent laboratory work also suggests that relatively efficient oil recovery can be achieved at pressures (in the reservoir) near (but still below) MMP, although further field-scale verification of the efficiency of the near-miscible CO_2-EOR process is still required.

2. Size of the CO_2-EOR Target Resource

Primary oil recovery (typically pressure depletion) and secondary oil recovery (typically water flooding) recover 25% to 45% of the original oil in-place in an oil reservoir, leaving behind a large volume of "left behind" oil.

Overall, the U.S. has recovered or proven a little over a third, 210 billion barrels, of its 624 billion barrels of original oil in-place endowment by using primary and secondary methods, Figure 4. As such, 414 billion barrels of oil have been "left behind", providing an attractive target for enhanced (tertiary) oil recovery methods, particularly the use of miscible and immiscible CO_2 injection.

A more rigorous examination of the characteristics and geologic settings of the 414 billion barrels of "left behind" oil indicate that 284 billion barrels is in oil fields and reservoirs technically feasible for using CO_2 as the enhanced oil recovery process. Excluded from the 414 billion barrel "left behind" oil volume are shallow as well as heavy oil fields that are not suitable for miscible or near-miscible oil recovery using CO_2. The distribution of the "left behind" oil in-place and the portion of this oil in-place that is technically favorable for CO_2-EOR is shown in Figure 5 for eight composite market regions of the country. With over 100 billion barrels of "left behind" oil technically favorable for CO_2-EOR, Figure 5 illustrates the importance of the Gulf Coast region (GOM offshore, Southeast and East/Central Texas) as the prime market area for delivery of new supplies of CO_2 for enhanced oil recovery.

Figure 4. Domestic Conventional* Oil Endowment and Target Resource for EOR

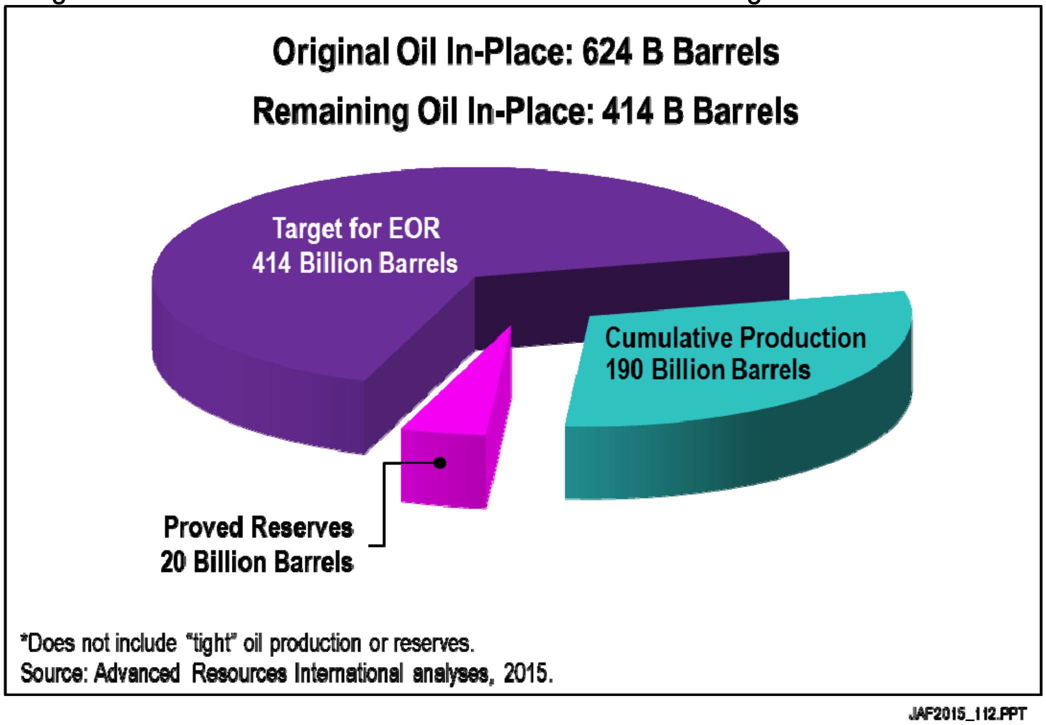
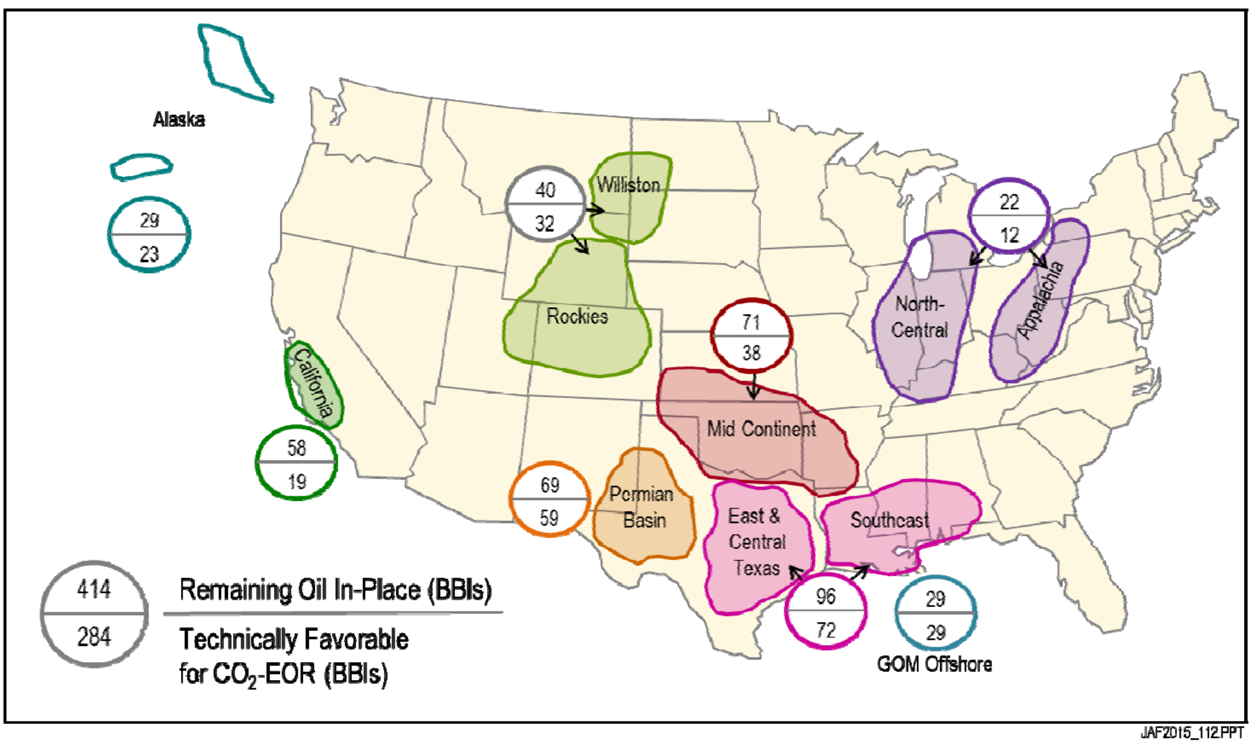


Figure 5. Regional Distribution of the Target Resource for CO_2-EOR

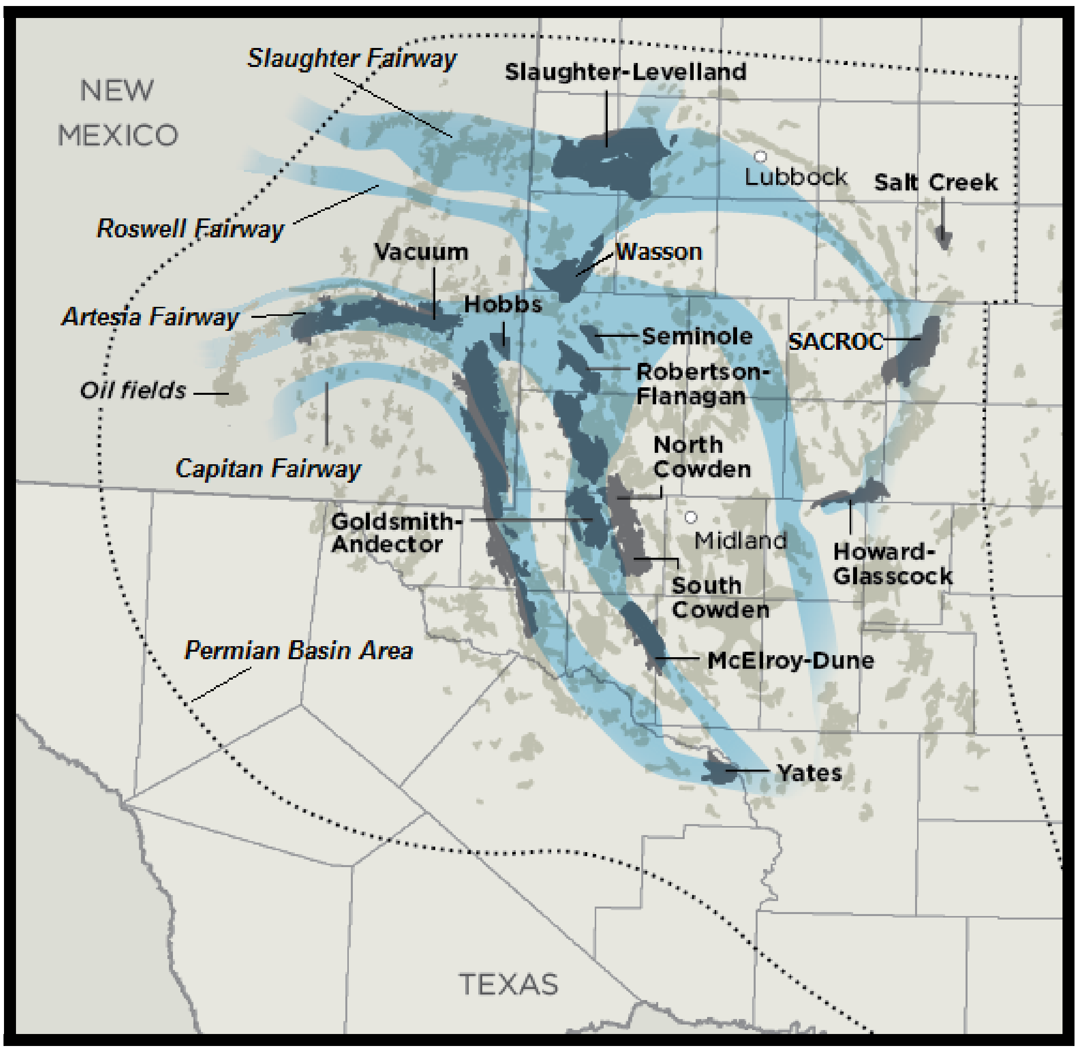


Source: Advanced Resources International, 2015.

In addition to the oil "left behind" after primary and secondary recovery in the main pay portion of an oil reservoir (above the reservoir's water-oil contact), a large remaining oil target often exists in the lower portion of an oil reservoir (below the reservoir's water-oil contact) called the residual oil zone (ROZ).

Recent work by Melzer and Trentham has identified a series of San Andres Formation residual oil zone (ROZ) "fairways" in the Permian Basin that have been created by nature's waterflooding of these oil reservoirs below their main pay zone, Figure 6.

Figure 6. San Andres ROZ "Fairways of the Permian Basin



Source: Melzer Consulting, 2014.

Advanced Resources has documented the presence of 112 billion barrels of residual oil in-place in the San Andres Formation's ROZ "fairways" in a four-county area of the Permian Basin, West Texas, Table 3. A significant portion of this ROZ resource, equal to 77 billion barrels of oil in-place, is in "higher quality" reservoir settings (porosity greater than 8% and remaining oil saturation greater than 25%). Reservoir modeling by Advanced Resources shows that 27 billion barrels of the ROZ oil in-place is technically recoverable using miscible CO_2-EOR, with the "higher quality" portions of this resource offering promise for commercial viability.

Table 3. San Andres ROZ "Fairway" Resources: Four County Area of Permian Basin, West Texas

County	Total Oil In-Place (B Bbls)	Quality of Oil In-Place (B Bbls)		Technically Recoverable (B Bbls)
		"Higher"	"Lower"	
Gaines	45.5	35.4	10.1	12.4
Yoakum	20.7	16.1	4.6	5.2
Terry	17.9	10.6	7.3	3.6
Dawson	27.8	14.6	13.2	5.9
Total	111.9	76.7	35.2	27.1

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Source: Advanced Resources International, 2015.

In addition to providing potential for additional production of domestic oil, the San Andres ROZ "fairway" resource also offers an additional geologically favorable setting for storing CO_2.

More recent work on the San Andres ROZ "fairway" resource of the Permian Basin, involving a detailed log- and core-based assessment by Advanced Resources, the University of Texas Permian Basin and Melzer Consulting identified 79 billion barrels of residual oil in-place in an eight-county San Andres ROZ "fairway" area south of the original four-county area. While the calculation of technical recoverability of this second large ROZ oil in-place resource has yet to be performed, the eight-county ROZ study did establish that 58 billion barrels of the larger 79 billion barrels of San Andres ROZ "fairway" oil in-place in this eight-county area was in "higher quality" reservoir settings (porosity greater than 8% and remaining oil saturation greater than 25%).

Table 4. San Andres ROZ "Fairway" Resources: Eight County Area of Permian Basin, West Texas

County	Total Oil In-Place (B Bbls)	Quality of Oil In-Place (B Bbls)	
		"Higher"	"Lower"
Andrews	37.1	31.2	5.9
Ector	7.0	5.5	1.4
Martin	6.7	4.8	1.9
Winkler	9.5	8.0	1.5
Crane	7.4	4.3	3.1
Upton	3.3	-	3.3
Ward	8.3	4.1	4.2
Midland	*	*	*
Total	79.3	57.9	21.3

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*The ROZ "fairway" resource in Midland County is in the Grayburg Fm.
Source: Advanced Resources International, 2015.

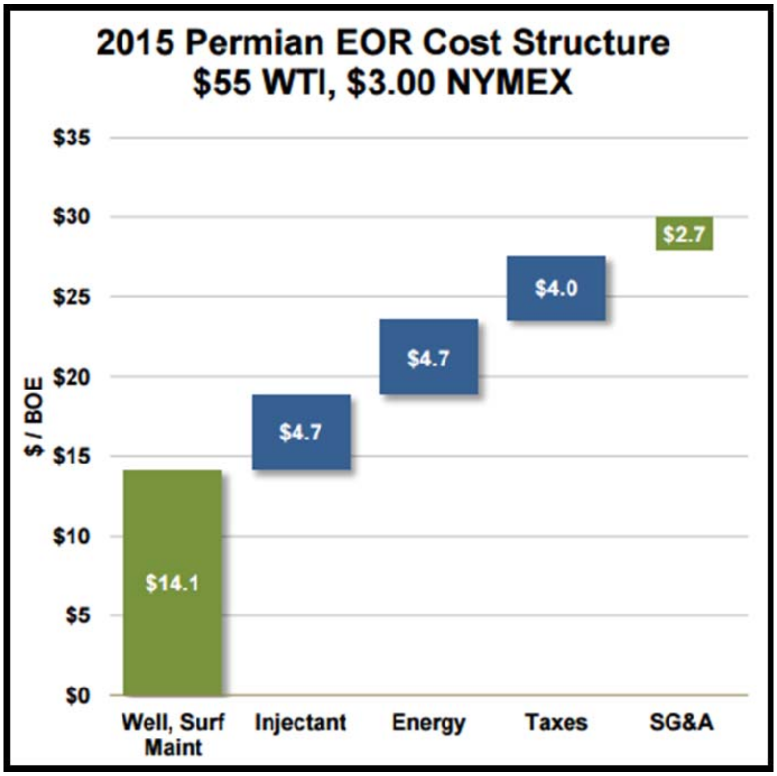
3. Economic Viability of CO_2-EOR

The recent decline in the price of oil has led some analysts to question the economic viability of CO_2 enhanced oil recovery at a time of lower oil prices. While many of the past studies of the economics of CO_2-EOR have been conducted using oil prices of $75 to $90 per barrel, a look at industry's cost data shows that the application of CO_2-EOR in higher quality oil fields can be economically viable at oil prices of $50 to $60 per barrel.

Permian Basin Examples

For example, as shown in Figure 7, Occidental Petroleum, the most active and largest CO_2-EOR operator in the U.S., with an extensive number of CO_2-EOR projects in the Permian Basin, shows that Permian CO_2-EOR projects can generate significant net operating revenues at a $55 per barrel (WTI) oil price. Included in the cost structure is an allocation of $4.70/B for the CO_2 injectant, $4.00/B for production taxes, $4.70/B for power and energy and $16.80 for other CO_2-EOR costs.

Figure 7. Typical Costs for a Permian Basin CO_2-EOR Project at Current Oil Prices

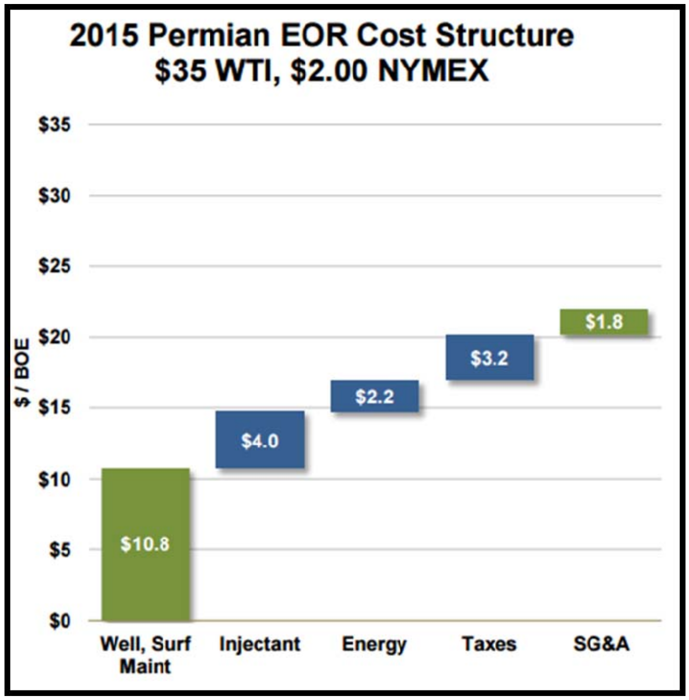


Source: Oxy Petroleum, 2015

Note that the above cost structure does not include the initial capital costs for wells and other facilities or a return on investment. However, a \$25/B net operating margin (oil price of \$55/B less CO_2 costs of \$30/B) provides considerable potential for covering capital investment plus a reasonable return on investment, particularly when a CO_2 flood is initiated in a field setting with already existing, usable water injection and oil production wells.

To further illustrate that CO_2-EOR can be economically viable at lower oil prices, Occidental Petroleum shows that CO_2-EOR can remain cash flow positive with a net operating margin of \$13/B even at a much lower oil price of \$35 per barrel (West Texas Intermediate, WTI). This is because a number of the costs of conducting a CO_2-EOR project, such as the power/energy and CO_2 supply costs, decline as oil prices decline, as illustrated on Figure 8. This important cost/oil price relationship topic is further developed below.

Figure 8. Typical Costs for a Permian Basin CO_2-EOR Project at Lower Oil Prices



Source: Oxy Petroleum, 2015

The information from the two CO_2-EOR project examples, in Figures 7 and 8, shows that a reduction in the oil price of $20/B is compensated by a reduction in CO_2-EOR operating costs of $8/B (consisting of $2.50/B for energy, $1.70/B for taxes and SG&A, $3.30/B for well and surface maintenance, and $0.70/B for the cost of CO_2 supply). For projects with a typical royalty of 20%, a $20/B drop in the oil price reduces the royalty payment (in dollars or share of production) by $4/B. As such, a $20/B decline in oil prices, from $55 per barrel to $35 per barrel, is compensated by a reduction in costs (including royalty payments) of about $12/B.

Gulf Coast Example

To further examine the economic viability of CO_2-EOR, we have tabulated the CO_2-EOR operating costs for Denbury Resources. This tabulation shows that a typical Gulf Coast CO_2-EOR project in the Gulf Coast provides a net operating margin of nearly $35/B, based on actual incurred costs of $21.40/B during the first half of 2015, and an oil price of $57/B, including a two dollar premium over WTI for light oil available in the Gulf Coast, Table 5.

Table 5. Typical Operating Costs for a Gulf Coast CO_2-EOR Projects

CO_2-EOR Operating Cost Items	Correlation w/Oil Prices	1st Half 2015 Costs ($/B)
1 CO_2 Supply	Direct	$5.00
2 Power and Fuel	High	$6.80
3 Labor and Overhead	None	$5.00
4 Repairs/Mnt/Workovers	Partial	$3.00
5 Other (Chemicals, etc.)	Partial	$1.60
	Total	$21.40

Source: Denbury Resources Investor Presentation, November 2015. JAF2015_058.XLS

Our analysis shows that CO_2-EOR is a lower cost, more economically viable option than many of the new sources of North American oil production, such as Canadian oil sands, non-core tight oil plays, exploration for conventional on-shore oil fields and pursuit of moderate-size, deep water Gulf of Mexico offshore oil fields.

As part of our more rigorous Phase II investigation of the “Market Potential for Ship-based Transportation of CO_2 for Use by U.S. Enhanced Oil Recovery Industry”, we will take a more in-depth look at the economic viability of CO_2-EOR under alternative outlooks for oil prices and costs for CO_2 supplies, including greater characterization of any regional- and/or resource-specific variability in the economic viability of CO_2-EOR

4. Markets for Industrial CO_2 Supplies

Last year, the CO_2-EOR industry purchased and injected a total of 3.5 billion cubic feet per day (Bcfd) (plus recycled CO_2) to produce 300,000 barrels of oil per day of enhanced production. Approximately 80% of the purchased CO_2 volume (2.8 Bcfd) was from naturally occurring CO_2, captured from geologic sources located in Colorado, New Mexico, and Mississippi. However, the volumes of these naturally occurring sources of CO_2 are limited and industry data shows that natural CO_2 supplies are set to decline.

As new CO_2-EOR projects, such as Conroe in East Texas and North Hobbs in the Permian Basin, are launched and CO_2-EOR technology improves enabling more oil fields to become economically viable for CO_2-EOR, the CO_2 market for EOR will increase considerably. With declining volumes of naturally occurring CO_2, the increased demand will need to be met by CO_2 supplies captured from industrial sources.

The availability of secure, affordable supplies of industrial CO_2 would help launch a new round of growth for CO_2–EOR supported by: (1) ship-bound transport of imported industrial CO_2 directed to high potential domestic oil fields and (2) the distribution of this CO_2 to oil fields using a series of large-volume CO_2 pipelines.

In this Phase I report, we discuss the near-term market for CO_2 supplies for four key regions - - the Gulf Coast, Mid-Continent, West Coast, and Offshore Gulf of Mexico. For these four regions, the Phase I report identifies the current demand for CO_2 in each region and the expected need for CO_2 supplies captured from industrial sources. A more in-depth evaluation of the projected demand for CO_2 by region will be provided in the Phase II portion of this study.

Gulf Coast CO_2 Market

The Gulf Coast CO_2-EOR market, consisting of East and South Texas, Louisiana, Mississippi, Alabama and Florida, is the location of a large number of mature light oil fields with reservoir properties favorable for CO_2-EOR, including large oil fields such as Conroe, Citronelle, and Hackberry West.

Significant numbers of CO_2-EOR projects have already been launched in the Gulf Coast region. Table 6 tabulates the 20 CO_2-EOR projects that are already operating in the Gulf Coast Region at 17 oil fields. In 2014, these 20 projects utilized a little over 1 Bcfd of CO_2 to produce nearly 50,000 barrels per day of additional oil.

The current one Bcfd of CO_2 supply for EOR in the Gulf Coast region is primarily natural CO_2 from Jackson Dome in Mississippi. However, this CO_2 volume also includes two new industrial sources of CO_2 - - from the Air Products hydrogen and the PCS nitrogen plants in Louisiana - - that recently came on-line and currently sell 75 million cubic feet per day (MMcfd) into Denbury's Green CO_2 pipeline for use by (and storage in) CO_2-EOR projects in SE Texas.

Table 6. Gulf Coast CO_2-EOR Projects

Operator	Field	Pay Zone	State	Start Date	Tot. Prod. (bbl/d)	Enh. Prod. (bbl/d)
Denbury Resources	Delhi	Paluxy/Tuscaloosa	LA	11/1/09	5,920	5,920
Denbury Resources	Lockhart Crossing	Wilcox	LA	12/07	1,140	1,140
Denbury Resources	Brookhaven	Lower Tuscaloosa	MS	1/05	2,500	2,500
Denbury Resources	Cranfield	Tuscaloosa	MS	07/08	1,460	1,460
Denbury Resources	East Mallalieu	Lower Tuscaloosa	MS	12/03	366	366
Denbury Resources	West Mallalieu	Lower Tuscaloosa	MS	1986	1,964	1,964
Denbury Resources	Eucutta	Eutaw	MS	3/06	2,810	2,810
Denbury Resources	Heidelberg, East	Eutaw	MS	6/11	1,196	1,196
Denbury Resources	Heidelberg, West	Eutaw	MS	12/08	5,234	5,234
Denbury Resources	Lazy Creek	Lower Tuscaloosa	MS	12/01	190	190
Denbury Resources	Little Creek	Lower Tuscaloosa	MS	1985	760	760
Denbury Resources	Martinville	Mooringsport	MS	3/06	165	165
Denbury Resources	Martinville	Rodessa	MS	3/06	135	135
Denbury Resources	Martinville	Wash-Fred 8500	MS	9/06	200	200
Denbury Resources	McComb	Lower Tuscaloosa	MS	11/03	1,580	1,580
Denbury Resources	Soso	Rodessa 11,180	MS	9/06	1,990	1,990
Denbury Resources	Soso	Bailey 11,701	MS	4/06	150	150
Denbury Resources	Tinsley	Woodruff	MS	01/07	9,640	9,640
Denbury Resources	Oyster Bayou	Frio	TX	5/1/10	4,780	4,780
Denbury Resources	West Hastings	Frio	TX	12/1/10	5,720	5,720
Total Production (bbl/d)					47,900	47,900

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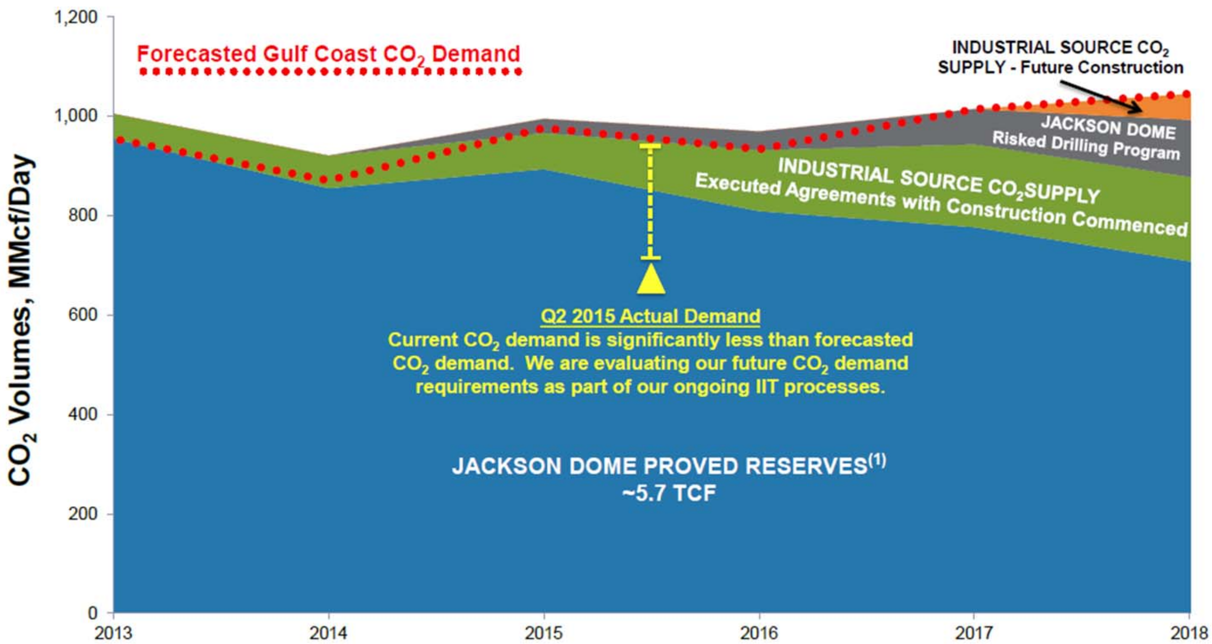
Given the expected decline in natural CO_2 supply from Jackson Dome, Figure 9, the incremental CO_2 supply for EOR in the Gulf Coast will need to be from industrial sources or imports of ship-transported CO_2. Potential new CO_2 supply sources for this region include 50 MMcfd of CO_2 capture from chemical plants in Louisiana and 235 MMcfd of CO_2 capture from two new power plants, the Kemper County IGCC in Mississippi and the W.A. Parrish power plant in Thompsons, East Texas, expected on line in 2016 and 2017, respectively.

Even with the availability of new industrial and power plant sources of CO_2, considerable additional demand for CO_2 for use by EOR exists in this market area.

Figure 9. Gulf Coast CO_2 Supply for CO_2-EOR



Source: Denbury Resources, 2015.

Mid-Continent CO_2 Market

The Mid-Continent CO_2-EOR market consists of light oil fields in Oklahoma, Kansas, Nebraska, Arkansas, and the Texas Panhandle. This region contains a significant number of oil fields technically amenable to CO_2-EOR, especially in Oklahoma and the Texas Panhandle, such as the large oil fields of Burbank, Oklahoma City, and Postle.

The Mid-Continent region contains nine active CO_2-EOR projects, Table 7. Two of the nine CO_2-EOR projects, NW Velma Hoxbar and Northeast Purdy have been in operation since the early 1980s. In total, these nine oil fields provided over 16,000 enhanced barrels of oil per day in 2014, utilizing 150 MMcfd of purchased CO_2, primarily from industrial sources.

Table 7. Mid-Continent CO_2-EOR Projects

Operator	Field	Pay Zone	State	Start Date	Tot. Prod. (bbl/d)	Enh. Prod. (bbl/d)
Chaparral Energy	Camrick	Morrow	OK	4/01	1,200	1,200
Chaparral Energy	North Perryton	Upper Morrow	OK	1/6	600	600
Chaparral Energy	Booker	Upper Morrow	TX	1/10	1,100	1,100
Chaparral Energy	Farnsworth	Upper Morrow	TX	3/10	2,280	2,180
Chaparral Energy	NW Velma Hoxbar	Sims	OK	9/82	310	260
Chaparral Energy	Burbank	Burbank	OK	4/13	2,160	1,000
Breitburn Energy	Postle	Morrow	OK	1/07-1/09	7,800	7,600
Merit Energy	Northeast Purdy	Springer	OK	9/82	1,800	1,800
Merit Energy	Bradley	Springer	OK	2/97	800	600
Total Production (bbl/d)					18,050	16,340

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A portion of the CO_2 purchased for CO_2-EOR in the Mid-Continent region, 35 MMcfd is natural CO_2 from the Bravo Dome in northeastern New Mexico. The CO_2 from Bravo Dome is delivered to the Postle oil field, through the Transpetco CO_2 pipeline. Breitburn Energy, the current operator of Postle, intends to increase the CO_2 supply and expand the CO_2-EOR operation in this oil field in the near future. Further development and expansion at other oil fields in the Mid-Continent, however, will need to rely on CO_2 supplies captured from other sources.

With regards to ship-based supplies of CO_2 for CO_2-EOR, CO_2 pipeline infrastructure could be extended from existing CO_2 pipelines in the Gulf Coast to Central Oklahoma, the location of the majority of the oil fields technically viable for CO_2-EOR in this region. The Phase II report will provide an in-depth look at the demand for ship-based CO_2 for use by oil fields in the Mid-Continent region.

West Coast CO_2 Market

The potential West Coast CO_2 market is primarily in central and southern California, in the Los Angeles, San Joaquin and Ventura basins. A large number of technically favorable for CO_2-EOR oil fields exist in these three basins, including large oil fields such as Elk Hills, Santa Fe and Ventura.

With the recent decision by the U.S. Department of Energy to suspend financial support to the $4 billion Hydrogen Energy California (HECA) clean coal project in western Kern County that had plans to capture and sell CO_2 to California oil fields, there is currently no readily available CO_2 available for the West Coast market. (A requirement to capture CO_2 from the refinery complexes in Southern California may provide some CO_2 supplies in the future, although there are no currently announced plans to such an activity.)

A longer-term market for CO_2 landed on the West Coast could be the oil fields of the Permian Basin, although a large-scale, long distance CO_2 pipeline would need to be installed to transport the CO_2 from a West Coast port to the Permian Basin of New Mexico and West Texas. A CO_2 pipeline connecting the West Coast port to the entry point of the planned Lobos Pipeline on the border of Arizona and New Mexico would provide a moderate distance transport option for delivering CO_2 from the West Coast to the Permian Basin. While the Lobos Pipeline project is currently on hold, the expansion of Permian Basin CO_2-EOR operations, supported by a more favorable outlook for oil prices could make both the Lobos CO_2 pipeline and its connection to the West Coast port feasible.

Offshore GOM CO_2 Market

A large number of oil fields exist in the offshore of the Gulf of Mexico that are technically amenable to use of miscible CO_2-EOR technology. The residual oil in-place of offshore oil fields favorable for CO_2-EOR is approximately 29 billion barrels. As CO_2-EOR technology improves, particularly with the use of sub-sea technology, these oil fields will become candidates for CO_2-EOR development.

One of the primary costs of offshore CO_2-EOR is construction of sub-sea pipelines for delivery of CO_2 to oil fields. Ship-based CO_2 supplies could provide a more viable solution to this problem, eliminating the need for a new pipeline system to deliver land-based CO_2 supplies to offshore oil fields. CO_2 supply ships could offload their CO_2 directly to offshore oil fields, or deliver supplies to port-based CO_2 hubs for distribution offshore. This method of delivery reduces the infrastructure required by land-based CO_2-EOR supplies and will help overcome one of the major barriers to offshore CO_2-EOR development.

Industrial CO_2 Capture Projects

As evidence of the potential for combining captured industrial CO_2 and storage of CO_2 with EOR, all of the active and planned North American CO_2 capture projects at coal-fired power plants will sell their captured CO_2 to oil fields for productive use by enhanced oil recovery with subsequent storage of the purchased CO_2.

- The “poster child” of capture and productive use of CO_2 for EOR is the 135 MMcfd of CO_2 captured from the Dakota Coal Gasification Plant and shipped to the Weyburn oil field in Canada for CO_2-EOR.

- The recently completed Boundary Dam project in Saskatchewan, Canada also sells its 60 MMcfd of post-combustion captured CO_2 to the Weyburn CO_2-EOR project

- The previously mentioned Mississippi Power project in the Gulf Coast will capture 165 MMcfd of CO_2 for CO_2-EOR in Mississippi, Louisiana, and East Texas.

- The Petra Nova Project to develop a commercial-scale post-combustion capture project at Unit 8 of WA Parish generating station southwest of Houston, Texas, that will capture 90% of CO_2 from flue gas slipstream providing 1.4 to 1.6 million metric tons per year of CO_2 to be used for EOR in West Ranch Field 80 miles away

Finally, our analysis shows that the market for CO_2 by the EOR industry becoming considerably more robust as EOR technology improves. Key technologies - - such as conformance control, targeting unswept portions of oil fields with horizontal wells and adding mobility control to the injected CO_2 - - would make more oil fields economically viable for CO_2-EOR, would more than double the potential oil recovery from CO_2-EOR, and would substantially increase the market demand for CO_2 by the EOR industry.

5. CO_2 Pipeline Infrastructure

Background

A safe, reliable, regionally extensive network of CO_2 transportation pipelines is already in place in more than a dozen U.S. states plus Saskatchewan, Canada. This system is an essential building block for linking the ship-based transportation of CO_2 with its productive use and storage in oil fields with CO_2 enhanced oil recovery.

The current CO_2 pipeline system consists of 50 individual CO_2 pipelines with a combined length of 4,765 miles, Table 8. While the bulk of the existing large-volume CO_2 pipelines connect natural sources of CO_2 (e.g., Bravo Dome, New Mexico) with CO_2-EOR projects in large oil fields (e.g., Wasson, West Texas), numerous additional CO_2 pipeline exist that connect point sources of industrial CO_2 with CO_2-EOR projects in nearby oil fields.

Table 8. Domestic CO_2 Pipeline Infrastructure

Region	Miles of CO2 Pipeline
Permian Basin (W. TX, NM, S. CO)	2,600
Gulf Coast (MS, LA, E. TX)	740
Rocky Mountains (N. CO, WY, MT)	730
Mid-Continent (OK, KS)	480
Other (ND, MI, Canada)	215
Total	**4,765**

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Source: U.S. DOE/NETL, 2015. "A Review of the CO2 Pipeline Infrastructure in the U.S.", DOE/NETL-2014/1681, April 2015.

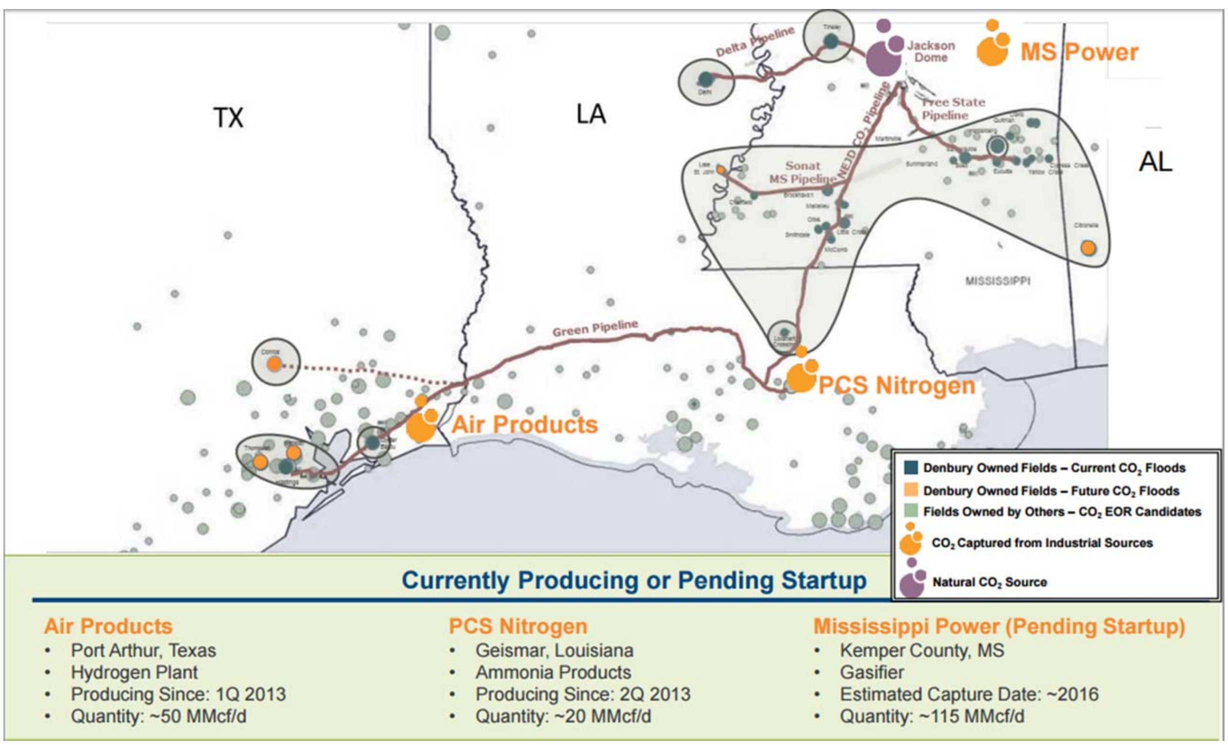
Today's CO_2 pipeline system had its beginnings in the 1970s, built for delivering CO_2 for use in the SACROC oil field in West Texas. This was followed by a series of large volume CO_2 pipelines connecting natural sources of CO_2 in Colorado and New Mexico with large oil fields in the Permian basin of West Texas and Eastern New Mexico. With the recent completion of two new long-distance CO_2 pipelines - - the Green Pipeline in Louisiana and Texas, and the Greencore Pipeline in Wyoming and Montana - - a much more geographically diverse CO_2 pipeline system is now in place. A variety of shorter and smaller volume laterals are being constructed to link these large-scale CO_2 pipelines to surrounding oil fields that are amenable to CO_2-EOR.

Of the 3.5 billion cubic feet (Bcf) per day (68 million metric tons per year [MMT]) of CO_2 transported, 0.7 Bcf per day (14 MMT per year) is from industrial sources, including gas processing plants. With new industrial CO_2 capture facilities coming on line (e.g., Air Products PCS Nitrogen plant in southern Louisiana, Southern Company's integrated gasification combined cycle (IGCC) plant in Kemper County, Mississippi, etc.) – including over 600 miles of new pipeline – the volume of industrial CO_2 captured and transported is expected to increase substantially.

Gulf Coast CO_2 Pipeline System

The recently constructed 740 mile Gulf Coast CO_2 pipeline network is owned and operated by Denbury Onshore LLC, Figure 10. Two main pipelines comprise the pipeline network, the North East Jackson Dome (NEJD) Pipeline and the Green Pipeline. These two pipelines connect the natural CO_2 source in Jackson Dome, Central Mississippi, as well as new industrial sources to Denbury's CO_2-EOR projects in Mississippi, Louisiana, and East Texas.

Figure 10. Southeast Gulf Coast CO_2 Pipeline Infrastructure



Source: Denbury Resources, 2015.

Table 9 lists the CO_2 transportation pipelines currently installed in the Gulf Coast region that connect natural and industrial sources of CO_2 with oil fields along the Gulf Coast.

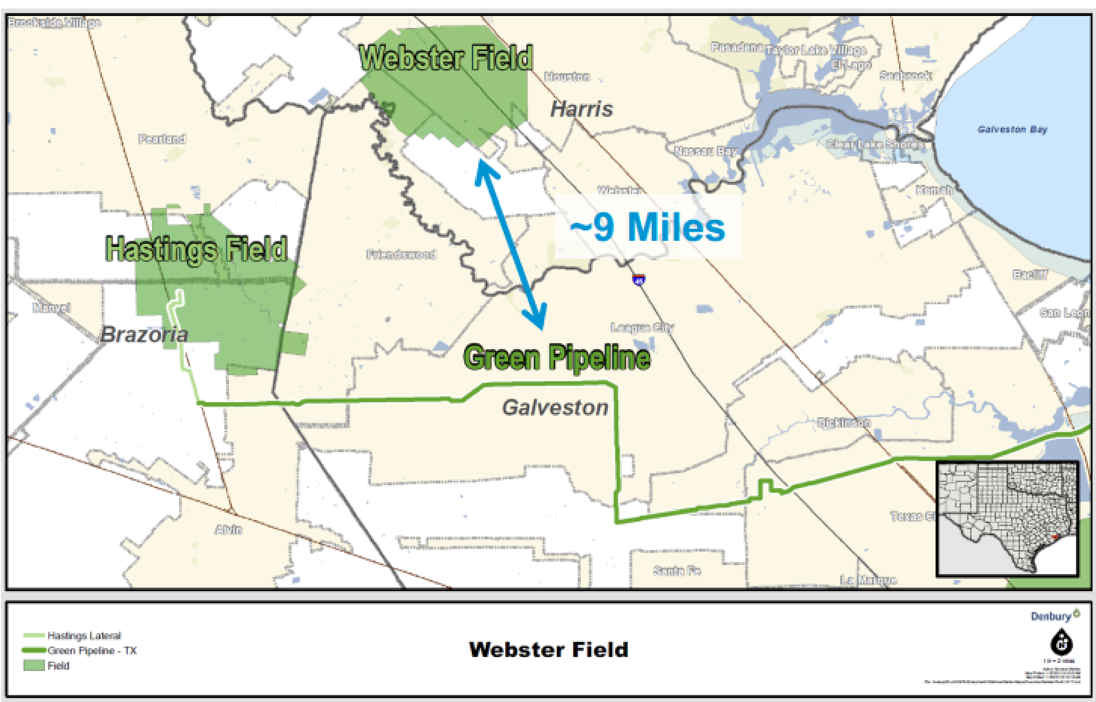
Table 9. Gulf Coast CO_2 Transportation Pipelines

Scale	Pipeline	Operator	Location	Length (mi)	Diameter (in)	Estimated Flow Capacity (MMcfd)
Large-Scale Trunk-lines	Green Line	Denbury Resources	LA, TX	314	24	930
	Delta	Denbury Resources	MS, LA	108	24	590
	Northeast Jackson Dome (NEJD)	Denbury Resources	MS, LA	183	20	360
Distribution Line	Free State	Denbury Resources	MS	85	20	360
	Sonat	Denbury Resources	MS	50	18	170

Source: Denbury Resources, 2015.

Denbury also has plans to build two significant CO_2 pipeline laterals from the Green Pipeline to oil fields in East Texas for launching additional CO_2-EOR projects in this region. Construction of the first pipeline, a 9-mile, 16-inch lateral from the Green Pipeline to the Webster oil field near Harris, Texas started in 2014, Figure 11. Delivery and injection of CO_2 is scheduled for 2016. The construction cost of this lateral is estimated at $23 million. The Webster CO_2-EOR project is expected to produce 15,000 barrels of oil per day.

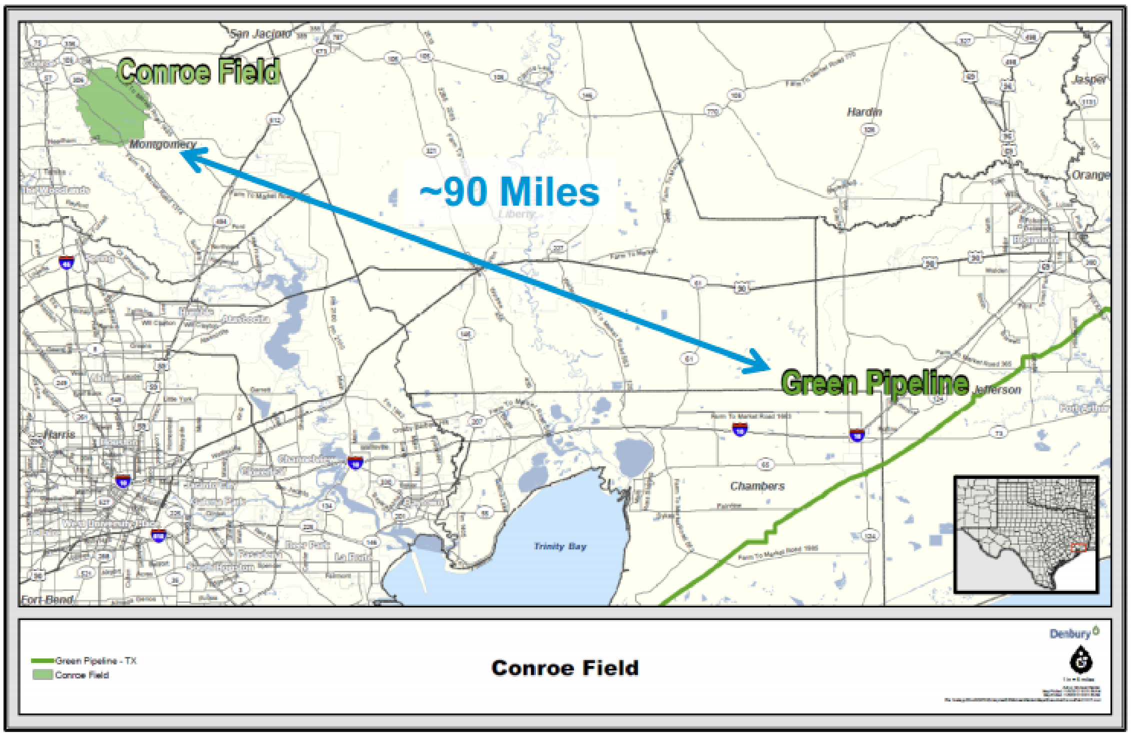
Figure 11. Planned Webster Oil Field CO_2 Lateral Pipeline



Source: Denbury Resources, 2015

Construction of a second pipeline lateral, connecting the Conroe CO_2-EOR project to the Green Pipeline, is also expected, with permitting and route selection currently underway. This lateral is expected to extend roughly 90 miles from the Green Pipeline near the border of Texas and Louisiana to the Conroe oil field, Figure 12. Construction on the 20-inch pipeline is expected to begin in 2016, with first delivery and injection of CO_2 in 2017 and first oil production in 2018. The Conroe CO_2-EOR project is expected to yield a peak production of between 15,000 and 20,000 barrels of oil per day.

Figure 12. Planned Conroe Oil Field CO_2 Lateral Pipeline



Source: Denbury Resources, 2015.

In addition to the Denbury Resources CO_2 pipeline system, a new 82 mile, point-to-point CO_2 pipeline is being constructed to deliver CO_2 from the Petra Nova Carbon Capture project at W.A. Parish power plant in Thompsons, TX to a new CO_2-EOR project at the West Ranch oil field of the Gulf Coast of Texas, Figure 13. Approximately 70 MMcfd of CO_2 will be delivered to the oil field starting in 2016.

Figure 13. Planned West Ranch Oil Field CO_2 Pipeline

Source: http://www.nrg.com/sustainability/strategy/enhance-generation/carbon-capture/west-ranch-oil-field/

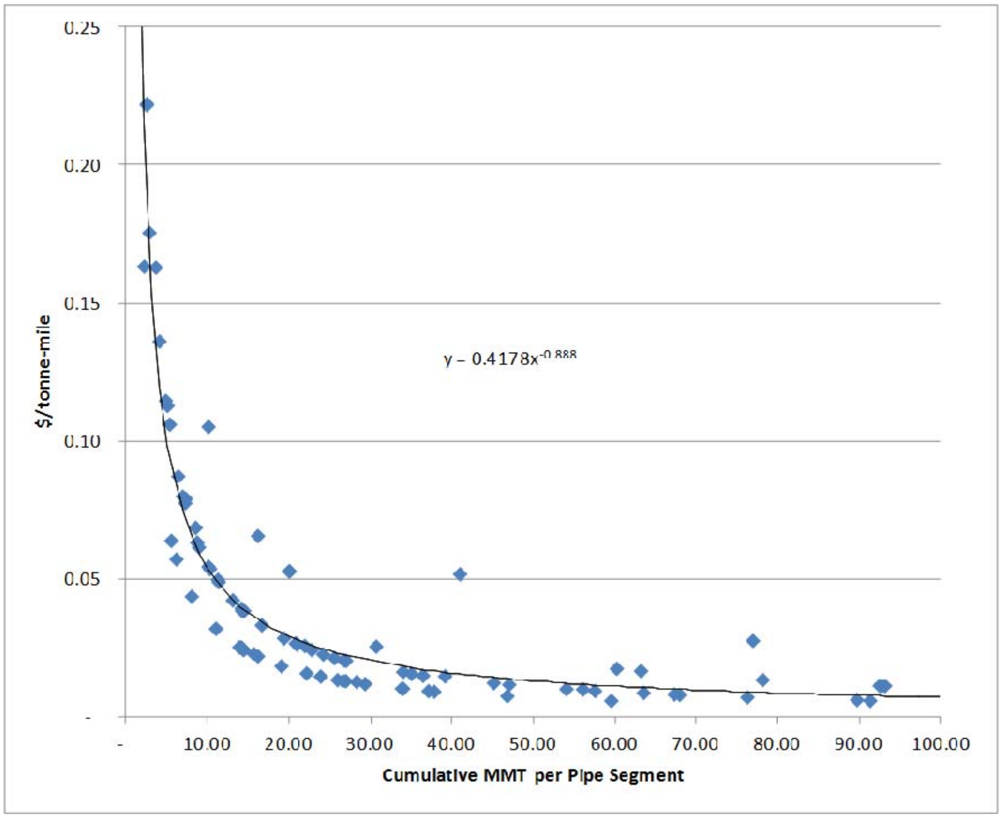
CO_2 Pipeline Costs

CO_2 pipeline development costs depend on a number of variables, including length, pipeline diameter, terrain, and other regional variations. Similar to oil field infrastructure development, capital costs for CO_2 pipelines are lowest in the Permian Basin. For example, the 216 mile, 16-inch Lobos Pipeline, with a capacity of 3,000 MMcfd, was expected to cost approximately $300 million. Other announced CO_2 pipelines in the Gulf Coast and Rocky Mountain regions cost between 25 percent and 33 percent more per inch-mile than the Lobos Pipeline due to more challenging terrain and navigation through denser populations.

Pipeline transportation costs depend heavily on the volume of CO_2 being transported Figure 14 shows that as the amount of CO_2 that is transported increases, there is a notable decrease in costs per ton of CO_2 delivered due to economies of scale.

In Phase II of the study, we will take a more detailed look at the CO_2 pipeline and transportation costs for linking CO_2 transported by ship to oil fields favorable for CO_2-EOR.

Figure 14. Transportation Cost as Function of CO_2 Throughput



Source: U.S. DOE/NETL, 2015. "A Review of the CO_2 Pipeline Infrastructure in the U.S.", DOE/NETL-2014/1681, April 2015.

6. Key Regulatory and Environmental Issues

Oil production with CO_2-EOR is a well-established technology in the U.S. Thus, regulatory barriers for producing oil from CO_2-EOR in the U.S. are minimal. CO_2 injection wells for EOR are regulated as Class II wells under the U.S. Environmental Protection Agency (EPA) Underground Injection Control (UIC) program.

For fields currently being developed and produced using CO_2-EOR, it is possible that some will eventually be converted to geologic settings used for permanent geologic storage of CO_2. EPA has promulgated requirements for geologic storage of CO_2, including the establishment of a new class of wells, Class VI, under the authority of the Safe Drinking Water Act's (SDWA's) UIC Program. These requirements, generally known as the Class VI rule and designed to protect underground sources of drinking water (USDWs), build upon existing UIC Program requirements.

The Class VI rule contains extensive, tailored requirements that address CO_2 injection for long-term storage to ensure that wells used for geologic storage are appropriately sited, constructed, tested, monitored, and closed. The rule is intended to provide owners and operators with the tools necessary to address CO_2 storage in various geologic settings, including oil and gas fields that are transitioned for use as CO_2 storage sites.

In December 2013, EPA published draft guidance on the conversion of Class II wells to Class VI wells, or, perhaps more appropriately, from CO_2-EOR operations to CO_2 storage operations. This draft guidance created considerable uncertainty among CO_2-EOR operators, since it seemed to deviate from what they perceived as the original intent of the Class VI rule. The guidance also led many to believe that in order for a CO_2-EOR operation to get “credit” for stored CO_2, a conversion from Class II to Class VI operations would likely be necessary.

Recent guidance issued by EPA confirms that CO_2-EOR operations can, in fact, result in stored CO_2, and a conversion to Class VI is not a requirement for assuring storage. Peter Grevatt, director of EPA's Office of Ground Water and Drinking Water, issued an April 24, 2014 guidance memo to the agency's regional water division directors that clearly states that existing CO_2-EOR wells do not need to transition from their current Class II permits for oil and gas operations to stricter Class VI permits to ensure storage, declaring that CO_2 can be safely stored under existing Class II permits. Importantly, the memo concludes that CO_2-EOR operations can switch from using a natural source to an anthropogenic source of CO_2 without triggering the need to upgrade to a stricter Class VI permit. But the memo leaves the door open to consider some CO_2-EOR wells for Class VI permits in cases where the Class II rules may not provide regulators with adequate tools to protect against “increased risks” to USDWs.

EPA has also established greenhouse gas reporting requirements under the Greenhouse Gas Reporting Program (GHGRP) for facilities that inject CO_2 underground for geologic storage and for all other facilities that inject CO_2 underground. Subpart UU of the GHGRP rules applies to CO_2 injected to enhance oil recovery; Subpart RR applies to CO_2 injected for geologic storage.

Nonetheless, regulatory barriers remain if credit for the CO_2 stored in the association with CO_2-EOR is sought. For example, under EPA “Clean Power Plan,” CO_2 storage with CO_2 -EOR is recognized as a potential compliance mechanism. If CO_2 storage is verified under Subpart RR of the GHGRP, many are concerned that Subpart RR fundamentally conflicts with state-level mineral property and resource conservation law.

Most significant concerns under Subpart RR include: (1) processes for and timeliness of EPA approval of monitoring, reporting, and verification (MRV) plans for CO_2-EOR projects, (2) what constitutes "new" activity in a CO_2-EOR project necessitating submittal of a new MRV plan, (3) how federal requirement relate to current state CO_2-EOR/Class II permitting processes, and (4) the extent to which MRV plans are subject to public litigation procedures.

Today, the main barrier to reaching higher levels of CO_2-EOR production, both in the U.S. and worldwide, is insufficient supplies of affordable CO_2. In fact, given this situation, the state of Texas may be the world's first example of a "demand pull" to encourage anthropogenic CO_2 capture. Legislative and regulatory activity in the State of Texas has evolved to support increasing CO_2 supplies from anthropogenic sources to serve the CO_2-EOR market.

Specifically, the Texas Railroad Commission (TRRC) administers the federal Underground Injection Control (UIC) Program addressing CO_2 injection wells used for EOR (State wide Rule 46), gaining approval from EPA on April 23, 1982. Rule 46 governs fluid injection into reservoirs productive of oil, gas, or geothermal resources. Rule 46 also addresses the application process, notice and opportunity for hearing, protested applications, special equipment requirements and modification, suspension, or termination of permits for one or more of several causes. Also included in Rule 46 are requirements regarding records maintenance, monitoring and reporting, testing; plugging, and penalties for violations of the rule.

In 2009, Senate Bill (SB) 1387 instructed the TRRC to write rules for geologic storage of CO_2. SB 1387 also created the anthropogenic CO_2 storage "Trust Fund" to cover long-term monitoring of geologic storage facilities, and ordered a study on management of geologic storage on state-owned lands. The TRRC adopted new rules effective December 20, 2010. The purpose of the rules is to protect the underground sources of drinking water while promoting the capture and storage of anthropogenic CO_2, and include requirements for applications, fees, geologic site characterization, permit issuance, construction, operation, testing, monitoring and closure. These do not apply to UIC Class II wells for EOR. Conversion of a well from use in EOR to use in geologic storage is not considered to be a change in the purpose of the well.

Oil produced from an approved new EOR project or expansion of an existing project in Texas is eligible for a special EOR severance tax rate of 2.3% of the production's market value (one-half of the standard rate) for 10 years after Commission certification of production response. For the expansion of an existing project, the reduced rate is applied to the incremental increase in production after response certification. Effective from September 1, 2007, the State Legislature also adopted an Advanced Clean Energy and EOR Tax Reduction Bill which further reduced the effective severance tax rate for use of anthropogenic CO_2 to 1.15% for the first 7 years of EOR production.

One major barrier to large-scale implementation of CO_2-EOR in Texas does remain. For Texas to fully benefit from potential new CO_2 supplies, the lack of a unitization policy in the State inhibits the ability to assure aggregation of hydrocarbon reservoir ownership for the target reservoirs for CO_2-EOR, as well as to ensure regulatory compliance and potential future assurance for the stored CO_2. Texas is the only state in the U.S. without a compulsory unitization policy. Legislation to change this has been introduced, but not passed, due primarily to opposition by landowners. This limitation has not posed a significant barrier in West Texas, but the more fragmented ownership of some of the large East and Central Texas fields may hinder CO_2-EOR deployment in some of these fields if they cannot be voluntarily unitized.

In Phase II of this study, we will take a more detailed look at the key regulatory and environmental issues that may impact CO_2 used in the U.S. enhanced oil recovery industry that is delivered by ship-based transportation.

Feasibility Study of Ship-Based Transportation of CO_2

Chapter 3
Status and Outlook for U.S. Natural Gas Liquids Supply and Demand: Phase 1

Prepared by:
Advanced Resources International, Inc.

Status and Outlook for U.S. Natural Gas Liquids Supply and Demand: Phase 1

Introduction

This report provides an overview of the current domestic Natural Gas Liquids (NGL) supply and demand situation. NGLs are composed of natural gas liquids (ethane, propane, iso – and normal butane, and pentanes plus (natural gasoline)) produced at natural gas processing plants. Additional sources of NGLs, called liquefied refinery gases (LRG), are produced as byproducts from crude oil processing at oil refineries. Almost all growth in NGLs production over the past decade has been attributable to natural gas liquids from gas processing plants and, therefore, gas plant NGLs will be the focus of this report.

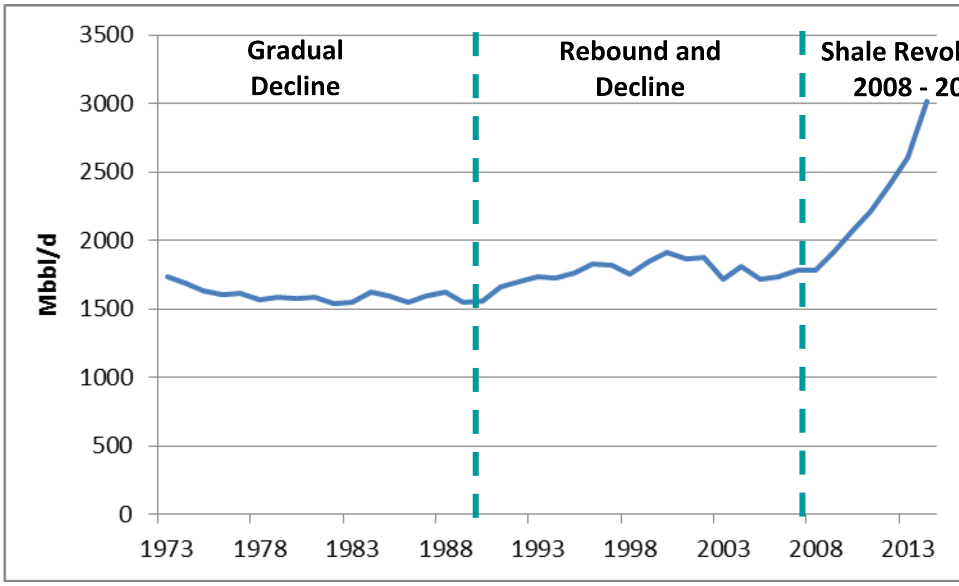
Background

After nearly twenty years of decline, domestic natural gas plant liquids (NGL) production hit a low of 1.6 million barrels per day (MMB/D) in 1990. With expectations of scarcity and higher prices for natural gas, much of the domestic petrochemical industry, particularly along the Mississippi River, relocated to areas with more secure, accessible supplies of NGLs as well as naphtha, an alternative to using NGLs as feedstock in chemical plants.

Subsequently, NGL production rebounded and then stayed relatively flat at 1.8 to 1.9 MMB/D through 2008, but this rebound was met with skepticism by industry as to its sustainability. As such, industry's pessimistic outlook for future NGL production remained entrenched and petrochemical operations continued to relocate overseas, relying primarily on naphtha as the preferred feedstock for ethylene production.

However, since 2008, U.S. production of NGLs (from gas plants) has surged -- from 1.8 million barrels per day in 2008 to 3.0 million barrels per day in 2014, Figure 1.

Figure 1. Domestic Natural Gas Liquids Production



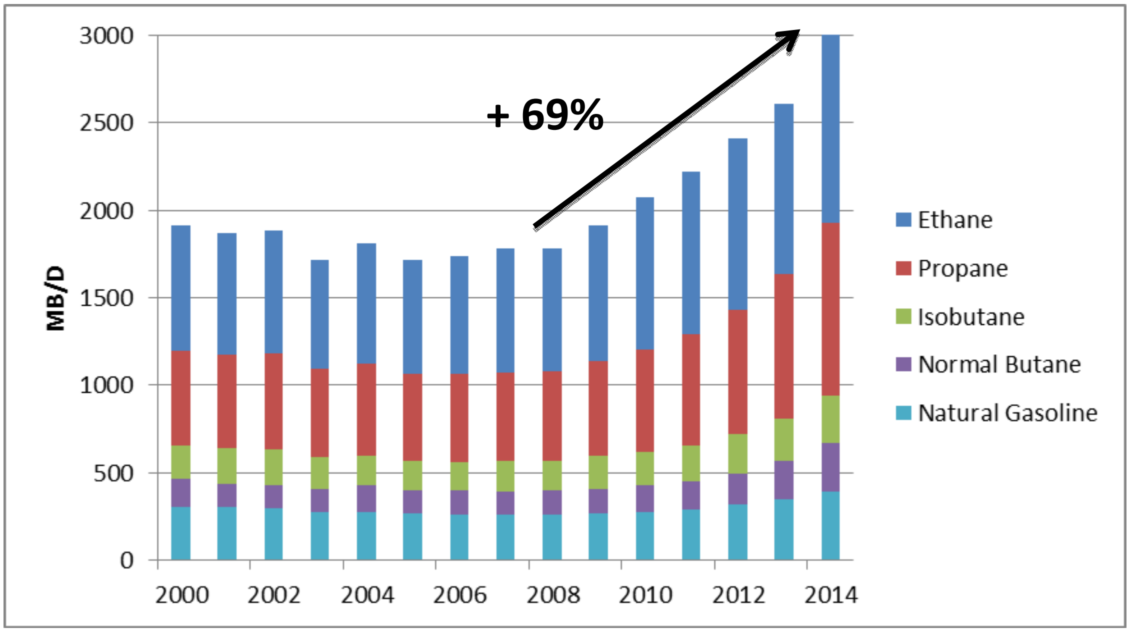
Source: U.S. EIA, 2015

This dramatic change in the domestic NGL supply situation has been brought about by the “shale revolution”, particularly the discovery and development of wet, liquids-rich shale gas plays such as the Woodford, SW Marcellus, and Utica. Additionally, liquids-rich associated gas from “tight oil” plays such as the Bakken, Eagle Ford and the stacked formations of the Permian further boosted NGL supply.

Status of Domestic NGL Supply

Much of the growth in domestic NGL supply has been from increased production of ethane and propane. Ethane production increased by 0.4 MMB/D -- from 0.7 MMB/D in 2008 to 1.1 in 2014 -- despite rejection of an estimated ~0.8 MMB/D of technically recoverable ethane in 2014. Meanwhile, propane production increased by 0.5 MMB/D over this same time period, from 0.5 MMB/D to 1.0 MMB/D. In addition, production of iso-butane, normal butane, and pentane (natural gasoline) increased by a combined 0.4 MMB/D, from 0.6 MMB/D to 1.0 MMB/D. Figure 2 illustrates the recent growth of NGL production by the five key product streams.

Figure 2. Growth of Domestic NGL Supply, by Product



Source: U.S. EIA and ARI, 2015

With the strong growth in domestic NGL production, in 2011 the US became a net exporter of natural gas plant liquids and liquefied refinery gases for the first time since the data for imports/exports of NGLs has been recorded.

NGL Demand

Ethane. The primary driver of ethane demand is feedstock for production of ethylene and other chemicals in competition with naphtha. With increasing production of low cost wet (liquids-rich) natural gas, the cost advantage of producing ethylene from ethane has stimulated expansion and new construction of ethane crackers. Additionally, dedicated ethane pipelines, export terminals, and tankers are under development. However, increases in domestic ethane production have greatly exceeded growth in domestic demand. As such, increased ethane exports are needed to remedy the current surplus situation and low price.

Propane. Propane, the most seasonal of the NGL streams, is used in a variety of capacities, from residential heating in the winter, to agricultural use in the fall and petrochemical use the year round. With the steady growth of domestic propane production, Figure 3, the US began exporting propane in 2011 and exported 0.4 MMB/D of propane in 2014 (0.3 MMB/D, net), Figure 4. The exports primarily depart from Gulf Coast terminals located in close proximity to the large NGL processing complex at Mont Belvieu, TX. Additionally, propane is also exported from the Marcus Hook facility on the East Coast. Proposed West Coast propane export terminals in Oregon and Washington are in the early stages of planning.

Figure 3. Growth of Domestic Propane Production

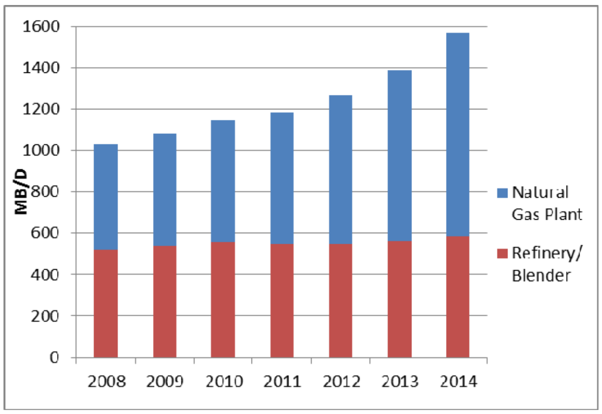
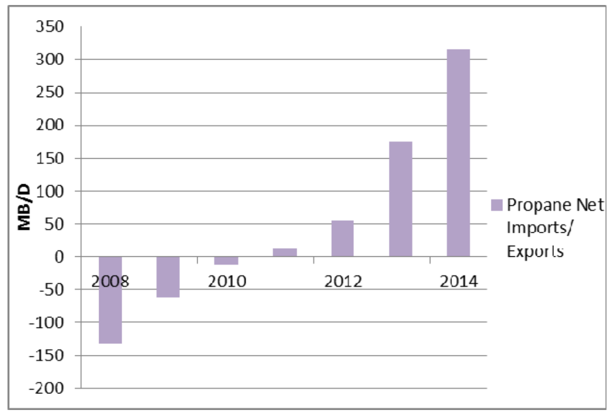


Figure 4. Imports and Exports of Propane

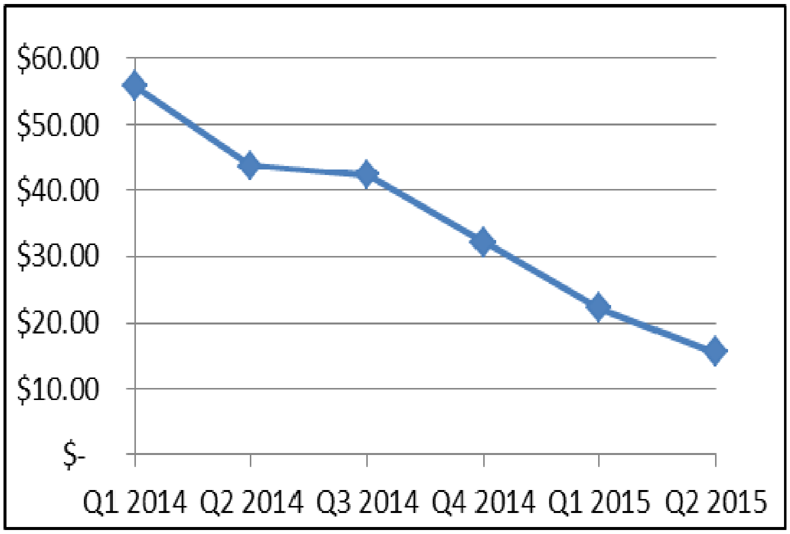


Butane and Pentane. Normal butane can be used for gasoline blending and as a petrochemical feedstock, whereas isobutene is primarily used in the production of motor gasoline by refineries. Pentane is primarily used as a blending stock for transportation fuel and as a diluent for heavy oil. These heavier NGL components, iso and normal butane and pentanes plus, are largely consumed domestically. However, in 2014 the US exported a modest volume of butane (55 MB/D, net) and a moderate volume of pentane (152 MB/D, net).

NGL Pricing

NGL prices have collapsed in the last two years due to oversupply and a decline in the price of oil. In the Marcellus, one of the primary regions of NGL supply growth, NGL prices have been hit particularly hard, declining by over 70% in the 18 month period ending in mid-2015. Figure 5 illustrates the decline in NGL sales price for a Marcellus operator, EQT, and demonstrates that the initial decline in NGL pricing started with the NGL over supply and then continued with the decline in oil prices.

Figure 5. Decline in Gross NGL Sales Price ($/B, EQT Corp)



Ethane, currently with a Mt. Belvieu price of $7.80/B ($0.19 /gal or ~$2.80/MMBtu), is being rejected widely as operators often receive more by keeping ethane in the gas stream than processing it. Similarly, propane prices have collapsed as well, with current prices of about $16.80/B ($0.40/gal or $4.40/MMBtu).

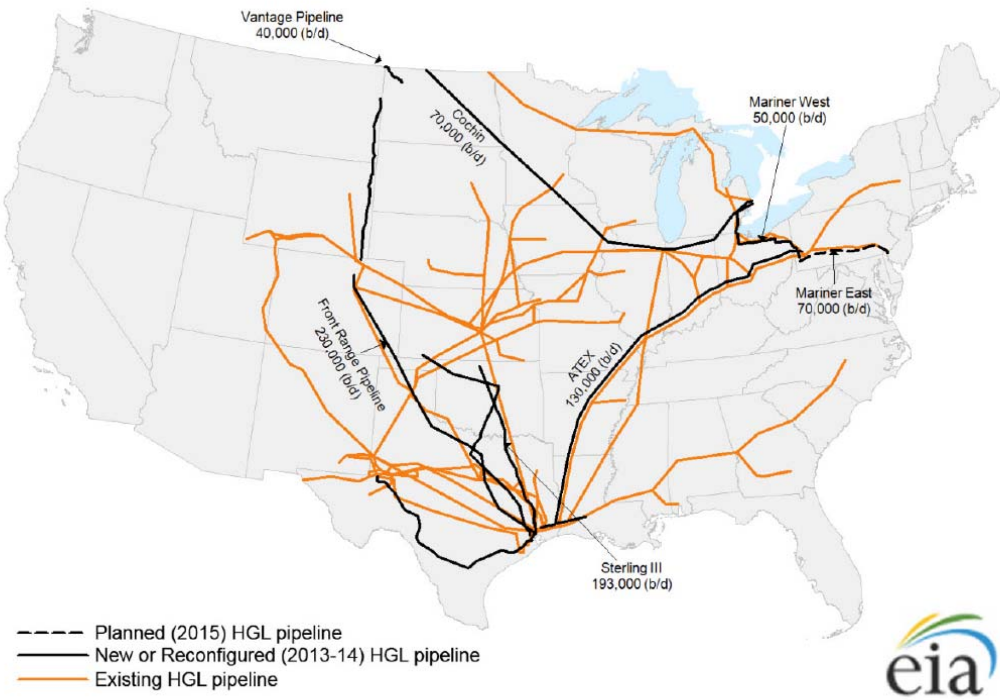
Driving the economics of exporting ethane is the price spread between ethane and naphtha, which has favored ethane over the past few years due to the lower cost of ethane and a higher oil price. Overseas, many of the crackers used for the production of propylene/ethylene, the basic building blocks of plastics, use naphtha as a feedstock. Naphtha pricing tracks global oil prices closely, meaning that in the high oil price world of 2012 through the first half of 2014, naphtha was at a disadvantage to ethane as a feedstock. The oil price decline has narrowed the spread between ethane and naphtha, potentially reducing the economic attractiveness of the multiple new “world scale” ethane crackers currently under construction in the U.S. However, the long term fundamentals of a growing ethane supply remain intact and exports and/or new domestic crackers are needed to balance supply and demand.

NGL Pipeline System and Exports

To reduce the NGL glut in regions such as the Appalachian Basin, major new NGL pipelines are on line or under construction, such as the Enterprise ATEX ethane pipeline, to transport NGLs to processing and export hubs on the Gulf Coast.

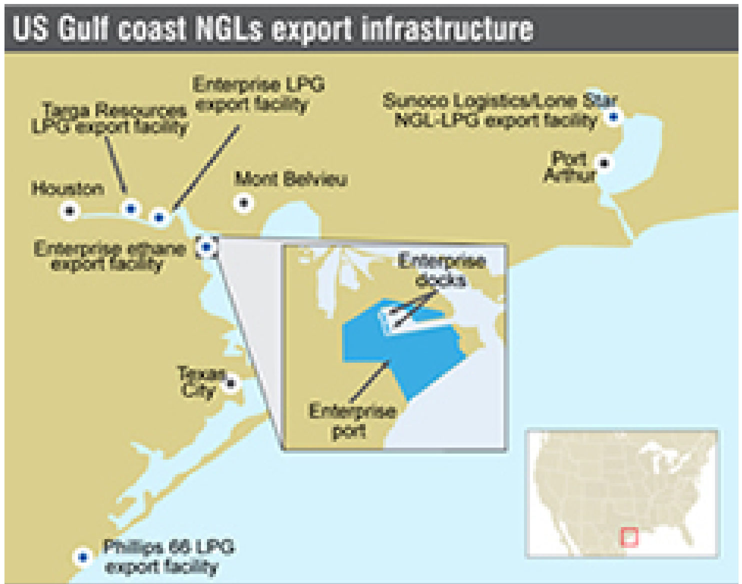
Ethane shipments to Canada from PADD 2, to be used by Canadian petrochemical facilities, have also commenced on newly built pipelines. The Mariner East project, which Sunoco is currently considering expanding, transports NGLs from the Marcellus Shale to the Marcus Hook export terminal on the East Coast. Companies like Ineos have contracted for the shipment of ethane from Marcus Hook for use at their ethane cracking facilities in Europe.

Figure 6. Domestic NGL Pipelines



Much of the domestic NGL storage, processing, and export infrastructure is located on the Texas Gulf Coast. In response to increasing domestic NGL supplies and in anticipation of the widening of the Panama Canal in 2016, which will allow for the transit of the largest NGL product ships to and from Asia, many NGL export terminals on the Gulf Coast are undergoing expansions, such as Enterprise's Houston Ship Channel and Targa Resource's Galena Park Marine Terminal. Also, a new LPG export terminal with initial export capacity of 4.4 million barrels per month is currently under construction in Freeport, TX, and is due on-line in the second half of 2016. These projects will enable the U.S. to maintain its position as the largest exporter of LPG in the world.

Figure 7. Gulf Coast NGL Export Infrastructure



Source: Argus Media. 2015

Phase II Work: The Outlook for NGL Supply and Demand

As part of our Phase II work, we would build on our review of the current status of domestic NGL supply, demand and exports to provide a longer outlook for this important hydrocarbon product for years 2015-2025. We would use our proprietary NGL data base and economic models, to provide this information.

Feasibility Study:

Liquid Gas Carrier with CO2 Back-Haul

Dated: 8 April 2016

Rev: 0

ABS Consulting
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Contents

1. Introduction

Fearnoil commissioned ABSG Consulting (ABSG) to perform a study to determine whether carriage of liquid CO_2 is a feasible option for natural gas liquids (NGLs) and liquefied petroleum gas (LPG) shippers. The object would be maximize utilization of existing or proposed vessels in liquefied gas service loading cryogenic liquid gases at US Gulf of Mexico or Atlantic coast ports as an alternative to returning to the US in ballast (empty of cargo). The source of the liquid CO_2 (LCO_2) would be CCS projects in Europe or other locations to be specifically determined at a future development phase. The study examined the technical, operational and regulatory compliance issues to be considered for liquefied-gas vessels to be used for backhaul cargos of LCO_2.

The report includes the results of the study, comprising a basic technical evaluation of the capability of liquefied-gas carriers to safely and routinely transition from carrying NGLs to CO_2 and vice versa, and any special equipment, systems or procedures to make it possible.

It also outlines the economic framework to determine commercial possibilities for more detailed studies if specific opportunities are identified as a result of this report.

This report will summarize and explain the results of the feasibility study with conclusions and recommendations for additional or more detailed areas of analysis where needed.

In the context of this report, for the avoidance of confusion with multiple marine vessel categories and types, the term liquefied gas carrier is used to cover the entire range of vessels with the technical capacity to carry liquid gases, including CO_2. The term natural gas liquids (NGLs) is used throughout this report and covers the spectrum of liquefied gases carried by ship. The term liquefied petroleum gas (LPG) is used in the shipping industry to refer mainly to propane and butane (see Table 1 below for description of NGLs).

To produce this report, ABSG interviewed liquefied gas ship owners, large international oil company geologists, marine cryogenic equipment suppliers, US based CO_2 pipeline operators, process systems engineers, US Coast Guard technical compliance staff and our own subject matter experts within the ABS Global Gas Solutions group. The information contained in this report was developed from phone conversations, email exchanges, internet research, peer review and ABSG's marine shipping technical knowledge and experience. It is believed to be the best currently available information as of the date of issue of this report.

1.1. Background

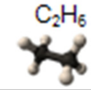
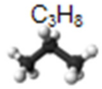
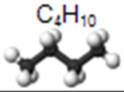
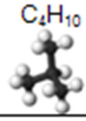
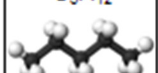
As a result of improved onshore oil and gas extraction technologies over the last decade, US domestic oilfields have produced significant quantities of oil, natural gas and natural gas liquids (NGLs). These products have become available for export as a result of supply exceeding demand in the US.

Until recently, US export capability has been limited, but major NGL export projects have been developed in the US and are now coming on stream to supply energy products to world markets. NGLs are in demand globally as a feedstock for various industrial and chemical processes (Table 1).

NGL exporting involves the use of specialized ships known as liquefied gas carriers with pressurized cargo tanks and cargo handling systems capable of carrying liquefied gases with temperatures as cold as -160°C (260°F) throughout a range of pressures. These ships are designed and built according to stringent international design criteria to permit safe transport and handling of cryogenic and pressurized liquid gases.

At the same time, carbon capture and storage (CCS) projects have created a potential need to transport captured CO2 from the emitter or capture location to the end-user or storage location. Carbon capture and storage is a set of technologies aimed at capturing, transporting, and storing CO2 emitted from power plants and industrial facilities. The goal of CCS is to prevent CO2 created in power generation, fossil fuel extraction and other industrial processes from reaching the atmosphere by injecting and storing it in suitable underground geological formations.

Table 1 Common Natural Gas Liquids (source: EIA)

NGL Attribute Summary				eia
Natural Gas Liquid	**Chemical Formula**	**Applications**	**End Use Products**	**Primary Sectors**
Ethane	C_2H_6 	Ethylene for plastics production; petrochemical feedstock	Plastic bags; plastics; anti-freeze; detergent	Industrial
Propane	C_3H_8 	Residential and commercial heating; cooking fuel; petrochemical feedstock	Home heating; small stoves and barbeques; LPG	Industrial, Residential, Commercial
Butane	C_4H_{10} 	Petrochemical feedstock; blending with propane or gasoline	Synthetic rubber for tires; LPG; lighter fuel	Industrial, Transportation
Isobutane	C_4H_{10} 	Refinery feedstock; petrochemical feedstock	Alkylate for gasoline; aerosols; refrigerant	Industrial
Pentane	C_5H_{12} 	Natural gasoline; blowing agent for polystyrene foam	Gasoline; polystyrene; solvent	Transportation
Pentanes Plus*	Mix of C_5H_{12} and heavier	Blending with vehicle fuel; exported for bitumen production in oil sands	Gasoline; ethanol blends; oil sands production	Transportation

C indicates carbon, H indicates hydrogen; Ethane contains two carbon atoms and six hydrogen atoms
*Pentanes plus is also known as "natural gasoline." Contains pentane and heavier hydrocarbons.

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1.2. Definitions and Acronyms

ABSG - ABS Group Consulting

BOG – boil-off gas, vapour generated by evaporation of liquid gas cargos

CO2 – CO_2, Chemical name and common acronym for carbon dioxide

C2 – common abbreviation of chemical name for ethane, C_2H_6

CCS – Carbon Capture and Storage

EIA – Energy Information Agency – US government agency that monitors and reports US energy statistics

EOR – Enhanced Oil Recovery, pressure injection of CO2 into oil reservoirs to improve oil and gas production

GGS- Global Gas Solutions, team of liquefied gas marine transportation subject matter experts within ABS

HGL – Hydrocarbon Gas Liquid, equivalent term for NGL and LPG

IEA – International Energy Agency, autonomous international NGO that examines energy issues and policies

IGC – International Gas Carrier Code

IMO – International Maritime Organization

LCO2 – Liquid Carbon Dioxide

LNG – Liquefied natural gas- primarily methane with ethane, propane, butane, pentane and other trace components

LPG- Liquefied Petroleum Gases – gases that have been liquefied by cooling or pressurizing for ease of transport and storage. In marine shipping, LPG refers mainly to propane and butatne.

NGL Natural Gas Liquids –hydrocarbons composed exclusively of carbon and hydrogen (see Table 1)

OCIMF – Oil Companies International Marine Forum, ship inspection and reporting service and data base

SIRE – Ship Inspection Report – standard format vetting inspection report used by charterers, shippers, terminals and others to determine vessel compatibility and suitability for hire

USCG – United States Coast Guard

1.3. Executive Summary

Discussion with ABS Global Gas Solutions technical experts, CO2 pipeline operators, US Coast Guard engineering and hazardous materials staff, cryogenic pump makers and LPG vessel operations executives indicate that from a technical standpoint, liquid CO2 can be carried aboard suitable liquefied gas vessels with approvals, precautions and handling procedures similar to those used for other liquefied gases carried as cargo aboard ships.

Quoting an email message received from a senior executive of a well-established European liquefied-gas carrier with long experience in the transport of cryogenic liquid gases, “Technically, transporting CO2 is not a big deal. (You) (j)ust have to choose temp/pressure to optimize your supply chain”.

The biggest challenge in utilizing existing liquefied-gas carriers is the maximum allowable working pressure of the cargo tank, which would be higher than that used for regular LPG service. Although there are existing liquefied gas carriers capable of carrying LCO2, because of the requirement for increased pressure capability, they are generally smaller and less suited to long-haul trans-Atlantic transport.

Basic vessel technical requirements are:

- Type 2G or 3G liquefied gas carrier with, or capable of being approved for, a Certificate of Fitness for liquid CO2
- Type C (pressure vessel) containment system with greater than 7 Bar g design pressure and appropriate safety margin
- Tanks and cargo systems suitable for cryogenic liquid gases colder than -55°C
- Permission from the relevant authorities to carry liquid CO2
- Sufficient cargo carrying capacity to allow competitive unit freight cost

Suitable vessels for LCO2 backhaul service would fall into the “handy-size” gas carrier category; vessels with approximately 15,000m3 to 30,000m3 capacity. The notional candidate vessels identified in this report have less than 15,000m3 cargo capacity.

Increased US NGL exports are driving requirements for more liquefied gas carriers to lift cargos from Gulf and East coast ports. Existing designs of handy-size liquefied gas carriers are a close fit, but would need to be tailored at the newbuilding design stage to make carriage of LCO2 possible. There may be an opportunity to take advantage of increased numbers of handy-size newbuild orders to specify LCO2 capable ships at a cost which should be only marginally higher than the cost of a standard liquefied gas carrier.

Potential time loss and the logistical and operational elements of changing cargo grades and voyage deviations will also significantly affect the feasibility of LCO2 backhaul on a specific trade route, charter or contract of affreightment. Potential for net hydrocarbon emissions increase also has to be evaluated in the context of environmentally responsible shipping and CCS project objectives.

A variety of economic and operational factors of moderate complexity and likelihood must be aligned in order for ship-owners to regard LCO2 backhaul as an attractive market. These include:

- Availability of suitable vessels with the requisite cargo tank design pressure
- Development of needed infrastructure (CO2 storage and marine transfer facilities)
- Long term commitment of project stakeholders, including shippers and CCS project developers and sponsors
- Sufficient economic inducement for all participants in the value chain

On the CO2 market development front, North American CO2 users are interested in new and additional supply sources, such as that represented by importing LCO2 from CCS projects overseas as part of a total supply chain carbon reduction strategy.

According to ABSG discussions with US oil major E&P geologists and drillers, a potential demand for additional CO2 supply exists due to a variety of factors:

- There is competition for EOR CO2 supply among onshore field operators
- Access to current sources of CO2 (underground geological structures) can be complicated
- EOR projects for the oil majors are long-term and not sensitive to current oil prices
- Oil majors are always on the lookout for reliable CO2 supply options.
- Opportunity to participate in "green" CCS projects that reduce overall value chain carbon emissions can be an incentive

Discussion with CO2 pipeline operator representatives also indicated that the US market can be fragmented and subject to variability with regard to supply and demand, concluding that a credit-worthy customer at the right price and a long term volume commitment could "get a deal done."

Significant expansion of US NGL exports will drive increasing numbers of liquefied -gas carriers to US Gulf Coast ports, increasing opportunities and competition among shippers and ship owners for backhaul cargos. As of 2015, the US was the top exporter of NGLs, with over 250 million barrels shipped, ahead of the next largest producer UAE, by over 1.25 million barrels.

In general, the CO2 backhaul concept is technically feasible with appropriate precautionary measures. Favorable shipping and logistics factors provide support and opportunity for development of the concept. Additional study identifying specific vessels, containment system modification requirements, trade routes, actual CO2 sellers and buyers, load and discharge ports and infrastructure requirements must be completed for proof of concept.

1.4. US Natural Gas Liquids Export Market Development

A number of projects have been proposed to export NGLs from US Gulf Coast and Atlantic ports. According to the US Energy Information Agency (EIA), "Several companies such as Phillips 66, Targa Resources Partners, Sunoco Logistics, and Enterprise Products Partners have announced plans to expand or build new HGL (hydrocarbon gas liquid) export facilities, mostly along the Gulf Coast to take advantage of a growing excess supply of propane, normal butane, and ethane"[1].The export projects rely partially on the use of liquefied gas carriers due to the special nature of the products they carry. It is expected that many ships used in NGL export service will return to the US from their discharge ports empty. Optimization of the transportation chain to include a cargo to be carried on the return voyage (sometimes referred to as backhaul) would reduce costs and increase operational efficiency by using fewer ships to move more cargo.

Table 2 Ethane and LPG Export Projects in the US (source: ABSC research)

Project	Location	Capacity	Start Date
Enterprise Products Morgan's Point	Houston Ship Channel Morgan's Point	2 marine berths 200,000bbl/d (32,000m3/d)	3Q 2016
Sunoco Logistics Mariner East I & 2	Marcus Hook, PA	Ph I 70,000 bbls/d (11,000 m3/d) Ph II 450,000 bbl/d (71,000m3/d)	Currently operating Phase II 2Q 2017
Targa Resources	Houston Ship Channel Galena Park Marine Terminal	4 marine berths Ph II Expansion 200,000 bbl/d (32,000m3)	Currently operating
Conoco Phillips	Freeport LPG Export Terminal Freeport, TX	2 marine berths 146,000 bbl/d (23,000m3/d)	3Q 2016

[1] EIA, Hydrocarbon Gas Liquids (HGL): Recent Market Trends and Issues, Nov 2014, pg 17

Figure 1 Galena Park Marine Terminal, NGL marine transfer facility on the Houston Ship Channel (source: Targa Resources)

1.4.1. Carbon Capture and Storage (CCS)

Additionally, an active and established market for CO2 used in enhanced oil recovery (EOR) exists in North America, with the majority of activity occurring in the Gulf of Mexico region. Most EOR operations involve transport of CO2 from existing geological formations to onshore oil fields in Texas, Louisiana, and Oklahoma. Transport is accomplished via pipeline with the CO2 compressed to super-critical pressure (124 bar g – 150 bar g / 1800 – 2200 psig) in its "dense" phase. According to discussion with exploration and production geologists and other specialists[2], EOR is a long term investment with a 10-15 year payback period that is less sensitive to current oil prices than other oil and gas drilling activities. Supply from geological resources can be structurally complicated and subject to competition from other oil major E&P customers. Due to these factors, North American CO2 users are interested in new and additional supply sources, such as that represented by importing LCO2 from CCS projects overseas as part of a total supply chain carbon reduction strategy.

[2] ABSC phone conversations with drilling specialists and geologists at oil major E&P subsidiary and major CO2 pipeline operator (names withheld for confidentiality reasons).

Table 3 CCS Projects for EOR in the US (source: Global CCS Institute)

Project Name	Stage	Operation Date	Industry	Capture Capacity (Mtpa)	Transport Type	Primary Storage Type
Air Products Steam Methane Reformer EOR Project	Operate	2013	Hydrogen Production	1	Pipeline	Enhanced oil recovery
Century Plant	Operate	2010	Natural Gas Processing	8.4	Pipeline	Enhanced oil recovery
Coffeyville Gasification Plant	Operate	2013	Fertilizer Production	1	Pipeline	Enhanced oil recovery
Enid Fertilizer CO2-EOR Project	Operate	1982	Fertilizer Production	0.7	Pipeline	Enhanced oil recovery
Lost Cabin Gas Plant	Operate	2013	Natural Gas Processing	0.9	Pipeline	Enhanced oil recovery
Shute Creek Gas Processing Facility	Operate	1986	Natural Gas Processing	7	Pipeline	Enhanced oil recovery
Val Verde Natural Gas Plants	Operate	1972	Natural Gas Processing	1.3	Pipeline	Enhanced oil recovery
Kemper County Energy Facility	Execute	2016	Power Generation	3	Pipeline	Enhanced oil recovery
Petra Nova Carbon Capture Project	Execute	2016	Power Generation	1.4	Pipeline	Enhanced oil recovery
Riley Ridge Gas Plant	Evaluate	2020	Natural Gas Processing	2.5	Pipeline	Enhanced oil recovery
Texas Clean Energy Project	Define	2019	Power Generation	2.4	Pipeline	Enhanced oil recovery

1.5. Carbon Dioxide Marine Transport

Carbon Dioxide is currently transported commercially in small quantities in liquid form aboard dedicated, converted or purpose built ships that carry the liquid at higher pressure than most LPG carriers could accommodate (Table 4). The transport routes are short hauls between ports in the Northern Europe / Scandinavia region[3]. Because of the higher pressures and resulting cargo tank specifications, the volume that can be carried is limited.

Table 4 Carbon Dioxide Carrier Yara Froya (source: DNV-GL registry of ships)

Vessel:	**Yara Froya**
Flag:	Norway
Port:	OSLO
Owner:	Yara Gas Ship AS
Manager:	Larvik Shipping AS

[3] Yara International website: http://yara.com/media/news_archive/new_liquid_co2_ship_for_yara.aspx

Gross Tons:	2,506
Net Tons:	752
Deadweight Tonnes:	3,486
Year Built:	2005
Yard:	Bodewes Scheepsw. B.V. (638)
Type:	170 - Liquefied Gas Carrier
Class Notation:	1A1 Tanker for liquefied CO2 E0 Ice(1A)
Ship type:	**3G (-30deg. C, 19bar, 1.074t/m3)**

From Table 4 above, it can be seen that the specifications for these dedicated CO_2 carriers compromise carrying capacity in order to carry CO_2 at higher temperatures and pressures. The CO_2 is used in the beverage, food storage and other industrial applications in smaller quantities than can be efficiently transported over longer distances.

Figure 2 Yara Froya during installation of Type C cargo tank for CO2 carriage (source: Yara International)

Two sister vessels to Yara Froya are in operation in Europe under the same owner. Note that Yara Froya is designated a type 3G ship, which indicates design for the least hazardous cargos (see 1.4 below for more details). There is also a purpose built CO_2 carrier in operation, the Coral Carbonic (built 1999), operated by Anthony Veder between ports in Northern Europe and Scandinavia. Like the

Yara vessels, Coral Carbonic carries the liquid CO2 at a temperature of -40 C and pressure up to 18 Bar, with 1250m3 capacity.

There is currently no long haul marine transportation of CO2 being conducted.

1.6. General Description of Liquefied-Gas Carriers

Liquefied Gas carriers can be divided into two main groups:

Liquefied Petroleum Gas (LPG) Carriers, which are designed to carry mainly butane, propane, butadiene, propylene, vinyl chloride monomer (VCM) and are able to carry anhydrous ammonia.

Ethylene / Ethane Carriers, designed for the colder temperatures (-104°C/-89°C at atmospheric pressure) required for those two commodities.

Liquefied Natural Gas (LNG) Carriers, which are designed to carry liquefied natural gas (which is mostly methane).

In general, large LNG Carriers (+ 125,000m3 capacity) and Very Large Gas Carriers (VLGC) (+80,000m3 capacity) are not suited for pressurized cargos and are outside the scope of this report. Recent developments in the small scale LNG marine fuel and other natural gas markets have resulted in design, construction and deployment of small carriers with pressurized “Type C” cargo tanks and liquefied-gas capability suitable for LNG and LPG and that could be suitable for CO2 service. These small scale LNG vessels would also be considered as candidates for CO2 backhaul service.

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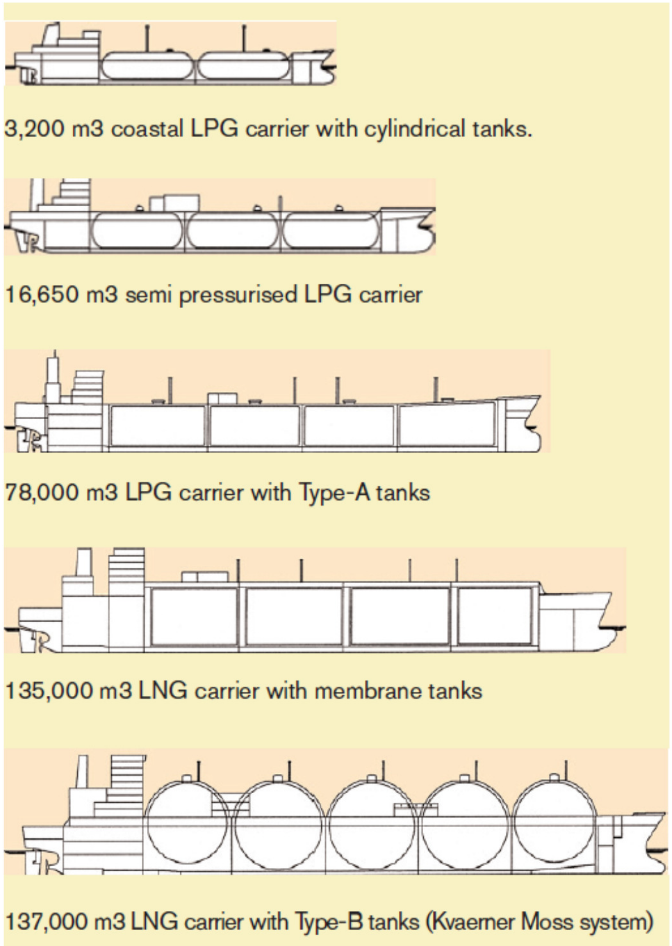
Figure 3 Gas Carrier Categories (source: UK P&I Club)



Gas carriers are classed by the International Maritime Organization (IMO)[4] into three designations based on level of cargo hazard. They are described in the International Code of Safety for Vessels Carrying Liquefied Gases in Bulk (IGC Code):

i) Type 1G, designed to carry the most hazardous cargoes

ii) Type 2G and 2PG, designed to carry cargoes having a lesser degree of hazard

iii) Type 3G, designed to carry cargoes of the least hazardous nature.

Under IMO, Class and USCG rules, vessel must apply for and exhibit an International Certificate of Fitness for the Carriage of Liquefied Gases in Bulk that certifies that the ship complies with the design and construction criteria of the IGC code and is certified to carry specific listed liquefied gases in bulk. Liquid CO2 is a listed cargo in the IGC Code. The certificate also lists the conditions of carriage of the

[4] Non-Governmental Organization of the UN that promulgates international safety standards for ships

various products, such as the cargo tank the cargo is to be loaded in, temperature, pressure, relief valve settings and other parameters.

An excerpt from the Gas Form C from the Oil Companies International Marine Forum (OCIMF)[5]Ship Inspection Report (SIRE) vessel data base is provided below (Table 5) as an example of the range of cargos that can be carried by a liquefied gas carrier.

Table 5 Gas Form C excerpt for 27,000m3 liquefied-gas vessel from OCIMF SIRE report (Source: Evergas)

B1 CARGO - GENERAL INFORMATION		
1.1 List products which the ship is Certified to carry		
Cargo	Temp at atm. Press (Celsius)	Density at atm. Press (kg/m3)
Methane	-163	545
Ethylene	-104	568
C-Ethane (0,5 mol% Methane in Liq. Phase)	-89	545
Propylene	-48	609
C-Propane (**2,5 mol% Ethane in Liq. Phase**)	-45	583
Vinyl Chloride Monomer (VCM)	**-14**	**969**
Iso-Butane	-12	594
Butylenes	-7	625
Butadiene	-5	650
N-Butane	0	602
Methyl Chloride		
DME	-25	734
Other Cargoes		
Acetaldehyde	20	778
Dimethyl Amine	7	666
Ethyl Chloride	13	903
Diethyl Ether	35	700
Isoprene (Monomer)	34	666
Isopropyl Amine	32	676
Monoethyl Amine	17	687
Pentanes/Pentenes	36 / 30	605 / 608
Vinyl Ethyl Ether	36	750

For transport efficiency, gas cargoes are transported in liquid form. Because of their physical and chemical properties, they are carried either at pressures greater than atmospheric or at temperatures below ambient, or a combination of both.

[5] OCIMF through its ship inspection reporting (SIRE) and subscription database program provides vetting, and quality assurance services and other information for shippers, terminal operators and charterers to make decision about the suitability of vessels for a particular trade

Gas carriers are generally grouped as follows:

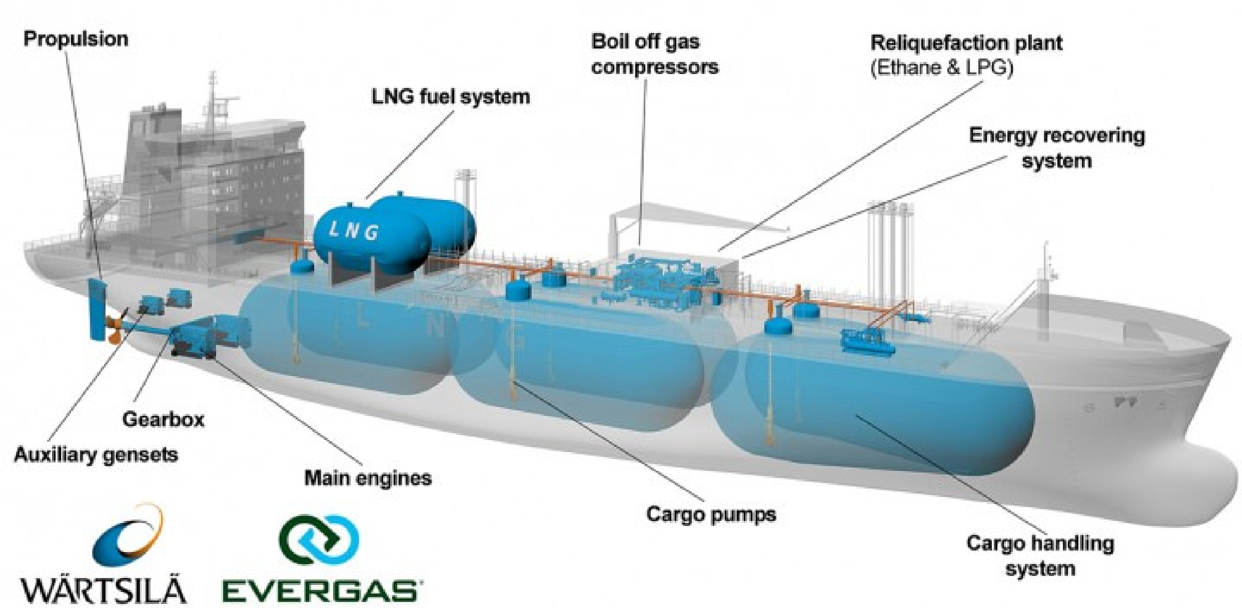
i) Fully Pressurized

ii) Semi-pressurized and refrigerated

iii) Fully refrigerated

Only ships with fully pressurized and semi-pressurized cargo tanks capable of handling liquid gas cryogenic cargos at more than 7 Bar g pressure could potentially be considered as suitable for LCO2 service.

Figure 4 Typical modern LPG carrier (source: Wartsila and Evergas)



2. Technical Evaluation

Carriage of liquid CO_2 requires special considerations. The study researched available information and resources about the requirements for safely transporting liquid CO_2, including discussion with CO_2 pipeline operators and liquefied gas carrier operations specialists.

2.1. CO2 Properties and Characteristics

For carriage as cargo aboard LPG carriers, CO_2 must be kept in its liquid state at temperatures and pressures above its triple point[6], approximately -56.6°C and 5.2 Barg (Fig 3).

Table 6 CO2 Properties

CO2 liquid properties:	
Density Solid at 1 atm and –78.5 °C Liquid at saturation –37°C Gas at 1 atm and 0 °C	 1562 kg/m3 1101 kg/m3 1.977 kg/m3
Liquid/gas equivalent (1.013 bar and 15 °C per kg of solid)	845x (vol/vol) expansion
Boiling point (Sublimation/deposition)	-78.45 °C
Vapor pressure (at 20 °C or 68 °F)	57.291 bar
Triple point temperature	-56.56 °C
Triple point pressure	5.187 bar

Table 7 Liquid Phase CO2 Pressure, Density and Temperature relationship at saturation (source: NIST Webbook)

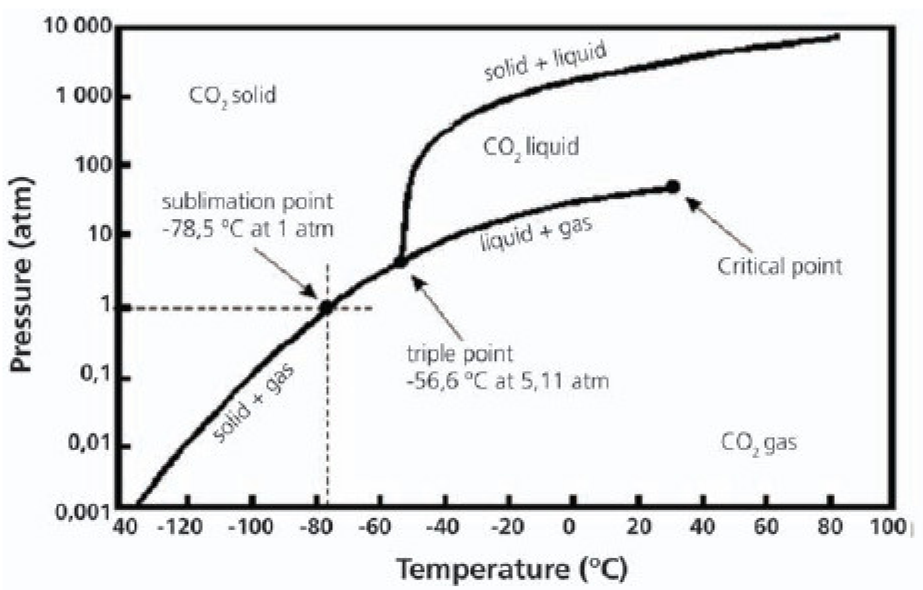
Pressure (Bar)	Temp (°C)	Density (kg.m3)
6	-53	1166
7	-49	1152
8	-46	1140
9	-43	1128
10	-40	1120
11	-37	1107
12	-35	1097
13	-33	1087
14	-31	1078
15	-29	1070

[6] Triple Point: The temperature and pressure at which the three phases (gas, liquid, and solid) of a substance coexist in thermodynamic equilibrium.

16	-27	1061
17	-25	1053
18	-23	1045
19	-21	1037
20	-20	1029

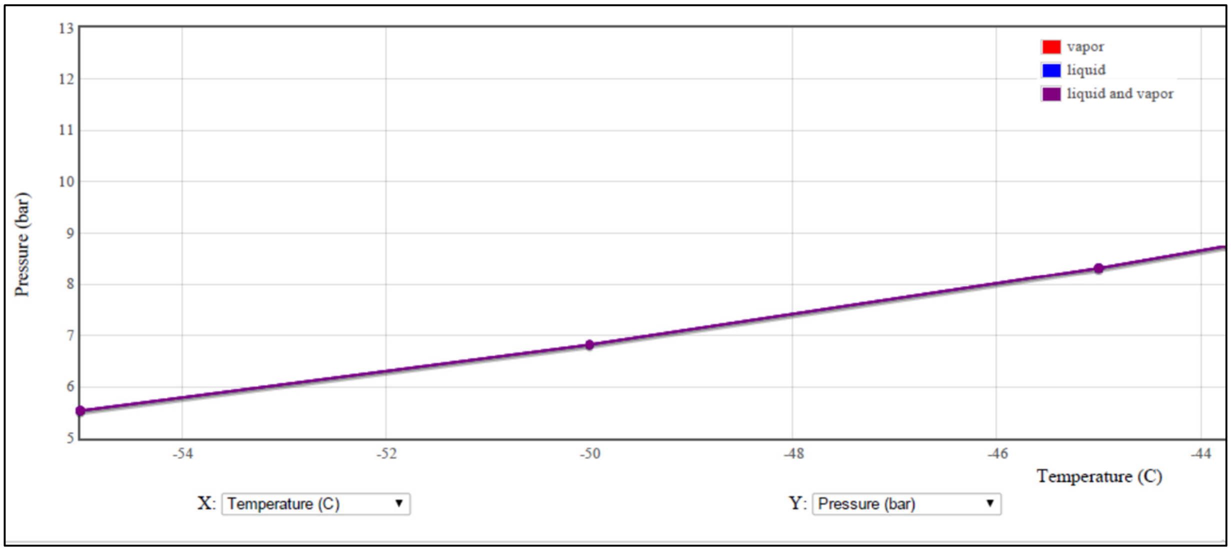
If the temperature falls below -56.6, the CO2 can solidify into dry ice which could damage cargo pumps and tank internals, block piping and valves (including safety relief valves), and cause delays in vessel and terminal operations. If the CO2 is allowed to warm, it could exceed the pressure setting of the safety relief valves resulting in venting of the CO2 vapor to atmosphere. Venting of CO2 vapor to atmosphere does not present a flammability hazard as other liquid gases do, and it would be a simple and effective way to maintain the required cargo tank pressure and temperature. An evaluation of the net emissions impact of purposely emitting CO2 would have to be performed for the specific vessel and voyage as it may be contrary to the CCS objective.

Figure 5 Carbon Dioxide temperature and pressure (source: Global CCS Institute)



The carbon dioxide must be carried within a temperature and pressure range that will prevent formation of solid CO2 (dry ice) and not exceed the maximum allowable relief valve settings (MARVS) of the ship's cargo tanks. As shown in Fig 3 above, the range of acceptable temperature would be between -55° C up to approximately -45°C. The saturation curve for LCO2 over the required range of temperature and pressure for carriage as cargo is shown in Fig 5.

Figure 6 Saturation Properties of Carbon Dioxide (source: NIST chemistry WebBook)



The range of acceptable cargo tank pressures with appropriate safety margins is shown in Fig 6.

Figure 7 Range of cargo tank pressure for liquid CO2 and safety margins (Source: Tebodin Netherlands BV)

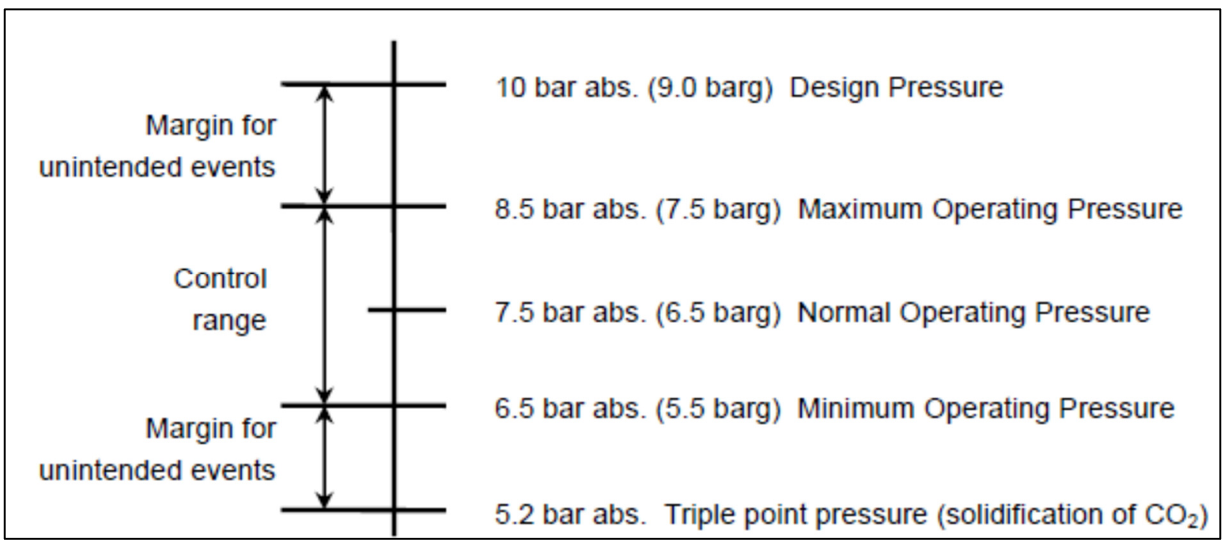


Figure 7 represents a conservative example of pressures and safety margins for a cargo tank with liquid CO2 cargo. From a physical characteristics perspective, if the selected ship's cargo tank and piping can handle up to 7 Bar g pressure, it can be concluded that liquid CO2 can be carried as cargo in existing fully or semi- pressurized containment liquefied gas carriers with precautions and handling procedures similar to those used for other liquefied gases carried as cargo aboard ships. Carriage of CO2 in a suitably capable ship would also require approval from the appropriate Flag-state authority of the vessel[7] and from the US Coast Guard for vessels trading to US ports. The USCG approval process is dependent on prior issuance of an IMO Certificate of Fitness by the flag state or recognized organization (classification society) to carry LCO2, but is normally routinely granted upon application with the appropriate documentation.

2.2. Liquefied Gas Carrier LCO2 Cargo Handling

Liquefied gas carriers are built according to the IGC code, which specifies design and construction criteria for the safe carriage of cryogenic liquid gases with varying levels of hazard.

Assuming that the ships are acceptable and approved for LCO2 loading, technical aspects of cargo loading, transport and handling must be considered. This report assumes that suitable LCO2 loading and discharge facilities are available. The vessel cargo transfer and handling system can be broken down as follows:

- Cargo transfer piping- Manifolds, piping, valves, flanges, gaskets, expansion joints, loops, bellows, safety relief valves, reducers and piping interconnections.
- Containment System- cargo tank, level gauging system, safety relief valves, tank hold space, support structure, access ways (hatches, manholes, inspection ports).
- Cargo handling equipment- Pumps, compressors, heat exchangers, refrigeration systems, pressure relief, boil-off gas systems, volume, flow, level, temperature and pressure indicating systems
- Auxiliary systems – inerting systems, cooling water, ballast, refrigerants, deck tanks, other connected systems.

2.2.1. Cargo Transfer Piping

The IGC code specifies requirements for cryogenic cargo piping. If the vessel is certified to carry cryogenic liquid gases, its piping system would be suited for the same cryogenic temperatures and pressures. Pressure relief in the event of trapped liquid or gas causing a potential overpressure is provided in the form of pressure relief valves that are designed to discharge excess pressure safely away from personnel, systems and equipment. Pressure relief systems are designed to ensure that any venting is in the vapor phase to avoid discharge of cold liquid that could be a hazard to personnel or ship structure. . Pressure relief vents are usually piped to a vent mast arrangement that discharges upward and safely away from working areas and hazardous locations. This design feature would prevent ejection of CO2 liquid or solids through the pressure relief system.

Cargo transfer piping is also fitted with valves that may be remotely, manually or automatically operated by the cargo transfer system and / or the emergency shutdown systems required by the IGC

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[7] IGC Code Model Form Paragraph 3: "Only products listed in chapter 19 of the Code *or which have been evaluated by the Administration* in accordance with paragraph 1.1.6 of the Code, or their compatible mixtures *having physical proportions within the limitations of tank design*, should be listed. In respect of the latter "new" products, any special requirements provisionally prescribed should be noted."

Code. These valves are actuated in the event that system parameters of temperature, pressure, level, gas detection or fire detection are exceeded.

Consideration of temperature and pressure changes within piping and flow across valves and other fittings installed in the piping must be considered by vessel cargo system operators.

2.2.2. Liquefied Gas Carrier Containment Systems

In order to carry liquefied gases at pressures greater than ambient, liquefied gas carriers are fitted with Type C containment systems as defined in the IGC code and incorporated into US regulation.. They are built to stringent pressure vessel standards. They are most commonly insulated with polyurethane panels or foam. (Figure 8).

Figure 8 Type C Tank design and construction features (source: www.clean-baltic-sea-shipping.com)

Type C tanks are independent of the vessel's hull, supported on tank saddles usually fitted to the tank hold space deck. One of the support saddles is fitted with a sliding arrangement to allow for tank expansion and contraction.

Design criteria are based on, among other things, the pressure, density and temperature of the cargo to be carried. This determines the thickness of the steel required for construction of the tank and therefore the maximum pressure the tank is built to withstand. Chapter 4 Section 4.2.4.4 of the IGC Code specifies the minimum design pressure to which the cargo tanks should be built to meet the Code requirement for a Type C tank. Design pressure is very often based on the operational profile of the vessel and may be higher than the minimum (Type C) design pressure. Factors of tank size, cargo liquid density at the design temperature and allowable stresses are included in the determination of the design pressure.

The material of construction is also specified for cryogenic liquids. Acceptable materials include low temperature carbon steel, stainless steel, aluminium and nickel steel alloys.

Liquefied gas carriers fitted with Type C cargo tanks and with IMO Certificates of Fitness (COF) to carry cryogenic liquid gases in the design pressure range for marine transport of LCO2 may be suitable candidates for consideration for backhaul cargos. Any candidate vessel's containment system would have to be specifically confirmed and permitted in accordance with the IGC Code design criteria prior to receiving approval to carry LCO2.

When an existing candidate vessel(s) has been selected, this would be part of the in-chartering and vetting process. In the event that a new-build vessel is specified for LCO2 backhaul, this would be part of the design review process.

2.2.3. Cargo handling equipment

In order to transfer the LCO2 from the ship to the shore reception facility, it must be pumped using the ship's cargo handling equipment. Most liquefied gas carriers are fitted with deepwell pumps with the pump volute and impeller within the cargo tank connected by a shaft to an electric motor mounted on the top of the tank. Alternatively, they may be fitted with submerged, centrifugal type pumps with capability to pump a wide range of liquids with differing densities (Fig 8).

According to discussion with liquefied gas ship operators and pump manufacturers, current installed pumps would be able to pump LCO2 as they would any other liquid cargo, with flow and head pressure according to the characteristics of the cargo. As a point of comparison, Vinyl Chloride Monomer (VCM) is a commonly carried liquefied gas cargo that has a density of 969 kg/m3 at -14°C(see Table 5), compared to LCO2 density of about 1152kg/m3 at saturation pressure for carriage as liquid (Table 7).

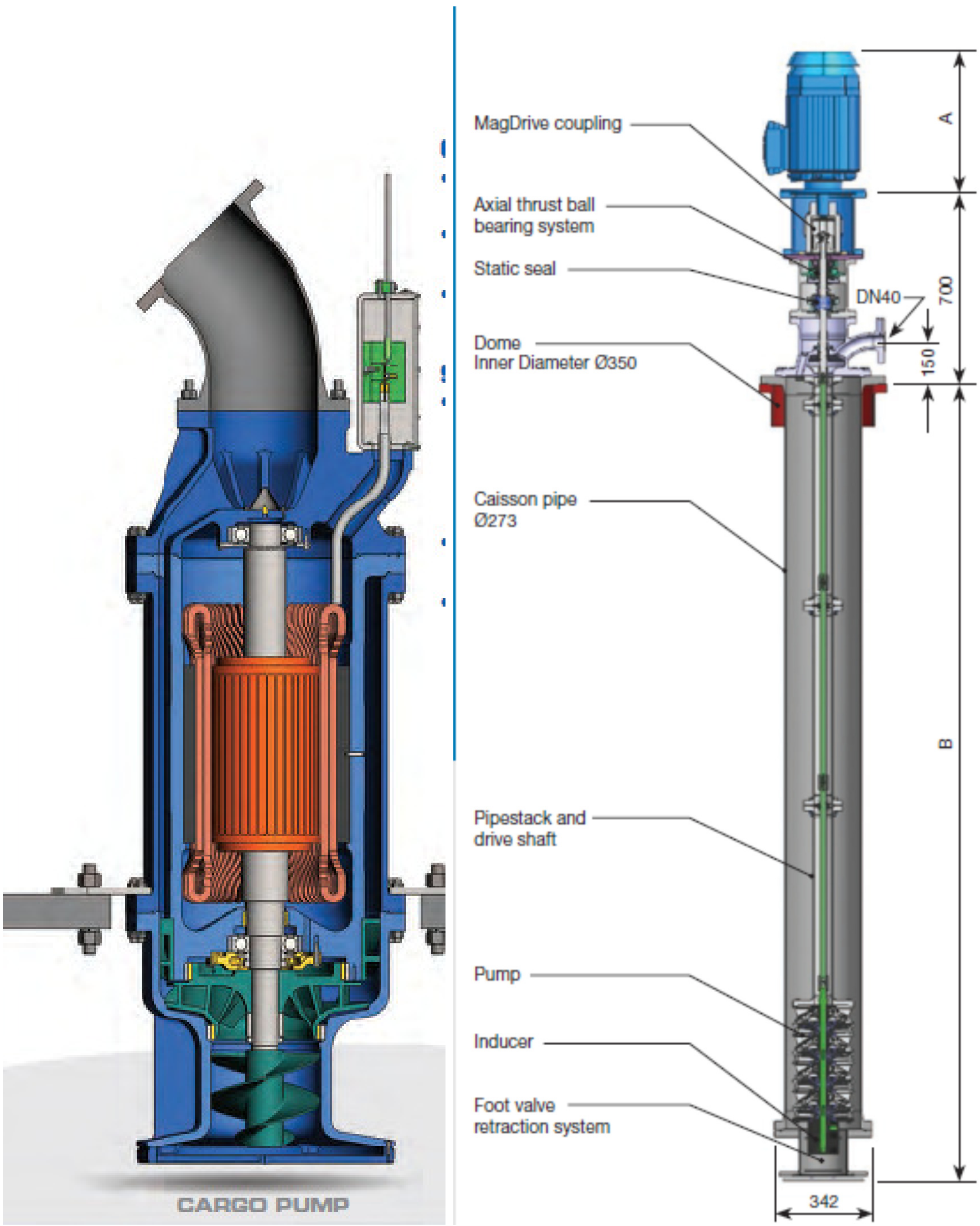
If a specific vessel were under consideration for LCO2 backhaul, part of the vetting process during the pre-chartering phase would be an examination of the vessel's pump specifications to confirm that the particular system could adequately handle the cargo. Further discussion with cryogenic pump manufacturer representatives indicates that pumps currently installed on liquefied gas carriers would be capable of LCO2 service but subject to specific analysis of the particular system and conditions of carriage.[8]

Safe operation of cargo pumps is dependent on maintaining the LCO2 within the temperature and pressure range that ensures it is always above the triple point to ensure that solidification and the resulting pump damage does not occur. Similar to the handling of liquefied gas cargos, strict attention to temperature, pressure and the required conditions of carriage is necessary. The IGC code specifies monitoring and control design features that would permit the operator to automatically maintain the required parameters for safe carriage of any liquefied gas cargo.

8 Phone conversation with Cryostar USA Sales Manager 21 March 2016

Variable frequency drive pumps to accommodate the higher density of LCO2, are recommended. Examination of the range of possible temperatures and pressures of the LCO2 flow in the system could identify the necessary cargo transfer parameters, safeguards and additional measures to ensure proper handling.

Figure 9 Typical submerged cryogenic pump (L) and deepwell pump (R) for liquefied-gas service (source: Ebara International Corporation, Wartsila Svanehoj)



2.2.4. Auxiliary Systems

Auxiliary systems for liquefied-gas carriers would include heat exchangers for cargo conditioning, re-liquefaction systems, deck tanks for cargo tank cooldown (if fitted), fuel supply systems that are integrated with the cargo system, inerting and drying systems, and other systems that may be integrated with or related to cargo transfer and handling equipment. Examination of these systems and potential operational issues would need to be identified and confirmed according to the particular vessel selected. According to discussion with LPG ship owner operators, the nature of liquefied gas carrier ship design criteria and operating philosophy provides for accommodation of a wide variety of cargos in the cryogenic liquid gases category as part of vessel technical capability drive by commercial flexibility.

Reliquefaction systems are used on many gas carriers to maintain the liquid at its required temperature and pressure. In general, re-liquefiers circulate cargo vapour using a compressor and heat exchanger arrangement to compress the vapor, lower its temperature by expansion and cooled across a heat exchanger to return it to liquid phase for re-injection into the cargo tank. If it is determined that LCO2 transport will require reliquefaction rather than controlled venting for temperature and pressure control, additional assessment of risks, limitations and safeguards would have to be conducted. There is also a requirement for examination of cargo grade change considerations, as re-liquefaction equipment would need to be completely purged of any residual cargo to avoid system damage or blockages due to solidification or deposition/sublimation.

As in other technical aspects of determining suitability for LCO2 service, specific examination of the selected ship and relevant systems is required as part of the normal vessel chartering due diligence process.

2.3. Shipping Considerations

Since the density of CO2 when carried in liquid form is greater than the density of the usual heaviest liquid gas cargo (i.e. Vinyl Chloride Monomer, VCM, 969kg/m3 @ -14°C), the filling level of the cargo tanks will be reduced. The main concern when carrying denser cargos is the additional stress that can be placed on the cargo tank and its support system. This results in a partial filling limitation that reduces the amount of cargo that can be safely carried.

Reducing the amount of volumetric capacity of the vessel can increase the cost of freight to carry the cargo. For this reason, larger vessels may be preferred, at the upper range of the Handy-size[9] category.

A cargo of liquid CO2 of about 15,000 tonnes would occupy a volume of about 13,600m3, slightly more than half the volumetric capacity of the largest Handy-size vessels when it reaches its load line (maximum allowed capacity). This inaccessible freight capacity can represent lost revenue (in

[9] "Handy-size" is a shipping term applied to LPG vessels in the 15,000m3 – 30,000m3 capacity range

comparison to other backhaul cargos, if available) to a ship owner that could possibly command a freight premium to LCO2 shippers.

Analysis of potential freight rates for CO2 backhaul should be the subject of more detailed economic analysis when specific vessels, trade routes and potential customers are identified (see Section 3.0).

Like other liquefied gas cargos, composition and quality variation can significantly affect the safe carriage of LCO2. Suppliers must be held to minimum quality and composition standards as variations in non-condensable gases can significantly affect the properties of the gas, with risk of solidification[10]. These minimum specifications would have to be agreed in the commercial arrangement between the buyer, seller and shipper. This would also be a factor in selecting suppliers to ensure that they can consistently meet the required specification.

2.3.3. Changing Cargos: Purging, Inerting and Preparation Operations

Changing cargos is part of normal, routine liquefied-gas carrier operations. Liquefied gas carriers are built with segregation capabilities to permit isolation of systems in order to carry more than one cargo at a time. They also routinely carry different cargos on different voyages according to the needs of their charterer. Liquefied gas carrier operators have developed specific procedures for safe change-over from one cargo to another based on the permitted cargos listed on the Certificate of Fitness and the particular requirements of the vessel's cargo system.

Changing from one cryogenic liquid gas cargo to another generally involves complete discharge of the first cargo, warming and vaporizing of the un-pumpable amount left on board, then purging the remaining gas atmosphere with an on-board inert gas generator (IGG) using flue gas from the ship's engine. Once the cargo tank and transfer piping are free of the previous cargo and fully inerted, gassing-in, cooling down and loading of the next cargo can begin.

It should be noted that the complete exchange of the cargo tank atmosphere from hydrocarbon cargo to LCO2 will result in release of additional hydrocarbons into the atmosphere. This may occur in any case as part of normal liquefied gas carrier operations when preparing for a different cargo, but the net hydrocarbon emissions should be quantified when examining a specific case.

Hydrocarbon emissions from ships is not currently explicitly regulated when conducting change of grade operations at sea, although there are regulations addressing release of cargo vapors during loading operations in port[11].

In the case of LCO2, following the specific vessel procedure and assuming that the emptying, warming, purging and inerting process was properly completed, it could be safely loaded after carriage of any liquefied gas cargo.

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[10] CO2 Liquid Logistics Shipping Concept (LLSC) Overall Supply Chain Optimization, Tebodin Netherlands BV Report for Vopak and Anthony Veder 21 June 2011, pg 51

[11] MARPOL Annex VI, Regulation 15.7, Volatile organic compounds (VOC) *This regulation shall also apply to gas carriers only if the type of loading and containment systems allow safe retention of non-methane VOCs on board or their safe return ashore.*

The preparation time for changing from one cargo to another is usually specified in the vessels Gas Form C. From figure 9 below, it can be seen that the required time can be as long as 7 days for a full change of a Handy-size liquefied gas carrier. This would have a potential operational impact on loading LCO2 for backhaul as this would need to be factored in to the ship's cargo lifting schedule and voyage economics An evaluation of methods and procedures to reduce preparation time should be made. Depending on the criticality of contamination of CO2 by the previous cargo, it is possible that inerting time could be significantly reduced or even omitted.

Figure 10 Excerpt from Gas Form C indicating change of cargo times (source: Evergas)

B15 CHANGING CARGO GRADES			
Indicate number of hours needed to change grades from the removal of pumpables to tanks fit to load and the estimated quantity of Inert Gas and or Nitrogen consumed during the operation:			
	Hours	Inert Gas (Air)	Nitrogen
From Propane to Butane	160	83 000 Nm3	105 000 Nm3
From Propane to Butadiene	160	83 000 Nm3	105 000 Nm3
From Propane to Ethylene	160	83 000 Nm3	105 000 Nm3
From Propane to Ammonia	N/A	N/A	N/A
From Propane to Vinyl Chloride Monomer	160	83 000 Nm3	105 000 Nm3

2.4. Candidate Liquefied Gas Carriers

Based on the criteria for carriage of CO2 and the initial shipping considerations described above, a small number of existing vessels have been identified as being potentially CO2 capable based on their capacity and permitted cargos. According to information from Clarkson's shipping database, there are approximately thirty pressurized liquefied gas carriers currently in service that could be considered suitable. (Table 8). These vessels represent part of the potential available pool from which CO2 backhaul candidates could be chosen. Further study would be needed to identify specific ships that meet the technical requirements to carry CO2 matched with trading routes that could facilitate CO2 backhaul cargos and ship owners and charterers with sufficient incentive to accept them.

Table 8 Candidate Ships based on potential LCO2 capability listed by capacity (source: Clarkson's)

Vessel Name	Type	Builder	Built Date	Capacity (cu m)	Tank Temp (C)	Tank Pressure (kgf sq m)	Owner Company
Donau	LPG Carrier	Meyer Werft	01/09/85	30200	-50	7.0	Exmar LPG BVBA
Norgas Napa	Ethylene/LPG	Zhonghua Shipyard	01/10/03	10208	-104	7.0	Teekay LNG Partners
Norgas Shasta	Ethylene/LPG	Zhonghua Shipyard	01/08/03	10208	-104	7.0	Norgas Carriers
Norgas Alameda	Ethylene/LPG	Zhonghua Shipyard	01/05/03	8556	-104	7.0	Norgas Carriers
Norgas Orinda	Ethylene/LPG	Zhonghua Shipyard	01/10/02	8556	-104	7.0	Norgas Carriers
Norgas Petaluma	Ethylene/LPG	Zhonghua Shipyard	01/03/03	8556	-104	7.0	GasMar AS
Norgas Sonoma	Ethylene/LPG	Zhonghua Shipyard	01/01/03	8556	-104	7.0	SGPC
Jemila	LPG Carrier	A.E.S.A.	01/03/83	8040	-48	8.0	Sonatrach Petroleum

Gaz Venezia	LPG Carrier	I.N.M.A.	01/12/95	7434	-48	7.5	Naftomar Shpg & Trad
Mores	Ethylene/LPG	I.N.M.A.	01/02/94	7414	-104	7.5	Lumaship S.r.l.
Virgen del Carmen B	LPG Carrier	I.N.M.A.	01/12/92	7350	-48	7.5	Transgas Shpg. Lines
Coral Palmata	Ethylene/LPG	Cant.Nav.Pesaro	01/06/94	7164	-104	7.0	Anthony Veder
Coral Pavona	Ethylene/LPG	Cant.Nav.Pesaro	01/07/95	7164	-104	7.0	Anthony Veder
Gas Optimal	LPG Carrier	Ast.De Mallorca	01/01/85	7115	-48	8.0	Nautilus Marine
PGC Strident Force	LPG Carrier	Higaki Zosen	01/06/99	6527	-48	7.0	Paradise Gas Carr.
Queen Phenix	Ethylene/LPG	HyundaiHI (Ulsan)	01/10/96	6481	-104	8.0	Daiichi Tanker Co.
Happy Bride	LPG Carrier	Hyundai HI (Ulsan)	01/04/99	6270	-48	7.0	Ultragas Aps
Tanja Kosan	LPG Carrier	Hyundai HI (Ulsan)	01/05/99	6270	-48	7.0	Lauritzen Kosan
Tilda Kosan	LPG Carrier	Hyundai HI (Ulsan)	01/02/99	6270	-48	7.0	Lauritzen Kosan
Syn Atlas	Ethylene/LPG	Cant. Nav. Morini	01/02/93	6073	-104	7.0	Synergas S.r.l.
Tenna Kosan	LPG Carrier	Hyundai HI (Ulsan)	01/09/98	5900	-48	7.6	Lauritzen Kosan
Tessa Kosan	LPG Carrier	Hyundai HI (Ulsan)	01/01/99	5900	-48	7.6	Lauritzen Kosan
Gaschem Weser	LPG Carrier	Malaysia S.Y. & Eng.	01/12/99	5734	-48	9.5	Hartmann Schiff.
Gaschem Hunte	LPG Carrier	Kodja Bahari	01/09/00	5730	-48	9.5	Hartmann Schiff.
Blue Dream	LPG Carrier	Meyer Werft	01/06/81	5647	-48	7.5	Arvina Trade Ltd.
Zuma Rock	LPG Carrier	Meyer Werft	01/01/75	5450	-48	8.3	Petrobulk Shipping
Gaschem Jade	LPG Carrier	J. Pattje	01/10/92	5322	-48	10.5	Hartmann Schiff.
Gaschem Jumme	LPG Carrier	J. Pattje	01/05/93	5322	-48	10.5	Hartmann Schiff.
Melina	LPG Carrier	Lindenau	01/09/84	5253	-48	11.2	Hellenic Petroleum
Habas	LPG Carrier	Usuki Zosensho	01/06/84	5060	-48	7.0	Habas Petrol

Note that this is a preliminary screening and that the ships listed above are notional candidates based on capacity and cargo type. Confirmation by the ship owner of LCO2 technical capability and issuance of a Certificate of Fitness listing LCO2 as a permitted cargo would be the required next step.

As can be seen from Table 8, the cargo capacities of the listed vessels are limited, although they are larger than the currently operating dedicated LCO2 carriers (see Table 4, Yara Froya).

To operate in US waters, a specific endorsement (Subchapter O endorsement (SOE) to carry liquid CO2 would be required on the USCG issued Certificate of Compliance (COC) for ships operating in US waters under 46 CFR 153.15 (Subchapter O). The SOE and Certificate of Compliance (COC) to foreign flag vessels calling on US ports are routinely issued by USCG as long as the vessel has a valid Certificate of Fitness for LCO2.

Further study would be needed to identify specific ships and confirm that they meet the technical requirements to carry CO2, that their trading routes could facilitate CO2 backhaul cargos and that the ship owner(s) and charterers could be sufficiently incentivized to accept them.

3. LCO2 Backhaul Economics

The specific economics of LCO2 backhaul depend on a variety of factors, including but not limited to:

- The particular vessel(s) selected:
  - Volumetric capacity
  - Deadweight
  - Cargo transfer rates
- The selected trade route
- The availability of other backhaul cargos
  - more operationally convenient
  - more economically attractive
- Suitable LCO2 marine transfer facilities at load and discharge ports
- Willing sellers, buyers, shippers and carriers

Specific analysis of a particular vessel, trade route or LCO2 shipping project is beyond the scope of this report, but the framework for economic analysis based on typical shipping industry voyage economics is described below.

3.1. Methodology

Once technical capability to carry LCO2 is established, a framework to establish economic feasibility must be developed. In anticipation of the planned and projected development of the US NGL export market, multi-gas carriers would typically transport cargoes from the US to Europe or the Mideast and return empty on the ballast voyage. There may be economies earned if multi-gas carriers could also transport cargo on the ballast (or back haul) leg, thus earning the vessel owner additional revenues on an otherwise empty vessel.

The economic analysis, taking into the account the factors described above and any other identified issues would compare the cost of Base Line to Alternative Voyages:

1. Base Line Voyage – Wherein vessel transports LPG from USAC or USG load port to European or Mideast disport, returning empty (ballast leg) to the USAC or USG load port. Determine revenue and cost of round-trip.

2. Alternative Voyage – Wherein vessel transports LPG from USAC or USG load port to European or Mideast disport, then transports CO2 from European or Mideast load port to USAC or USG disport. Determine cost of round-trip, front-haul and backhaul.

3. Breakeven Analysis – The difference between the costs of the Base Line and Alternative Voyage is the breakeven point; which is the amount of revenue needed to receive for the backhaul voyage to determine economic viability.

4. Market Analysis and Conclusion – ABS Consulting to determine:

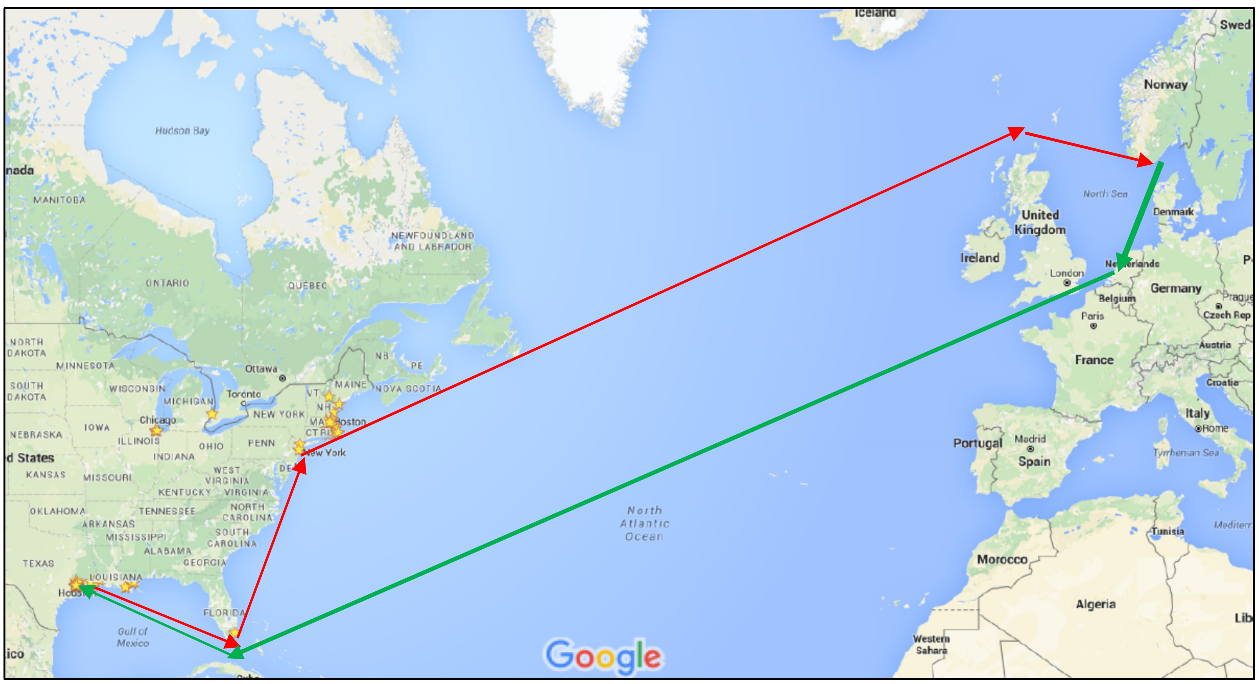
a. If there exists a sufficient market, supply and demand, of CO2, and vessel availability to support a back-haul trade.

b. Minimum revenue necessary to support the back-haul trade.

3.2. Required Data

The analysis will first need to identify various trade-routes including load and discharge ports for both LPG and CO2; i.e. transport LPG from Marcus Hook to Norway, then sail to Scotland or Rotterdam to load CO2 and transport to Houston, returning to Marcus Hook to repeat(Fig 11). Note that this voyage is hypothetical and will depend on the development of the required infrastructure and trade route opportunities.

Figure 11 Hypothetical LCO2 backhaul voyage: loading Ethane in Marcus Hook, discharging in NW Europe(red line), loading LCO2 in Rotterdam, discharging in USGC (green line) (Source: ABSC / google maps)



3.2.3. Market

a. Identify potential CO2 market:

i. Annual supply and demand requirements.

ii. Typical voyage size.

iii. Frequency of voyages.

2. Client
    a. Identify Client; vessel owner or charterer.
    b. Type of contract under which vessel operates; bareboat, time charter, contract of affreightment, etc.
        i. Specifics of contract, particularly will contract allow operator back haul movements.
    c. Most current copies of all contract documents which impact ownership or right to use of the vessel, such as trust agreements, participation agreements, etc.
3. Ports
    a. Identify all potential load and disports by cargo type; LPG and CO2.
    b. Identify any port restrictions, i.e. draft, LOA, Dwt restrictions, etc.
    c. Typical and usual port costs for each port.
    d. Unusual conditions, if any, which may exist for a specific port requiring additional time and/or costs.
    e. Usual or contractual port time allowed before incurring demurrage, (generally 24 hours all-in).
    f. Standard distance between each port.
4. Vessels
    a. Based on anticipated / projected US NGL export expansion from the US to Europe and Mideast, identify all vessels currently active in this market.
    b. Vessel type and requirements
        i. Identify total fleet capable of carrying LPG and CO2.
        ii. Identify vessel particulars; volumetric capacity, deadweight, specialized cargo handling equipment capable of providing the cargo at the required temperature and pressure for the said trade.
        iii. Identify specific vessels for said trade.
        iv. Expected vessel speed, both laden and ballast.
    c. Daily Operating Costs

i. Typical daily operating costs, including crewing/manning, consumables, supply operations, catering, maintenance expenses, licensing fees, regulatory fees, classification fees, insurance, etc. of the vessel. Exclude depreciation and taxes.

d. Preparation cargo conversion time and costs

i. Identify necessary measures, such as cleaning, temperature and pressure adjustment, including associated cost and time required to prepare vessel to transform from carriage of LPG to CO2 (and back again).

e. Other costs, including social/environmental

i. Is the added distance and fuel expended to accommodate the backhaul offset by the amount of carbon captured and stored?

4. Conclusions and Recommendations

Although it is technically feasible to carry LCO2 in the liquefied gas carriers identified in Table 8, it is important to recognize that there are many challenges to be met before CO2 backhaul can be incorporated into current trading routes.

Existing LCO2 dedicated vessels are not suited for long haul, cost efficient transport of LCO2. The LCO2 capable liquefied gas carriers listed in Table 8 may not have sufficient cargo carrying capacity for cost efficient trans-Atlantic voyages.

Absent the current lack of CO2 supply, active CO2 trading markets and supporting infrastructure, the most significant challenge is to find existing or on-order ships with cargo tanks that can accommodate the higher pressure required to safely and efficiently carry CO2.

Further study to include direct surveys of ship owners with vessels operating in LPG service is recommended to identify specific ships meeting the criteria:

- Type 2G or 3G liquefied gas carrier with, or capable of being approved for, a Certificate of Fitness for liquid CO2
- Type C (pressure vessel) containment system with greater than 7 Bar g design pressure and appropriate safety margin (Note that lower design pressures may be possible if confirmed by operational evaluation)
- Tanks and cargo systems suitable for cryogenic liquid gases
- Permission from the relevant authorities to carry liquid CO2
- Sufficient cargo carrying capacity to allow competitive unit freight cost

Existing designs of Handy-size liquefied gas carriers are a close fit, but would need to be modified at the newbuilding stage with cargo tanks of sufficient design pressure to accommodate carriage of CO2.

It is possible that newbuild vessels designed for LCO2 as well as NGLs may provide a better marine transport solution as the US NGL export market and the CCS market evolves.

Liquefied gas carriers could be changed to accommodate carriage of CO2 by increasing the cargo tank design pressure. It is expected that the cost of the required modifications should be only marginally higher than for a standard liquefied gas carrier, but an evaluation of cost in relation to the specific LCO2 opportunity is recommended.

The expanding US NGL export market provides an opportunity to integrate new build ships with LCO2 capability with projected / potential CCS transport requirements. The framework for further economic analysis outlined in Section 3.0 of this report is recommended as a guide to determine the best solution.

In order for the concept to work as intended, sufficient monetary inducements to charterers to offset the daily hire rate of the vessel must be offered.

There is also an opportunity cost to be quantified depending on a number of factors:

- Cost to deviate or reposition from the load and discharge ports specified in the charter
- Charterer's willingness to deviate from set voyage routes,
- Available backhaul cargos that are more attractive economically, operationally or logistically
- Potential for delayed or missed scheduled loading and related commercial penalties
- Cargo changeover and preparation time costs,
- Environmental impacts- hydrocarbon emissions from cargo changeover, carbon emissions offset considerations from potential CO2 venting

Current CO2 marine storage and transfer infrastructure is currently not sufficiently developed to support large scale movement of LCO2. Collaboration in the form of a joint industry project (JIP) or similar venture between CCS projects, ship owners, LPG shippers, CO2 end users, regulatory bodies and industry organizations is recommended to develop a coordinated solution incorporating marine transportation of CO2 that optimizes existing and planned transportation, storage and distribution infrastructure.

Feasibility Study of Ship-Based Transportation of CO_2

Appendix 1
Overview of Likely Legal and Regulatory Issues Associated with the Maritime Shipment of Bulk Carbon Dioxide Primarily for Use in EOR

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Overview of Likely Legal and Regulatory Issues Associated with the Maritime Shipment of Bulk Carbon Dioxide Primarily for Use in EOR

This memorandum provides an initial "issue spotting" overview of likely legal and regulatory issues associated with the maritime transportation of commodity quantities of carbon dioxide ("CO_2"): (1) between and among the United Gulf Coast, the United States California Coast, northwest Europe, China, Japan and South Korea; and (2) for purposes of use in carbon dioxide-enhanced oil recovery ("CO_2-EOR"), CO_2-EOR with associated storage, and potentially deep saline sequestration. Likely shipping routes include: (1) northwest Europe to the United States; and (2) Far East to Indonesia or California on backhaul of LPG/ethane carriers.

Executive Summary

The contemplated commercial activities are novel and thus would be expected to raise numerous complex, time-consuming, and unanticipated legal and regulatory hurdles, not all of which may be surmountable.

Based upon our initial review, international and domestic laws and regulations fail to provide clear answers regarding how the contemplated commercial activities may be authorized, permitted, or otherwise allowed.

Given the technical similarities between liquefied CO_2 and other materials being transported in bulk (e.g., LPG, LNG), analogies may be drawn that provide regulators and policymakers with comfort that the bulk maritime transport of CO_2 is environmentally sound. Still, we would anticipate that the project proponents here would have to commit considerable time and resources in convincing regulators and policymakers in the relevant jurisdictions that these activities should proceed.

Analysis

I. Overview

Legal issues related to the transboundary movement of CO_2 for use in EOR – or EOR storage – are novel.

Most of the literature and analyses published to date on this topic – as confirmed by our separate research -- assumes that the CO_2 is being transported for storage because that is the likely scenario for the foreseeable future for the following reasons: (1) each marginal ton of captured CO_2 going forward is likely to be subject to some form of climate regulation in either the exporting or importing country; (2) the marginal costs associated with implementing such a CO_2 value chain are likely only supported where an additional economic value, reflected in the "storage" activity, is liberated; (3) in areas of the world where natural CO_2 exists or is used – e.g., the Permian Basin – there is already sufficient domestic demand for the CO_2 that it is difficult to conceive of a commercial scenario where the natural CO_2 is exported; (4) evidence suggests that even natural CO_2 from the domes may come under regulation in countries such as the United States in the coming years[1]; (5) even business-as-usual CO_2-EOR operations in the United States are having to face "storage" regulatory issues whether they want to or not[2]; and (6) post the 2015 Paris Agreement, the political climate is such that commercial proposals for the transboundary movement of "unregulated" CO_2 "merely" for EOR purposes are likely to face withering and unrelenting public opposition and scrutiny.

For these and related reasons, this memorandum draws upon legal analyses that assume, as a worst case and where relevant, that the CO_2 being transported also must be stored as a legal matter.

We recognize that a commercial case may be made for the transboundary movement of CO_2 for non-storage EOR purposes. We are aware of at least two such examples:

- ✓ *U.S. (Dakota Gasification Plant)/Canada (Weyburn).* From a climate regulatory perspective, we consider this situation to be an historic anomaly given the current political and regulatory climate surrounding these topics. The operation is likely effectively grandfathered from a CO_2 regulation point of view, plus the case could be made that the CO_2 isn't really unregulated given the storage assessments at Weyburn.

- ✓ *Interstate Movement of CO_2 for EOR within the United States.* A robust network of interstate pipelines moves CO_2 for EOR purposes within certain regions of the United States. Those pipelines largely are regulated by the States, with a relatively minor federal role in safety standards. This pipeline network is already facing regulatory uncertainties regarding the potential introduction of additional volumes of CO_2 from anthropogenic sources, even if such sources are not currently regulated by EPA, because they could become regulated in the near future. The existence of these and related regulatory uncertainties has arguably contributed to an uncertain investment environment.

In sum, we believe that building a commercial case around the assumption that going forward CO_2 may be shipped from country to country for use in EOR without consideration of storage requirements would be legally unwise and imprudent.

The Global CCS Institute has noted that CO_2 transport touches upon different areas of law, to include the following[3]:

- ✓ Legal definition of CO_2: is it a waste or a commodity? Different legal consequences could stem from classifying CO_2 in either of these categories[4];

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[1] Natural CO_2 suppliers, for example, must report under Subpart PP of the U.S. Environmental Protection Agency's GHG Reporting Program. Normally such reporting is a precursor to emission regulation.
[2] For example, the source of some of the CO_2 used for EOR operations in the United States is natural gas separation plants. New natural gas separation plants and existing natural gas separation plants undergoing "major" modifications are subject to EPA's GHG emission control regulations.
[3] http://hub.globalccsinstitute.com/publications/legislation-relating-co2-transport-storage/international-transboundary-transport-regulation-co2-storage.

- ✓ Conflicting country jurisdictions over pipeline control and management when CO_2 pipelines cross national boundaries – a situation still relevant where the bulk of the transport is via the maritime mode;

- ✓ Health and safety guidelines and procedures, which need to be established or adapted from other transportation regimes in order to deal with potential risks to human health or the environment;

- ✓ Liability for harm caused by accidents or leaks from CO_2 pipelines or other transport facilities;

- ✓ Permitting issues;

- ✓ Third-party access to the transportation network, transit rights and property rights with respect to infrastructure routes in the exporting and importing countries; and

- ✓ Environmental impact assessment and planning procedures, taking into account public participation in the decision-making process and wider public perception of CCS and storage via CO_2-EOR.

Our preliminary research confirms that many of these issues remain unresolved in the arguably "easier" case of pipeline transport, let alone the maritime shipping case.

Our views in this memorandum are further informed by: (1) recent failed efforts to move fossil fuels across boundaries (i.e., the Keystone XL pipeline); (2) the lengthy political horse trading required in related contexts (i.e., the new U.S. law that enables the export of oil in return for renewable energy tax incentives and other pro-renewable policies); and (3) the challenged condition of CCS projects generally worldwide (e.g., if Germany will not allow CO_2 pipelines to be built domestically, what reason is there to believe that they will support the construction of the same infrastructure for the export of CO_2 through Norway?).

II. Transportation Considerations

a. International Maritime Transportation Conventions and Codes

The bulk shipment of liquefied CO_2 by sea would be expected to raise novel regulatory issues arising under international transportation conventions and codes because the "use of ships for transporting CO_2 across the sea is … in an embryonic stage." [5] Indeed, "[t]here are no regulations specific to transport of

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[4] In the United States, EPA has taken the position that CO_2 being "stored" is a "solid waste" for purposes of the Nation's federal hazardous waste law and regulations. http://www3.epa.gov/epawaste/nonhaz/industrial/geo-sequester/faqs.htm.

[5] *IPCC Special Report on Carbon Dioxide Capture and Storage*, chapter 4, p. 186 (IPCC 2005). *Accord Preliminary Feasibility Study on CO_2 Carrier for Ship-based CCS*, p. 4 (Global CCS Institute 2011) (hereinafter "*GCCSI Study*") ("[Maritime] [t]ransportation in CCS … has not been addressed … and the necessity for ship-based CO_2 transportation does not exist"); Jung, J., *CO_2 Transport Strategy for the Offshore CCS in Korea* (GHGT-11 2013) ("To date, there is no ship for CO_2 transport with some exceptions for food industries"); *Neele, F., Ship Transport of CO_2 – Breaking the CO_2-EOR Deadlock*

CO_2 by ship and, in Europe, there are presently no specific guidelines for such transport either."[6] And although "[n]othing in [any] of these potentially applicable conventions and codes" would imply that transportation of CO_2 would be prevented," that outcome cannot be entirely discounted either.

Transportation considerations in this regard fall into three broad categories – i.e., is bulk liquefied CO_2 regulated by conventions and/or codes governing: (1) the bulk carriage of chemicals; (2) the bulk carriage of liquefied gases; and/or (3) atmospheric emissions of CO_2 from maritime vessels? We address each of these separately below.

i. Bulk Carriage of Chemicals

Liquefied CO_2 transported by sea is not currently specifically addressed under applicable conventions and codes pertaining to the bulk carriage of chemicals. It is likely that bulk quantities of CO_2 being transported by sea would not be regulated under such regimes but instead would be addressed as a liquefied gas, discussed separately below. Because the regulation of CO_2 as a "chemical" in transport cannot be entirely discounted, however, we discuss it here.

The maritime carriage of chemicals in bulk is covered by regulations in the Safety of Life at Sea Convention ("SOLAS" -- Chapter VII: "Carriage of dangerous goods") and the International Convention for the Prevention of Pollution from Ships ("MARPOL" -- Annex II: "Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk"). Both conventions require chemical tankers built after July 1, 1986 to comply with the International Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk ("IBC Code").

The IBC Code provides an international standard for the safe carriage in bulk by sea of dangerous chemicals and noxious liquid substances listed in chapter 17. To minimize the risks to ships, their crews and the environment, the IBC Code prescribes the design and construction standards of ships and the equipment they should carry, with due regard to the nature of the products involved. In December 1985, the IBC Code was extended to cover marine pollution aspects and applies to ships built after July 1, 1986.

In October 2004, IMO adopted revised MARPOL Annex II Regulations for the control of pollution by noxious liquid substances in bulk. This incorporates a four-category categorization system for noxious and liquid substances and it entered into force on January 1, 2007.[7]

Carbon dioxide is not listed under any of these regimes.[8] However, the bulk carriage of any liquid product other than those defined as oil (subject to MARPOL Annex I) is prohibited unless the product

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(GHGT-12 2014) ("Although transportation of CO_2 by ship has been commonplace for more than 20 years, the purpose of this transportation has not been related to EOR … [and] [u]p until now, there have only been small tonnage ships (approx.. 1000 tons) for supplying CO_2 to the food industry and other relatively speaking, small scale purchasers"). Earlier this year, Norwegian company Yara International ASA announced an upgrade to its vessels used to transport CO_2 for the food and related industries. http://worldmaritimenews.com/archives/169201/yara-adds-new-co2-ship/.

[6] Brownsort, P., *Ship Transport of CO_2 for Enhanced Oil Recovery – Literature Survey* (Jan. 2015) (hereinafter "*Brownsort Review*").

[7] For background on MARPOL, *see* http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx.

has been evaluated and categorized by inclusion in Chapters 17 or 18 of the IBC Code. Such an assessment may be required here.

ii. Bulk Carriage of Liquefied Gases

The "International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk" ("IGC Code") applies to gas carriers constructed on or after July 1, 1986. Gas carriers constructed before that date should comply with the requirements of the "Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk" or the "Code for Existing Ships Carrying Liquefied Gases in Bulk."

The purposes of these codes is to provide an international standard for the safe transport by sea in bulk of liquefied gases and certain other substances, by prescribing the design and construction standards of ships involved in such transport and the equipment they should carry so as to minimize the risk to the ship, its crew and to the environment, having regard to the nature of the products involved.

The basic philosophy is one of ship types related to the hazards of the products covered by these codes, each of which may have one or more hazard properties. A further possible hazard may arise owing to the products being transported under cryogenic (refrigerated) or pressure conditions.

Application of the IGC Code to the bulk maritime transport of liquefied CO_2 in this and related contexts has been the subject of academic papers.[9] A 2011 study funded by the Global CCS Institute applied the IGC Code to the design of a liquefied CO_2 carrier and reached the following conclusions[10]:

> The physical properties of CO_2, specifically the vapor liquid equilibrium properties of CO_2, are such that the design of a storage tank for the containment of liquid carbon dioxide is very similar to existing designs for intermediate pressure liquefied petroleum gas (LPG) containment systems. The design methodology for LPG cargo tanks is well understood and is regulated by international standards (specifically the [IGC Code]) and Classification Societies (such as DNV, BV and LRS). The design methodology employed in this study which is for the maritime transport of [liquefied] CO_2 is exactly the same as described by the IGC [C]ode and subject to Classification rules. These design rules are well proven with literally hundreds of LPG carriers operating worldwide in an industry that has an excellent safety record since the advent of LPG bulk marine transport in the early 1960s.

The 2015 Brownsort Review reached a similar conclusion[11]:

> The review of available literature on ship transport of CO_2 shows that, while experience is limited to small scales, there is a good level of

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[8] http://www.dnv.lt/binaries/IBC%20CH-17_tcm173-487486.pdf.

[9] *See, e.g.*, Kokubun, N. et al., *Cargo Conditions of CO_2 in Shuttle Transport by Ship* (GHGT-11 2013); *GCCSI Study*; *Brownsort Review*, p. 32; *Transport of CO_2 by Ship Tankers* (Global CCS Institute web site, last visited Dec. 21, 2015).

[10] *GCCSI Study*, p. 18.

[11] *Brownsort Review*, pp. 36-37.

> understanding and definition of what would be needed for scale-up to capacities relevant to CCS or CO_2-EOR. Although many publications note EOR as a potential user of ship transport, there is very little coverage of any specific requirements for EOR, it being included under general CO_2 storage considerations. This may be justified for most of a ship-based liquid CO_2 supply chain, however, there may be requirements specific to EOR at the interface between shipping and reservoir, that is, at the injection stage of the system, which have not been fully considered in the literature.
>
> Shipping of CO_2 is most effective as a liquid at temperature and pressure conditions close to the triple point. The technology required is based on that for other cryogenic liquids such as LPG or LNG …
>
> The proposed role for shipping in the development of CO_2-EOR … is supported by the body of literature in general. Shipping of liquid CO_2 at large scale is feasible with known technologies and can provide a transport system that is flexible in terms of space and time ….

Despite this optimism in the literature, as well as the existence of relatively small vessels used to transport CO_2 for the food and related industries, the fact remains that carriers of a size needed to support onshore EOR operations in a third-party country have not yet been built[12]:

> Ship size and tank is … another issue. Ships in use for commercial transport of CO_2 are only around 1000 t. Larger ships have been proposed and different designs have been proposed … In certain studies, ships up to 20,000 tons have been discussed. However, no such tankers have so far been built.

This means, at minimum, that the first ship of such size would need to clear the certification and related procedures of the IGC Code.[13]

iii. Atmospheric Emissions of CO_2 from Maritime Vessels

Incidental emissions of CO_2 from bulk carriers may be subject to new and evolving codes addressing greenhouse ("GHG") emissions from vessels. The MARPOL Convention addresses air pollution and emissions from ships under Annex VI, first adopted in 1997. A revised Annex VI was adopted in 2005 and entered into force in 2010, phasing in a progressive reduction in sulfur oxides from ships and further reductions in nitrogen oxides emissions from marine engines. Amendments adopted in 2011 set mandatory measures to reduce emissions of GHGs from international shipping, with the so-called "Energy Efficiency Design Index" made mandatory for new ships, and the "Ship Energy Efficiency

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[12] *Neele, F., Ship Transport of CO_2 – Breaking the CO_2-EOR Deadlock*, p. 2642.
[13] For background on the IGC Code, *see* http://www.imo.org/en/OurWork/Environment/PollutionPrevention/ChemicalPollution/Pages/IGCCode.aspx.

Management Plan" made a requirement for all ships. These amendments entered into force on January 1, 2013.[14]

Application of these requirements to incidental CO_2 emissions from bulk carriers is unclear but cannot be discounted given the novelty of the situation.

b. United Nations Convention on the Law of the Sea

Entering into force in 1994, the United Nations Convention on the Law of the Sea ("UNCLOS") accomplishes several tasks, including dividing the oceans into various zones and protecting the marine environment.[15] Parties to UNCLOS include China, the EU, Japan and South Korea. The United States is not a party.

Application of UNCLOS to the maritime shipment of bulk CO_2 is unclear. It is most likely to apply to offshore injection and storage activities, which are not contemplated here.[16] Still, the inadvertent leakage of CO_2 from loading/offloading platforms could trigger UNCLOS scrutiny, as follows[17]:

- ✓ UNCLOS does not expressly prohibit CCS activities, but its provisions may well have an impact where the activities are deemed to constitute pollution, which is defined in Article 1(4) as:

  > the introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities.

- ✓ There is no conclusive opinion as to whether CCS would constitute pollution in accordance with this definition.

- ✓ UNCLOS applies to the seabed and its subsoil. However, there remains uncertainty as to whether its provisions would apply in order to regulate CCS activities undertaken beneath the subsoil.

- ✓ The right of a coastal state to exploit its Exclusive Economic Zone ("EEZ") is, to some extent, curtailed by the provisions of Part V of UNCLOS. UNCLOS places some

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[14] For more information, *see* http://www.imo.org/en/MediaCentre/HotTopics/GHG/Pages/default.aspx, http://www.ics-shipping.org/docs/default-source/resources/environmental-protection/shipping-world-trade-and-the-reduction-of-co2-emissions.pdf?sfvrsn=6, http://www.marpol-annex-vi.com/emissions/co2-emissions/, and http://www.imo.org/en/MediaCentre/PressBriefings/Pages/55-paris-agreement.aspx.

[15] http://www.un.org/depts/los/convention_agreements/convention_overview_convention.htm.

[16] If offshore injection and storage activities are contemplated, additional agreements could also apply, including but not limited to: (1) the OSPAR Convention; (2) Marine Strategy Framework Directive (2008/56/EU); and (3) offshore provisions of EU Directive 2009/31/EC.

[17] http://hub.globalccsinstitute.com/publications/offshore-co2-storage-legal-resources/united-nations-convention-law-sea-unclos.

restrictions upon countries with regard to the erection of installations and structures in their EEZ. Article 56 requires states to “have due regard to the rights and duties of other States” when undertaking activities in the EEZ; while Part V prohibits the placement of installations, structures and their accompanying safety zones where they may interfere with recognized international sea lanes, which are essential to international navigation.

✓ Under the provisions of UNCLOS, the transport of CO_2 by ship or pipeline to an injection platform could be considered as dumping and subject to additional requirements. The London Convention of 1972 and the later Protocol of 1996 contain global rules and standards with regard to dumping and marine pollution.

c. The UNECE Convention on Environmental Impact Assessment in a Transboundary Context

The 1991 UNECE Convention on Environmental Impact Assessment in a Transboundary Context (“Espoo Convention”) is intended “to prevent, reduce and control significant adverse transboundary environmental impact from proposed activities.”[18] The Convention requires states to carry out an environmental impact assessment (“EIA”) for all activities listed in Appendix I which are “likely to cause significant adverse transboundary impact” in another state. The EIA, which is defined as a “national procedure for evaluating the likely impact of a proposed activity on the environment,”, must be carried out before any decision to authorize or undertake the proposed activity and must include a series of elements listed in Appendix II (a description of the activity, of reasonable alternatives, of the environment likely to be affected, of the potential impacts and of mitigation measures to minimize the impact, etc.). The state of origin must also ensure that affected states are notified of the proposed activity.

Appendix I includes, among other things, oil refineries, coal gasification plants, certain large thermal power stations, large diameter oil and gas pipelines, trading ports, waste disposal installations for incineration, chemical treatment or landfill of toxic and dangerous wastes, offshore hydrocarbon production and major storage facilities for petroleum, petrochemical and chemical products. Any of the concerned states can also convene discussions on whether other proposed activities, not listed in Appendix I, are likely to cause a significant adverse transboundary impact and should be treated as if they were listed (subject to the agreement of all the states). Guidance on criteria to be taken into account in determining significant adverse impact is given in Appendix III (size of the activity, proximity to areas of specialized environmental sensitivity or importance, activities with particularly complex and potentially adverse effects, etc.).

The EU and many European countries individually are parties. The United States is a signatory but has not ratified it.[19]

Application of the Espoo Convention to, for example, bulk CO_2 loading/unloading facilities offshore EU is unclear.

[18] For background information, see http://www.unece.org/env/eia/welcome.html and http://www.unece.org/env/eia/eia.html.
[19] https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-4&chapter=27&lang=en.

d. International Maritime Shipping Requirements

The bulk maritime shipment of liquefied CO_2 is subject to the International Maritime Dangerous Goods ("IMDG") Code, which establishes standards for packing, marking, labeling, documentation, stowage, quantity limitations, exceptions and notifications for preventing pollution by harmful substances. Carbon dioxide is classified under: (1) UN1013 with a proper shipping name of "Carbon Dioxide"; and/or (2) UN2187 with a proper shipping name of "Carbon Dioxide, refrigerated liquid." The latter would almost certainly apply in this situation. Its hazard class is 2.2 (Non-Flammable/Non-Toxic Gas).

Since EOR-scale quantities of CO_2 are not currently being shipped by sea, it is possible that authorities implementing the IMDG Code would require that new hazard assessments be conducted.

e. International CCS/CCUS-Related Codes/Standards

ISO, through Technical Committee 265 ("TC265"), is currently developing the world's first technical standards for CCS and storage via CO_2-EOR.[20] The work is divided by topic among Working Groups ("WG") with two WG's of particular relevance here: (1) WG2/Transportation; and (2) WG6/CO_2-EOR Storage)[21]. TC265 should conclude its initial work by 2017-2018.

WG2/Transportation is primarily focused on pipeline transportation. We nonetheless would encourage maritime interests to get involved in the process as the scope of the standard may change over time.

WG6/CO_2-EOR Storage also should be of relevance to parties interested in future cross-border CO_2-EOR transactions as the standard that emerges from this process should facilitate these types of commercial activities where incidental storage is claimed or is required by domestic law or regulation.

f. Non-Maritime Modes of Transportation

The movement of CO_2 by non-maritime modes of transportation (e.g., pipeline, rail, road, barge) separately would be regulated by: (1) international/multilateral transportation codes; and (2) domestic transportation laws and regulations in each country. Among the former are: (1) the European Agreement Concerning the International Carriage of Dangerous Goods by Road (the so-called "ADR")[22]; (2) the European Agreement Concerning the International Carriage of Dangerous Goods by Rail (the so-called "RID")[23]; and (3) the European Agreement Concerning the International Carriage of Dangerous Goods by Inland Waterway (the so-called "ADN")[24]. Comparable dangerous goods/hazardous materials transportation regulations exist in most countries.

While we do not envision issues per se arising under these non-maritime transportation regulatory regimes, depending upon the quantities of CO_2 being transported the applicable codes and/or regulations may require that additional risk assessments, hazard classifications and similar steps be performed before the specific mode of transportation is authorized.

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[20] For background on TC265, *see* http://www.iso.org/iso/iso_technical_committee?commid=648607.
[21] The author of this memorandum is the chair of WG6/CO_2-EOR Storage.
[22] http://www.unece.org/trans/danger/publi/adr/adr_e.html.
[23] http://www.unece.org/transport/areas-of-work/dangerous-goods/legal-instruments-and-recommendations/ghs/transdangerpublighsimplementation-e/legal-inst-list.html.
[24] http://www.unece.org/trans/danger/publi/adn/adn_e.html.

III. Import/Export Considerations

a. Preparing CO_2 for Transport & Onshore/Offshore Loading/Unloading

Numerous steps are required to transport CO_2, each of which would be expected to raise a host of novel (as this has not been done before for bulk CO_2) and potentially burdensome and time-consuming permitting considerations under the relevant laws and regulations of each country. These steps include:

- ✓ *Liquefaction*. It is assumed that the CO_2 will be liquefied prior to transport.[25] Using LNG export terminals in the United States as an example, permitting of such facilities triggers numerous federal, State and local permitting and related approvals. These approvals include, but are not limited to: (1) air permits for criteria pollutants; (2) GHG permits (to include the potential use of CO_2-EOR as a Best Available Control Technology for CO_2); (3) water permits; (4) zoning; (5) climate impact assessments under the National Environmental Policy Act; (6) State and local approvals for linear infrastructure; (7) Endangered Species Act assessments; (8) fish and mammal assessments; (9) historic assessments; (10) safety plans & assessments; and (11) approvals by the U.S. Coast Guard.

  A 2011 assessment focused on Japan identified the following domestic laws and regulations that could be triggered by the proposed construction of this type of facility in that country: (1) Marine Pollution Prevention Law; (2) High Pressure Gas Safety Act; (3) Ship Safety Act; (4) Industrial Safety and Health Act; (5) Ports and Harbors Act; (6) Act on Port Regulations; (7) Coast Act; (8) Maritime Traffic Safety Act; (9) Act on Development of Fishing Ports and Grounds; (10) Act on the Protection of Fishery Resources; (11) Marine Resources Development Promotion Act; (12) Fishery Act; (13) Mining Law; and (14) Mine Safety Act.[26]

- ✓ *Intermediate Storage at Loading Point.* CO_2 capture and liquefaction are continuous processes, whereas ship transport of liquefied CO_2 is a discrete, batch process. Hence, “there is a need to provide buffer storage holding at least the volume of a ship.”[27] Based on our preliminary review of laws and regulations in the subject jurisdictions, this activity is not specifically regulated because it has not yet occurred as a commercial endeavor. It is likely not exempt from regulation, either. Permitting this activity would thus raise issues of first impression in most, if not all, countries.

- ✓ *Ship Loading.* The precise manner in which CO_2 would be loaded is unclear.[28] Various ideas have been proposed[29]:

  > As there could be various means of CO_2 transport from capture points to [the loading] terminal, all … means of

[25] *Brownsort Review*, p. 16.
[26] *GCCSI Study*, pp. 89-90.
[27] *Brownsort Review*, p. 17.
[28] *Brownsort Review*, p. 17; *see also GCCSI Study*, which assumed a hypothetical, detailed CO_2 loading system.
[29] *Transport of CO_2 by Ship Tankers* (Global CCS Institute web site, last visited Dec. 21, 2015).

> transport must converge at the loading terminal … Considering that there could be barriers towards accumulating huge stocks of CO_2 near populated areas, a transition station, such as a Floating Production Storage and Loading (FPSL) Vessel, can be provided in order to provide a safe distance between the CO_2 temporary storage and landing area and the shore. This concept is actually adopted from the currently used Floating Production, Storage and Offloading (FPSO) vessel in the oil and gas industry. The FPSO is a type of floating tank system equipped with all necessary facilities and designed to take all the oil and gas for offloading onto waiting tankers.

Based on our preliminary review of laws and regulations in the subject jurisdictions, this activity is not specifically regulated because it has not yet occurred as a commercial endeavor. It is likely not exempt from regulation, either. Permitting this activity would thus raise issues of first impression in most, if not all, countries similar to those discussed above for "Intermediate Storage at Loading Point."

✓ *Ship Offloading*. Based upon a relevant 2015 literature review, most "publications … assume offshore unloading to an injection well via some form of single point mooring (SPM) system to either a platform or a subsea wellhead connection."[30] Offloading to shore is also a possibility.

Based on our preliminary review of laws and regulations in the subject jurisdictions, this activity is not specifically regulated because it has not yet occurred as a commercial endeavor. It is likely not exempt from regulation, either. Permitting this activity would thus raise issues of first impression in most, if not all, countries similar to those discussed above for "Intermediate Storage at Loading Point."[31]

All of the above assumes, of course, that technical standards exist for the construction of each type of infrastructure in the first instance.

b. <u>Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal</u>

Adopted in 1989, the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal ("Basel Convention") endeavors to accomplish the following:

✓ The reduction of hazardous waste generation and the promotion of environmentally sound management of hazardous wastes, wherever their place of disposal;

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[30] *Brownsort Review*, p. 21; *see also GCCSI Study*, which assumed a hypothetical, detailed CO_2 unloading system.

[31] *Transport of CO_2 by Ship Tankers* (Global CCS Institute web site, last visited Dec. 21, 2015). *Accord Neele, F., Ship Transport of CO_2 – Breaking the CO_2-EOR Deadlock* ("Unloading CO_2 in open waters is a particular challenge when it comes to [EOR] … If introducing CO_2 to an offshore oil field which is not already prepared to receive the CO_2, this would require reconstruction of the platform and shut down of oil production for a prolonged period of time") (thereafter proposing technical solutions).

- ✓ The restriction of transboundary movements of hazardous wastes except where it is perceived to be in accordance with the principles of environmentally sound management; and

- ✓ A regulatory system applying to cases where transboundary movements are permissible.

Numerous countries/jurisdictions relevant here are parties to the Basel Convention, including China, the European Union, Japan and South Korea.[32] The United States has signed the Basel Convention but not yet ratified it. For this reason, the United States cannot participate in waste transfers with Basel Convention parties without a separate and equivalent bilateral or multilateral agreement. The United States has entered into several bilateral agreements and one multilateral agreement. The United States currently maintains a multilateral agreement with the members of the OECD, for example, governing transboundary movements of waste for recovery purposes. In addition, the United States has established two bilateral agreements, with Canada and Mexico, for importing and exporting hazardous waste. Finally, Costa Rica, Malaysia and the Philippines have entered into separate agreements with the United States. Under these three agreements, the United States may receive waste from Costa Rica, Malaysia, and the Philippines but may not export waste to these countries. EPA regulates these activities for the United States.[33]

Application of the Basel Convention would turn on whether applicable countries deemed bulk CO_2 being transported for EOR to be a waste within the meaning of the agreement. As previously noted, the United States (via EPA) has taken the position that CO_2 being "stored" geologically is a "solid waste" and could be a "hazardous waste" in some circumstances.[34]

Based upon our initial research, the issue of the classification of bulk CO_2 being shipped for EOR under the Basel Convention is unresolved and thus would be a matter of first impression for commercial operators and countries undertaking the activities.[35] So far, the only clarifications on this point have been provided by the amendment to Article 6 of the London Protocol[36] on the export of waste and the amendments to EU waste legislation made by the EU Directive on geological storage of carbon dioxide, application of which in this context are unclear.

With respect to this situation, the Global CCS Institute has stated[37]:

> Until there is an international consensus on the classification of CO_2 for geological storage, the effect of [the Basel Convention] upon CO_2

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32 http://www.basel.int/Countries/StatusofRatifications/PartiesSignatories/tabid/4499/Default.aspx#US16.

33 http://www3.epa.gov/epawaste/hazard/international/basel3.htm.

34 http://www3.epa.gov/epawaste/nonhaz/industrial/geo-sequester/faqs.htm.

35 A similar agreement -- the 1991 Convention on the Ban of the Import into Africa and the Control of Transboundary Movement and Management of Hazardous Wastes within Africa (the so-called "Bamako Convention") – potentially could apply to comparable CO_2 shipments to and within Africa.

36 For more details on the London Protocol, see http://hub.globalccsinstitute.com/publications/legislation-relating-co2-transport-storage/london-protocol-co2-transport-storage.

37 http://hub.globalccsinstitute.com/publications/legislation-relating-co2-transport-storage/international-transboundary-transport-regulation-co2-storage.

> transport will remain uncertain … The Intergovernmental Panel on Climate Change … has stated that CO_2 is unlikely to fall within the scope of the provisions of [the Basel Convention], unless CO_2 is mixed with other prohibited substances. Nevertheless, in the absence of clarification on this point, there will continue to be uncertainty about the legal status of CO_2 and the applicability of international agreements restricting international transport of hazardous wastes.

We agree with these sentiments.

IV. Domestic Environmental, Energy & Related Laws in Each Jurisdiction

a. Offshore Infrastructure

Depending on the precise offshore infrastructure being proposed and its location, domestic environmental and oil & gas laws and regulations would have to be satisfied. We would need more information about the offshore infrastructure to conduct this analysis. Since these facilities would be novel, we would expect permitting and compliance to be time-consuming and potentially complicated in each country.

b. Onshore Infrastructure

Depending on the precise onshore infrastructure being proposed and its location, domestic environmental and oil & gas laws and regulations would have to be satisfied. We would need more information about the offshore infrastructure to conduct this analysis. Since these facilities would be novel (except, perhaps, CO_2 pipelines in the United States), we would expect permitting and compliance to be time-consuming and potentially complicated in each country.

c. Domestic CO_2-EOR Regulations

Each importing country presumably would need to have separate regulations regarding the use of CO_2 for EOR, whether storage is claimed or not. Such regulations exist in the United States. They do not, however, in all other countries under consideration here. For example, China does not have domestic CO_2-EOR regulations. Such regulations would presumably have to be implemented before CO_2 could be imported into that country for that purpose.

V. Effective Prohibitions for Political Reasons

We believe it highly unlikely that the State of California would allow – for the foreseeable future at least – the import or export of CO_2 for EOR due to the climate change regulatory environmental in that jurisdiction. Further, California currently lacks laws and regulations governing the activity, which does not squarely fit within the state's primary climate regulatory programs: (1) cap-and-trade under AB32; and (2) the Low Carbon Fuel Standard.

The California Air Resources Board is currently in the midst of developing protocols and regulations regarding CCS and storage via EOR. Those efforts are supposed to conclude by late 2017, with public hearings beginning in early 2016. These efforts are unlikely to address import/export scenarios.

VI. International/Multilateral Climate Considerations

The following scenarios would only potentially apply where the CO_2 being transported was subject to a GHG emissions control requirement in either the country of import and/or export. For the reasons stated above, we below that assumption would apply here.

a. 2015 Paris Agreement

The 2015 Paris Agreement, slated to take effect in 2020 upon acceptance by the requisite number (and size) of parties, includes in Article 6 a framework for international emissions trading.[38] It is too early to assess if and how that framework would enable cross-bounder emissions trading in the context of CO_2-EOR. The implementing procedures will be issued in the years ahead. Further, the countries participating in the CO_2 transaction would need to agree to that approach – and we note that the United States, in its INDC, indicated that it did "not intend to utilize international market mechanisms to implement its 2025 target."[39]

If the Kyoto Protocol's Clean Development Mechanism ("CDM") may be used a model, we anticipate that post-2020 CCUS-based projects should be eligible to monetize or otherwise take credit for applicable emission reductions under the Paris Agreement. Doing so, however, is not anticipated to be easy as, for example, comparable GHG regulatory regimes likely would have to be in place in both the CO_2 exporting and CO_2 importing countries. It is conceivable that the ISO CCUS standards currently under development may facilitate such transactions.

b. Kyoto Protocol

We do not believe that the Kyoto Protocol, which is currently slated to lapse in 2020 when it is replaced by the 2015 Paris Agreement, is a relevant consideration given that the commercial activities under consideration here are likely to take place in 2020 or later.

In the event that CO_2 shipments were to occur prior to 2020, application of the Kyoto Protocol to the transactions contemplated here would be subject to substantial legal uncertainty despite the fact that the CDM Executive Board recognized CCS/EOR-based projects as potentially eligible offset projects. We based this conclusion on: (1) the Kyoto Protocol's numerous and well-documented implementation struggles; (2) declining country participation in the Second Commitment Period; (3) lack of robust CCS/EOR-storage implementation regulations in nearly all countries (with the potential exception of the United States); and (4) general skepticism about the technologies within the Kyoto Protocol's administering bodies.

In a 2012 staff paper prepared under the auspices of the UNFCCC's Subsidiary Body for Scientific and Technological Advice, the authors outlined numerous legal, regulatory and policy issues that would have to be resolved before transboundary CCS projects could be recognized under any of the Kyoto Protocol's mechanisms, including the CDM.[40] To the best of our knowledge, none of the recommendations has been implemented.

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[38] *Paris Agreement*, art. 6 (FCCC/CP/2015/L.9/Rev.1).

[39] http://www4.unfccc.int/submissions/INDC/Published%20Documents/United%20States%20of%20America/1/U.S.%20Cover%20Note%20INDC%20and%20Accompanying%20Information.pdf.

[40] http://unfccc.int/resource/docs/2012/tp/09.pdf.

c. EU-ETS

Similar to the status of CCS/EOR storage under the Kyoto Protocol, the status of the same technologies under the EU-ETS remains subject to substantial uncertainties, despite the existence of the EU Directive on geologic storage. Numerous commentators have noted that the EU-ETS has failed to support the development of domestic CO_2 storage industries, let alone enable CO_2 import/export markets for similar activities elsewhere. The Global CCS Institute has published recommendations regarding how the EU-ETS could be reformed post-2020 to enable CCS/EOR storage.[41] Unless and until such reforms are implemented, we are pessimistic that the activities contemplated here would ever be recognized under or authorized by the EU-ETS.

Regards,

Kipp Coddington
Director

[41] http://hub.globalccsinstitute.com/publications/global-ccs-institute-submission-european-commission%E2%80%99s-consultation-revision-eu-emissions-trading-system-eu-ets-directive/eu-ets-ccs-enabling-policy.

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