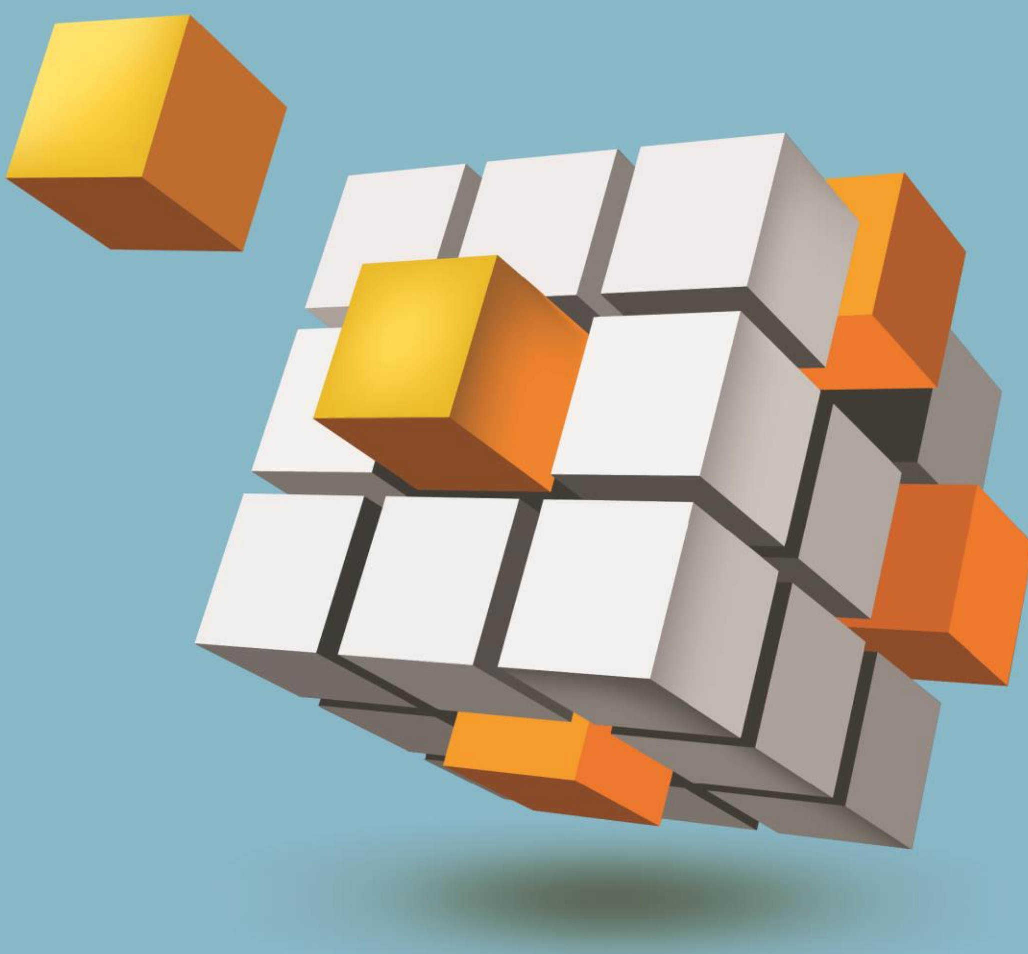
NATIONAL COALCOUNCIL

CO_2 BUILDING BLOCKS

ASSESSING CO_2 UTILIZATION OPTIONS



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The National Coal Council is a Federal Advisory Committee to the U.S. Secretary of Energy. The NCC advises, informs and makes recommendations to the Secretary on matters requested by the Secretary relating to coal or the coal industry.

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The National Coal Council (NCC) was chartered in 1984 based on the conviction that an industry advisory council on coal could make a vital contribution to America's energy security. The NCC's founders believed that providing expert information could help shape policies relevant to the use of coal in an environmentally sound manner. It was expected that this could, in turn, lead to decreased dependence on other less abundant, more costly, less secure sources of energy.

These principles continue to guide and inform the activities of the NCC. Coal has a vital role to play in the future of our nation's electric power, industrial, manufacturing, and energy needs. Our nation's primary energy challenge is to find a way to balance our social, economic, and environmental objectives.

Throughout its 32-year history, the NCC has maintained its focus on providing guidance to the Secretary of Energy on various aspects of the coal industry. The NCC has retained its original charge to represent a diversity of perspectives through its varied membership and continues to welcome members with extensive experience and expertise related to coal.

The NCC serves as an advisory group to the Secretary of Energy, chartered under the Federal Advisory Committee Act (FACA), providing advice and recommendations to the Secretary of Energy on general policy matters relating to coal and the coal industry. As a FACA organization, the NCC does not engage in lobbying activities.

The principal activity of the NCC is to prepare reports for the Secretary of Energy at his/her request. The NCC has prepared more than 30 studies for the Secretary, at no cost to the Department of Energy. All NCC studies are publicly available on the NCC website.

Members of the NCC are appointed by the Secretary of Energy and represent all segments of coal interests and geographic distribution. The NCC is headed by a Chair and Vice Chair who are elected by its members. The Council is supported entirely by voluntary contributions from NCC members and receives no funds from the Federal government. Studies are conducted solely at the expensive of the NCC and at no cost to the government.

The National Coal Council values the opportunity to represent the power, the pride, and the promise of our nation's coal industry.

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[INSERT TRANSMITTAL LETTER FROM MIKE DURHAM TO SECRETARY MONIZ.]

The Secretary of Energy
Washington, DC 20585

February 23, 2016

Dr. Michael Durham
Chairman, The National Coal Council, Inc.
1101 Pennsylvania Avenue, NW, 6th Floor
Washington, DC 20004

Dear Chairman Durham:

I am writing to request the National Coal Council (NCC) develop an expanded white paper assessing opportunities to advance commercial markets for carbon dioxide (CO_2) from coal-base power generation.

The white paper should focus on profit-generating opportunities for CO_2 utilization, both for Enhanced Oil Recovery (EOR) and for non-EOR applications. The questions to be addressed are:

(1) What is the extent to which commercial EOR and non-EOR CO_2 markets could incentivize deployment of Carbon Capture and Storage (CCS) / Carbon Capture, Utilization, and Storage (CCUS) technologies?

(2) What economic opportunity does deployment of commercial-scale CCS/CCUS technology represent for the U.S.?

The white paper would be managed under the auspices of the Executive Advisory Board within the NCC. I ask that the white paper be completed no later than August 31.

Upon receiving this request and establishing your internal working groups, please advise me of your schedule for completing the white paper. The Department looks forward to working with you in this effort.

Sincerely,

Ernest J. Moniz

CO_2 BUILDING BLOCKS
Assessing CO_2 Utilization Options

Table of Contents

Executive Summary

Fossil fuels – including coal, natural gas and oil – will remain the dominant global energy source well into the future by virtue of their abundance, supply security and affordability. There is a growing consensus among industry, the environmental community and governments that future carbon dioxide (CO_2) emission reduction goals cannot be met by renewable energy sources alone and that carbon capture, utilization and storage (CCUS) technologies for all fossil fuels will have to be deployed to achieve climate objectives in the U.S. and globally and to insure a reliable power grid. Advancing CCUS is not just about coal, nor is it just about fossil fuels generally. Rather, it is a sine qua non for achieving stabilization of greenhouse gas (GHG) concentrations in the atmosphere.

Carbon dioxide enhanced oil recovery (CO_2-EOR) represents the most immediate, highest value opportunity to utilize the greatest volumes of anthropogenic CO_2, thereby incentivizing CCUS. Assuming a price for CO_2 of $33/metric ton ($1.75/Mcf) delivered to the oil field at pressure and a $70 per barrel oil price, and using 0.45 metric tons of purchased (net) CO_2 per barrel of recovered oil, utilization of CO_2 for EOR results in a transfer of $14.90 of the $70 per barrel price to firms involved with capture and transport of CO_2. The economic value is sensitive to the price of oil, of course, and will vary in response to oil market conditions.

Policymakers should continue to focus on advancing geological storage options through support for research, development and demonstration (RD&D) and adoption of incentives. As part of Mission Innovation, the U.S. Department of Energy (DOE) should reinvigorate its RD&D program on advanced ("next generation") CO_2-EOR technologies. Deployment of these advanced technologies could more than double the market for CO_2 – from 11 billion MT with today's technologies to 24 billion MT with next generation technologies. DOE should sponsor a full evaluation of the technically recoverable and economically viable domestic residual oil zone (ROZ) resource to more completely understand the market for CO_2 from EOR. Regulatory impediments to the expansion of CO_2-EOR should be reduced.

Aside from CO_2-EOR and other geologic pathways, research is underway on two general CO_2 utilization pathways – breaking down the CO_2 molecule by cleaving C=O bond(s) and incorporating the entire CO_2 molecule into other chemical structures. The latter pathway holds relatively more promise as it requires less energy and tends to "fix" the CO_2 in a manner akin to geologic storage. Utilizing CO_2 in non-geologic applications faces hurdles, including yet-to-be resolved issues associated with thermodynamics and kinetics involved in the successful reduction of CO_2 to carbon products. Still, these technologies are worthy of continuing evaluation and many hold long-term potential in specific applications.

There is benefit to establishing a technology review process that is as objective as possible to assess the benefits and challenges of different CO_2 utilization technologies and products. Evaluation criteria fall into three broad categories: (1) environmental considerations; (2) technology/product status; and (3) market considerations. Collecting data on these evaluation criteria should be undertaken. Using the criteria, a technology ranking system which can then be used to prioritize candidates for RD&D and product investment should be developed.

The extent to which CO_2 utilization technologies may incentivize CCUS deployment is dependent on numerous policy and market factors. U.S. law recognizes CO_2-EOR and other geologic storage technologies as compliance options; non-geologic technologies may be used only if EPA determines they are as effective as geologic storage. U.S. and international GHG reduction objectives and timeframes (2050) further dictate the need to employ CO_2 utilization technologies that can be quickly commercialized at significant scale.

CO_2 utilization markets may not be well aligned with the regulatory or investment requirements of the power and industrial sectors. For example, a technology developer offering a utilization opportunity would likely require a return on investment in less than 10 years, while the plant owner would require a CO2 control technology that will allow the plant to operate for the remainder of its useful life – which may be another 40 years or more for a power plant. Additionally, an owner of a CO_2-emitting facility must consider whether a CO_2 user may discontinue the project due to bankruptcy, market changes or other reasons, leaving the facility owner without a viable regulatory compliance strategy.

The array of potential bases for misalignment of needs highlights the fact that even if a CCU project is deemed economically viable, access to geological storage may be necessary to advance the project. In this way, CCU may be helpful to the deployment of a broader CCUS infrastructure by providing some revenue and also encouraging characterization and well permitting activities for geological CO_2 storage.

In sum, monetary, regulatory and policy investments in CO_2 utilization technologies should be roughly prioritized from geologic to non-geologic, with exceptions made for any non-geologic technologies that are found to be as effective as geologic storage. To identify the most expeditious and impactful technology options, NCC suggests applying a reasonable market potential threshold of 35 MTPY, which is roughly equivalent to the annual CO_2 emissions from about 6 GWe or a dozen 500 MWe coal-based power plants. Full GHG lifecycle assessments of CO_2 utilization technologies should also be conducted with the assessments taking into account the incumbent products' GHG emissions that the new technologies displace.

Aligning CO_2 production and utilization markets may require relaxing terms of compliance for CO_2 emitting utilities and industrial facilities, as well as providing for establishment of an inventory of unused CO_2 in geologic storage. Appropriate policy and regulatory relief for higher-risk CCUS projects may also incentivize investment from the venture capital community.

The U.S. enhances its chance of success in meeting its CO_2 emission reduction goals when it commits with urgency to the deployment of CCUS technologies. That commitment begins with the establishment of policies and incentives to level the playing field for CCUS. Upon this level foundation, the building blocks of CO_2 utilization can be constructed to further expedite the reduction of CO_2.

A. Key Findings & Recommendations

Key Findings

Chapter B: Introduction – The Value of Coal

- Fossil fuels – including coal, natural gas and oil – will remain the dominant global energy source well into the future by virtue of their abundance, supply security and affordability.
- There is a growing consensus among industry, the environmental community and governments that future CO_2 emission reduction goals cannot be met by renewable energy sources alone and that CCUS technologies for all fossil fuels will have to be deployed to achieve climate objectives in the U.S. and globally and to ensure a reliable power grid.
- Each component of the CCUS value chain is critical - CO_2 capture, utilization and storage – and must be advanced in tandem to expeditiously advance CCUS deployment.
- CO_2 utilization can help to reduce CCUS costs and incentivize the technology's deployment.
- CCUS is not exclusively a "clean coal" strategy and will ultimately need to be adopted for all fossil fuels in the power and industrial sectors.

Chapter C: The CO_2 Utilization Imperative

- U.S. law requires new major stationary sources and major modifications to existing sources of greenhouse gases (GHGs) to reduce their emissions, with geologic storage options (specifically including CO_2-EOR) as preferred mitigation technologies.
- These U.S. legal requirements are reinforced by the 2015 Paris Agreement, which largely envisions the decarbonization of major energy systems through the use of CCUS and other technologies by the 2050 timeframe.
- Fossil fuels generally and coal specifically are dependent upon CCUS technologies to comply with U.S. GHG emission reduction requirements.
- CO_2-EOR still represents the most immediate, highest value opportunity to utilize the greatest volumes of anthropogenic CO_2.
- Aside from CO_2-EOR and other geologic pathways, research is underway on two general CO_2 utilization pathways – breaking down the CO_2 molecule by cleaving C=O bond(s) and incorporating the entire CO_2 molecule into other chemical structures. The latter pathway holds relatively more promise as it requires less energy and tends to "fix" the CO_2 in a manner akin to geologic storage.
- Utilizing CO_2 in non-geologic applications faces hurdles, including yet-to-be resolved issues associated with thermodynamics and kinetics involved in the successful reduction of CO_2 to carbon products.

Chapter D: Criteria for Review of CO_2 Utilization Technologies

- There is benefit to establishing a technology review process that is as objective as possible to assess the benefits and challenges of different CO_2 utilization technologies and products.
- Evaluation criteria fall into three broad categories: (1) environmental considerations; (2) technology/product status; and (3) market considerations.
- Relatively simple comparison tools can be used to compare different technologies to identify near-term and long-term opportunities for research and investment.
- Benefits of applying evaluation criteria include: (1) making relative comparisons among technologies; (2) identifying priority technology candidates; (3) creating a more comprehensive ranking of the suite of CO_2 utilization technologies; and (4) enabling revisions to technological assessments as market conditions change.

Chapter E: CO_2 Utilization Market Review

- Geological CO_2 utilization options have the greatest potential to advance CCUS by creating market demand for anthropogenic CO_2. Non-geological CO_2 utilization options are unlikely to significantly incentivize CCUS in the near- to intermediate-term because of technical, GHG LCA considerations, lack of scalability and related reasons.
- CO_2-EOR – including production and storage activities in ROZs – remains the CO_2 utilization technology with the greatest potential to incentivize CCUS.

- Joint industry/government R&D supportive of “next generation” CO_2-EOR technologies would greatly expand the economically viable market for CO_2 use by the EOR industry. With the benefit of this R&D, the market for CO_2 (from the EOR industry) would more than double – from 11 billion metric tons with today’s technologies to a potential of 24 billion metric tons with “next generation” technology.
- Gaining a more complete understanding of the geological uses of CO_2 for EOR would be greatly enhanced by further evaluations of the domestic ROZ resource and its viability for CO_2-EOR.

- Other geologic utilization markets – including rich-shale formations, enhanced coal bed methane (ECBM) and enhanced water recovery (EWR) – also hold current and future promise as incentives for CCUS.
- Non-geologic utilization opportunities exist, including: (1) inorganic carbonates and bicarbonates; (2) plastics and polymers; (3) organic and specialty chemicals; and (4) agricultural fertilizers. All of these opportunities face a variety of technical and economic challenges that are likely to impede their ability to incentivize CCUS in the immediate future. Unlike transportation fuels, however, they tend to “fix” CO_2 so have the advantage of potentially serving as preferred carbon management solutions.

Chapter E: CO_2 Utilization Market Review (continued)

- CO_2 may also be utilized through chemical and biological processes to produce transportation fuels, which is a very large market. This pathway is also unlikely to incentivize CCUS in the immediate future for a variety of technical and economic reasons, including: (1) the fact that transportation fuels are ultimately combusted and thus release CO_2 to the atmosphere and (2) current U.S. policy favors geologic-based utilization pathways for Clean Air Act (CAA) compliance. And while the case could be made that some CO_2-derived transportation fuels have lower GHG emissions than fossil-based fuels on a GHG LCA basis, non-fossil-based transportation fuels still face significant market competition and displacement hurdles.

Chapter F: Extent to Which CO_2 Utilization Technologies May Incentivize CCUS Deployment

- U.S. law currently favors geologic storage/utilization technologies; non-geologic CO_2 uses must demonstrate that they are as effective as geologic storage.
- Timing of U.S. and international climate goals point towards the use of CO_2 utilization technologies that are either already commercialized or near commercialization.
- There is a misalignment of needs between industries who would utilize CO_2 and the power sector.
- CCUS technology deployments face a host of unresolved impediments that are unlikely to be mitigated by market demand for CO_2 alone in any near- to intermediate-term scenario.
- With the exception of geological utilization under appropriate circumstances, CO_2 utilization is unlikely by itself to incentivize CCUS technologies.

Chapter G: Economic Opportunity for the U.S. Associated with Commercial-Scale CCUS Deployment

- Assuming a price for CO_2 of $33/metric ton ($1.75/Mcf) delivered to the oil field at pressure and a $70 per barrel oil price, and using 0.45 metric tons of purchased (net) CO_2 per barrel of recovered oil, utilization of CO_2 for EOR results in a transfer of $14.90 of the $70 per barrel oil price to firms involved with capture and transport of CO_2. The economic value is sensitive to the price of oil, of course, and will vary in response to oil market conditions.
- The economic incentive potential of all other pathways (to include all non-geologic options) is largely unquantifiable based on publicly available data. Moreover, such options face a host of known technical, economic and policy hurdles.

Key Recommendations

Chapter B: Introduction – The Value of Coal

- An expanded coalition of fossil fuel users and producers should collaborate to help develop and commercially deploy CCUS technologies on an accelerated time schedule.
- Efforts should be undertaken to build on the expanding consensus among industry, the environmental community and governments in support of deployment of CCUS technologies.

Chapter C: The CO_2 Utilization Imperative

- Federal CCUS policy should continue to focus on encouraging geologic utilization and storage pathways, including but not limited to CO_2-EOR.
- Some non-geologic CO_2 utilization pathways nonetheless hold promise as niche opportunities, and research into them should be encouraged. Polymers with the potential to make use of the entire intact CO_2 molecule are an example.
- CO_2 utilization pathways that are both economic and that "fix" the CO_2 in a manner akin to geologic storage should be prioritized from research and policy perspectives.

Chapter D: Criteria for Review of CO_2 Utilization Technologies

- Evaluation criteria should be used to gather information about and compare various CO_2 utilization technologies.
- Collecting data on evaluation criteria – including environmental considerations, technology/product status, and market considerations – should be undertaken.
- Using the evaluation criteria, a technology ranking system which can then be used to prioritize candidates for RD&D and product investment should be developed.

Chapter E: CO_2 Utilization Market Review

- Policymakers should continue to focus on advancing geological storage options through support for RD&D and adoption of incentives.
- As part of Mission Innovation, DOE should reinvigorate its RD&D program on advanced ("next generation") CO_2-EOR technologies.
- DOE should sponsor a full evaluation of the technically recoverable and economically viable domestic ROZ resource to more completely understand the market for CO_2 from EOR.
- Additional technical and economic research should be directed towards the following non-geologic utilization products and pathways: (1) inorganic carbonates and bicarbonates; (2) plastics and polymers; (3) organic and specialty chemicals; and (4) agricultural fertilizers.
- GHG LCA of all CO_2 utilization options should be undertaken.

Chapter F: Extent to Which CO_2 Utilization Technologies May Incentivize CCUS Deployment

- A regulatory based, incentive and tax compliant framework that provides a well-defined no-regrets economic calculus that limits the loss-of-capital to the investment community in FOAK (first-of-a-kind) CCUS projects should be developed.
- Monetary, regulatory and policy investments in CO_2 utilization technologies should be roughly prioritized from geologic to non-geologic, with exceptions made if non-geologic technologies are found to be as effective as geologic storage. Full GHG lifecycle assessments of CO_2 utilization technologies should also be conducted, with the assessments taking into account the incumbent products' GHG emissions that the new technologies displace.
- Coordinate State and Federal regulations to provide flexibility to accommodate an acceptable and broad range of potential commercial constructs (among CO_2 producers, intermediaries, investors and ultimate users of the users of CO_2). Each party should be responsible in a well-defined chain-of-custody, with clearly defined monitoring, reporting & verification (MRV) requirements and shared and definitive ultimate economic responsibilities for subsequent CO_2 releases.

Chapter G: Economic Opportunity for the U.S. Associated with Commercial-Scale CCUS Deployment

- More economic and technical research and analysis need to be conducted on CO_2-utilization in non-geologic options, including chemicals and fuels. The focus of this additional research and analysis should, where data exist, take into account the criteria for review of CO_2 utilization technologies detailed in Chapter D of this report.
- Additional research should be supported regarding advancing the following technologies toward commercialization: (1) inorganic carbonates and bicarbonates; (2) plastics and polymers; (3) organic and specialty chemicals; and (4) agricultural fertilizers.

B. Introduction: The Value of Coal

Key Findings

- Fossil fuels – including coal, natural gas and oil – will remain the dominant global energy source well into the future by virtue of their abundance, supply security and affordability.
- There is a growing consensus among industry, the environmental community and governments that future CO_2 emission reduction goals cannot be met by renewable energy sources alone and that CCUS technologies for all fossil fuels will have to be deployed to achieve climate objectives in the U.S. and globally and to ensure a reliable power grid.
- Each component of the CCUS value chain is critical – CO_2 capture, utilization and storage – and must be advanced in tandem to expeditiously advance CCUS deployment.
- CO_2 utilization can help to reduce CCUS costs and incentivize the technology's deployment.
- CCUS is not exclusively a "clean coal" strategy and will ultimately need to be adopted for all fossil fuels in the power and industrial sectors.

Key Recommendations

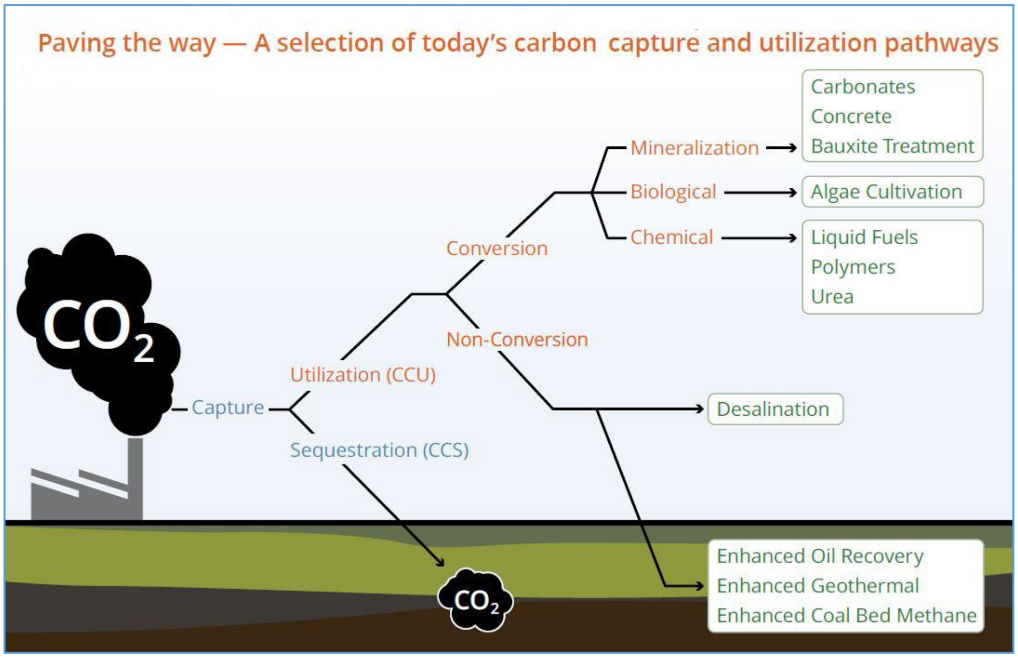
- An expanded coalition of fossil fuel users and producers should collaborate to help develop and commercially deploy CCUS technologies on an accelerated time schedule.
- Efforts should be undertaken to build on the expanding consensus among industry, the environmental community and governments in support of deployment of CCUS technologies.

Advancing Climate Goals with CCUS

Achieving global climate objectives will require a portfolio of approaches that balance economic realities, energy security and environmental aspirations. The most impactful action the U.S. can employ to reduce CO_2 emissions is to incentivize the rapid deployment of CCUS technologies.

Each component of the CCUS equation is critical. As detailed in this report and highlighted in Figure B-1, commercial markets for CO_2 from fossil fuel-based power generation and CO_2-emitting industrial facilities have the potential to provide a business incentive for CCUS. The extent of that economic opportunity will depend on many factors, including but not limited to expediting the development of and reducing the cost associated with CO_2 capture technologies. And while commercial markets may provide significant opportunities for CO_2 utilization, the global scale of CO_2 emissions suggests a continued need to pursue geologic storage options with significant CO_2 storage potential, including CO_2-EOR and initiatives such as those being undertaken by DOE through its Regional Carbon Sequestration Partnerships Program and related programs.

Figure B-1. CCUS: Building a climate change solution



Source: Global CCS Institute

In its January 2015 report *"Fossil Forward: Bringing Scale & Speed to CCS Deployment"*, the National Coal Council (NCC) noted that without CCUS, it is highly improbable that CO_2 emissions reduction goals will be met and that without CCUS the projected costs of achieving these goals will be much higher – on the order of 70-138 percent more expensive. This is due in large part to the world's continued reliance on abundant, secure and affordable fossil fuels – including coal, natural gas and oil.

Coal's Continued Global Energy Role

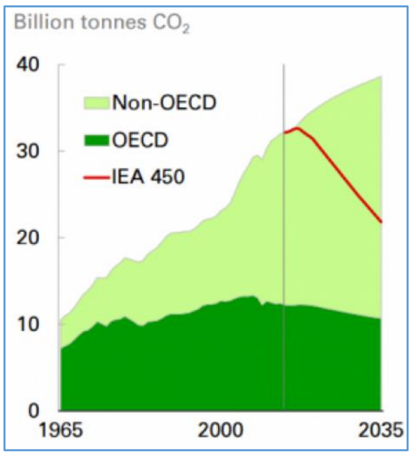
According to the BP Energy Outlook 2016, fossil fuels remain the dominant source of energy powering today's global economies. It is projected that these fuels will account for almost 80 percent of total energy supplies in 2035. Population and income are driving an increased demand for energy, even despite gains in energy efficiency. The world's population is projected to increase by 1.5 billion, reaching 8.8 billion people by 2035, and GDP is expected to more than double during this same period. More than half of the increase in global energy consumption is for power generation, continuing the trend toward global electrification.

The International Energy Agency's (IEA) Coal Industry Advisory Board recently conducted an assessment of the impact of coal utilization on energy security of key world regions. The report concludes that coal contributes not only to affordable energy prices, allowing broader access to electricity, but also improves the industrial competitiveness of the economy. Applying advanced coal technologies, including CCUS and high-efficiency/low-emissions (HELE) technologies, contributes to improving environmental impacts as well as leading to security of supply. Coal-based power plants provide dispatchable capacity due to their ability to operate flexibly and compensate for fluctuations in intermittent energy supplies such as wind and solar. Coal plants also provide cost-efficient reserve capacity needed when there is insufficient wind or solar power.

The CO_2 Challenge

The BP Energy Outlook 2016 notes that the level of CO_2 emissions is expected to continue to grow, increasing by 20 percent between 2014 and 2035 (see Figure B-2). The gap between the projected path for CO_2 emissions and IEA's 450 Scenario demonstrates the challenge associated with reducing GHG emissions.

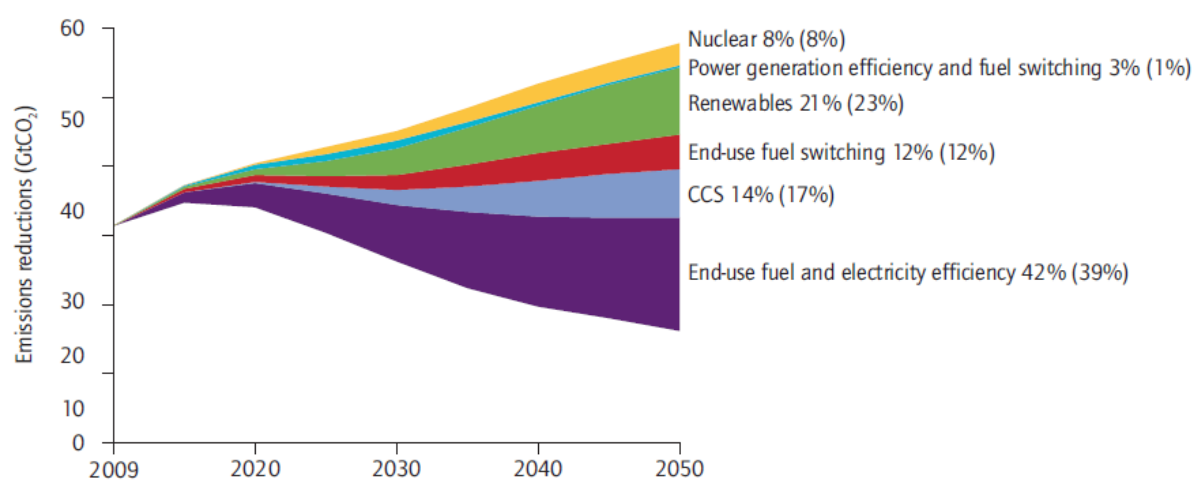
Figure B-2. CO_2 Emissions



Source: BP Energy Outlook 2016

Both the IEA and the United Nation's Intergovernmental Panel on Climate Change (IPCC) have concluded that CCUS is essential to limit global warming to 2°C. IEA estimates that CCUS can achieve 14 percent of the global GHG emissions reductions needed by 2050 (see Figure B-3).

Figure B-3. IEA Technology Roadmap



Note: numbers in brackets are shares in 2050. For example, 14% is the share of CCS in cumulative emission reductions through 2050, and 17% is the share of CCS in emission reductions in 2050, compared with the 6DS.

Source: International Energy Agency 2013

In its report "*Leveling the Playing Field: Policy Parity for CCS*", the NCC notes that CCUS is the only large-scale technology that can mitigate CO_2 emissions not just from coal-based power plants, but from other fossil generation and industrial sectors. IEA concurs, noting that CCUS is more than a strategy for clean coal and must be adopted by biomass and natural gas power plants, as well as by emission-intensive industry sectors, including cement, iron and steel, and chemicals manufacturing.

CCUS must be considered as one of the tools in a clean energy arsenal to address climate issues. This includes advancing financial incentives and policy measures to achieve policy parity for CCUS with other low-carbon technologies as detailed in the NCC's Policy Parity report. The magnitude of the climate challenge dictates the need for an expanded coalition of government-industry stakeholders both within the U.S. and internationally. The 2015 Paris Agreement establishes significant objectives for GHG emission reductions, the successful achievement of which will depend on the continued deployment of innovative energy technologies, including CCUS. In fact, many countries have specifically included CCUS technology in their Intended Nationally Determined Contributions (INDCs), including Canada, China, Norway, Saudi Arabia and the United Arab Emirates. The U.S. similarly has adopted an "all-of-the-above" strategy that includes CCUS.

The U.S. enhances its chance of success in meeting its CO_2 emission reduction goals when it commits with urgency to the deployment of CCUS technologies. That commitment begins with the establishment of policies and incentives to level the playing field for CCUS. Upon this level foundation, the building blocks of CO_2 utilization can be constructed to further expedite the deployment of CO_2 mitigation technologies.

C. The CO_2 Utilization Imperative

Key Findings

- U.S. law requires new major stationary sources and major modifications to existing sources of greenhouse gases (GHGs) to reduce their emissions, with geologic storage options (specifically including CO_2 enhanced oil recovery (CO_2-EOR)) as preferred mitigation technologies.
- These U.S. legal requirements are reinforced by the 2015 Paris Agreement, which largely envisions the decarbonization of major energy systems through the use of CCUS and other technologies by the 2050 timeframe.
- Fossil fuels generally and coal specifically are dependent upon CCUS technologies to comply with U.S. GHG emission reduction requirements.
- CO_2-EOR still represents the most immediate, highest value opportunity to utilize the greatest volumes of anthropogenic CO_2.
- Aside from CO_2-EOR and other geologic pathways, research is underway on two general CO_2 utilization pathways – breaking down the CO_2 molecule by cleaving C=O bond(s) and incorporating the entire CO_2 molecule into other chemical structures. The latter pathway holds relatively more promise as it requires less energy and tends to “fix” the CO_2 in a manner akin to geologic storage.
- Utilizing CO_2 in non-geologic applications faces hurdles, including yet-to-be resolved issues associated with thermodynamics and kinetics involved in the successful reduction of CO_2 to carbon products.

Key Recommendations

- Federal CCUS policy should continue to focus on encouraging geologic utilization and storage pathways, including but not limited to CO_2-EOR.
- Some non-geologic CO_2 utilization pathways nonetheless hold promise as niche opportunities, and research into them should be encouraged. Polymers with the potential to make use of the entire intact CO_2 molecule are an example.
- CO_2 utilization pathways that are both economic and that “fix” the CO_2 in a manner akin to geologic storage should be prioritized from research and policy perspectives.

Overview

CO_2-EOR remains the most immediate, highest value opportunity to utilize CO_2 at scale and with the promise of some amount of economic return.

Utilizing CO_2 in non-geologic applications faces a host of hurdles, including:

- current U.S. policy arguably favors geologic uses;
- the immature status of nearly all non-geologic CO_2 utilization technologies;
- logistical and infrastructure issues related to either siting CO_2 utilization facilities in the immediate vicinity of fossil fuel-based power plants and CO_2-emitting industrial plants or transporting CO_2 from said plants to more centralized CO_2 processing facilities;
- market limits and impediments – e.g., products derived from CO_2 presumably would be competing against, and endeavoring to displace, comparable products made from other feedstocks; and
- technical barriers involved in the successful reduction of CO_2 to carbon products, including thermodynamics and kinetics.

In recent years extensive research has been conducted into the two primary pathways of utilizing CO_2 – the first involving the cleavage of the C=O bond(s) and the second involving the reuse of the intact CO_2 molecule without breaking the C=O bond(s). Both hold promise but the latter has advantages over the former as the former requires more energy and typically results in fuels that are in turn combusted, resulting in the emission of CO_2 to the atmosphere. The latter, in contrast, typically takes less energy and may result in products such as polymers that are highly stable, long-lived and thus capable of "fixing" the CO_2 in a manner akin to geologic storage.

Analysis

Fossil fuels generally and coal specifically are dependent upon CCUS technologies to comply with U.S. GHG emission reduction requirements.

PSD/Title V Permitting. Sources that emit enough conventional pollutants to trigger compliance with the CAA's Prevention of Significant Deterioration (PSD) and Title V operating permit programs must then address GHGs, including CO_2. For the PSD program, this means that EPA may subject these sources to Best Available Control Technology (BACT) requirements for their CO_2 emissions. Because all major coal-based stationary sources emit both conventional pollutants and CO_2, this means that if PSD requirements are triggered for a conventional pollutant that also means that these sources must also apply a BACT assessment for GHGs. The current GHG emissions rate that triggers the BACT requirements is 75,000 tons per year (CO_2e), although by future rulemaking EPA may establish a different de minimis emission threshold.

Crucially, the core of these requirements has been upheld by the U.S. Supreme Court despite the fact that specific aspects of the regulatory program remain in flux. (Massachusetts v. Environmental Protection Agency, 549 U.S. 497 (2007); Utility Air Regulatory Group v. Environmental Protection Agency, 573 U.S. ___ (2014)).

Current EPA policy under the PSD program focuses on CO_2-EOR as potential BACT to control emissions of CO_2. EPA does not apply GHG LCA for these purposes.

GHG Performance Standards for New Coal-Based Power Plants. EPA's Standards of Performance for GHG Emissions from New, Modified, and Reconstructed Electric Utility Generating Units, which remain subject to litigation, are premised almost entirely upon the use of CO_2-EOR to store CO_2 to satisfy the emission limit of 1,400 lbs CO_2/MWh, although EPA acknowledges that the emission limit may also be met by co-firing with natural gas. The standard may also be met with non-CO_2-EOR geologic storage, such as saline, but at present those compliance pathways face economic headwinds. Non-geologic storage technologies may also be used but only if they "will store captured CO_2 as effectively as geologic sequestration" and "not cause or contribute to an unreasonable risk to public health, welfare or society" (80 Fed. Reg. 64510, 64655 (Oct. 23, 2015)).

Clean Power Plan. The existing coal fleet may also use geologic storage technologies to comply with the Clean Power Plan (CPP) – which remains subject to litigation and a February 9, 2016 stay by the U.S. Supreme Court – although retrofitting CO_2 capture technology to an existing coal-based power plant may be economically and/or physically challenging in some situations. Non-geologic technologies may also be used for CPP compliance on a case-by-case basis provided EPA receives evidence regarding "the ultimate fate of the captured CO_2 and the degree to which the method permanently isolates the captured CO_2 or displaces other CO_2 emissions from the atmosphere" (80 Fed. Reg. 64662, 64884 (Oct. 23, 2015)).

BIOENERGY WITH CCS

Bioenergy with Carbon Capture and Storage (BECCS) has been advanced by IEA and others as having tremendous potential for CO_2 reductions, particularly in the post-2050 time frame.

A typical BECCS scenario might involve, for example, the co-firing of biomass with coal in a coal-based utility, the capture of the resulting CO_2, then the utilization of that CO_2 in a non-emitting utilization application such as geologic storage. Combining bioenergy with CCS has the potential to create net negative CO_2 emissions.

BECCS involves no new CO_2 utilization technologies per se. It nonetheless is important for policymakers to keep in mind the vital role that coal-based power plants can play in the deployment of BECCS technology in the years ahead.

International GHG Mitigation Goals. The United States' 2050 climate goal (80-83 percent GHG reduction by 2050) is broadly consistent with the December 2015 Paris Agreement's goal of "[h]olding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels..." (Paris Agreement, Art. 2.1(a)). The U.S. signed the Paris Agreement on April 22, 2016. The Paris Agreement's goal, in turn, is broadly understood to require effective decarbonization of energy systems by the 2050 timeframe, with CCUS playing a significant role. IEA analysis, for example, shows that CCUS "is an integral part of any lowest-cost mitigation scenario … particularly for 2°C scenarios". In the IEA's 2°C scenario, CCUS "is widely deployed in both power generation and industrial applications" with capture and storage rates growing to "thousands of megatonnes of CO_2 in 2050 in order to address the emissions reduction challenge".

To make meaningful progress towards the 2°C goal, CCUS technologies need to start to be deployed at scale in the relatively near-future given the time required to plan, finance, develop and build major infrastructure. In its 2015 *Fossil Forward* report, the NCC noted that a "review of every major new technology introduced into the power industry since the 1950s shows that commercializing a new technology is both time consuming and costly." The NCC highlighted that despite the success of fluidized bed technology demonstrations in the 1970s, that technology was only now starting to be installed in plants in the 500-600 MW range.

Finally, the recently announced North American Climate, Clean Energy and Environment Partnership Action plan similarly includes "a goal for North America of 50% clean power generation by 2025 ... including … carbon capture and storage technologies…."

CO_2-EOR Represents the Most Immediate, Highest Value Opportunity to Utilize the Greatest Volumes of CO_2. The NCC's conclusion from 2015 remains valid:

> *CO_2 utilization can improve the economics of early adopter plants. However, the magnitude of the amount of CO_2 that must be captured to meet CO_2 emission reduction goals is much greater than the potential economic uses. For the most part, utilization is able to handle millions of tons, leading to perhaps some modest total of billions of tons. Reduction requirements will be in the thousands of billions of tons. Utilization must be considered as a storage option.*

THERMODYNAMICS & KINETICS OF CO_2

The CO_2 molecule is particularly stable and has a Gibbs energy of formation of -394.4 kJ/mol – which must be overcome.

Thus, breaking the C=O bond(s) and forming C-H or C-C bond(s), or producing elemental carbon, is possible. However, such molecules are at a much higher energy state, meaning that a tremendous amount of energy must be used. Converting CO_2 to fuels or other high energy state molecules requires more energy input than could ever be derived from the end products.

CO_2 can also be incorporated into various chemicals as a C_1 building block. This is not thermodynamically challenged because the entirety of the CO_2 molecule is used and thus the C=O bonds are not broken. For this application, the principal challenge is the scale of available reactants and market for products, both of which are dwarfed by global CO_2 emissions.

As reflected in both current U.S. and international carbon management policy, CO_2-EOR remains the most immediate, highest value opportunity to utilize CO_2 at scale and with the promise of some amount of economic return. Other large-scale geologic storage opportunities that are capable of generating economic returns include ROZs and ECBM.

Utilizing CO_2 in non-geologic applications faces a host of hurdles, including: (1) current U.S. policy arguably favors geologic uses; (2) the immature status of nearly all non-geologic CO_2 utilization technologies; (3) logistical and infrastructure issues related to either siting CO_2 utilization facilities in the immediate vicinity of fossil fuel-based power plants and CO_2-emitting industrial facilities or transporting CO_2 from said plants to more centralized CO_2 processing facilities; (4) market limits and impediments – e.g., products derived from CO_2 presumably would be competing against, and endeavoring to displace, comparable products made from other feedstocks; and (5) technical barriers involved in the successful reduction of CO_2 to carbon products, including thermodynamics and kinetics (see Text Box: Thermodynamics & Kinetics of CO_2). More specifically as to the latter, CO_2 is a very stable, almost inert, molecule, with the result that energy generally must be supplied to drive the desired transformation.

This does not mean that further investments in CO_2 utilization technologies should not be undertaken. On a case-by-case basis (at a specific coal-based power plant, for example), for example, deployment of a CO_2 utilization technology may hold promise for turning an uneconomic project into an economic one. A nascent CO_2 utilization technology may emerge that manages to overcome the hurdles identified in this report in ways that the authors could not have anticipated. A broadly deployed mix of CO_2 utilization technologies may also help to advance CCUS even incrementally – and given the hurdles facing the technology, every little bit helps. CO_2 utilization technologies do not need to provide full-scale carbon management solutions – although that would be ideal, of course. They instead only need to provide sufficient incentive to keep CCUS technologies moving forward.

In recent years extensive research has been conducted into the two primary pathways of utilizing CO_2 – the first involving the cleavage of the C=O bond(s) and the second involving the reuse of the intact CO_2 molecule without need to break C=O bond(s). Both hold promise but the latter has advantages over the former as the former requires more input energy and typically results in fuels that are in turn combusted, resulting in the emission of CO_2 to the atmosphere. The latter, in contrast, typically takes less energy and may result in products such as polymers that are highly stable, long-lived and thus capable of “fixing” the CO_2 in a manner akin to geologic storage. This report explores these and related topics.

D. Criteria for Review of CO_2 Utilization Technologies

Key Findings

- There is benefit to establishing a technology review process that is as objective as possible to assess the benefits and challenges of different CO_2 utilization technologies and products.
- Evaluation criteria fall into three broad categories: (1) environmental considerations; (2) technology/product status; and (3) market considerations.
- Relatively simple comparison tools can be used to compare different technologies to identify near-term and long-term opportunities for research and investment.
- Benefits of applying evaluation criteria include: (1) making relative comparisons among technologies; (2) identifying priority technology candidates; (3) creating a more comprehensive ranking of the suite of CO_2 utilization technologies; and (4) enabling revisions to technological assessments as market conditions change.

Key Recommendations

- Evaluation criteria should be used to gather information about and compare various CO_2 utilization technologies.
- Collecting data on evaluation criteria – including environmental considerations, technology/product status, and market considerations – should be undertaken
- Using the evaluation criteria, a technology ranking system which can then be used to prioritize candidates for RD&D and product investment should be developed.

Introduction

There are a number of existing and emerging CO_2 utilization technologies that could be advanced to significantly expand commercial markets for CO_2 from fossil fuel-based power generation and CO_2-emitting industrial facilities. A 2011 report from the Global CCS Institute (GCCSI) estimated current global demand for CO_2 at about 80 million tons per year (MTPY) and suggested potential future demand could grow by an order of magnitude, reaching nearly 300 MTPY for each of a handful of technologies and more modest growth for an additional group of technologies (GCCSI 2011). CO_2-EOR is one of several technologies showing large potential growth in CO_2 demand. This was underscored in a recent IEA CO_2-EOR study suggesting that by 2050, conventional CO_2-EOR could lead to storage of 60,000 MTPY of CO_2 and, through the application of advanced technologies, so-called EOR+, could increase to 240,000 – 360,000 MTPY of CO_2 (IEA 2015).

This report identifies a number of CO_2 utilization technologies and organizes them into geological and non-geological categories. Geological utilization is typically related to energy production and includes: enhanced oil or gas recovery (EOR, EGR); hydrocarbon production from ROZ and shale; ECBM; and enhanced geothermal applications such as earth batteries, heat storage, and EWR. Non-geological utilization is typically related to use of CO_2 as a raw material in products including: beverages and food; inorganic chemicals; building materials; plastics and polymers; organic and specialty chemicals; fuels; fertilizers; and agricultural goods. CO_2 is also used as a solvent in some industrial processes.

To aid policymakers and technology developers in prioritizing R&D and commercial investment decisions in these CO_2 utilization technologies and products, this report suggests that evaluation criteria be developed and used, with the criteria focused on what technologies – from the perspective of the CO_2 source – are most apt to incentivize CCUS. It can be challenging to compare these technology options because they face different growth and economic challenges. For example, some are more mature than others; some require infrastructure while others require additional R&D; and some create large potential demand for CO_2 while others are more modest. The development of a review process that is as objective as possible can help to identify technology strengths and weaknesses, therefore contributing to a more robust technology development and investment strategy.

The benefit of this kind of review process is that it requires full consideration of a number of different aspects of a technology and reveals relative comparisons among technologies. The review can point to the top candidates and can be useful in creating a more comprehensive ranking of the suite of technologies. Further, by articulating strengths and weaknesses, it will be easier to revisit these assessments as market conditions change.

Evaluation Criteria for Assessing CO_2 Utilization Technologies and Products

There are a number of potentially relevant considerations for evaluating CO_2 utilization technologies and products. Important factors for consideration include:

Environmental Considerations

- What is the security, reliability, and longevity of associated CO_2 storage or reductions?
- Are there additional environmental benefits such as multiplier effects?
- What is the net carbon balance of the technology or product? Stated another way, applying GHG LCA, does the technology or product provide demonstrable benefits from the perspective of the fossil fuel-based power plant and/or CO_2-emitting industrial facility?
- What is the impact of the technology or product on the transition to less carbon intensive energy over time?
- How does or would EPA regulate the activity?
- Would the activity enable the CO_2 source to meet, in whole or in part, its CO2 emission reduction obligation?

Technology/Product Status

- How much energy and raw materials are required by the process?
- Is the technology feasible?
- Is the technology at or near commercial status – e.g., DOE's Technology Readiness Level (TRL) evaluation protocol?
- What is the current and future demand for the product?
- How can market demand be enhanced and over what timeframe?
- Are there any special requirements for the CO_2 used in the technology? Can it come from coal-based sources?
- How is the technology and market for products geographically distributed?
- Is there general customer acceptance of the technology process in general, or, more importantly, the product itself (e.g., would polycarbonates from power plant flue gas CO_2 be acceptable for customers in the food/beverage/medical sector)?

Market Considerations

- Is the potential market demand for CO_2 on a scale commensurate with coal-based power plants or other alternative uses of coal? A reasonable threshold for market potential is 35 MTPY, which is roughly equivalent to the annual CO_2 emissions from about 6 GWe or a dozen 500 MWe coal-based power plants.[1]
- Does the potential technology or product – in comparison to other investment operations – maximize economic value for the CO_2 source?
- Is the infrastructure in place to support market expansion? If not, what are the needs?
- What is the necessary structure of deal flow to establish commercial production? Are policies, incentives or other changes needed to support financeable deal structures? What are the potential concerns of buyers, sellers and investors?
- What is the range of necessary CO_2 price/cost for profitability? What are the competing sources of CO_2?
- What is the impact of CO_2 price/cost on demand for the product?
- Are there other market dynamics that should be considered such as competing markets for equal or substitute products?
- Is there an acceptable investment environment to encourage private sources of capital for projects? What are the investment risks, such as liability, loss of equity investment or inability to obtain debt, to obtain a financeable debt/equity balance and are there options for addressing them?
- Is the technology scalable? How can it be modularized or expanded?
- Are there displacement risk considerations?
- What potential market drivers are necessary or helpful such as policy directives or financial incentives? How do policies and incentives affect different market participants?

[1] Note: This calculation uses the estimate from the MIT 2007 study that CO_2 emissions from an average 500 MW coal-based plant are roughly 3 MTPY.

E. CO_2 Utilization Market Review

Key Findings

- Geological CO_2 utilization options have the greatest potential to advance CCUS by creating market demand for anthropogenic CO_2. Non-geological CO_2 utilization options are unlikely to significantly incentivize CCUS in the near- to intermediate-term because of technical, GHG LCA considerations, challenge regarding scalability and related reasons.
- CO_2-EOR – including production and storage activities in residual oil zones (ROZ) – remains the CO_2 utilization technology with the greatest potential to incentivize CCUS.

- Joint industry/government RD&D supportive of "next generation" CO_2-EOR technologies would greatly expand the economically viable market for CO_2 use by the EOR industry. With the benefit of this RD&D, the market for CO_2 (from the EOR industry) would more than double – from 11 billion metric tons with today's technologies to a potential of 24 billion metric tons with "next generation" technology.
- Gaining a more complete understanding of the geological uses of CO_2 for EOR would be greatly enhanced by further evaluations of the domestic ROZ resource and its viability for CO_2-EOR.
- Other geologic utilization markets – including rich-shale formations, enhanced coal bed methane (ECBM) and enhanced water recovery (EWR) – also hold current and future promise as incentives for CCUS.

- Non-geologic utilization opportunities exist, including: (1) inorganic carbonates and bicarbonates; (2) plastics and polymers; (3) organic and specialty chemicals; and (4) agricultural fertilizers. All of these opportunities face a variety of technical and economic challenges that are likely to impede their ability to incentivize CCUS in the immediate future. Unlike transportation fuels, however, they tend to "fix" CO_2 so have the advantage of potentially serving as preferred carbon management solutions.

- CO_2 may also be utilized through chemical and biological processes to produce transportation fuels, which is a very large market. This pathway is also unlikely to incentivize CCUS in the immediate future for a variety of technical and economic reasons, including: (1) the fact that transportation fuels are ultimately combusted and thus release CO_2 to the atmosphere and (2) current U.S. policy favors geologic-based utilization pathways for CAA compliance. And while the case could be made that some CO_2-derived transportation fuels have lower GHG emissions than fossil-based fuels on a GHG LCA basis, non-fossil-based transportation fuels still face significant market competition and displacement hurdles.

Key Recommendations

- Policymakers should continue to focus on advancing geological storage options through support for RD&D and adoption of incentives.
- As part of Mission Innovation, DOE should reinvigorate its RD&D program on advanced ("next generation") CO_2-EOR technologies.
- DOE should sponsor a full evaluation of the technically recoverable and economically viable domestic ROZ resource to more completely understand the market for CO_2 from EOR.
- Additional technical and economic research should be directed towards the following non-geologic utilization products and pathways: (1) inorganic carbonates and bicarbonates; (2) plastics and polymers; (3) organic and specialty chemicals; and (4) agricultural fertilizers.
- GHG LCA of all CO_2 utilization options should be undertaken.

Market Overview

Applying the evaluation criteria in Chapter D to the extent reliable data were available, this chapter provides a comprehensive review of existing CO_2 utilization technology and potential products that could be generated from CO_2. The individual subchapters provide assessments of total potential use of CO_2 in each market and a general assessment of the technology required to create the products as well as the state of development. To the extent possible economic potential is also addressed.

This chapter is divided into two groupings of markets – geologic and non-geologic utilization. Geologic markets include technologies such as EOR, ECBM, CO_2 shale, and less developed options such as storage batteries and EWR (see Figure E-1). Non-geologic markets include chemical products and other value-added schemes that offer higher potential revenue but are limited relative to the size of potential carbon consumption in geological applications.

It should be noted that nearly 50 percent of all CO_2 represented in this market survey is used in food and beverage applications which, as noted below, are a relatively small market compared to geologic volume potentials.

Finally, no attempt has been made to match sources of CO_2 with geographical markets. To the extent possible, this report simply defines and estimates market potentials, much of which is in North America where reasonably reliable data are available.

Figure E-1. CO_2 Utilization Markets

Source: National Energy Technology Laboratory (www.netl.doe.gov)

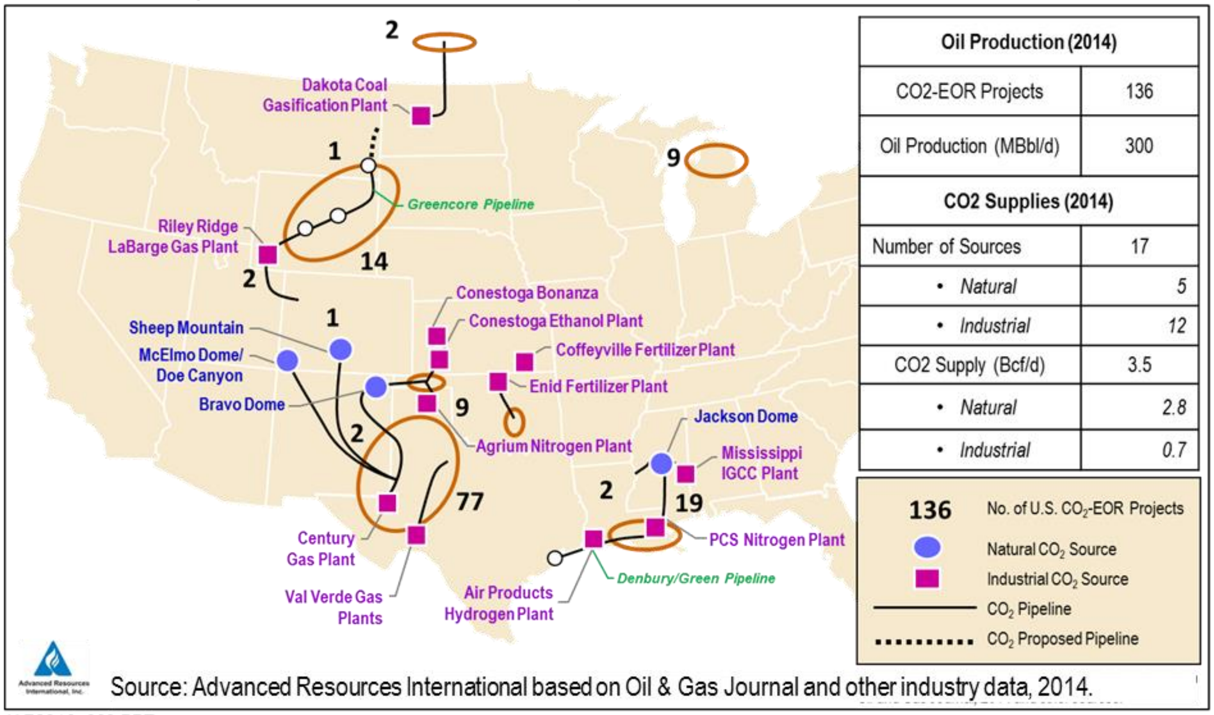
1. Geological Uses of CO_2

1.1. Utilization of CO_2 for Enhanced Oil Recovery (CO_2-EOR)

Background and Status on EOR

Based on the 2014 Oil and Gas Journal Survey, 136 significant CO_2-EOR projects produced 300,000 barrels per day of crude oil by injecting 3.5 Bcfd (67 MMmt per year) of newly sourced CO_2, with 0.7 Bcfd of that total from industrial sources (see Figure E-2). The CO_2 that returns to the surface with the produced oil is captured, processed to remove hydrocarbons and reinjected. Because of the "closed loop" nature of the CO_2 flood, the volume of stored CO_2 in the reservoir is essentially equal to the volume of purchased CO_2. With growth in CO_2-EOR activity in the past two years and including co-production of natural gas liquids, the current CO_2-EOR production estimate today is 400,000 B/D, with increased volumes of CO_2 used by the CO_2-EOR industry being provided by industrial sources.

Figure E-2. Current CO_2-EOR Operations and CO_2 Sources (2014)



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The CO_2-EOR industry is dominated by three major players – Occidental Petroleum, Kinder Morgan and Denbury Resources.[2] These three companies account for nearly 70 percent of current CO_2-EOR liquids (oil and NGLs) production, with numerous companies, large and small, providing the remaining volumes (see Table E-1).

Table E-1. The CO_2-EOR Industry

Company	Number of Projects	CO2-EOR Production (B/D, gross)
Occidental Petroleum	33	120,000
Kinder Morgan	4	80,000
Denbury Resources	25	55,000
Other Companies	74	145,000
Total	**136**	**400,000**

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Source: Advanced Resources International, based on company reports (2016)

[2] See Appendix 1 for additional information on Occidental Petroleum, Kinder Morgan and Denbury Resources.

CO_2 Utilization/Storage and Oil Recovery Potential Offered by CO_2-EOR

The original U.S. oil in-place endowment is estimated by Advanced Resources International (ARI) at 624 billion barrels in several thousand already discovered domestic oil fields. Traditional primary recovery and water flooding have recovered about a third of this original oil in-place, leaving behind a massive oil resource of 414 billion barrels (Figure E-3).

Figure E-3. Original and Remaining Oil Endowment

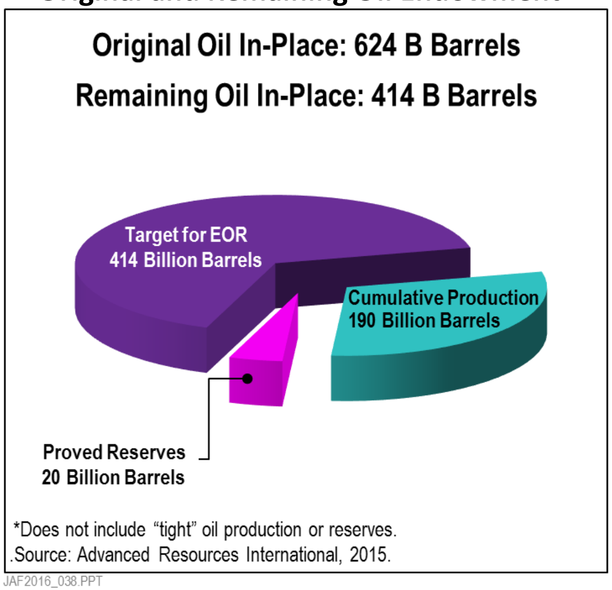
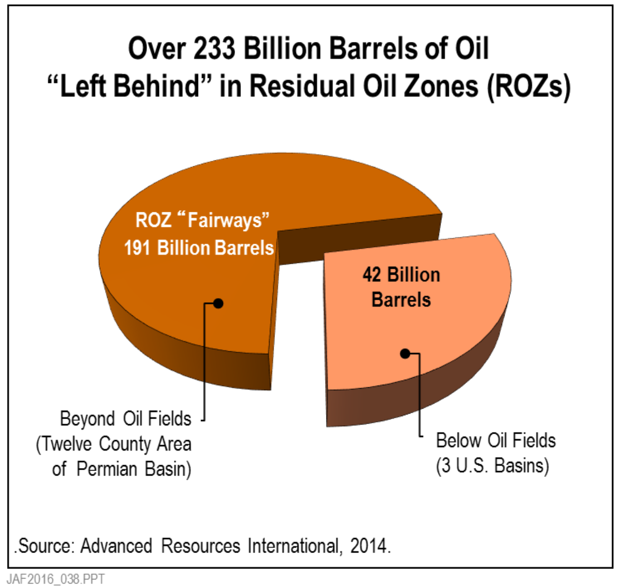


Figure E-4. Residual Oil Zone Resources



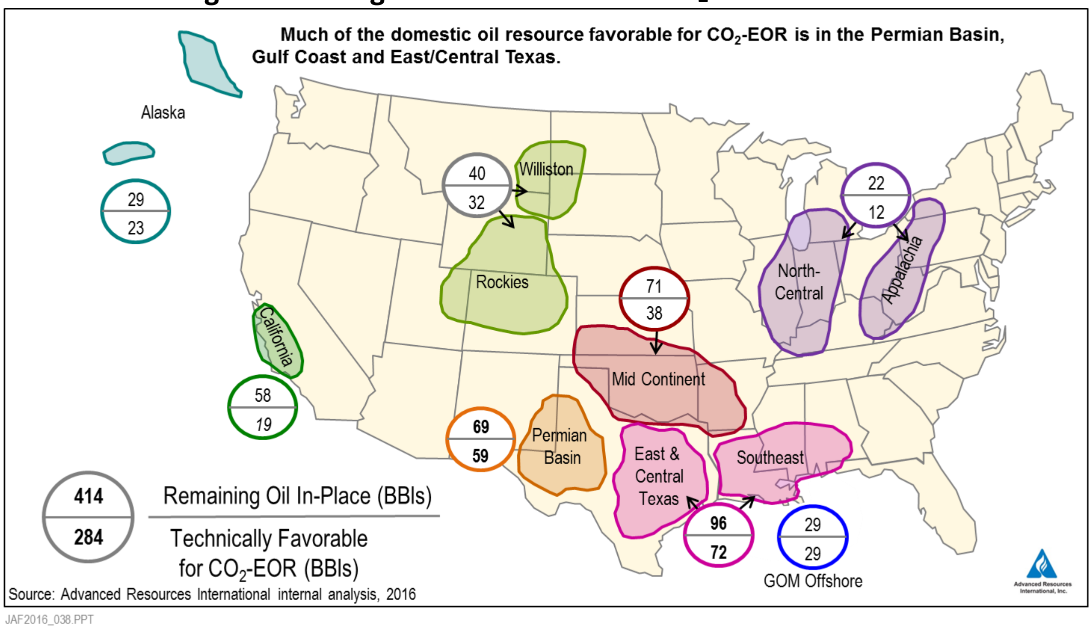
A significant portion of this 414 billion barrels of remaining U.S. oil endowment is technically favorable for application of CO_2-EOR, estimated by ARI at 284 billion barrels. Much of this oil resource is located in the Permian Basin of West Texas and East New Mexico, in various oil basins of East and Central Texas, in the onshore and offshore of the Gulf Coast, in the Mid-Continent and throughout the Rockies. Additional, though smaller resources favorable for CO_2-EOR exist in Alaska, Appalachia, California and Michigan (Figure E-5).

In addition to the remaining oil in-place in the Main Pay Zone of discovered fields, significant additional volumes of oil in-place exist in the ROZs below existing oil fields and in ROZ "fairways" (Figure E-4).

Onshore, Lower 48 CO_2-EOR Potential. Among the many geological options for utilizing and storing CO_2 using EOR, the vast number of already discovered onshore Lower 48 oil reservoirs offers an immediate and immense potential.

A five-part methodology was used to assess the CO_2 utilization/storage and oil recovery opportunities offered by these oil reservoirs: (1) assembling and updating the Major Oil Reservoirs Database; (2) calculating the minimum miscibility pressure for applying CO_2 -EOR; (3) screening reservoirs favorable for either miscible or near-miscible CO_2-EOR; (4) calculating oil recovery from applying "State of Art" (SOA) as well as "Next Generation" CO_2-EOR technology; and (5) using an updated cost and economic model to estimate economically viable CO_2 utilization/storage and oil recovery.

Figure E-5. Regional Distribution of CO_2-EOR Potential



Source: Advanced Resources International internal analysis, 2016.

CO_2-EOR has been underway in onshore, Lower 48 oil reservoirs for over 40 years, with 136 CO_2-EOR projects active (as of end of 2013). Given this extensive history, the assessment of the CO_2 utilization/storage potential for the Lower 48 onshore entailed a field-by-field (reservoir-by-reservoir) assessment, involving 1,374 individual oil reservoirs technically favorable for CO_2-EOR, located in nine distinct regions.

From a technical point of view (without consideration of volatile oil price cycles and economics), initiation of CO_2-EOR into onshore, Lower 48 oil fields technically favorable for CO_2-EOR would create a demand for CO_2 of 22,270 to 33,050 million metric tons (MMmt) and an oil recovery potential of 56 to 106 billion barrels, depending on CO_2-EOR technology. The economically viable portion (using an oil price of $85 per barrel) is less, though still substantial, equal to 8,880 MMmt to 17,330 MMmt of CO_2 demand and 24 to 61 billion barrels of additional oil (depending on CO_2-EOR technology) (Table E-2).[3]

[3] See Appendix 2 for a region-by-region summary of CO_2-EOR potential in the Lower 48 states.

Table E-2. The CO_2 Utilization / Storage and Potential Offered by Lower 48 Onshore Oil Fields

		State of Art (SOA) CO_2-EOR Technology	"Next Generation" CO_2-EOR Technology
Oil Recovery (Billion Barrels)			
	▪ Technical	55.6	105.5
	▪ Economic	24.3	60.7
CO_2 Demand (Million Metric Tons)			
	▪ Technical	22,270	33,050
	▪ Economic	8,880	17,330

Source: Advanced Resources Int'l/DOE/NETL-2011/1504, July 2011.

Offshore CO_2-EOR Potential. The Gulf of Mexico's Federal Offshore (GOM/OCS), an important domestic petroleum province, produces 1.7 million barrels of crude oil per day and accounts for about 20 percent of domestic oil production. So far, only a handful of CO_2-EOR projects have been conducted in the GOM/OCS, mostly in the 1980s in near-shore shallow water oil fields. GOM/OCS offers promise for utilizing CO_2 for EOR in three distinct areas: (1) mature, shallow water oil fields; (2) recently discovered, deep water oil fields; and (3) undiscovered oil fields, primarily in deep and ultra-deep waters.

The most recent evaluation of the CO_2 storage potential from EOR was performed in 2013 by ARI. This study examined 238 offshore oil fields containing 8,228 reservoir (sands) and showed that, from a technical perspective, the GOM/OCS offers potential for utilizing and storing CO_2 – 12,640 MMmt to 15,060 MMmt depending on CO_2-EOR technology (Figure E-6). The volumes of additional oil recovery from use of CO_2-EOR in the Gulf of Mexico oil fields is also substantial, with the technical potential ranging from 23,500 to 52,900 million barrels (Figure E-7). However, conducting CO_2-EOR in the offshore can be costly, requiring the implementation of more complicated CO_2 transmission, injection and recycling capabilities than used onshore. For nearly all coal-based power plants, the lack of a CO_2 pipeline network to get the CO_2 offshore is a non-trivial impediment.

Figure E-6. GOM/OCS CO_2 Storage Potential

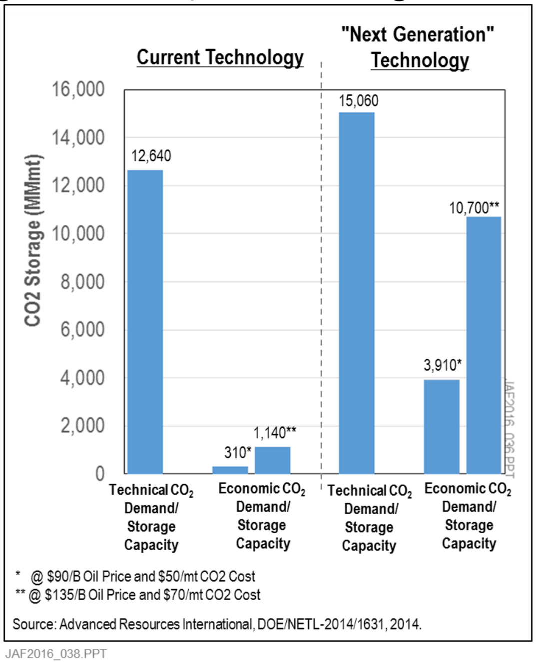
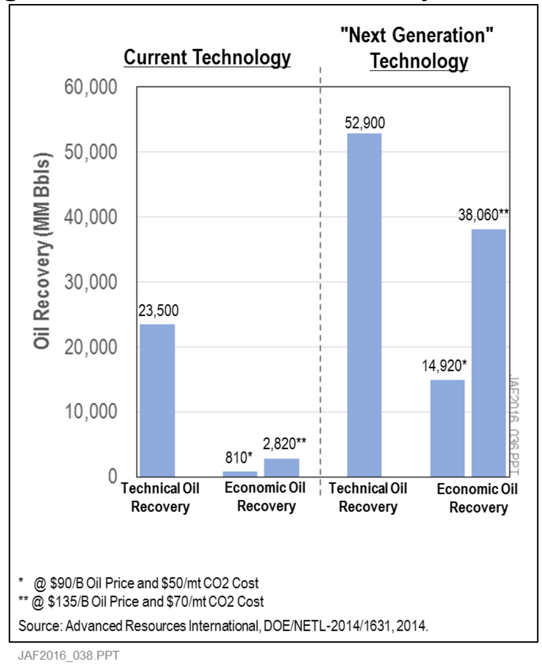


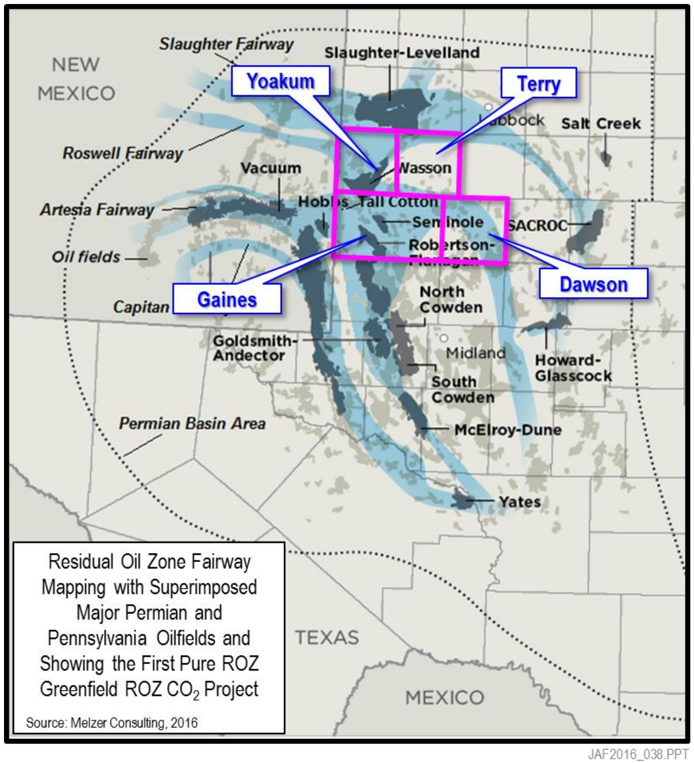
Figure E-7. GOM OCS Oil Recovery Potential



Alaska CO_2-EOR Potential. With its large but mature and rapidly declining oil fields, such as Prudhoe Bay and Kuparuk, Alaska is a high priority candidate for EOR and particularly CO_2-EOR. Alaska's oil production had declined to 0.5 million barrels per day as of mid-2016, with remaining proved crude oil reserves of 2,855 million barrels (end of 2014). While Alaska's oil fields are technically viable for CO_2-EOR (as demonstrated by their miscible gas injection projects), activity is constrained by a lack of CO_2 supplies. For nearly all coal-based power plants, the lack of a CO_2 pipeline network to get the CO_2 to Alaska is a challenge.

The Residual Oil Zone CO_2-EOR Potential. In addition to the large volumes of remaining oil in-place in the Main Pay Zones (MPZs) of Lower 48 onshore, offshore and Alaskan oil fields, recent work has identified similarly large volumes of remaining ("stranded") oil in ROZs. Pioneering work by Melzer, Trentham, Koperna and others, has shown that ROZ resources exist below the structural closure of existing oil fields and in ROZ "fairways" beyond the limits of oil fields (Figure E-8).

Figure E-8. Residual Oil Zone "Fairways" of the Permian Basin



The geologic setting and nature of ROZs is illustrated in Figure E-9, derived from the Wasson (Denver Unit) oil field. Figure E-9A shows the oil saturation of the reservoir at discovery and prior to an industry operated waterflood. The MPZ, defined as the reservoir interval above to base of the producing water-oil contact (OWC), holds high (70 to 80 percent) oil saturation. Below the base of the producing OWC is an extensive interval of much lower oil saturation, resulting from basin uplift and hydrodynamics, called the ROZ. Here natural waterflooding has reduced the oil saturation to 30 to 35 percent. Figure E-9B shows that after industry's waterflood, the oil saturation in the flushed portions of the MPZ has also been reduced to 30 to 35 percent, similar to the oil saturation in the ROZ. As such, both the MPZ and the underlying ROZ are technically attractive geologic settings for utilizing and storing CO_2 with CO_2–EOR while producing additional domestic oil.

Recently completed assessments of ROZ resources by ARI for the Research Partnership to Securing Energy for America and the U.S. DOE/NETL have defined a resource totaling 233 billion barrels of oil-in-place. A major portion of the ROZ oil, 191 billion barrels, is in the San Andres ROZ "fairways" in a 12-county area of the Permian Basin. An additional 42 billion barrels exists below oil fields in three U.S. basins.

Preliminary work performed by ARI for U.S. DOE/NETL on the resource in the ROZ "fairway" of a four-county area of the Permian Basin and below oil fields in three U.S. oil basins, shows that the ROZ offers the potential for significant utilization and storage of CO_2 equal to 25 billion metric tons along with by-product recovery of 42 billion barrels of oil (Table E-3).

Figure E-9. Main Pay and Residual Oil Zone Development: Wasson (Denver Unit) Oil Field

Figure E-9A. Pre-Waterflood

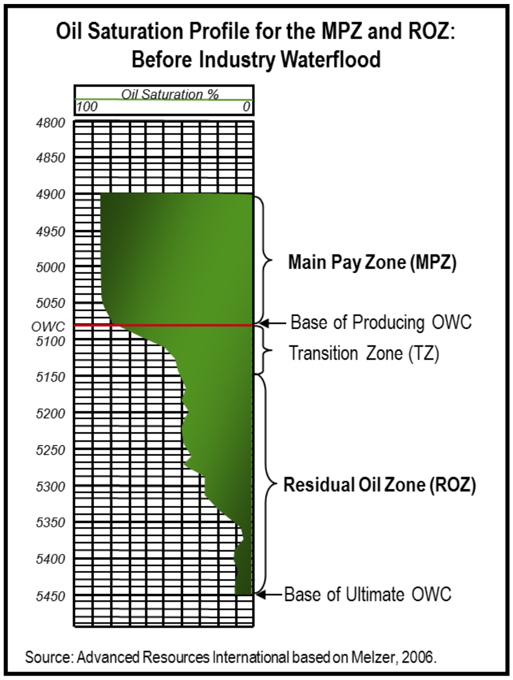


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Figure E-9B. Post Waterflood

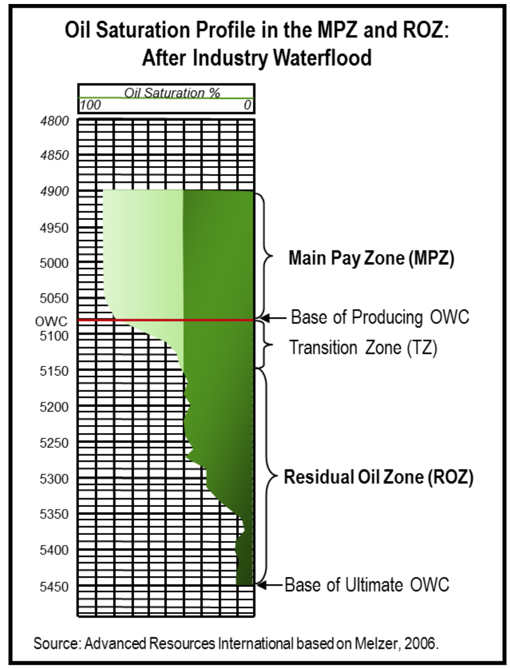

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Table E-3. Currently Assessed ROZ Resources

Basins		Oil In-Place (Billion Barrels)	Technical Potential	
			Oil Recovery (Billion Barrels)	CO_2 Demand (Billion Metric Tons)
Permian Basin				
San Andres ROZ Fairways				
▪	Four Counties	111.9	25.7	17.1
▪	Eight Counties	79.5	n/a	n/a
Other ROZ Fairways		n/a	n/a	n/a
Below Oil Fields		30.7	11.9	6.0
Other Basins (Below Oil Fields Only)				
▪	Big Horn	4.4	1.1	0.6
▪	Williston	6.8	3.3	1.6
Total ROZ Resources		**233.3**	**42.0**	**25.3**

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Source: Kuuskraa, V.A., et al, 2015

Summary of CO_2 Utilization/Storage and Oil Recovery Potential Offered by CO_2-EOR

CO_2-EOR offers major potential for utilizing and storing CO_2 in a diversity of geological settings (Tables E-4 and E-5).

- CO_2 floods in the MPZ of discovered oil fields (onshore L-48, Alaska and Offshore GOM) offer a technical potential for utilizing and storing 38,320 to 52,240 MMmt of CO_2 (depending on CO_2-EOR technology) with significant associated production of crude oil (Table E-4).
- While the economically viable potential from the MPZ (at an oil price of $85 per barrel and with CO_2 costs linked to oil prices) is more limited, the CO_2 utilization and storage volumes are still significant at 10,740 to 23,580 MMmt (depending on CO_2-EOR technology) plus 28 to 81 billion barrels of economically viable oil recovery (Table E-5).
- CO_2 floods in the ROZ resources assessed to date could provide an additional 25,300 MMmt of technically viable CO_2 utilization and storage, and significant volumes of associated oil recovery (Table E-4). Advances in CO_2-EOR technology such as those embedded in the suite of "Next Generation" technologies would enable these ROZ resource to be efficiently recovered.
- Further RD&D is required to establish the economically viable CO_2 utilization and storage potential provided by the ROZ resources, although initial work indicates that these volumes will be substantial.

Table E-4.
Technically Recoverable Domestic Oil and CO_2 Storage Capacity, State of Art and "Next Generation" CO_2-EOR Technology

Basin/Area	Technically Recoverable Oil (Billion Barrels)		Technical CO2 Demand/Storage (Million Metric Tons)	
	SOA	"Next Generation"	SOA	"Next Generation"
1. Main Pay Zone CO2-EOR				
Lower-48 Onshore	55.6	105.5	22,270	33,050
Alaska	5.8	8.8	3,320	4,110
Offshore GOM	23.5	52.9	12,640	15,060
Sub-Total	**84.9**	**167.2**	**38,230**	**52,220**
2. Residual Oil Zone CO2-EOR				
ROZ Fairways*	n/a	25.7	n/a	17,100
Below Oil Fields	n/a	16.3	n/a	8,200
Sub-Total	**n/a**	**42.0**	**n/a**	**25,300**
Total	**84.9**	**209.2**	**38,230**	**77,520**

*Four County Permian Basin San Andres ROZ fairway.

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Source: Advanced Resources Int'l/DOE/NETL-2011/1504, July 2011 and DOE/NETL-2014/1631, 2014

Table E-5. Economically Recoverable Domestic Oil and CO_2 Storage Capacity, State of Art (SOA) and "Next Generation" CO_2-EOR Technology

Basin/Area	Economically Recoverable Oil** (Billion Barrels)		Economic CO_2 Demand/Storage** (Million Metric Tons)	
	SOA	"Next Generation"	SOA**	"Next Generation"
1. Main Pay Zone CO2-EOR				
Lower-48 Onshore	24.3	60.5	8,940	17,340
Alaska	2.6	5.7	1,490	2,330
Offshore GOM	0.8	14.9	310	3,910
Sub-Total	**27.7**	**81.1**	**10,740**	**23,580**
2. Residual Oil Zone CO2-EOR				
ROZ Fairways	n/a	n/a	n/a	n/a
Below Oil Fields	n/a	n/a	n/a	n/a
Sub-Total	**n/a**	**n/a**	**n/a**	**n/a**
Total*	**27.7**	**81.1**	**10,740**	**23,580**

*Includes 2.6 billion barrels already produced or placed into reserves with miscible CO_2-EOR. JAF2016_036.xls

**At an oil price of $85 per barrel and a CO_2 cost of $40 per metric ton with ROR at 20% before tax.

Source: Advanced Resources Int'l/DOE/NETL-2011/1504, July 2011 and DOE/NETL-2014/1631, 2014

Outlook for CO_2 Supplies for CO_2-EOR

The growth of CO_2-EOR has always depended on the availability of secure, affordable sources of CO_2. While currently the majority of CO_2 used by the EOR industry comes from natural sources, such sources are limited and increasingly expensive to develop. As such, significant additional CO_2 supplies, captured from industrial and fossil fuel-based power plant CO_2 emissions, will be needed to accelerate EOR development and to enable CO_2-EOR to realize its full potential.

Natural Sources of CO_2. We estimate that about 27 Tcf (1,400 MMmt) of natural CO_2 proved reserves remain in a series of geologic formations such as McElmo Dome, Bravo Dome, Doe Canyon, St. John's Dome and Jackson Dome. These natural sources of CO_2 currently provide 2.6 Bcfd (50 MMmt per year) of CO_2 to the EOR industry, primarily in the Permian Basin and the Gulf Coast. Experts anticipate that the supply of natural CO_2 for EOR will peak and then plateau at 3.4 Bcfd (65 MMmt/yr) before slowly declining and will be consumed in the next 15 to 20 years (Table E-6).

Table E-6. Status of Three Major Natural CO_2 Resources.

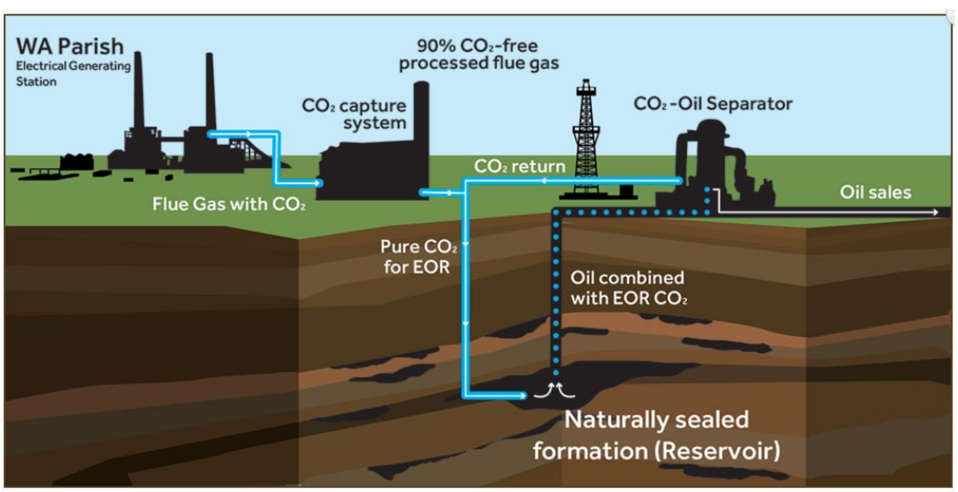
CO_2 Source	Location	Remaining Deliverability	Operator
McElmo Dome	SW Colorado	20+ years	KMI
Doe Canyon	SW Colorado	10+ years	KMI
Bravo Dome	NE New Mexico	10+ years	Oxy

Given an overall technical demand for CO_2 by the EOR industry of 38,320 to 77,540 MMmt and an economic demand of 10,740 to 23,580 MMmt, natural sources will only be able to meet a small portion of total CO_2 demand from CO_2-EOR.

Natural Gas Processing Plants. Capture of by-product CO_2 from the natural gas producing plants sparked the modern era of CO_2 flooding at SACROC and North Cosset. Today, these original natural gas processing plants plus the newly constructed Century Plant provide 200 to 300 MMcfd (4 to 6 MMmt/yr) of CO_2 to Permian Basin CO_2 floods. However, the underlying reserves in these CO_2 containing natural gas fields are limited and will deplete in the next 20 years. The largest source of CO_2 from natural gas processing plants, equal to about 400 MMcfd (8 MMmt/yr), is from the massive complex in western Wyoming – at La Barge and Riley Ridge – supplemented by CO_2 supplies from the Lost Cabin Plant. While the underlying CO_2 (plus methane and helium) reserves in this area are large, the development of additional CO_2 from this area is limited by distance to oil fields, limitations in plant productive capacity, and the size of the Rocky Mountain CO_2-EOR market. Currently, natural gas processing plants provide about 600 to 700 Bcfd (12 to 14 MMmt/yr) of CO_2 and will likely remain at this level for the next 20 years.

Industrial Facilities and Power Plants. The use of CO_2 captured from industrial plants has grown steadily in recent years from facilities such as fertilizer plants in the Mid-Continent and hydrogen and nitrogen plants along the Gulf Coast. Overall utilization of industrial CO_2 emissions by the CO_2-EOR industry is estimated at 200 MMcfd (4 MMmt/yr). In addition, CO_2 captured from two power plants – Mississippi Power's Kemper County IGCC plant and NRG/Petra Nova's WA Parish power plant – will shortly add 230 MMcfd (4 MMmt/yr) of CO_2 supplies to the EOR market (Figure E-10). The sheer magnitude of the capital investments required for these CO_2 projects and uncertainties governing regulations and the physical availability of CO_2 storage sites have contributed to slow progress in this area.

Figure E-10. Schematic Illustration of the Peta Nova WA Parish Carbon Capture System



Source: NRG 2016

Next Generation CO_2-EOR Technologies

As shown by the above estimates of CO_2 demand, utilization and subsequent storage, the impact and viability of CO_2-EOR depend greatly on the status of CO_2-EOR technology, particularly the development and implementation of "next generation" technology. "Next generation" technology encompasses four major themes including: (1) advanced reservoir monitoring and feedback (surveillance); (2) improved reservoir conformance; (3) advanced reservoir characterization; and (4) improved mobility control.

Given the high payoff from advances in CO_2-EOR technology and the still limited R&D dollars devoted to this area, a joint industry/federal research program on the various aspects of "next generation" CO_2-EOR technology would be most productive.

The Economic Benefits Provided by CO_2-EOR

Integration of CO_2-EOR and CO_2 storage would provide significant new revenues to a variety of stakeholders (Table E-7).

Table E-7. Distribution of the Revenue and Benefits of CO_2-EOR

Notes		CO_2-EOR Industry	Private Mineral Owners	Federal/ State Treasuries	Power Plant/Other Capturers of CO_2
1	**Domestic Oil Price ($/B)**	**$70.00**			
2	Less: Royalties	($12.00)	$10.00	$2.00	
3	Production Taxes	($2.90)	($0.50)	$3.40	
4	CO2 Purchase Costs	($14.90)			$14.90
5	CO2 Recycle Costs	($5.20)			
6	O&M/G&A Costs	($14.00)			
7	CAPEX	($6.00)			
	Total Costs	**($55.00)**			-
	Net Cash Margin	**$15.00**			
8	**Income Taxes**	**($5.30)**	**($3.30)**	**$8.60**	**-**
	Net Income ($/B)	**$9.70**	**$6.20**	**$14.00**	**$14.90**

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1 Assumes $70 per barrel of oil (WTI).
2 Royalties are 17%; 1 of 6 barrels produced are from federal and state lands.
3 Production and ad valorem taxes of 5%, from FRS data.
4 CO_2 sales price of $33/tonne, including transport; 0.45 tons of purchased CO_2 per barrel of oil.
5 CO_2 recycle cost of $10/tonne; 0.52 tons of recycled CO_2 per barrel of oil.
6 O&M/G&A costs from ARI CO_2-EOR cost models.
7 CAPEX from ARI CO_2-EOR cost models.
8 Combined Federal and state income taxes of 35%, from FRS data.

Source: Advanced Resources International, 2016

- **Capturers and Transporters of CO_2.** The first revenue stream accrues to the capturers and transporters of CO_2 emissions, helping lower the overall cost of conducting CCUS. In this report, we assume a price for CO_2 of $33/metric ton ($1.75/Mcf), delivered to the oil field at pressure. Using 0.45 metric tons of purchased (net) CO_2 per barrel of recovered oil, this results in a transfer of $14.90 of the $70 per barrel oil price to firms involved with capture and transport of CO_2.

- **State, Local and Federal Treasuries.** A second revenue stream accrues to local and state governments and the Federal Treasury from royalties, severance and ad valorem taxes and corporate income taxes. About $14 of the $70 per barrel oil price is transferred to these entities. For states such as Texas and Wyoming, production taxes provide much of the funding for school systems and other services.

- **The CO_2-EOR Industry.** The third revenue stream of $9.70 of the $70 per barrel oil price accrues as return on investment on the CO_2-EOR project, as well as the recovery of $6 per barrel of capital investment in the CO_2-EOR project.

- **Other Beneficiaries.** Finally, the general economy gains $19.20 of the $70 per barrel oil price from purchase of equipment and services and payment of salaries, with private mineral owners realizing the remaining $6.20 of the $70 per barrel oil price.

With a potential for 81 billion barrels of economically viable oil recovery from mature oil fields and the residual oil zone (assuming the use of "Next Generation" technology), the various CO_2-EOR stakeholders would gain valuable revenue and economic benefits as set forth below:

Recipients of CO_2-EOR Revenues*	Revenues
• CO_2 Capture and Transporters	$1,210 billion
• State, Local and Federal Treasuries	$1,130 billion
• CO_2-EOR Investors (including Return on Capital)	$1,270 billion
• General Economy/Mineral Owners	$2,060 billion
Total	**$5,670 billion**

***Assuming an oil price of $70/B.**

1.2. Utilization of CO_2 in Organically Rich Shale Formations

Background

In recent years, the largest booms in oil and gas development have been in unconventional tight formations (<10 mD), such as the Bakken, Eagle Ford and Marcellus, where fluid flow is dominated by natural and artificially induced fractures. The tight oil resources in the United States are massive, with several hundreds of billions of barrels of oil in place in the Bakken petroleum system (herein referred to as simply "the Bakken") alone (Energy Information Administration (EIA), 2013). The Eagle Ford resource appears to be of comparable magnitude, and emerging tight oil plays such as the Niobrara and Tuscaloosa further underscore the growing importance of unconventional oil production in America's energy portfolio.

Given their size and broad geographic distribution (Figure E-11), tight oil formations and shale gas plays may be great opportunities to simultaneously store large amounts of CO_2 while increasing the recoverable reserves of oil and natural gas by injecting CO_2. Current methodologies for estimating the potential for CO_2-EOR, EGR and CO_2 storage capacity in those tight, organic-rich reservoirs are based on knowledge gained over the last 40 years from commercial CO_2-EOR operations in moderate- to high-permeability conventional reservoirs (Jarrell and others, 2002; U.S. Department of Energy, 2008, 2010, 2012; IEA Greenhouse Gas R&D Programme, 2009).

However, there is a lack of field-based understanding as to the storage capacity, EOR and EGR potential, and sweep/storage efficiency in unconventional tight oil and gas formations, which has thus far precluded them as primary targets for EOR, EGR or storage. The widespread exploitation of tight oil and gas resources is a relatively recent development (within the last 8 to 10 years); thus the current level of knowledge of mechanisms and factors affecting incremental oil and gas production from and injection of CO_2 into tight formations is relatively low when compared to knowledge of conventional reservoirs (over 40 years of history).

Potential for CO_2 Storage and EGR in Organic-Rich Shales

The use of CO_2 for EGR has been demonstrated in laboratory- and field-based studies (Nutall and others, 2006; Godec and others, 2013a). Those efforts have demonstrated that organic materials such as black shale and coal have greater sorption affinity for CO_2 than methane. Upon injection of CO_2, shale absorbs the injected CO_2 and releases methane, which, in turn, results in increased methane production and a potentially significant amount of CO_2 storage (Uzoh and others, 2010).

Figure E-11. U.S. Regions with Potential to Produce Oil and Gas from Shales and Other Unconventionally Tight Rock Formations

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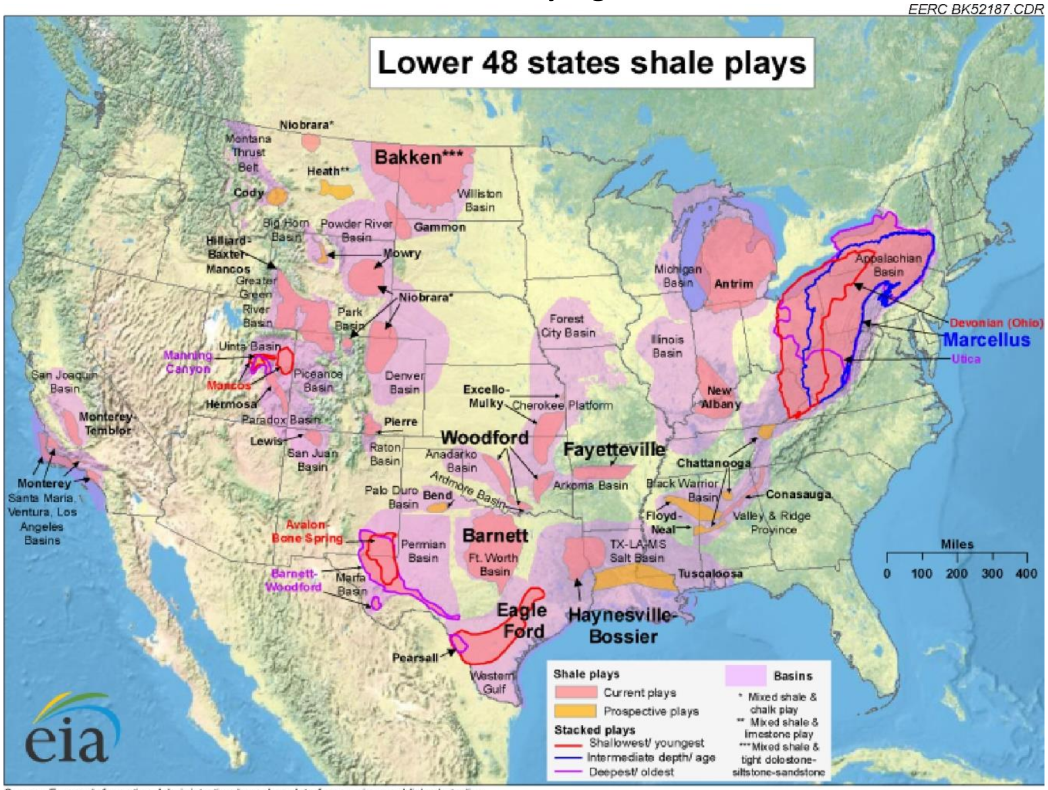


Source: Energy Information Administration based on data from various published studies.
Updated: May 9, 2011

Source: Energy Information Administration, 2011

Some work has been published on the potential storage capacity of tight, natural gas-rich shale formations, including studies on gas shales in Kentucky (Nutall and others, 2005), Texas (Uzoh and others, 2010) and the Appalachian region (Godec and others, 2013b). The authors of those studies assumed that the CO_2 storage, and subsequent methane recovery, in organic-rich gas shales will be controlled by adsorption and desorption mechanisms similar to CO_2 storage and methane recovery in coal seams. In those cases, the sorptive capacity of the organic content in the shales plays a prominent role in estimating their potential CO_2 storage capacity.

Nutall and others (2005) used drill cuttings and sidewall core samples of the Ohio Shale and New Albany Shale formations in Kentucky to conduct laboratory-based determinations of the CO_2 adsorption capacity of those natural gas-rich shales. The results of those determinations were then applied to develop initial volumetric estimates of the CO_2 storage capacity of the Devonian Shales in Kentucky, which indicate a CO_2 storage capacity of as much as 28 billion tons (Nutall and others, 2005). Godec and others (2013b) used previously published CO_2 sorption/methane desorption data coupled with geologic characterization and modeling efforts to develop estimates of the potential for CO_2 storage and EGR in the Marcellus Shale. That work estimated that the entire Marcellus Shale play in New York, Pennsylvania, Ohio and West Virginia could store up to 55 billion tons of CO_2 while producing 423 trillion cubic feet of incremental methane.

Potential for CO_2 Storage and EOR in Tight Oil Formations

Recent laboratory- and modeling-based investigations (Hawthorne and others, 2013, 2014; Sorensen and others, 2014) have examined the viability of injecting CO_2 into the Bakken for simultaneous CO_2 storage and EOR. The results of that work suggest that: (1) CO_2 has the ability to mobilize significant amounts of oil from Bakken shale and Middle Bakken reservoir rocks; (2) diffusion of CO_2 appears to be an important mechanism for moving oil from the reservoir matrix into the fracture network; and (3) the oil production response of a Bakken reservoir to CO_2 injection may be delayed, but the increase in oil production rates could be as high as 50 percent (Kurtoglu and others, 2013; Hawthorne and others, 2013; Liu and others, 2014; Sorensen and others, 2014).

Sorensen and others (2012) developed a first-order, reconnaissance-level estimate of the potential CO_2 storage capacity of the Bakken Formation in North Dakota. The approach that has been taken in previous evaluations of potential storage in organic-rich shales has been to assume that the CO_2 storage, and subsequent methane recovery, in organic-rich gas shales will be controlled by essentially the same adsorption and desorption mechanisms as CO_2 storage and methane recovery in coal seams. In those cases, the sorptive capacity of the organic content in the shales is assumed to play a significant role in determining the CO_2 storage capacity of those shales. Unfortunately, those approaches have limited applicability to tight oil formations such as the Bakken, since substantial portions of those formations are not organic-rich shale but, rather, oil- and brine-saturated tight (low porosity/ permeability) carbonates, siltstones and sandstones. This is true for other tight oil formations such as the Eagle Ford and Niobrara, which also have relatively complex lithofacies as compared to gas-producing organic-rich shales. With these characteristics in mind, published methods to estimate the storage capacity of oil reservoirs may be more applicable to estimating the potential CO_2 storage capacity of the Bakken.

To develop first-order CO_2 storage capacity estimates for the Bakken in North Dakota, an approach was used that estimates the amount of CO_2 needed for EOR in the Bakken. Specifically, the methodologies for estimating CO_2 storage capacity in oil formations based on production and volumetrics as presented in the *Carbon Sequestration Atlas of the United States and Canada* (U.S. Department of Energy, 2007) were applied to the Bakken Formation in North Dakota. In both of these approaches, it is assumed that the stored amount of CO_2 would be equal to the purchased quantity. Through the EOR process, the gross mass (volume) would be greater. The results of these CO_2 storage capacity estimation efforts are presented in Table E-8.

Table E-8. Estimated CO_2 Storage Capacity Results for the Bakken in North Dakota

Scenario	North Dakota OOIP,[1] stb[2]	Incremental Recovery Factor	Net Utilization Factor, ft^3/bbl	Mass of CO_2 Storage, tons
1	170,000,000,000	0.04	8000	3,155,200,000
2	170,000,000,000	0.04	5000	1,972,000,000
3	10,500,000,000	0.04	8000	194,880,000
4	10,500,000,000	0.04	5000	121,800,000
	ND Cum. Production	**Recovery Factor**	**Rounded OOIP**	
3 and 4	732,000,000	0.07	10,500,000,000	

[1] Original oil in place. [2] Stock tank barrel.

The first method, referred to as the volumetrics method, is largely based on estimating the original oil in place (OOIP) of the Bakken according to known reservoir properties (U.S. Department of Energy, 2007). The storage efficiency factor (Eoil/gas) is derived from local CO_2-EOR experience or reservoir simulation as standard volume of CO_2 per volume of OOIP. Using OOIP data from Nordeng and others (2010) for North Dakota, an estimate of a 4 percent increase in oil recovery (4 percent of OOIP) and two utilization factors, the mass of CO_2 needed for a Bakken EOR effort (i.e., the potential CO_2 storage capacity of the Bakken in North Dakota) ranges from 1.9 to 3.2 billion tons.

A second approach, generally applied to mature oil fields or those for which key reservoir property data are unavailable, to determine OOIP is to use cumulative production divided by a recovery factor (e.g., 36 percent). In the case of the Bakken in North Dakota, a recovery factor of 7 percent was used along with a cumulative production of 732 billion barrels. This approach results in a predicted OOIP of 10.5 billion barrels and a corresponding CO_2 storage capacity for the Bakken ranging from 121 to 194 million tons.

The estimates using the reservoir property-based OOIP approach are likely too high because the U.S. Department of Energy method was developed based on knowledge derived from decades of studies and experience related to CO_2 injection, utilization and storage in conventional oil reservoirs. While the OOIP of the Bakken is known to be high (LeFever and Helms, 2008; Continental Resources Inc., 2012), the extremely tight nature of the formation may adversely affect injectivity and storage efficiency and thus reduce the storage capacity estimates. It is possible that the negative impact of the tight porosity and permeability may be at least somewhat positively offset by the potential adsorption of CO_2 into the high-organic-content shales of the Bakken. However, the extent of that impact is unknown because of the lack of field-scale data on CO_2 behavior in tight oil formations, which is why two utilization factors (5 mcf/bbl and 8 mcf/bbl) were used in the estimation exercise.

Alternatively, the estimates using the cumulative production approach are likely too low. Having just started in the mid-2000s, the Bakken play in North Dakota is still in its early stages of development, and the effects on CO_2 storage estimation are twofold. First, the North Dakota

Department of Mineral Resources has estimated that Bakken production will likely continue for at least another 20 to 30 years. This means that the cumulative production numbers used in this CO_2 storage capacity exercise are likely only a small fraction of what the ultimate cumulative production of oil from the Bakken will be, and therefore the capacity estimates likely represent too small a fraction of the CO_2 storage resource. Also, because the play is in the early stages, there are only a few wells for which long-term decline curve data are available.

The lack of such decline curve data means that operators and regulators are still in the process of determining the typical estimated ultimate recovery (EUR) of a Bakken well. Reported Bakken EUR values have been rising over the past few years, which again would strongly suggest that the CO_2 storage capacity estimates based on current cumulative production are too low. Since the high end of the estimated storage capacity range may be too high and the low end is likely too low, it is clear that more data from laboratory- and field-based research efforts are required to develop improved CO_2 storage capacity estimates for tight oil formations. Future evaluations of CO_2 storage potential in tight oil formations like the Bakken may consider using a hybrid method that combines some elements of the shale gas capacity methods with elements of the oilfield methods.

Conclusions on CO_2 Utilization in Shale Formation

The results of the research activities described above suggest that CO_2 may be effective in enhancing the productivity of oil and gas from organic-rich gas-producing shales such as the Marcellus Shale and tight oil formations such as the Bakken Formation. Those rock formations, and others like them, may also hold the ability to geologically store significant amounts of CO_2.

However, there are no clear-cut answers regarding the most effective approach for injecting CO_2 into unconventional rocks for storage or enhanced resource recovery. The results underscore the notion that an unconventional resource will likely require unconventional methods of both assessment and implementation when it comes to the injection of CO_2 and recovery of incremental oil and/or gas.

With that in mind, it is clear that additional knowledge is necessary to make informed decisions regarding the design and implementation of potential injection and production schemes. In particular, a better understanding of the fundamental mechanisms controlling the interactions between CO_2, oil and other reservoir fluids in these unique formations is necessary to develop accurate assessments of potential CO_2 storage. Improvements in modeling and simulation software packages to incorporate the unique properties of these tight, unconventional reservoirs in terms of their impact on CO_2 behavior are also needed. These knowledge gaps can be filled by conducting scaled-up laboratory activities integrated with improved modeling and simulation techniques, the results of which will provide a robust foundation for pilot-scale field injection tests. Finally, field-based data on injection, fluid production and long-term monitoring from pilot-scale CO_2 injection tests in the Bakken are necessary to verify and validate the findings of the laboratory- and modeling-based research efforts.

1.3. Enhanced Coal Bed Methane

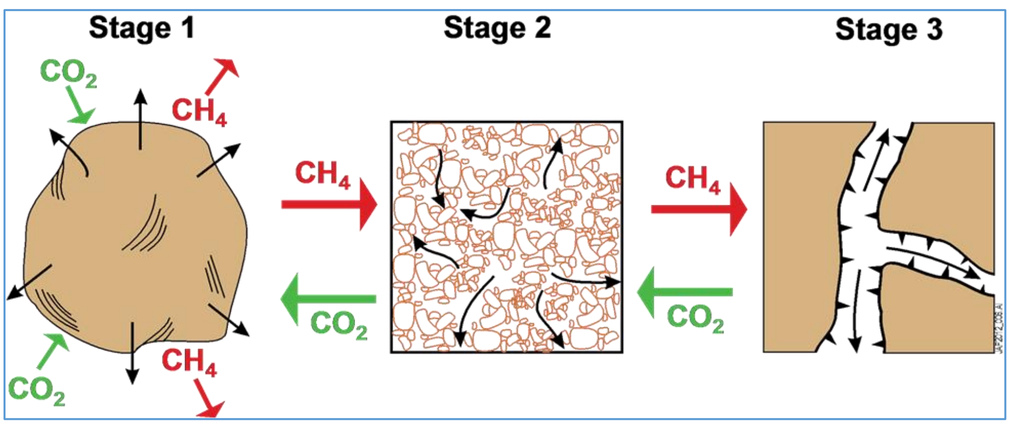
Introduction

In the early 1990s, Puri and Lee and MacDonald, separately, proposed the concept of ECBM recovery involving injection of nitrogen (N_2) and/or CO_2 to increase recovery of methane without excessively lowering reservoir pressure. The concept of ECBM using CO_2 predates this; in 1972, Every and Dell'osso found that methane was effectively removed from crushed coal by flowing a stream of CO_2 through it at ambient temperature.

ECBM has several significant effects on reducing GHG emissions. First, injected CO_2 can be sequestered. Second, the recovered methane can be used as a fuel that could supplement coal and oil, with far lower CO_2 emissions when combusted. Third, methane has a greater global warming potential than CO_2, although it has a shorter life span in the atmosphere. Coal mining releases coal bed methane emissions to the atmosphere.

The traditional process of ECBM and storage of CO_2 in coal seams involves capturing CO_2 from a flue gas stream, compressing it for transport to an injection site, followed by injection of CO_2 into the coal to enhance methane recovery and/or store CO_2. Methane desorbs from the micro-pores of the coal matrix when the hydrostatic pressure is reduced, such as from the drilling of a well, and flows through the cleats to a well bore. The main methods which can induce methane release from coal formations are to reduce the overall pressure, usually by dewatering the formation, generally through pumping; or to reduce the partial pressure of the methane by injecting another inert gas into the formation, such as CO_2, where the methane on the surface gets displaced by the other gas (Figure E-12).

Figure E-12. Schematic of the Flow Dynamics of CO_2 and CH_4 in Coal Seams



When injected, CO_2 moves through the coal seam along its natural fractures (the cleat system), and from there diffuses to the coal micro-pores where it is preferentially adsorbed. In coal, CO_2 has a higher affinity to become adsorbed onto the reservoir rock surfaces than methane that is naturally found within them. Upon injection, the CO_2 displaces methane from some of the adsorption sites. The ratio of CO_2 to methane varies from basin to basin, but has been linked to the maturity of the organic matter in the coal.

As much as another 20 percent of the original gas in place in the coal seam could potentially be recovered through the application of CO_2-ECBM. In addition, the fact that some coalbed methane (CBM) is high in CO_2 content shows that, at least in some instances, CO_2 can safely remain stored in coal for geologically significant time periods.

Thus, coal deposits have long been regarded as a potential CO_2 storage option, particularly in association with ECBM production. In 1998, the IEA Greenhouse Gas R&D Programme (IEAGHG) assessed the global potential for CO_2-ECBM based on data from the one successful pilot project at the time in the San Juan Basin in the USA. At that time, it was concluded that there was significant geological storage capacity globally in unmineable coal seams.

Summary of Lessons Learned from R&D to Date

Research to date demonstrates that there may be cases where CO_2-ECBM can be technically and economically successful. However, none of the demonstration projects conduced to date were commercially profitable; thus, the potential commercial viability of large scale CO_2-ECBM has yet to be demonstrated. Nonetheless, review of efforts to date highlight key lessons applicable to CO_2-ECBM and CO_2 storage in coal beds, specifically:

- With a depleted reservoir due to previous gas production operations, initial injection rates can be quite robust.
- Injection rates will decline due to re-pressurization and swelling of the coal reservoir.
- The presence of hydraulic fractures may complicate operations.
- N_2 (as a tracer) may be a strong indicator of pending breakthrough. That is, if N_2 is injected with CO_2, it tends to travel through the coal seam more quickly than CO_2, thereby serving as a useful monitoring tool for ensuring effective CO_2 storage.

In cases where the rank and permeability are not adequate for enhanced recovery and storage operations, there may be opportunities for pulsing and/or mixing N_2 into the injection stream to improve injectivity during storage and enhanced recovery operations. Moreover, while the executed field tests to date do provide some insights into the long-term viability of enhanced recovery and storage in shales and coal seams, it is clear that there is much more to learn.

Technical Potential for CO_2 Storage and Enhanced Gas Recovery in Coals

A comprehensive study sponsored by the IEAGHG, reassessed the status of research and development in CO_2-ECBM and CO_2 storage. In this assessment, the primary objectives were to: (1) assess the global status of CBM production and the potential effects on CO_2 storage; (2) review the current status of research into ECBM and geological storage of CO_2 in coals; and (3) develop an updated assessment of the global potential for ECBM and geological storage of CO_2 in coal formations.

The estimates for primary CBM and ECBM potential, along with the associated potential CO_2 storage capacity in unmineable coal seams, are summarized by country in Table E-9. As shown, it is estimated that 79 trillion cubic meters (Tcm) (2,790 trillion cubic feet (Tcf)) CBM are potentially recoverable globally, 29 Tcm (1,024 Tcf) from conventional CBM, and 50 Tcm (1,766 Tcf) from the application of ECBM. This would facilitate the potential storage of nearly 488 billion tons, or gigatons (Gt) of CO_2. While the volumes potentially recovered and stored using N_2 injection with CO_2 would be different than those quoted here, that option was not assessed in this study.

Getting to Commercial ECBM

Creating commercially viable ECBM production will require creating “win-win” opportunities for CCUS with ECBM, most likely involving the matching of areas amenable to ECBM with areas of high levels of CO_2 emissions. To achieve this, the following factors, in relative importance, need to be met:

- The availability of existing infrastructure, most likely associated with CBM production, to be utilized to allow cost-effective ECBM.
- Proximity to existing CO_2 emissions sources.
- Willingness, need and/or ability of existing producers to pursue an ECBM pilot.
- Characteristics for viable ECBM, including areas amenable to CO_2 mixed with N_2 (nitrogen) for ECBM.

CO_2 injection is critical for coal bed methane recovery. However, N_2 reduces coal swelling caused by CO_2 injection. Coal swelling is a limiting factor for both ECBM recovery and for the space to store volumes of injected CO_2.

Where the rank and permeability of a coal seam are not adequate for commercial ECBM production using CO_2 alone, there appear to be opportunities for mixing N_2 into the injection stream to improve injectivity and gas recovery from ECBM. Allowing N_2 in the injection stream can also serve to improve CO_2 capture economics, thereby making profitable ECBM CCUS projects possible based on capital and operating costs as well as recovered methane revenue.

Specifically, for a given coalfield, the range of optimum gas mixtures would depend upon whether CO_2 storage or methane recovery was the primary objective, operational constrains (e.g., the degree of N_2 impurity that could be tolerated in the gas stream) and the economics associated with gas treatment (e.g., enriching flue gas with CO_2 would incur additional costs). Finally, the acceptable level of N_2 purity in the produced gas stream to a large extent is dictated by how the produced gas will be utilized (e.g., sold for pipeline transport or used on site, where use of a lower quality gas stream may be acceptable). The costs associated with this will be very site specific, as will be the revenues, since the gas prices paid for methane production associated with ECBM depend on how prices are determined at a specific site.

Next Steps for ECBM

Even though a substantial amount of research has been conducted regarding ECBM and the geological storage of CO_2 in coals, key knowledge gaps and technical barriers remain. These include:

- A lack of critical formation-specific information on the available storage capacity in coal seams in all but a few, targeted settings.
- A lack of geological and reservoir data for defining the favorable settings for injecting and storing CO_2 in coals; this is also true for assessing methane production potential.
- Understanding the nearer- and longer-term interactions between CO_2/N_2 and coals, particularly the mechanisms of swelling in the presence of CO_2 and N_2, shrinkage with release of methane and the physics of CO_2/N_2/methane exchange under reservoir conditions.
- Developing integrated, cost-effective strategies for ECBM and CO_2 storage in coals.

Finally, much about the mechanisms and potential for ECBM and storing CO_2 in coal seams remain unknown. At field scale, only a few projects of any appreciable scale have been performed. Thus, additional future research is essential. Nonetheless, a new CO_2/N_2 ECBM CCUS project is starting in western China which is expected to provide key information for the future of ECBM.

Table E-9. CO_2 Storage and Methane Production Potential of the World's Coal Basins

	Estimated Methane Recovery (Tcm)			CO_2 Storage	CO_2 Storage
COUNTRY	**PRIMARY**	**ECBM**	**TOTAL**	**Tcm**	**Gt**
UNITED STATES	4.82	7.54	12.4	52.82	86.16
CANADA	5.21	4.35	9.6	17.85	29.11
MEXICO	0.04	0.09	0.1	0.34	0.55
Total North America	**10.06**	**11.99**	**22.1**	**71.01**	**115.82**
BRAZIL	0.15	0.00	0.2	0.57	0.93
COLOMBIA	0.10	0.22	0.3	1.29	2.11
VENEZUALA	0.07	0.30	0.4	3.57	5.83
Total S. & Cent. America	**0.32**	**0.52**	**0.85**	**5.44**	**8.87**
CZECH REPUBLIC	0.06	0.00	0.1	0.00	0.00
GERMANY	0.45	0.00	0.5	0.62	1.01
HUNGARY	0.02	0.04	0.1	0.10	0.17
KAZAKHSTAN	0.28	0.00	0.3	0.50	0.82
POLAND	0.14	0.94	1.1	4.07	6.63
RUSSIAN FEDERATION	5.66	12.61	18.3	35.20	57.41
TURKEY	0.28	0.00	0.3	0.58	0.94
UKRAINE	0.71	1.72	2.4	4.54	7.41
UNITED KINGDOM	0.43	1.03	1.5	2.73	4.46
Total Europe & Eurasia	**8.04**	**16.35**	**24.39**	**48.34**	**78.84**
				0.00	0.00
Botswana	0.45	1.06	1.5	9.18	14.97
Mozambique	0.37	0.89	1.3	1.84	3.01
Namibia	0.44	1.05	1.5	2.18	3.56
South Africa	0.25	0.61	0.9	1.26	2.05
Zimbabwe	0.25	0.61	0.9	3.44	5.62
Total Middle East & Africa	**1.77**	**4.22**	**5.99**	**17.90**	**29.20**
AUSTRALIA	0.95	0.67	1.62	9.01	14.70
CHINA	5.52	7.13	12.64	47.83	78.01
INDIA	0.57	0.63	1.2	4.04	6.60
INDONESIA	1.93	8.05	9.97	95.40	155.60
Total Asia Pacific	8.96	16.47	25.43	156.28	254.91
Total World	29.15	49.55	78.7	298.97	487.64

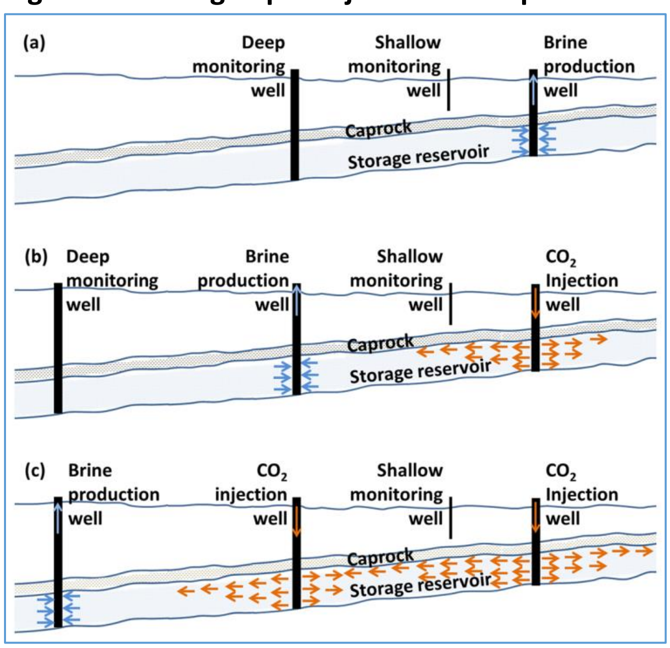
1.4. Additional Geologic Opportunities

Enhanced Water Recovery

EWR can generally be classified as a CO_2 utilization option, although in reality the technology should be considered a necessary development activity prior to CCUS being fully commercially deployable. In fact, some researchers have suggested that in specific compartmentalized storage formations, it may be necessary for the volume of brine to be removed to be the same as the volume of CO_2 to be injected (Buscheck et al., 2016a). For example, if 750 million tons of CO_2 were stored in a particular aquifer over 50 years, it was estimated that 1 km^3 of saline fluid must leave that formation either through production or naturally as a consequence of subsurface migration (Surdam et al., 2013). DOE is currently investigating this further under its Brine Extraction Storage Test Program.

When CO_2 is injected into a confined saline aquifer for permanent storage, the pressure of that aquifer will increase. The increased pressure may be associated with several undesirable affects, including fracturing of the formation and/or seals, induced seismicity and kilometer-scale pressure fronts that would require additional monitoring. One proposed method to manage increased formation pressure is through brine production and treatment (Figure E-13). In some CCUS projects it may even be advantageous or even necessary to produce brine prior to CO_2 injection (Buscheck et al., 2016a; 2016b). Reservoir pressure management through brine production has other benefits, such as allowing for control and steering of the CO_2 plume and therefore greatly reducing the environmental footprint of the project.

Figure E-13. Staged pre-injection brine production



As shown: (a) Pre-injection brine production reduces pressure, making room for CO_2 storage. (b) The brine-production well in (a) is repurposed for CO_2 injection and the deep monitoring well is repurposed for brine production. (c) The brine-production well in (b) is repurposed for CO_2 injection and brine production is moved to a third deep well (Source: Buscheck et al. 2016a).

Around the world, there is also a considerable need for new sources of fresh water and EWR may be a viable option. China has expressed particular interest in CCUS paired with EWR. The water in potential CO_2 storage reservoirs is not fresh water and would need to be treated for most uses. Commercial technologies exist to treat this brine, including reverse osmosis (RO), although depending on the quality of the produced brine, additional treatment steps, such as nanofiltration, may also be required. One beneficial characteristic of the produced brine is that it can be brought to the surface at higher pressure, which reduces the energy costs associated with RO.

While costs for brine water treatment will be highly site specific, some researchers have projected that the cost benefit of treated water could be in the range of $450 to $650 per acre-ft, while some agricultural users on the Colorado River drainage currently pay more than $700 per acre-ft, so in some places the water production could be self-supporting (Surdam et al., 2013). In addition to potable water, water-treatment trains produce a stream of concentrated brine. The concentrated stream may contain additional products of value (i.e., extractable salts and metals). After all products of value have been removed, the remaining highly concentrated brine could be reinjected into its original or another geological formation for disposal.

Recognizing that storing CO_2 and producing usable water could offer a major opportunity, the DOE announced the selection of two projects that will assess the feasibility of producing usable water from brine produced from CO_2 storage sites (DOE, 2016).

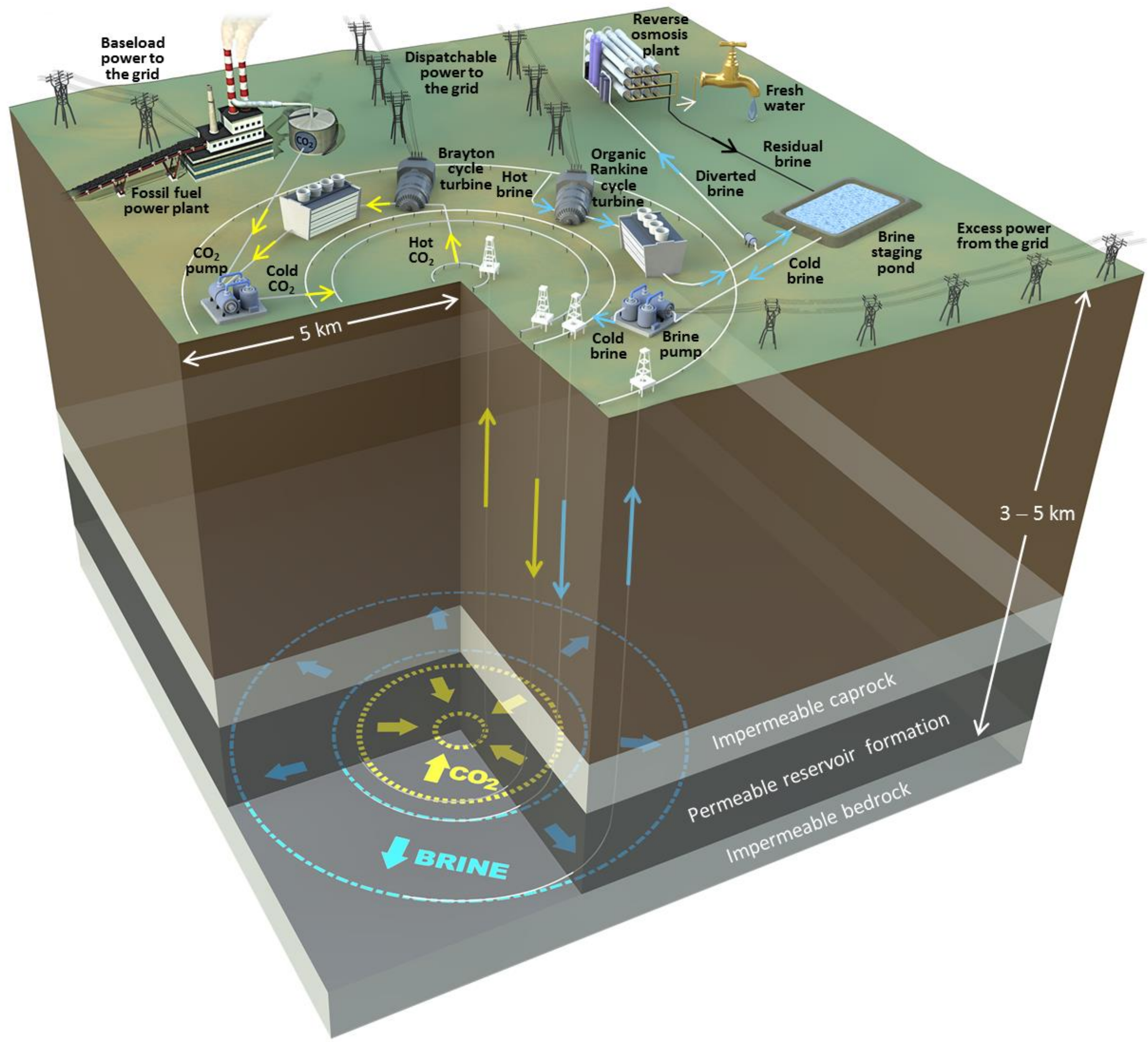
In addition to the prospect of producing new water resources, the saline fluid produced from various sites may contain useful chemicals, although this is an emerging area that is likely site specific and largely uncharacterized currently. One example of a potential production opportunity was highlighted by University of Wyoming researchers when they discovered elevated concentrations of lithium dissolved in the saline waters near Rock Springs, WY, during a CO_2 storage project funded by the DOE (University of Wyoming, 2013). Lithium, a key component of lithium-ion batteries, is a material in which the U.S. is highly dependent on imports.

While brine production and the purification technologies are largely commercially available, CO_2 storage reservoir and plume control management – which are likely necessary for the widespread deployment of CCUS – have not been demonstrated at scale. For early mover CCUS projects that store CO_2 in saline aquifers, before CO_2 injection commences brine production may be an important component in an overall risk mitigation strategy (Buscheck et al., 2016a; 2016b). Thus, while EWR associated with CO_2 storage presents a major opportunity for new sources of water in an increasingly water-scarce world, it is also likely an important component to accelerate widespread commercially deployed CCUS.

Enhanced Geothermal Energy and Subsurface Energy Storage

Similar to the concept of producing and purifying brine from potential CO_2 storage sites, another concept is to use the heat in geological brine to generate electricity, essentially by harnessing geothermal energy. Some researchers have also proposed using CO_2 injection strategically to increase the pressure and improve the geothermal resource (Buscheck et al., 2016c). Taking this a step further, it may even be possible to inject heated brine, using heat generated by solar thermal or baseload thermal power resources such as pulverized coal, natural gas combined cycle and nuclear power plants (Figure E-14). This concept would store energy in the form of pressure and heat when it is not needed and dispatch that energy when it is demanded (Buscheck et al., 2014). This would essentially create a grid-scale option for energy storage that could function on diurnal and seasonal time scales while simultaneously storing CO_2. This concept could potentially be deployed in either saline aquifers or in depleted oil and gas fields. This research field is in the early stages of R&D and requires considerable vetting, although the concept demonstrates another potential opportunity for CCUS that could enable many different types of energy in a GHG constrained world.

Figure E-14.
Multi-fluid Geo-energy System with Four Rings of Horizontal Injection and Production Wells



Supercritical CO_2 from a fossil fuel power plant is injected in the second well ring. After reaching the inner well ring, produced CO_2 is sent through a Brayton cycle turbine and returned to the reservoir via the second well ring. Brine produced at the inner and outer well rings is sent through a geothermal power plant, stored in a staging pond, and injected in the third well ring, using excess power from the grid. Pressure is managed by diverting some of the produced brine for consumptive use. Thermal energy from an above-ground heat source can be stored by heating brine and injecting via the third well ring (Source: Buscheck et al. 2016c).

2. Non-Geological Uses of CO_2

2.1. Food and Beverage Industry

The consulting company IHS reports that in 2014 more than 50 percent of the CO_2 used globally for commercial applications (excluding oil and gas operations) was in the beverage industry.

Commercially utilized CO_2 is used primarily in the carbonation of soda and water with the next largest uses being dry ice and baking soda (sodium bicarbonate). There are a number of other smaller applications such as cooling grapes, as a solvent in decaffeinating coffee, making flavors and fragrances, etc. but these are all minor in relation to the first three.

The IHS statistics are global in scope, but we can use U.S. figures to accurately depict U.S. domestic markets and then approximate global markets. According to the American Beverage Industry Association, the U.S. consumes an average of 44.7 gallons of carbonated soft drinks per person per year and 28.3 gallons of carbonated water drinks per year for a total of 73 gallons per person. On average a soft drink contains 2.2 ounces of CO_2 per 12-ounce drink. Calculating this (using soft drinks as a surrogate for water) the U.S. consumes approximately 325,000 tons of CO_2.

Based on the report that beverages are 50 percent or more of the market, we could infer that the total U.S. commercial market for CO_2 is approximately 650,000-700,000 tons per year.

Dry ice is the next largest use and entails a fairly simple manufacturing process. Dry ice is simply frozen CO_2. It has many uses but all are classed into two categories: freezing/coolants and blast cleaning. Most are familiar with the cooling applications across many industries. Dry ice blasting has replaced many other products as it has the advantage that the dry ice ultimately sublimates leaving no blasting residue. There is little information available on either liquid CO_2 or dry ice pricing. Both are shipped in fairly small quantities and are extremely sensitive to shipping costs (generally the largest part of product cost) and application.

The next largest application is baking soda and related products. Total U.S. consumption of these products equate to about 20,000 tons of CO_2 annually in food applications.

Currently there are two power plants capturing CO_2 and selling it into commercial applications. AES's Warrior Run plant began capturing a slip stream (6 percent) of the plant's flue gas through a monoethanolamine solvent process and selling the compressed CO_2 through a commercial industrial gas company in the mid-1990s. This output goes to carbonate beverages in the Mid-Atlantic states around Washington, D.C. Little commercial information about this market is in the public domain.

AES's Shady Point power plant in Oklahoma also went on line during the same time period and it uses the same process on a similar size slip stream to capture CO_2 which is converted into dry ice that is used to freeze chickens in nearby processing plants.

While this total use of CO_2 is interesting, because all of the uses ultimately work through the final processes of either release from the carbonated beverage or sublimation of the dry ice, none of these applications is considered permanent capture and storage. Thus focusing on these uses of CO_2 could produce some revenue but will not ultimately reduce the carbon footprint of the CO_2 source for purposes of mitigating climate impacts.

2.2. Inorganic Carbonates and Bicarbonates

CO_2 has been proposed as a feedstock for producing a variety of inorganic compounds that contain carbon. In particular, research has been conducted on the production of carbon products, carbon monoxide (CO), and inorganic carbonates and bicarbonates. Carbon products and inorganic carbonates and bicarbonates are discussed below, with major focus on carbonates/bicarbonates. CO, while an inorganic chemical by definition, is primarily used in the synthesis of organic chemicals, and therefore, is discussed later under organic and specialty chemicals.

Carbon Products include materials such as carbon black, activated carbons, carbon nanofibers and graphene. These products are specialty chemicals marketed based on their performance characteristics. Individual product markets are relatively small, but their value can be large when compared to commodity chemicals.

Feedstocks used today for the production of activated carbons and other carbon products are primarily waste materials generated by other industries, such as residual oils from petroleum refining, coal tars and biochars produced from agricultural wastes (e.g., coconut shells). These by-product materials are inexpensive, since there may be a cost associated with waste disposal. Carbon nanomaterial production can require higher-quality carbon sources, and there is considerable effort on developing lower-cost production methods, which can employ a wider range of feedstocks.

The energetics of stripping two oxygen atoms from a CO_2 molecule to produce reasonably pure carbon is quite poor. In order to result in a net reduction of CO_2 emissions, a near zero-carbon source will be needed to provide massive amounts of energy for the conversion process. This puts CO_2 at a significant cost disadvantage relative to most existing feedstocks with lower energy requirements.

Technologies for producing carbon products from CO_2 are at the earliest stages of R&D. To overcome the disadvantages of starting with CO_2, efforts will need to focus on developing new carbon products with novel properties and applications, which can preferentially be made using

CO_2 versus other cheaper sources of carbon. For example, a research effort funded by the Climate Change and Emissions Management Corporation aims to react CO_2 with graphite to produce carboxylated graphene. The modified graphene may have applications in cement manufacturing as an additive to improve mechanical strength, water purification as a selective membrane to improve the efficiency of water purification, and other areas requiring superior material performance.

Cement and Aggregate Products are used in the production of concrete, the largest volume man-made material used by modern society. Aggregate is coarse material such as gravel and sand that provides concrete with its strength, and cement is the ingredient that binds the aggregate together. Cement and aggregate have other applications. Inorganic cements are used in stucco and mortar, and aggregates are used in other construction materials such as asphalt and as clean-fill. Concrete manufacturers face increasing demand for more durable, more sustainable and higher performing materials. In response, the industry is becoming more specialized, with a broader portfolio of concrete mixtures and products that are more tailored for specific end uses. CO_2 containing products can be used as cements (binders), or as aggregates depending on the material properties.

The process of converting CO_2 to mineral carbonates (carbonation) requires a source of metal ions (e.g., iron, calcium, magnesium), "alkalinity" (i.e. base capacity) and water. The metal and alkalinity can often be provided together, such as in the case of calcium oxide (CaO) or magnesium hydroxide ($Mg(OH)_2$). CaO is often made by releasing CO_2, so on a GHG LCA basis, the emission reduction benefits of this pathway would be diminished and likely not recognized as storage by regulators. In the environment, the conversion of CO_2 to carbonates occurs naturally and is initiated by silicate dissolution reactions leading to the formation of iron, calcium and magnesium carbonates. Such geologic reactions are exceedingly slow, and do not comprise an effective mitigation or a beneficial use of CO_2. On the other hand, reactions leading to the *engineered precipitation of carbonates* are well understood and researched. Because magnesium and calcium form more stable carbonates, abundant magnesium- and calcium-silicate minerals (such as serpentine and olivine) have been a focus of previous research on aqueous/non-aqueous carbonation.

Challenges faced by the industry include significantly reducing direct CO_2 emissions from product manufacturing; as well as, indirect CO_2 emissions associated with entire life-cycle of their products. At the same time, the industry is challenged by the reduced availability of low-cost, high-quality aggregate. Barriers for the production of building materials/secondary construction materials (SCM) from CO_2 include the cost of obtaining/transporting 'waste' CO_2, market reluctance to the use of non-virgin materials, and the need to conform with materials performance specifications. Not all of the produced SCMs or carbonate materials will have the required physical and chemical properties for engineering applications, and this may limit potential technology applications. For example, the ASTM International has standards for setting times and compressive strength for Portland Cement-sand mixtures. Further, ASTM C-150 permits 5 percent ground limestone and 5 percent inert extender to be blended with clinker. ASTM C-1157 and C-33 specify standards for hydraulic cement and concrete aggregate respectively.

Buffers and Other Chemical Products. Bicarbonate materials, primarily sodium bicarbonate (baking soda) and potassium bicarbonate have a number of uses in industrial processes, as animal feed, as a cleaning agent and as a chemical buffer. Other bicarbonates, such as magnesium and calcium bicarbonate are consumed in processes but are not produced and sold commercially as they are highly water soluble and drying results in decomposition to the associated carbonate material. Bicarbonates are mined, extracted in brine or industrially produced. Bicarbonates are produced industrially through either the Solvay process via the reaction of brine with ammonia and CO_2 or through the reaction of carbonates with additional CO_2 in an aqueous environment. Generally, the CO_2 used in the production of bicarbonates from carbonates is liberated during the use of the bicarbonate, such as the release of CO_2 from baking soda during baking or during acid neutralization.

In the U.S., almost all sodium carbonate and bicarbonate production is from mined sources of the mineral trona – a mixture of sodium carbonate and bicarbonate. In the Searles Valley Mineral Facility in Trona, California, up to 800 tons per day (270,000 tons per year) of CO_2 is used for the treatment of trona to each of these products (IMC Global Inc. Soda ash plant, Trona). However, other more modern trona processing facilities do not use external CO_2 as an input to sodium carbonate or bicarbonate production and it is unlikely that future plants would use the same process, limiting the potential of this technology to utilize large quantities of CO_2.

2.3. Plastics & Polymers

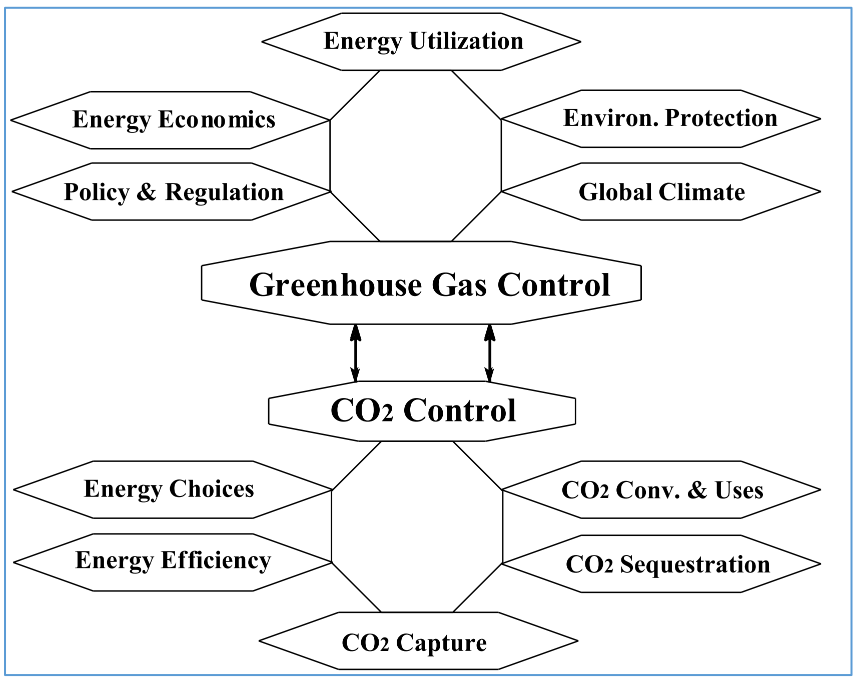
The types of polymers and plastics that can be made using CO_2 include: (1) functional polymers that incorporate CO_2 in the polymer structure, such as polycarbonate synthesized using cyclic carbonates; and (2) polymers that can be synthesized using monomers that can be made using CO_2 hydrogenation such as ethylene and propylene. The main motivations for using CO_2 to produce polymers and fine chemicals are to realize alternative synthesis routes that are more environmentally friendly and the potential to obtain functional products that incorporate at least a part of CO_2 in the final products.

Some of the chemicals described above, such as urea, carbonates and acrylic acid are indeed used currently in synthesizing polymer materials in industry (Peters 2011; Quadrelli et al. 2011). There are industrial initiatives for using CO_2 in manufacturing existing or new polymer materials, and some are in pilot plant stages. For example, Bayer is supporting research and development to produce polyols and polyurethanes; BASF is developing CO_2-based polypropylene carbonates; Asahi Kasei in Japan has commercialized a new phosgene-free production of aromatic polycarbonate using CO_2, bisphenol-A and ethylene epoxie (Quadrelli et al. 2011). A German consortium, including a CO_2 source (RWE), alternative energy suppliers (Siemens) and a polymer manufacturer (Bayer) have received €118M in funding to use CO_2 in poly(urethane) production on a commercial scale (Styring-2011) in a process referred to as DREAM chemistry (Peters, *et al.*, 2011). A recent publication summarizes the industrial projects in Germany on using CO_2 for making industrial chemicals and materials (FONA, 2014).

2.4. Organic & Specialty Chemicals

Importance and Market Size for Chemicals
CO_2 conversion and utilization as chemicals, materials and fuels is considered to be an important and integral part of the CO_2 management, as shown in Figure E-15 (Song, 2006).

Figure E-15. Key factors in CO_2 control including CO_2 conversion and utilization as chemicals, materials and fuels for CO_2 management



Source: Song, 2006

CO_2 can be used to make a number of basic and specialty chemicals, as summarized in several reviews (Peters et al. 2011; Ampelli et al. 2015). The large-volume basic chemicals that can be made using CO_2 include urea, methanol, ethylene, propylene and butenes. Urea production and consumption in the world was 169 MTPY in 2013 (NPK, 2015). Global methanol production was estimated to be about 130 MTPY in 2015, that of ethylene was estimated to be around 170 MTPY in 2015, while that of propylene was about 125 MTPY in 2015 (Eramo, 2013).

It was estimated that if all the organic chemicals and polymers (plastics, fibers and rubbers) in the world were manufactured using CO_2 as a feedstock, the global chemical industry would consume 651 MTPY of CO_2; and the corresponding U.S. chemical industry would consume

163 million tons (Song, 2002). Based on the recent industrial research and development trends, the European chemical industry is taking the lead in using CO_2 to make industrial chemicals (Scott, 2013; FONA, 2014; Ampelli et al. 2015; Quadrelli and Fussler, 2015).

Urea and Salicylic Acid

CO_2 can be used as a building block. There exist some chemical processes for CO_2 conversion in chemical industry, for which synthesis of urea from ammonia and CO_2 (Eq. 1) and the production of salicylic acid from phenol and CO_2 (Eq. 2) are representative examples. Urea is used in the organic chemical industry. It is a preferred solid nitrogen fertilizer because of its high nitrogen content (46 percent). Urea is also used for making various polymer materials and also for producing fertilizers. As an example of the usefulness of salicylic acid, acetyl salicylic acid is used for making Aspirin, a widely used common medicine.

Urea Synthesis

$CO_2 + 2\ NH_3 = H_2N\text{-}CO\text{-}NH_2 + H_2O$ (1)

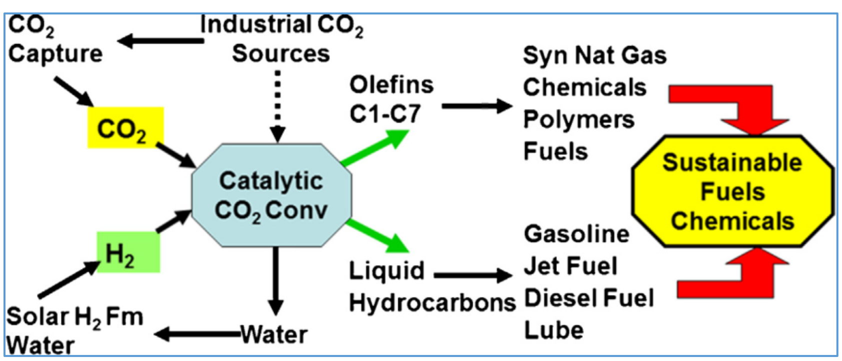
Salicylic Acid Synthesis

$C_6H_5\text{-}OH + CO_2 = C_6H_4(OH)COOH$ (2)

Ethylene and Propylene

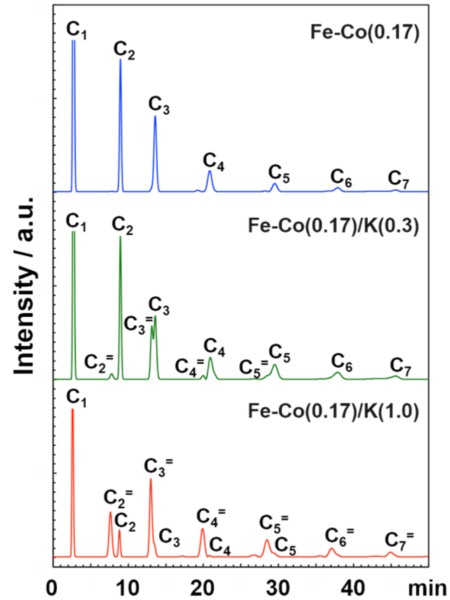
CO_2 can be converted by catalytic hydrogenation (Figure E-16) into ethylene, propylene and butenes which are currently made using petroleum and natural gas as feedstocks for steam crackers. One previously known indirect route is to convert CO_2 by hydrogenation to methanol, followed by methanol conversion to olefins (MTO) which has been commercialized as coal-based olefins production in China and also in the U.S. Recently, laboratory work at Penn State with a fixed-bed flow reactor at 300°C using new bimetallic catalysts, such as Fe-Co modified by potassium, has shown that CO_2 can be converted in one single step into C_2-C_4 olefins at 40-50 percent CO_2 conversion and most of the C_2-C_4 gaseous products are lower olefins, e.g. ethylene, propylene and butenes, as shown in Figure E-17 (Satthawong et al. 2013, 2014, 2015).

Figure E-16. Conceptual system for CO_2-based sustainable chemicals and fuels



Source: Satthawong et al. 2013

Figure E-17. C2-C4 lower olefins can be obtained from catalytic CO_2 hydrogenation in one single step using new bimetallic catalysts



Source: Satthawong et al. 2015

Dimethylcarbonate Synthesis

CO_2 can be used as an environmentally friendly raw material to replace toxic material in synthesis of some industrial chemicals. The traditional route of dimethylcarbonate (DMC) synthesis uses phosgene, which is a more toxic chemical. The use of CO_2 in synthesis of DMC presents an environmentally friendly and also attractive approach, since CO_2 can replace phosgene and chlorine and phosgene is a very toxic chemical (Aresta, 1997). Shown below is a comparison of different chemical processes for DMC, which is an industrially useful chemical, a versatile compound and a solvent with pleasant odor. In 2009, DMC and propylene carbonate were excluded from the list of volatile organic compounds by the U.S. EPA (EPA, 2009). Thus DMC has grown in popularity and applications as a replacement for methyl ethyl ketone, tert-butyl acetate, and parachlorobenzotrifluoride.

Conventional Route (SNPE, 1970s):

$CO + Cl_2 = COCl_2$ (Phosgene) (3)

$COCl_2 + 2\ CH_3OH = CH_3OCOOCH_3 + 2\ HCl$ (4)

New Ube Chemical Process – 3000 tons/Yr

$CO + 2\ RONO = ROC(O)OR + 2\ NO$ (5)

New DMC Process by EniChem – 12000 tons/Yr

$CO + 1/2\ O_2 + 2\ CH_3OH = CH_3OCOOCH_3 + H_2O$ (6)

New CO_2-Based Route

$CO_2 + 2\ CH_3OH = CH_3OCOOCH_3 + H_2O$ (7)

Acrylic Acid
Acrylic acid is an industrial chemical that is currently made using catalytic vapor phase oxidation of propylene. It can be made using CO_2 and ethylene in a new and alternative route as shown in the following reaction. BASF and the German government have invested 36 million Euros in supporting research at universities in developing new CO_2-based synthesis of acrylic acid (Quadrelli et al. 2011; FONA, 2014).

$$CH_2{=}CH_2 + CO_2 = CH_2{=}CH\text{-}COOH \qquad (8)$$

Recently, BASF started a new commercial acrylic acid plant in Brazil in 2015 with a capacity of 160,000 ton/yr of acrylic acid (Ondrey, 2015). The most important use of this chemical is for synthesizing superabsorbent polymers that are commonly used in making baby diapers and other hygiene products. Butyl acrylate, another important derivative of acrylic acid, is used to produce adhesives, construction chemicals and decorative paints (Ondrey, 2015).

Solvents
At the end of 2013, the global demand for merchant CO_2 totaled 52,000 metric tons per day (19.1 MM mt/y) and is growing at 3-5 percent per year (Josef 2014). This includes compressed CO_2 cylinders, liquid CO_2, and dry ice. Supercritical CO_2 can be used both as a tunable solvent and a reaction medium. A most important application of SC-CO_2 solvent is for coffee decaffeination. Methanol and liquid hydrocarbons that can be synthesized from CO_2 hydrogenation can also be used as solvents. Another important industrial organic solvent that can be made using CO_2 is DMC, described above.

2.5. Fuels

Utilization of CO_2 for transportation fuels represents a significant opportunity in terms of market share and economic incentive. However, because transportation fuels are combusted, thus resulting in the re-emission of CO_2, they ultimately hold less promise as an ultimate carbon management solution. Utilization of CO_2 for transportation fuels also faces significant market displacement considerations in that the new fuels would face tough competition from existing fossil-based fuels. Still, this could represent an area for further evaluation should resources be available.

The size of the fuels market is on the same order of the CO_2 emissions from fossil-fueled power plants (Song, 2002). Table E-10 shows the order of magnitude estimates for the worldwide capacity of CO_2 utilization for chemicals, materials and fuels (Song, 2002). Catalytic conversion of CO_2 to hydrocarbons and alcohols have been reported in a number of studies, as summarized in the reviews by Song (2006), Centi (2009), Wang et al. (2011), Quadrelli et al. (2011) and Ampelli et al. (2015). Conventional catalysts for CO_2 hydrogenation are based on transition metals, including noble metals. Compared to the well-established hydrogenation processes for

CO, the general problems for CO_2 hydrogenation are characterized by lower reactivity of CO_2 and the lack of selectivity and activity of the catalysts studied so far.

Table E-10. Order of Magnitude Estimates for the Worldwide Capacity of CO_2 Utilization

Option of CO_2 Utilization	Worldwide Capacity (Order of Magnitude in Giga Ton Carbon)
Non-chemical Utilization	0.01 – 0.1 GtC per year
Chemicals & Materials	0.1 – 1 GtC per year
Synthetic Liquid Fuels	1 – 10 GtC per year

Source: Song, 2002

Catalytic hydrogenation of CO_2 is the most likely choice in the near future for producing drop-in fuels from CO_2 for the transportation fuels market. Because fossil fuels were formed originally from CO_2, it is important to consider and re-incorporate CO_2 in making fuels using renewable energy in order to build a sustainable fuel supply chain by making use of renewable energy in CO_2 recycling. Nuclear energy could also be used. The CO_2 hydrogenation reaction is illustrated in the following equation (Eqs. 9-10). The H_2 would need to be produced using renewable energy such as solar and wind.

$$n\ CO_2 + (3n+1)\ H_2 = C_nH_{2n+2} + 2n\ H_2O \qquad (9)$$
$$n\ CO_2 + 3n\ H_2 = C_nH_{2n+1}OH + (2n-1)\ H_2O \qquad (10)$$

The process technology that may hold some promise for near-term feasibility for converting CO_2 to fuels would be a catalytic CO_2 hydrogenation to either hydrocarbon or alcohol fuels. The most important costs in fuel synthesis using CO_2 are the capital and operating expenses for CO_2 capture, and the costs of H_2 production. Because the CO_2 hydrogenation reactions are exothermic, the real major energy consumption is that for H_2 production.

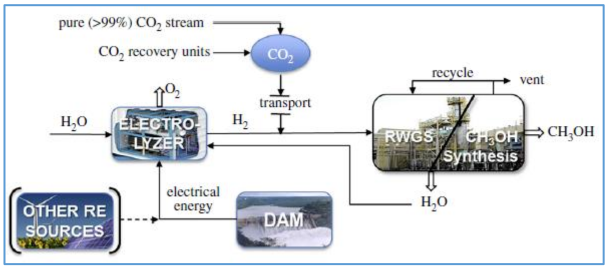
There are several other ways by which CO_2 can be converted to fuels. CO_2 can be used for making synthetic gas (syngas) through either dry reforming or tri-reforming of methane (Song and Pan, 2004). Using well-established commercial technologies, syngas can be used in either Fischer-Tropsch synthesis for making ultra-clean diesel and jet fuels, or methanol synthesis which can be used for making fuels (such as DME, MTG) or chemicals (such as MTO, formaldehyde). Some industrial initiatives are described below. CO_2 hydrogenation using H_2 can be directed towards producing C_2-C_4 olefins (Satthawong et al. 2015), followed by olefin oligomerization to make clean liquid fuels.

Methanol

Methanol can be synthesized using CO_2 and H_2. Most current processes for methanol synthesis use synthesis gas consisting of CO and H_2. When CO_2 is used, the economics of the technical process involve costs of CO_2 capture and separation plus the cost of H_2 production.

$$CO_2 + 3\ H_2 = CH_3OH + H_2O \qquad (11)$$

Figure E-18.
Simplified block diagram of different material flows for conversion of CO_2 to methanol



Source: Ampelli et al., 2015

Carbon Recycling International (CRI) in Iceland has built a plant for converting CO_2 to methanol, which is located in Svartsengi, near Grindavik, Iceland, and began production in 2011 (CRI, 2016; Quadrelli and Fussler, 2015). The concept is similar to that shown in Figure E-18. The process technology includes (1) water (H_2O) electrolysis to make H_2 and O_2 using renewable (geothermal) energy (electricity) and (2) catalytic CO_2 hydrogenation to methanol using H_2. In 2015, CRI expanded the plant from a capacity of 1.3 million liters/year to more than 5 million liters/year. The plant uses a Cu-ZnO catalyst, and now recycles 5.5 thousand tons of CO_2 a year (captured from flue gas of a geothermal power plant), which would otherwise be released into the atmosphere, using renewable energy (electricity) from geothermal source.

The conventional methanol process has an ability to take a variety of carbon feedstocks that could and does include CO_2. The front end of a methanol plant is designed to be very robust from a feedstock perspective, including both pre-reforming and steam methane reforming (some technologies include auto-thermal reforming in a hybrid configuration that also requires the addition of oxygen from a cryogenic oxygen plant). The process also includes a pressure swing adsorption unit to provide hydrogen on an as-needed basis to create a balanced syngas. The process feedstock in the United States is natural gas but with the robust front end the composition of the natural gas can swing widely and also include CO_2. As long as the predominate feed is methane, other sources of carbon including CO_2 can be added to both increase throughput and to provide the carbon molecules needed to create a synthesis gas that feeds the methanol synthesis process. To be used, CO_2 needs to be price-competitive with methane on a MCF, not BTU, basis. If CO_2 was available in large quantities in a steady manner at a competitive prices, a methanol plant could use it.

In the United States, there are 5 or 6 new world-scale methanol plants in design, under construction, or starting up or now operating. There is an equal number in development. World consumption of methanol is increasing at around 8 percent year-over-year. In addition to its traditional chemical derivatives end product uses, methanol is, with China leading the way, increasing its use as a supplement in the gasoline fuel market.

Hydrocarbon Fuels

Catalytic CO_2 hydrogenation can be used to produce C_5+ hydrocarbons as liquid transport fuels for gasoline, diesel and jet fuels, while the light gaseous products can be used as light fuel or recycled to the reactor along with unconverted CO_2 and H_2. CO_2 hydrogenation can be used to produce synthetic natural gas (SNG) or methane, which can be carried out with over 95 percent selectivity using relatively inexpensive transition metal catalysts. A major issue for the CO_2 to SNG is the cost of H_2 used for CO_2 conversion, but this type of reaction can be accomplished using existing types of industrial reactor facilities.

Sunfire GmbH in Germany built a "Power to Liquid Fuels" pilot facility in 2013-2014 to produce 160 liters (1 barrel) of hydrocarbons per day based on CO_2 hydrogenation (Quadrelli and Fussler, 2015; McSpadden, 2015). Their process technology consists of: (1) high-temperature steam (H_2O) electrolysis (using systems similar to solid oxide fuel cell) to make H_2 and O_2 using renewable energy (electricity); (2) catalytic CO_2 reduction to CO using H_2; and (3) Fischer-Tropsch synthesis to produce naphtha, diesel, kerosene and wax fractions. The process has a 65 percent energy efficiency and is claimed to create a CO_2 abatement of 60 to 90 percent compared to the current diesel production processes. The fuel produced by Sunfire has been highlighted by Audi as "Audi e-diesel" (McSpadden, 2015).

Biological Processes

The use of algae and other carbon-consuming microorganisms offers an option for reducing CO_2 emissions from electric generating units and other industrial sources. Algae are among nature's most prolific and efficient photosynthetic organisms. Chemosynthetic microbes perform a similar function using chemical catalysts instead of sunlight to convert CO_2 to organic matter. Together, these autotrophic microbes transformed Earth's early atmosphere into the oxygen-rich one we enjoy now by converting vast quantities of CO_2 into carbohydrates and lipids that eventually became the petroleum we consume today.

These organisms thrive on concentrated sources of CO_2. To provide the optimal environment for growth, today's algae developers purchase commercial CO_2 as a feedstock at significant expense. Co-location of algae or other microbial production with post-combustion capture from coal-powered electric generating units (EGUs) and other industrial sources of CO_2 offers the potential to drive down the cost of both fuel production and CO_2 mitigation.

IEA's Clean Coal Centre identified several appealing advantages to biological approaches to CCUS:

- High purity CO_2 gas is not required for algal culture. Flue gas containing varying amounts of CO_2 can be fed directly to the microalgal culture, reducing or eliminating the need for CO_2 separation from flue gas. Several algae strains demonstrate optimal growth rates at coal flue gas CO_2 concentrations.

- Some combustion products such as NO_x or SO_x can be effectively used as nutrients for microalgae. This could potentially negate the use of flue gas scrubbing systems for power plants.
- Microalgae could yield high value commercial products. The sale of these high value products could offset the capital and operating costs of the process.
- The envisioned process is a renewable cycle with minimal negative impacts on the environment.

Production platforms include open raceway pond systems and closed photobioreactor systems, including flexible plastic film systems, tubular reactors, and flat panel systems.

Fuels can be produced through whole biomass conversion such as hydrothermal liquefaction (HTL), lipid extraction or fermentation of carbohydrates. Some strains of algae, such as certain cyanobacteria, are capable of excreting fuel or fuel pre-cursors, obviating the need for extraction or conversion.

DOE has observed that algae-based CO_2 conversion offers a number of economic and environmental benefits. Algae offer high potential yield per acre, the ability to grow on land not suited for agriculture and in brackish or wastewater, absorption of CO_2 and relative ease of conversion into fuels and products.

Algae's potential for GHG reductions is among its most desirable characteristics. EPA analyses of algae-based fuel pathways under the Federal Renewable Fuel Standard (RFS) program found GHG reductions of 69-85 percent on a full lifecycle basis versus petroleum-based alternatives. Algae-based renewable diesel is also approved by EPA under the RFS as a qualified advanced biofuel with lifecycle GHG emissions reductions of greater than 50 percent verses petroleum-based diesel.

CO_2 procurement is one of the leading operational costs of algae production, with commercial CO_2 typically priced at \$40 per ton delivered. CCU systems that deliver CO_2 at costs less than \$40 per ton are thus likely to be attractive to algae project developers. DOE's 2016 Billion Ton Report found an average delivered CO_2 cost of \$22 per ton for algae projects co-located with coal-based EGUs, suggesting algae CCU may offer the opportunity for low-cost, no-cost or negative-cost CO_2 mitigation.

Leading algae production systems report 100 gallons of biofuel produced per ton of CO_2, so the value of biofuel produced from algae-based CCU is likely to exceed \$150 per ton of CO_2 even if crude oil prices remain low and without consideration of co-products. Algae-based CCU also does not require the added expense and parasitic load of CO_2 compression and underground injection associated with CCUS. Algae producers are therefore likely to be well positioned for CO_2 offtake.

A key question remains whether algae-based fuels can be produced at costs competitive with petroleum-derived fuels. DOE projects algae fuel production cost will reach $5.90 per gasoline gallon equivalent by 2022, but several algae project developers already report production costs below this benchmark.

DOE's model also does not account for co-product value, but a number of very high value markets for algae-derived products have already emerged (Table E-11).

Table E-11. Microalgae Products and Prices

Product	Substitutes	Price	Unit[a]
Biodiesel	Diesel	$2.27	USD/gal
Bio-ethanol	Gasoline	$3.96	USD/gal
Bio-methane (fuel)	Liquified petroleum gas	$1.92	USD/gal
Jet fuel (bio-jet)	Jet fuel	$2.49	USD/gal
Electricity	Fossil energy	$0.13–$0.21	USD/kWh
Bio-methane (electricity)	Natural gas	$0.05–$0.06	USD/kWh
Biofertilizers	Synthetic fertilizers	$0.25–$0.63	USD/kg
Biostimulants	Growth promoters	$37.50–$312.50	USD/kg
Biopesticides	Synthetic pesticides	$5.00	USD/acre
Bioplastics	Fossil based plastics	$1.75	USD/kg
Food	Proteins, carbohydrates, oils	$50.00	USD/kg
Beta-carotene	Synthetic/natural	$275.00–$2,750.00	USD/kg
Omega-3 polyunsaturated fatty acids	Fish	$50.00	USD/g
Aquaculture	Fishmeal/fish oil	$68.75–$625.00	USD/kg
Livestock feed	Soybean meal	$300.00	USD/tonne
Feed additives	Botanicals, antibiotics	$20.00	USD/kg

Source: Adapted from https://bioenergykdf.net/billionton2016/overview

A number of very high value algae-derived nutraceuticals, such as astaxanthin and beta-carotene, already have small but well-established and growing markets with values that can exceed $1 million per ton. These niche markets are unlikely to significantly impact CCU fuel cost, but can be a component of a multi-product production model.

Animal feed and feed ingredients hold potential to provide substantial co-product value, however – particularly aquafeeds for fish and shellfish. Algae are uniquely suited to substitute for traditional wild fish sources of proteins and oils for aquafeed because they serve as the base of the marine food chain upon which many fish meal species feed. Bloomberg estimates the potential market size for fish feed is $9 billion and for livestock feed is $370 billion and expected to grow up to 40 percent in the next 20 years.

Several major feed companies, including ADM and Bunge, have recently launched algae-derived aquafeed products.

In summary, the catalytic hydrogenation of CO_2 is a most promising area for CO_2 conversion to fuels and for CO_2 recycling into hydrocarbons or alcohols which can have a major impact on reducing CO_2 emissions from coal utilization and adding value to the management of CO_2. More research on the catalytic CO_2 conversion is needed in both experimental and computational areas for developing novel catalytic materials and reaction processes for selective CO_2 conversion to the desired liquid or gaseous products. Algae-based fuels also have promise.

It should be noted that new ideas and new results continue to emerge in the literature on CO_2 conversion and utilization. For example, a most recent paper in July 2016 reports on the O_2-assisted Aluminum/CO_2 electrochemical cell as a system for CO_2 capture and conversion as well as electricity generation (Sadat and Archer, 2016). The potential for its application remains to be determined.

2.6. CO_2 in Agricultural Fertilizers

Deforestation in the U.S. and worldwide, has vastly reduced the uptake of CO_2 by trees and other plants. These sources were absorbing the CO_2 from the atmosphere and, in the presence of sunshine through photosynthesis, were converting it into healthy growth of plants. Such a natural process is greatly curtailed due to uncontrolled deforestation. Thus the CO_2 in the atmosphere remains high, and blocks the sunshine needed by the plants. As one alternative, agricultural plants are increasingly being fed carbon-based fertilizers.

According to several recent studies, traditional chemical fertilizers lack carbon and contain a higher percentage of nitrogen than plants can process at application time. The results of these studies are summarized below:

- Chemical fertilizers contribute to increased food waste, ground water saturation and potentially hazardous runoff conditions.
- These chemical fertilizers contain significant quantities of salts and heavy metals and cause interference with carbon absorption by plants. Carbon serves as a source of maximum benefits to agricultural crops.

- Carbon-based fertilizer products are a source of high efficiency carbon/oxygen food for plants and trees, while balancing nitrogen for efficient uptake of already present nutrients.
- Carbon serves as an intake enhancer of various other elements and minerals in the fertilizer, e.g., nitrogen, phosphorous, zinc.
- Carbon acts as a buffer against heavy metals and toxins in the soil, and assists in balancing the pH.
- Soil carbon in the presence of oxygen, improves positive ion exchange capacity of plants and water holding capacity of sandy soils. It also contributes to the structural integrity of clay soils by helping to bind particles into aggregates.
- Carbon in the fertilizer prevents nutrient leaching and is integral to the organic acids that make minerals available to plants. It also buffers soil from strong changes toward acidity. It is widely accepted that the carbon content of soil is a major factor in maintaining a healthy soil.

Presence of carbon and oxygen in fertilizers generally help improve utilization of nitrogen, phosphorous, potassium, boron, magnesium and zinc, while stabilizing the soil pH. Carbon in the fertilizer also helps neutralize the increase of alkalinity caused by the presence of calcium in the fertilizer, and helps maintain water in the soil which otherwise could cause hazardous runoff.

Table E-12 below illustrates the efficiency enhancement of various minerals by plants in the presence of carbon:

Table E-12. Role of Carbon as Average Intake Efficiency Enhancer by Plants

Nutrient	Efficiency Enhancement	Completed Studies
Nitrogen (N)	10-20%	20
Phosphorous (P)	12-22%	22
Potassium (K)	15-22%	17
Ca & Mg	20-40%	5
Zn & Mn	20-50%	5
Boron (B)	15-22%	2

**Total nutrient removal basis from replicated field and greenhouse studies.*

Source: FB Sciences, Inc. 2015

The addition of carbon in industrial fertilizers in some cases seems to increase crop yields significantly and results in:

- >8 percent increase in corn,
- 27 percent increase in tomatoes, and
- 30 percent higher yield in grapes.

Research being conducted by institutions, universities and small businesses indicate that the addition of carbon in fertilizers positively impacts yield of farm crops. Preliminary results of these experiments showing yield increases in various farm crops is presented in Table E-13 below.

Table E-13. Estimated Crop Yield Increase with Carbon Addition in Fertilizers

Type of Crop	Estimated Increase in Yield With Carbon Addition
Wheat	3%
Corn	8%
Soy Beans	8%
Potatoes	11%
Almonds	12%
Alfalfa	12%
Sweet Corn	20%
Tomatoes	25%
Grapes	30%
Apples	32%

Source: FB Sciences, Inc. 2015

2.7. Other Non-Geologic CO_2 Uses

Other non-geologic markets for CO_2 potentially exist. These include, for example, the use of supercritical CO_2 as a buffer or coolant in small modular nuclear reactors. By and large, these opportunities face numerous challenges, including relatively small market potential.

F. Extent to Which CO_2 Utilization Technologies May Incentivize CCUS Deployment

Key Findings

- U.S. law currently favors geologic storage/utilization technologies; non-geologic CO_2 uses must demonstrate that they are as effective as geologic storage.
- Timing of U.S. and international climate goals point towards the use of CO_2 utilization technologies that are either already commercialized or near commercialization.
- There is a misalignment of needs between industries who would utilize CO_2 and the power sector.
- CCUS technology deployments face a host of unresolved impediments that are unlikely to be mitigated by market demand for CO_2 alone in any near- to intermediate-term scenario.
- With the exception of geological utilization under appropriate circumstances, CO_2 utilization is unlikely by itself to incentivize CCUS technologies.

Key Recommendations

- A regulatory based, incentive and tax compliant framework that provides a well-defined no-regrets economic calculus that limits the loss-of-capital to the investment community in FOAK (first-of-a-kind) CCUS projects should be developed.
- Monetary, regulatory and policy investments in CO_2 utilization technologies should be roughly prioritized from geologic to non-geologic, with exceptions made if non-geologic technologies are found to be as effective as geologic storage. Assessments should include in all CO_2-dependent products a full life-cycle CO_2 accounting of the displacement of current fossil sources of captured CO_2 by those that utilize CO_2 capture from fossil resources.
- Coordinate State and Federal regulations to provide flexibility to accommodate an acceptable and broad range of potential commercial constructs (among CO_2 producers, intermediaries, investors and ultimate users of the users of CO_2). Each party should be responsible in a well-defined chain-of-custody, with clearly defined MRV requirements and shared and definitive ultimate economic responsibilities for subsequent CO_2 releases.

Overview

Monetary, regulatory and policy investments in the following CO_2 utilization and storage technologies, in descending order, are most likely to incentivize the deployment of CCUS technologies:

1) **Current CO_2-EOR technology**. It is imperative for the government to clarify the existing regulatory structure, provide support for infrastructure, such as pipeline networks, and offer financial incentives for carbon capture deployment so that the promise of this existing commercial technology is fully realized.

2) **"State-of-the-Art" CO_2-EOR technologies**. The potential for these technologies has been separately documented.

3) **Other geologic storage technologies that provide economic return**. ECBM and CO_2 injections into ROZs provide market demand for CO_2 under certain general oil and gas market conditions. They also fit within the current U.S. legal framework that gives preference to geologic storage over non-geologic uses of CO_2. Not all geologic formations (ECBM, for example) have access to protocols and/or methodologies to document storage.

4) **Saline storage**. Saline storage remains EPA's gold standard for CO_2 storage and may be required to provide a back stop for CO_2 utilization projects. The hurdles facing saline storage are primarily economic and regulatory, which current DOE policy recognizes – i.e., the new CarbonSAFE program. The fact remains, however, that the federal government needs to: (1) put more resources into these projects and (2) reduce the regulatory impediments currently facing them.

5) **Non-geologic storage technologies that provide economic return and that are effective as geologic storage**. The current U.S. legal framework prefers geologic storage over other CO_2 uses. However, non-geologic technologies that keep the CO_2 out of the atmosphere may be credited for the purposes of federal programs with appropriate evidence of atmospheric benefit.

6) **Non-geologic storage technologies that provide economic return yet are not as effective as geologic storage if appropriate EPA research waivers may be obtained**. On a case-by-case basis, a CO_2 utilization technology may exist or emerge that provides an economic return to a fossil fuel-based power plant or a CO_2-emitting industrial facility. The technology nonetheless could be helpful in lowering the cost of capture. Appropriate legal recognition would be needed, however, for purposes of compliance with emission reduction obligations.

Analysis

CO_2-EOR and other certain geologic utilization technologies, such as ECBM, are already commercialized. Other geologic technologies, including saline storage, remain subject to ongoing research and have not yet emerged as commercially available technologies at scale. With respect to non-geologic utilization technologies, the market analysis chapter of this report identified the following as being commercialized at reasonable scale: (1) carbonization of soda and water; (2) dry ice; and (3) baking soda, all of which are unlikely to permanently store the CO_2.

Answering this question requires initial consideration of the amount of CCUS deployment needed over a given time frame in light of existing legal and policy frameworks that already require fossil fuel-based stationary sources to reduce their emissions of CO_2. Even if a specific CO_2 utilization technology could create some amount of market demand for CO_2, the technology may fail to incentivize CCUS if it cannot satisfy current legal requirements under any foreseeable timeframe from a compliance perspective.

U.S. Law Recognizes CO_2-EOR and Other Geologic Storage Technologies for Compliance Purposes; Non-Geologic Storage Technologies May Be Used Only If EPA Determines They Are As Effective as Geologic Storage

A key issue informing the answer to the question regarding the extent to which EOR and non-EOR technologies could incentivize the deployment of CCUS technologies is whether non-geologic utilization technologies could comply with U.S. legal requirements mandating proof of storage that is as effective as geologic technologies.

Sources that emit enough conventional pollutants to trigger compliance with the CAA's Prevention of Significant Deterioration (PSD) and Title V operating permit programs must then address GHGs, including CO_2. For the PSD program, this means that EPA may subject these sources to Best Available Control Technology (BACT) requirements for their CO_2 emissions. Because all major coal-based stationary sources emit both conventional pollutants and CO_2, this means that if PSD requirements are triggered for a conventional pollutant that also means that these sources must also apply a BACT assessment for GHGs. The current GHG emissions rate that triggers the BACT requirements is 75,000 tons per year (CO_2e), although by future rulemaking EPA may establish a different de minimis emission threshold.

Current EPA policy under the PSD program focuses on EOR and CCUS as potential BACT to control emissions of CO_2. Indeed, for the foreseeable future, EPA has built its CO_2 compliance options for fossil fuels largely around the use of CO_2-EOR. By contrast, the utilization or reuse of CO_2 in unspecified products is either not referenced, disincentivized or subject to other regulatory hurdles.

In addition, the EPA has adopted the CPP, which requires States to adopt plans to reduce CO_2 emissions by a specified amount by 2030. This rule is currently subject to litigation and a February 9, 2016 stay by the U.S. Supreme Court. In the rule, EPA stated a willingness to consider what it described as "carbon capture and utilization" (CCU) technologies on a case-by-case basis if evidence was provided regarding "the ultimate fate of the captured CO_2 and the degree to which the method permanently isolates the captured CO_2 or displaces other CO_2 emissions from the atmosphere" (60 Fed. Reg. 64662, 64884 (2015)). The latter hints at the possible use of GHG LCA to compare new and incumbent CO_2 utilization technologies or other market outcomes.

EPA provided a similar compliance path for non-geologic storage technologies under the Standards of Performance for GHG Emissions from New, Modified, and Reconstructed Electric Utility Generating Units, which also remains subject to litigation. There, EPA stated that applicants would need to demonstrate that the proposed non-geologic storage technology "will store captured CO_2 as effectively as geologic sequestration", and that the proposed technology "will not cause or contribute to an unreasonable risk to public health, welfare or society."

These legal standards suggest that a coal-based power plant could not rely upon the three largest non-EOR commercialized technologies utilizing CO_2 – i.e., carbonization of soda/water, dry ice and baking soda – as at first blush none of them "store[s] CO_2 as effectively as geologic sequestration." Indeed, the first two result in immediate re-release of CO_2 to the atmosphere upon use.

Non-Binding Climate Goals Require CCUS Technologies Be Deployed At Scale In The Near Future

Another issue informing the answer to the question regarding the extent to which CO_2 utilization technologies could incentivize the deployment of CCUS technologies is whether they could be commercialized quickly enough to satisfy looming low-carbon policies.

The current U.S. Administration's 2050 climate goal (80-83 percent GHG reduction by 2050) is broadly consistent with the December 2015 Paris Agreement's goal of "[h]olding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (2015 Paris Agreement, art. 2, para. 1(a)). The U.S. signed the Paris Agreement on April 22, 2016. The Paris Agreement's goal, in turn, is broadly understood to require effective decarbonization of energy systems by the 2050 timeframe, with CCUS playing a significant role.

The IPCC has taken the position that the "widespread deployment of bioenergy with carbon dioxide capture and storage" technologies – i.e., not just carbon neutral, but carbon negative action – will be required in the second half of the current century to achieve the 2°C goal, let alone the ambition to hold the increase to no more than 1.5°C.

Additionally, IEA analysis, for example, shows that CCUS "is an integral part of any lowest-cost mitigation scenario … particularly for 2°C scenarios." In the IEA's 2°C scenarios, CCUS "is widely deployed in both power generation and industrial applications" with capture and storage rates growing to "thousands of megatonnes of CO_2 in 2050 in order to address the emissions reduction challenge" (IEA Technology Roadmap: Carbon Capture and Storage 2013).

In other words, to make meaningful progress towards the 2°C goal, CCUS technologies need to be deployed at scale in the relatively near-future given the time required to plan, finance, develop and build major infrastructure. In its 2015 *Fossil Forward* report, the NCC noted that a "review of every major new technology introduced into the power industry since the 1950s shows that commercializing a new technology is both time consuming and costly." The NCC highlighted that despite the success of fluidized bed technology demonstrations in the 1970s, the technology was only now starting to be installed in plants in the 500-600 MW range.

This suggests that primary focus should be placed on CO_2 utilization technologies that are currently commercialized or on the cusp of achieving that status, because less developed uses are less capable of being deployed in time and at scale to make a meaningful difference in achieving international climate targets. And even though the international climate targets are not binding, their mere existence is expected to influence investment decisions in power markets going forward. This is not to suggest that promising nascent utilization technologies, especially the under-development geologic utilization options, should be ignored. They may have a vital role to play in future CO_2 mitigation efforts.

Misalignment of Needs between the CO_2 Utilization Industry and Power Sector

While often mentioned as an opportunity, applying CO_2 utilization through conversion – i.e., non-geologic options – would be challenging, especially in the power sector where potential CO_2 users may not be ideally aligned with the regulatory compliance requirements of the power industry. The difference in the quantity of CO_2 emissions versus the quantity that could potentially be used has been described elsewhere in this report. However, other factors could strongly discourage the use of CO_2 without a geologic storage backup option.

Technology developers focused on CO_2 utilization through conversion are likely to require a return on investment in a time frame considered relatively short by the power industry. For example, assume that a company proposes to produce a specific chemical from power plant CO_2 and that an adequate market for that chemical exists. The technology developer offering the utilization opportunity would likely require a return on investment in less than 10 years, while the plant owner would require a CO_2 control technology that will allow the plant to operate for the remainder of its useful life, which may be another 40 years or more.

Any mitigation of CO_2 emissions, whether for utilization or storage, requires evaluation of both costs and risks. An owner of a CO_2-emitting facility must consider whether a CO_2 user may discontinue the project due to bankruptcy, market changes or other reasons, leaving the facility owner without a viable regulatory compliance strategy. Similarly, if the facility – e.g., a power plant – has an unplanned outage, becomes uneconomical or changes operation for any other reason, it would result in the CO_2 utilization project being stranded, which may be an unacceptable risk for the CO_2 utilization technology developer.

These concerns are more intense for niche CO_2 utilization projects aimed at conversion, but could also apply to some geological CO_2 utilization applications. While the operational and return on investment timelines may be better aligned for some geological utilization applications, power plants owners and operators may still consider CO_2 geologic storage a necessary backup to ensure compliance is always achievable.

CO_2 pipeline networks could be constructed to alleviate some of these risks by connecting groups of CO_2 producers and users. However, this approach could be relatively expensive, slow and infeasible in some areas. It would require that all CO_2 be of pipeline quality, although some utilization technologies will not require pipeline quality CO_2.

The array of potential bases for misalignment of needs highlights the fact that even if a CCU project is deemed economically viable, access to geological storage may be necessary to advance the CCU project. Thus, while it is possible that CCU projects could, in a limited number of cases provide a revenue-generating opportunity, there is also a strong probability that a geological CO_2 storage option will also be necessary. In this way, CCU may be helpful to the deployment of a broader CCUS infrastructure by providing some revenue and also encouraging characterization and well permitting activities for geological CO_2 storage.

In summary, there are profound disconnects between the market demands of both producers of CO_2 (e.g., utilities that must meet electricity demand) and their associated regulatory requirements and CO_2 users and their products (e.g., chemical and fuel producers that must meet contractual delivery requirements for their CO_2-derived products). The answer to accommodating these different market demands may be achieved by relaxing the temporal terms of compliance for utilities as well as providing for the establishment of an inventory of unused CO_2 that can be offset by other indirect means.

Capital Market Investment in CCUS Technology

There exists a vibrant and well capitalized venture capital (VC) investment community that is searching for acceptable higher risk investments that provide return on capital above that of currently available fixed income (low risk/low return) investments. This is a resource that CCUS needs to address. VC firms search for those projects that provide an acceptable risk-based return of capital and losses and would be more willing to invest provided that there is a backstop against the total loss of their invested capital. These backstops can be provided by appropriate policy and regulatory relief for higher-risk CCUS projects.

Numerous Impediments to the Deployment of CCUS-Related Technologies Have Been Previously Identified and Remain as Hurdles

Numerous studies have previously documented the economic, government support and regulatory hurdles that must be overcome to incentivize CCUS in the 2020-2030 timeframe. Perhaps not surprisingly in light of the considerations noted above, none of them has identified market demand for CO_2 for use in utilization technologies as a sufficient CCUS incentive.

- In its January 2015 report “Fossil Forward: Revitalizing CCS – Bringing Scale and Speed to CCS Deployment,” the NCC identified the following CCUS deployment challenges: (1) the infrastructure for transportation and storage of massive quantities of captured CO_2 does not exist; (2) financing power plants with CCUS is a major issue; (3) legal and regulatory issues still remain unresolved; (4) public acceptance is still an issue; (5) first generation technologies are costly; (6) General Equilibrium Models can be helpful as tools to provide guidance, but should be used with caution; and (7) there is a policy mismatch between CCUS technology and other DOE energy programs.

  Specifically with respect to CO_2 utilization, the NCC stated the following, which remains valid today:

  > CO_2 utilization can improve the economics of early adopter plants. However, the magnitude of the amount of CO_2 that must be captured to meet CO_2 emission reduction goals is much greater than the potential economic uses. For the most part, utilization is able to handle millions of tons, leading to perhaps some modest total of billions of tons. Reduction requirements will be in the thousands of billions of tons. Utilization must be considered as a storage option.

- In its report entitled "The Global Status of CCS: 2015," the Global CCS Institute identified the following factors as needed to spur CCUS: (1) predictable policies for investors that do not disadvantage CCUS; (2) further deployment of CCUS-specific laws and regulations; (3) incentives for the selection and characterization of storage sites to support final investment decisions by projects; (4) research and development efforts to advance more cost-effective capture technologies; and (5) more progress in developing countries.

- In a 2014 study, the IEA identified seven factors that should be implemented to incentivize CCUS between then and 2020: (1) introduce financial support mechanisms; (2) implement policies that encourage storage exploration, characterization and development; (3) develop national laws and regulations that effectively require new fossil-plants to be CCUS-ready; (4) prove capture systems at pilot scale in industrial applications; (5) significantly increase efforts to improve understanding among the public and stakeholders; (6) reduce the cost of electricity from power plants equipped with CO_2 capture technology; and (7) encourage the development of CO_2 transport infrastructure.

- In its August 2010 report, the U.S. Interagency Task Force on Carbon Capture and Storage (Task Force) recommended that five to ten commercial-scale demonstration projects be in place by 2016. To meet this goal, the Task Force suggested the following policies be pursued: (1) creation of a federal roundtable to provide support for technology development and deployment; (2) provision of legal and regulatory clarity and support; and (3) public outreach.

As separately documented by the NCC last year, incremental progress has been made in overcoming some of these many economic, government support and regulatory hurdles, but much work remains to be done. Until these existing hurdles are surmounted, relying upon CO_2 market demand from not-yet-commercialized CO_2 utilization technologies to advance CCUS may likely be overly optimistic.

Developments in China

China is advancing several demonstration projects involving both EOR and non-EOR uses of CO_2. Specifically as to EOR, several demonstration projects are underway; at least one such project in the Ordos Basin is the subject of U.S.-China collaboration under the U.S.-China Clean Energy Research Center.

China's investments in non-EOR CO_2 utilization technologies are separately notable with the following relatively small-scale demonstration projects planned or under development:

Table F-1. Select Non-Geologic CO_2 Utilization Projects in China

Name	Location		Demonstration Features	CO_2 Utilization (tons per year)
Zhongke Jinlong CO_2 Chemical Utilization Project	Taixing, Suzhou		CO_2 chemical utilization in alcohol plant	~ 8000
CNOOC CO_2-Based Degradable Plastics Project	Dongfan, Hainan		CO_2 separation from natural gas and utilization for chemicals production	~ 2100
ENN Group Microalgae Carbon Fixation Bioenergy Demonstration Project	Dalad Banner, Inner Mongolia		Bio-utilization of coal chemical fuel gas	~20,000

Large-scale demonstration projects – i.e., those utilizing one million tons of CO_2 per year or greater – have not yet been developed.

In 2014, China's Ministry of Science and Technology (MOST) published the results of its comprehensive scientific assessment of geologic and non-geologic CO_2 utilization technologies in the country. MOST highlighted the following technologies as holding particular promise: (1) CO_2-EOR, with and without EWR; (2) use of CO_2 from coal conversion technologies for use in ECBM, with the resulting methane used thereafter to generate feedstocks to produce syngas, liquid fuels, methanol and other products; and (3) use of CO_2 from steel and cement production for mineralization of bulk solids (such as slag and phosphogypsum) and cultivation of microalgae that could, in turn, be used for fertilizer or as a feedstock for fuels and other chemicals.

By and large, these and related technologies remain at the early stage of development. However, with sufficient policy support and reductions in economic barriers, MOST identified the following potential for emissions reductions and economic benefits in 2030 for various CO_2 utilization technologies:

To put these numbers into perspective and taking China's upper estimate (251.8 million tpa) of its total potential CO_2 geologic and non-geologic utilization in 2030 at face value, that usage would constitute approximately 18 percent of total CO_2 emissions from the U.S. coal fleet in 2015 (1,364,000,000 tons). While 18 percent of total U.S. emissions is a non-trivial amount in terms of managing total U.S. coal-based emissions, said amount – coupled with volumes of CO_2 that separately could be purchased by the EOR industry – could be quite helpful in terms of generating marginal CO_2 demand to further incentivize CCUS.

Table F-2. Potential Emission and Economic Benefits of Various CCUS Technologies in China (estimated)

Category	Product	Combined Emission Reduction Potential ('0000 tons per year)		Combined Economic Benefits ('00 m RMB/yr)	
		2020	2030	2020	2030
Increased energy output and more efficient utilization	Oil, coalbed methane, natural gas, shale gas, and other such energy products	323-330	2495-2620	58	452
	Conversion and production of syngas/liquid fuels	1500	5250		
Increased mining and utilization of mineral resources	Microalgae biofuel	2.6	5.1	0.3	7
	Potash, iodides, boric acid, bromine, lithium salts, etc.	10	300-600		
	Uranium mining	50-100	5280		
	Waters for industrial and agricultural use	60	3400-3700		
Conversion, synthesis, and utilization of organic chemicals	Methanol	2000	5000	1080	>2000
	Organic carbonates and derived materials	534-546	855		
Increased biological and agricultural output and utilization	Technology for conversion of microalgae-fixed CO_2 into biofertilizers, etc. (food and feed additives)	10.4	132	63	
Synthesis and utilization of inorganic chemicals and materials	Carbonate products and materials	520	1840	9	115
	Potash	10	200		
Total		**5020-5090**	**25,000-25,180**	**>1200**	**>3000**

Can Market Demand for CO_2 for Use in Utilization Technologies Incentivize CCUS?

Against this backdrop, can market forces alone – through CO_2 demand for use in EOR and non-EOR markets – incentivize CCUS?

Except as noted below and with the exception of CO_2-EOR, the answer at present is “no” if the goal is to ensure significant CO_2 reductions that satisfy current legal requirements and looming low-carbon policy goals. As more specifically documented in this report, CO_2 utilization in non-geologic contexts faces the following hurdles:

- *Cost of capture*. The current major user of CO_2 – the EOR industry – typically cannot offer a “price” for CO_2 that overcomes the cost of capture for a coal-based utility. This conclusion applies even in the face of existing economic incentives, such as the section 45Q CCUS tax incentive. The economics of CO_2 pricing in other markets is either publicly unavailable or speculative. Still, it is reasonable to assume that CO_2 utilization in non-geologic markets would face many of the same economic challenges currently facing the EOR industry.

- *Insufficient scope of the market/supply considerations*. For the reasons stated above, only CO_2-EOR holds promise for incentivizing CCUS at any reasonable scale for compliance purposes for coal-based utilities.

- *Nearly all non-geologic CO_2 utilization technologies are not yet commercialized.* Even if some of the nascent utilization technologies being explored in China and elsewhere hold potential for use at scale, they face a decades long slog along the technology development pathway and face similar “valley of death” investment hurdles. These timeframes suggest that on their current trajectory, the identified utilization technologies will not be available commercially in time to influence CCUS deployment in the context of the 2050 goals.

- *Geographic/Infrastructure Considerations*. Unless the utilization technology is deployed aside every coal-based facility, the captured CO_2 must be transported to the industrial facilities making use of the CO_2. This issue remains a challenge even for EOR, let alone nascent technologies that are not yet commercial.

- *Legal & Regulatory Considerations*. Under current law, CO_2-EOR owners and operators must: (1) conduct their injections under Class II of the Underground Injection Control (UIC) Program; and (2) opt into Subpart RR of the Greenhouse Gas Reporting Program, which includes a federally approved MRV requirement, if they wish to demonstrate regulatory compliance under the CPP or section 111(b) rule for long-term storage of CO_2. Companies conducting non-EOR geologic storage must: (1) conduct their injections under Class VI of the UIC Program; and (2) report under Subpart RR. Each of these compliance pathways is potentially problematic.

- *CO_2-EOR Storage*. Some in the U.S. CO_2-EOR industry have expressed the position that the MRV requirement is inconsistent with oil and gas law. They have noted, for example, that an EOR operator may not be authorized to conduct storage operations under existing mineral leases. On the other hand, EPA recently approved the first MRV plan for a CO_2-EOR operation. There is not uniform agreement within the U.S. CO_2-EOR industry on these and related issues. The International Organization for Standardization, through the efforts of Working Group 6 under Technical Committee 265, is separately endeavoring to address these and related issues as part of the ongoing efforts to prepare the world's first technical standard governing CO_2 storage in association with EOR operations.

- *Non-EOR Storage*. The current Class VI permit process creates a disincentive and unnecessary hurdle. For example, the Archer Daniels Midland Decatur CO_2 storage project, which was part of the Regional Carbon Sequestration Partnerships Development Phase III program and partly funded by DOE, submitted its application for Class VI well permits in July and September of 2011, but the permits were not granted until April 2014 (MIT, 2016). Similarly, North Dakota has envisaged and made progress toward a CO_2 storage program. After a lengthy process with EPA to shape its submission, the State finally made an application for Class VI primacy regulatory authority in June 2013, which has not been granted by the EPA more than three years later, in essence delaying vital work on CCUS that is necessary to advance the technology (Connors, 2013).

Suggestions for Future Research in CO_2 Utilization Technologies

Despite the barriers indicated above, further investments in CO_2 utilization technologies should be undertaken. On a case-by-case basis (at a specific coal-based power plant, for example), for example, deployment of a CO_2 utilization technology may hold promise for turning an uneconomic project into an economic one. A nascent CO_2 utilization technology may emerge that manages to overcome the hurdles identified in this report in ways that the authors could not have anticipated. A broadly deployed mix of CO_2 utilization technologies may also help to advance CCUS even incrementally – and given the importance of the technology, every little bit helps. CO_2 utilization technologies do not need to provide full-scale carbon management solutions – although that would be ideal, of course. They instead only need to provide sufficient incentive to keep CCUS technologies moving forward.

To that end, it is critical for the Federal government to continue to investment in CO_2 utilization technologies that hold promise. Comparable private-sector and/or public-private partnership investment opportunities are also worthwhile. These include, but are not limited to: (1) the Global CO_2 Initiative; (2) the Carbon XPrize; (3) the International CO_2 Capture Test Network; (4) the Breakthrough Energy Coalition; and (5) the DOE/NETL University Coalition for Fossil Energy Research.

Research investments in CO_2 utilization technologies should be prioritized according to the following criteria – the ability of the CO_2 utilization technology to:

- Make use of CO_2 at scale.
- Make use of CO_2 at scale in the 2020-2030 time frame.
- Be commercially demonstrated prior to 2020 or as soon as possible thereafter.
- Be deployed onsite at fossil fuel-based power plants and CO_2-emitting industrial facilities.
- Have realistic market potential, taking into account displacement considerations.
- Be as effective as geologic technologies.
- Provide non-trivial economic returns.
- Favorably score under existing and forthcoming GHG LCA.

Based upon application of these criteria, this report concludes that further monetary, regulatory and policy investments in the following CO_2 utilization technologies, in descending order, are most likely to incentivize the deployment of CCUS technologies:

THE ROLE OF GHG LIFECYCLE ANALYSES UTILIZATION

Lifecycle analysis (LCA) is used to assess a product's cradle-to-grave environmental impacts. GHG-based LCAs, for example, take into account the climate impacts associated with the production, transportation and use of a product.

Current regulatory programs, to include EPA's Renewable Fuel Standard and California's Low Carbon Fuel Standard, already use GHG LCAs. The use of GHG LCAs is apt to grow in the future, to include the evaluation of CO_2 utilization technologies.

1) **Current CO_2-EOR technology**. It is imperative for the government to clarify the existing regulatory structure, provide support for infrastructure such as pipeline networks and offer financial incentives for carbon capture deployment so that the promise of this existing commercial technology is fully realized.

2) **"State-of-the-Art" CO_2-EOR technologies**. The potential for these technologies has been separately documented in this report.

3) **Other geologic storage technologies that provide economic return**. ECBM and CO_2 injections into residual oil zones provide market demand for CO_2 under certain general oil and gas market conditions. They also fit within the current U.S. legal framework that gives preference to geologic storage over non-geologic uses of CO_2. Not all geologic formations (ECBM, for example) have access to protocols and/or methodologies to document storage.

4) **Saline aquifer storage**. Saline aquifer storage remains EPA's gold standard for CO_2 storage and may be required to provide a back stop for CO_2 utilization projects. The hurdles facing saline storage are primarily economic and regulatory, which current DOE policy recognizes – i.e., the new CarbonSAFE program. The fact remains, however, that the Federal government needs to: (1) put more resources into these projects and (2) reduce the regulatory impediments currently facing them.

5) **Non-geologic storage technologies that provide economic return and that are effective as geologic storage**. The current U.S. legal framework prefers geologic storage over other CO_2 uses. However, non-geologic technologies that keep the CO_2 out of the atmosphere may be credited for the purposes of federal programs with appropriate evidence of atmospheric benefit.

6) **Non-geologic storage technologies that provide economic return yet are not as effective as geologic storage if appropriate EPA research waivers may be obtained**. On a case-by-case basis, a CO_2 utilization technology may exist or emerge that provides an economic return to a fossil fuel-based power plant or CO_2-emitting industrial facility. The technology nonetheless could be helpful in lowering the cost of capture. Appropriate legal recognition would be needed, however, for purposes of compliance with emission reduction obligations. In the final CPP rule, for example, and in the context of algae-based and other non-geologic CCUS technologies, EPA stated that it is "committed to working collaboratively with stakeholders to evaluate the efficacy of alternative utilization technologies, to address any regulatory hurdles, and to develop appropriate monitoring and reporting protocols to demonstrate CO_2 reductions" (80 Fed. Reg. 64662, 64884 (2015)).

G. Economic Opportunity for the U.S. Associated with Commercial-Scale CCUS Deployment

Key Findings

- Assuming a price for CO_2 of $33/metric ton ($1.75/Mcf) delivered to the oil field at pressure and a $70 per barrel price of oil, and using 0.45 metric tons of purchased (net) CO_2 per barrel of recovered oil, utilization of CO_2 for EOR results in a transfer of $14.90 of the $70 per barrel oil price to firms involved with capture and transport of CO_2. The economic value is sensitive to the price of oil, of course, and will vary in response to oil market conditions.
- The economic incentive potential of all other pathways (to include all non-geologic options) is largely unquantifiable based on publicly available data. Moreover, such options face a host of known technical, economic and policy hurdles.

Key Recommendations

- More economic and technical research and analysis need to be conducted on CO_2 utilization in non-geologic options, including chemicals and fuels. The focus of this additional research and analysis should, where data exist, take into account the criteria for review of CO_2 utilization technologies detailed in Chapter D of this report.
- Additional research should be supported regarding advancing the following technologies toward commercialization: (1) inorganic carbonates and bicarbonates; (2) plastics and polymers; (3) organic and specialty chemicals; and (4) agricultural fertilizers.

Analysis

Applying various evaluation criteria, the primary economic opportunity for the United States associated with commercial-scale CCUS deployment remains geologic storage associated with energy production. These include: (1) CO_2-EOR; (2) ROZ; (3) organically-rich shales; and (4) ECBM.

Assuming a price for CO_2 of $33/metric ton ($1.75/Mcf) delivered to the oil field at pressure, and using 0.45 metric tons of purchased (net) CO_2 per barrel of recovered oil, utilization of CO_2 for EOR results in a transfer of $14.90 of the $70 per barrel oil price to firms involved with capture and transport of CO_2. An economic benefit of $15/barrel coupled with CCUS-based tax incentives such as section 45Q should go some way towards incentivizing CCUS.

The economic value is sensitive to the price of oil, of course, and will vary in response to oil market conditions. A typical CO_2 offtake contract would index the price of CO_2 to an oil price benchmark. This means that the coal-based utility would not be able to rely upon a fixed CO_2 price return over the life of a CCUS project, a situation that could complicate project finance.

Geologic storage associated with energy production also provides ancillary benefits – including long-term removal of CO_2 from the atmosphere in a manner that is currently favored by EPA policy – yet itself continues to face a variety of economic and policy hurdles, as documented in prior studies. Until these hurdles are mitigated, the full incentive potential of these pathways are likely to remain unfulfilled.

Non-geologic utilization opportunities exist, including: (1) inorganic carbonates and bicarbonates; (2) plastics and polymers; (3) organic and specialty chemicals; and (4) agricultural fertilizers. All of these opportunities face a variety of technical and economic challenges that are likely to impede their ability to incentivize CCUS in the immediate future.

CO_2 may also be utilized through chemical and biological processes to produce transportation fuels, which is a very large market. This pathway is also unlikely to incentivize CCUS in the immediate future for a variety of technical and economic reasons, including: (1) the fact that transportation fuels are ultimately combusted and thus release CO_2 to the atmosphere and (2) current U.S. policy favors geologic-based utilization pathways for CAA compliance. And while the case could be made that some CO_2-derived transportation fuels have lower GHG emissions than fossil-based fuels on a lifecycle basis, the former still faces significant market competition and displacement hurdles.

H. References

Chapter B

U.S. Department of Energy, Regional Carbon Sequestration Partnership Initiative. www.netl.doe.gov/research/coal/carbon-storage/carbon-storage-infrastructure/rcsp

Global CCS Institute. www.globalccsinstitute.com/insights/authors/DuncanKenyon/2015/03/13/ccus-building-climate-change-solution

National Coal Council "Fossil Forward: Bringing Scale & Speed to CCS Deployment" January 2015. www.nationalcoalcouncil.org/studies/2015/Fossil-Forward-Revitalizing-CCS-NCC-Approved-Study.pdf

BP Energy Outlook 2016. www.bp.com/content/dam/bp/pdf/energy-economics/energy-outlook-2016/bp-energy-outlook-2016.pdf

Coal Industry Advisory Board – International Energy Agency, "The Role of Coal for Energy Security in World Regions" May 2016. www.iea.org/ciab/The_role_of_coal_for_energy_security_in_world_regions.pdf

International Energy Agency 450 Scenario sets out an energy pathway consistent with the goal of limiting global temperature increase to 2^{o}C by limiting concentration of greenhouse gases in the atmosphere to 450 parts per million of CO_2. www.iea.org/publications/scenariosandprojections/

International Energy Agency CCS Roadmap. https://www.iea.org/publications/freepublications/publication/CCS_roadmap_foldout.pdf

National Coal Council, "Leveling the Playing Field: Policy Parity for CCS Technologies" November 2015. www.nationalcoalcouncil.org/studies/2015/Leveling-the-Playing-Field-for-Low-Carbon-Coal-Fall-2015.pdf

International Energy Agency "Energy Technology Perspectives 2015". https://www.iea.org/publications/freepublications/publication/EnergyTechnologyPerspectives2015ExecutiveSummaryEnglishversion.pdf

United Nations Framework Convention on Climate Change, The Paris Agreement. http://bigpicture.unfccc.int/#content-the-paris-agreemen

Chapter C

Code of Federal Regulations (2016). Title 40, Part 60 – Standards of Performance for New Stationary Sources, section 60.5555(g).

Conference of the Parties to the United Nations Framework Convention on Climate Change, Twenty-First Session (2015). Durban Platform for Enhanced Action (decision 1/CP.17), Adoption of a protocol, another legal instrument, or an agreed outcome with legal force under the Convention applicable to all Parties, Adoption of the Paris Agreement, draft decision -/CP.21, Annex, Paris Agreement, Art. 2, sec. 1(a). unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf and http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

GHG Daily Monitor (2016). Achieving Paris Agreement Goals Requires CCUS, Groups Say, GHG Daily Monitor, Vol. 1, No. 74. www.exchangemonitor.com/publication/ghg-daily-monitor/achieving-paris-agreement-goals-requires-ccus-groups-say/

Global Carbon Capture and Storage Institute (2015). CCS Status Report, GCCSI. hub.globalccsinstitute.com/sites/default/files/publications/196843/global-status-ccs-2015-summary.pdf

Interagency Task Force on Carbon Capture and Storage (2010). Final Report. energy.gov/sites/prod/files/2013/04/f0/CCSTaskForceReport2010_0.pdf

Intergovernmental Panel on Climate Change (2015). Climate Change 2014, Synthesis Report, p. 23. ar5-syr.ipcc.ch/ipcc/ipcc/resources/pdf/IPCC_SynthesisReport.pdf

International Energy Agency (2013). Technology Roadmap, Carbon Capture and Storage. www.iea.org/publications/freepublications/publication/TechnologyRoadmapCarbonCaptureandStorage.pdf

International Energy Agency (2014). CCS 2014: What Lies in Store for CCS, Insight Series 2014. www.iea.org/publications/insights/insightpublications/Insight_CCS2014_FINAL.pdf

Jacob Schneider et al. (2012). "Thermodynamics and Kinetics of CO_2, CO, and H^+ Binding to the Metal Centre of CO_2 Reduction Catalysts," Chem. Soc. Rev., 41, 2036-2051.

National Coal Council (2015). Fossil Forward: Revitalizing CCS, Bringing Scale and Speed to CCS Deployment. www.nationalcoalcouncil.org/studies/2015/Fossil-Forward-Revitalizing-CCS-NCC-Approved-Study.pdf

National Research Council (2001). "Carbon Management: Implications for R&D in the Chemical Sciences and Technology: A Workshop Report to the Chemical Sciences Roundtable." www.ncbi.nlm.nih.gov/books/NBK44146/

"New and Future Developments in Catalysis: Activation of Carbon Dioxide" (2013). Elsevier. books.google.com/books?id=oxPCJFoXLYwC&pg=PA559&lpg=PA559&dq=thermodynamic+and+kinetic+barriers+to+using+CO_2+for+products&source=bl&ots=St4NnVDFUJ&sig=hIHvR0f9oHK2-Ed_yShhCk0it8Q&hl=en&sa=X&ved=0ahUKEwjTz76R9vrNAhXJ64MKHZmuD-04ChDoAQgrMAM#v=onepage&q=thermodynamic%20and%20kinetic%20barriers%20to%20using%20CO_2%20for%20products&f=false

"Novel Materials for Carbon Dioxide Mitigation Technology" (2015). Elsevier. books.google.com/books?id=qCdrBgAAQBAJ&pg=PA252&lpg=PA252&dq=thermodynamic+and+kinetic+barriers+to+using+CO_2+for+products&source=bl&ots=ABpnwUuerz&sig=mtRxaqqpn_GkBh9OvCmMaWXaWko&hl=en&sa=X&ved=0ahUKEwjb-eDl8_rNAhVm8IMKHVx2ByUQ6AEILjAC#v=onepage&q=thermodynamic%20and%20kinetic%20barriers%20to%20using%20CO_2%20for%20products&f=false.

North American Climate, Clean Energy, and Environment Partnership Action Plan (2016). www.whitehouse.gov/the-press-office/2016/06/29/north-american-climate-clean-energy-and-environment-partnership-action

U.S. Environmental Protection Agency (2015). Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units, 80 Fed. Reg. 64662, 64884. www.gpo.gov/fdsys/pkg/FR-2015-10-23/pdf/2015-22842.pdf

U.S. Environmental Protection Agency (2011). PSD and Title V Permitting Guidance for Greenhouse Gases, EPA-457/B-11/001, Pages 36, 43. www.epa.gov/sites/production/files/2015-12/documents/ghgpermittingguidance.pdf

U.S. Environmental Protection Agency (2015). Standards of Performance for Greenhouse Gas Emissions from New, Modified, and Reconstructed Stationary Sources: Electric Utility Generating Units, 80 Fed. Reg. 64510, 64581. www.gpo.gov/fdsys/pkg/FR-2015-10-23/pdf/2015-22837.pdf

Vello Kuuskraa et al. (2013). "CO_2 Utilization from 'Next Generation' CO_2 Enhanced Oil Recovery Technology," Energy Procedia, Elsevier. www.adv-res.com/pdf/CO2%20Utilization%20from%20_Next%20Generation_%20CO2%20Enhanced%20Oil%20Recovery%20Technology.pdf

Chapter D

Global CCS Institute (GCCSI) (2011), Parsons Brinckerhoff, Accelerating the uptake of CCS – industrial use of captured carbon dioxide. www.globalccsinstitute.com/publications/accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide

Massachusetts Institute of Technology (MIT) (2007). The Future of Coal – Summary Report, 2007. web.mit.edu/coal/The_Future_of_Coal_Summary_Report.pdf

National Coal Council (2015). Leveling the Playing Field for Low Carbon Coal: Policy Parity for CCS Technologies. www.nationalcoalcouncil.org/page-NCC-Studies.html

National Coal Council (2015). Fossil Forward - Revitalizing CCS: Bringing Scale and Speed to CCS Deployment. www.nationalcoalcouncil.org/page-NCC-Studies.html

Organization for Economic Cooperation and Development (OECD) and International Energy Agency (IEA) (2015), Storing CO_2 through Enhanced Oil Recovery. France. www.iea.org/publications/insights/insightpublications/Storing_CO2_through_Enhanced_Oil_Recovery-145x206.pdf

US Department of Energy (DOE-2011) Technology Readiness Assessment Guide, DOE G 413.3-4A. www2.lbl.gov/dir/assets/docs/TRL%20guide.pdf

Chapter E

Enhanced Oil Recovery & Residual Oil Zones

Advanced Resources International, Evaluating the Potential for "Game Changer" Improvements in Oil Recovery Efficiency from CO_2 Enhanced Oil Recovery, U.S. Department of Energy, Office of Oil and Natural Gas, Office of Fossil Energy, August 2005. www.fe.doe.gov/programs/oilgas/eor/Game_Changer_Oil_Recovery_Efficiency.html

Goodyear, S.G., and P.M. Jensen, Past Experiences and Future Challenges for CO_2 Injection, First Regional Symposium on Carbon Management, Dammam, Saudi Arabia, 22–24 May 2006.

Green D.W. and G. P. Willhite, SPE, 1998. "Enhanced Oil Recovery", SPE Textbook Series Vol 6, ISBN 1-55563-077-4.

Kootungal, L., 2014 Worldwide EOR Survey", Oil & Gas Journal, EOR/Heavy Oil Survey issue, April 7, 2014/Volume 112.4, pp. 79-91.

Koperna, G. J., Melzer, L. S., & Kuuskraa, V. A. (2006, January 1). Recovery of Oil Resources from the Residual and Transitional Oil Zones of the Permian Basin. Society of Petroleum Engineers. doi:10.2118/102972-MS.

Koperna, G. J., Kuuskraa, V. A.; "Technical Oil Recovery Potential from Residual Oil Zones: Permian Basin, Big Horn Basin and Williston Basin ", prepared for U.S. Department of Energy, Office of Fossil Energy - Office of Oil and Natural Gas, February, 2006.

Kuuskraa, V.A., and M. Wallace, "CO_2-EOR Set for Growth as New CO_2 Supplies Emerge", Oil & Gas Journal, EOR/Heavy Oil Survey issue, April 7, 2014/Volume 112.4, pp. 67-76.

Kuuskraa, V.A., Wallace. M. and DiPietro, P., "An In-Depth Look at "Next Generation" CO_2-EOR Technology, prepared under U.S. DOE contract DE-FE0004001, ESPA Task 150.07.02, July 16, 2013.

Kuuskraa, V., Van Leeuwen, T. and M. Wallace, "Improving Domestic Energy Security and Lowering CO_2 Emissions with "Next Generation" CO_2-Enhanced Oil Recovery (CO_2-EOR)", DOE/NETL-2011/1504, July 2011, prepared by Advanced Resources International, Inc.

Kuuskraa, V.A., Malone, T. and P. DiPietro, "CO_2-EOR Offshore Resource Assessment", prepared for the U.S. Department of Energy/NETL, DOE NETL Contract Number DE-FE0004001, report DOE/NETL-2014/1631, June 5, 2014.

Melzer, L.S. Residual Oil Zones (ROZs): Why all the Buzz. Colorado School of Mines, Golden, Colorado, April 4-5, 2012.

Melzer, L.S., 2006. "Stranded Oil in the Residual Oil Zones." U.S. Department of Energy Report. February 2006. fossil.energy.gov/programs/oilgas/publications/eor_CO2_Melzer_Document_with_figures.pdf

Trentham, R.C., Melzer, L.S., Kuuskraa, V.A., and G. Koperna, 2015. Case Studies of the ROZ CO_2 Flood and the Combined ROZ/MPZ CO_2 Flood at the Goldsmith Landreth Unit, Ector County, Texas. Using "Next Generation" CO_2-EOR Technologies to Optimize the Residual Oil Zone CO_2 Flood. DOE Award No.: DE-FE0005889, Final Report, in press.

Trentham, R.C., Melzer, L.S. and D. Vance, 2012. Commercial Exploitation and the Origin of Residual Oil Zones: Developing a Case History in the Permian Basin of New Mexico and West Texas, performed under RPSEA contract 81.089 08123-19-RPSEA, June 28, 2012.

Wallace, M. et al., 2015. "A Review of the CO_2 Pipeline Infrastructure in the U.S." DOE NETL Contract Number DE-FE0004001 under ESPA Task 200.01.03. DOE/NETL-2014/1681, April 21, 2015.

CO_2 Use in Shale Formations

Continental Resources Inc., 2012, Bakken and Three Forks: www.contres.com/operations/bakkenand-three-forks (accessed May 30, 2013).

Energy Information Administration, 2016, Drilling productivity report: U.S. Department of Energy, https://www.eia.gov/petroleum/drilling/pdf/dpr-full.pdf (accessed 2016).

Energy Information Administration, 2016, Marcellus Region drilling productivity report: U.S. Department of Energy, www.eia.gov/petroleum/drilling/pdf/marcellus.pdf (accessed 2016).

Energy Information Administration, 2011, Review of Emerging Resources—U.S. shale gas and shale oil plays: U.S. Department of Energy, Washington, D.C., www.eia.gov/analysis/studies/usshalegas/pdf/usshaleplays.pdf (accessed July 2016).

Energy Information Administration, 2013, Technically recoverable shale oil and shale gas resources—an assessment of 137 shale formations in 41 countries outside the United States: U.S. Department of Energy, Washington, D.C., www.eia.gov/analysis/studies/worldshalegas/pdf/fullreport.pdf (accessed 2016).

Godec, M., Koperna, G., Petrusak, R., and Oudinot, A., 2013a, Assessment of factors influencing CO_2 storage capacity and injectivity in eastern U.S. gas shales: Energy Procedia, v. 37, p. 6644–6655.

Godec, M., Koperna, G., Petrusak, R., and Oudinot, A., 2013b, Potential for enhanced gas recovery and CO_2 storage in the Marcellus Shale in the eastern United States: International Journal of Coal Geology, v. 118, p. 95–104.

Hawthorne, S.B., Gorecki, C.D., Sorensen, J.A., Miller, D.J., Harju, J.A., and Melzer, S.L.,

Hawthorne, S.B., Gorecki, C.D., Sorensen, J.A., Steadman, E.N., Harju, J.A., and Melzer, S., 2013, Hydrocarbon mobilization mechanisms from Upper, Middle, and Lower Bakken reservoir rocks exposed to CO_2: Presented at the Society of Petroleum Engineers (SPE) Unconventional Resources Conference – Canada, Calgary, Alberta, Canada, November 5–7, p. 9, SPE 167200.

IEA Greenhouse Gas R&D Programme, 2009, Development of storage coefficients for CO_2 storage in deep saline formations: 2009/12, October 2009.

Jarrell, P.M., Fox, C.E., Stein, M.H., and Webb, S.L., 2002, Practical aspects of CO_2 flooding: Society of Petroleum Engineers Monograph, Henry L. Doherty Series, Richardson, Texas, v. 22, p. 220.

Kurtoglu, B., Sorensen, J., Braunberger, J., Smith, S., and Kazemi, H., 2013, Geologic characterization of a Bakken reservoir for potential CO_2-EOR: Presented at 2013 Unconventional Resources Technology Conference, Denver, Colorado, August 12–14, URTeC 1619698.

LeFever, J., and Helms, L., 2008, Bakken Formation reserve estimates: North Dakota Geological Survey white paper, Bismarck, North Dakota, p. 6.

Liu, G., Sorensen, J.A., Braunberger, J.R., Klenner, R., Ge, J., Gorecki, C.D., Steadman, E.N., and Harju, J.A., 2014, CO_2-based enhanced oil recovery from unconventional resources—a case study of the Bakken Formation: Society of Petroleum Engineers, SPE-168979-MS.

Nordeng, S.H., LeFever, J.A., Anderson, F.J., Bingle-Davis, M., and Johnson, E.H., 2010, An examination of the factors that impact oil production from the middle member of the Bakken Formation in Mountrail County, North Dakota: North Dakota Geological Survey, RI-109.

Nuttall B., Eble, C.F., Drahovzal, J.A., and Bustin, M., 2005, Analysis of Devonian black shales for potential carbon dioxide sequestration and enhanced natural gas production: Kentucky Geological Survey Report DE-FC26-02NT41442 for U.S. Department of Energy National Energy Technology Laboratory, p. 120.

Sorensen, J.A., Braunberger, J.R., Liu, G., Smith, S.S., Klenner, R.C.L., Steadman, E.N., Harju, J.A., 2012, CO_2 storage and utilization in tight hydrocarbon-bearing formations—a case study of the Bakken Formation in the Williston Basin: Presented at the 11th International Conference on Greenhouse Gas Control Technologies (GHGT-11), Kyoto, Japan, November 18–22, 2012.

Sorensen, J.A., Hawthorne, S.A., Smith, S.A., Braunberger, J.R., Liu, G., Klenner, R., Botnen, L.S., Steadman, E.N., Harju, J.A., and Doll, T.E., 2014, CO_2 storage and enhanced Bakken recovery research program: Subtask 1.10 final report for U.S. Department of Energy Cooperative Agreement No. DE-FC26-08NT43291, May, p. 79.

U.S. Department of Energy National Energy Technology Laboratory, 2012, Carbon sequestration atlas of the United States and Canada (4th ed.).

U.S. Department of Energy National Energy Technology Laboratory, 2010, Carbon sequestration atlas of the United States and Canada (3rd ed.).

U.S. Department of Energy National Energy Technology Laboratory, 2008, Carbon sequestration atlas of the United States and Canada (2nd ed.).

U.S. Department of Energy, 2007, Carbon sequestration atlas of the United States and Canada: U.S. Department of Energy Office of Fossil Energy, March, www.precaution.org/lib/carbon_sequestration_atlas.070601.pdf (accessed September 9, 2014).

Uzoh, C., Han, J., Hu, L.W., Siripatrachai, N., Osholake, T., and Chen, X., 2010, Economic optimization analysis of the development process on a field in the Barnett Shale formation: EME 580 Final Report.

Enhanced Coal Bed Methane

Puri, R., Yee, D., "Enhanced coalbed methane recovery," SPE Paper No. 20732 presented at the Society of Petroleum Engineers 65th Annual Technical Conference and Exhibition, New Orleans, LA, September 23–26, 1990.

Gunter W.D., T. Gentzis, B.A. Rottenfusser, and R.J.H. Richardson, "Deep coalbed methane in Alberta, Canada: A fuel resource with the potential of zero greenhouse gas emissions," *Energy Conversion and Managemen*t, Volume 38, Number unknown, pp. 217-222, 1997

Every, R.L. and Dell'osso Jr., L., "A new technique for the removal of methane from coal," *CIM Bulletin*, 65: 143-150, 1972.

http://www.ieaghg.org/docs/general_publications/8.pdf

Gale, John and Paul Freund, "Coal-Bed Methane Enhancement with CO_2 Sequestration Worldwide Potential," *Environmental Geosciences*, Volume 8, Issue 3, pages 210–217, September 2001.

Koperna, George J., and David Riestenberg, "Carbon Dioxide Enhanced Coalbed Methane and Storage: Is There Promise?" SPE Paper SPE 126627 presented at the 2009 SPE International Conference on CO_2 Capture, Storage, and Utilization held in San Diego, California, USA, 2–4 November 2009.

Godec, Michael, George Koperna, and John Gale, "CO_2-ECBM: A Review of its Status and Global Potential," *Energy Procedia,* Volume 63, 2014, Pages 5858-5869.

Additional Geologic Uses of CO_2

Buscheck T.A., Bielicki, J.M., Chen M., Sun Y., Hao Y., Edmunds T.A., Saar M.O., and Randolph J.B., 2014. Integrating CO_2 storage with geothermal resources for dispatchable renewable electricity*, Energy Procedia*, **63**:7619-7630.

Buscheck, T.A., White, J.A., Carroll, S.A., Bielicki, J.M., and Aines, R.D., 2016a. Managing geologic CO_2 storage with pre-injection brine production: A strategy evaluated with a model of CO_2 injection at Snøhvit, *Energy and Environmental Science*, **9**: 1504-1512.

Buscheck, T.A., Bielicki, J.M., White, J.A., Sun, Y., Hao, Y., Bourcier, W.L., Carroll, S.A., and Aines, R.D., 2016b. Pre-injection brine production in CO_2 storage reservoirs: An approach to augment the development, operation, and performance of CCS while generating water, *International Journal of Greenhouse Gas Control*, http://dx.doi.rg/10.1016/j.ijggc.2016.04.0181750-5836

Buscheck, T.A., Bielicki, J.M., Edmunds, T.A., Hao, Y., Sun, Y., Randolph, J.M., and Saar, M.O., 2016c. Multi-fluid geo-energy systems: Using geologic CO_2 storage for geothermal energy production and grid-scale energy storage in sedimentary basins, *Geosphere*, **12**(3), doi:10.1130/GES01207.1

Geological CO_2 storage characterization: The key to deploying clean fossil energy technology (2013). Chapter 11: Displaced fluid management—the key to commercial-scale geological CO_2 storage, Ed. Ronald C. Surdam, Springer Environmental Science and Engineering

University of Wyoming (2013). UW researchers' lithium discovery could boost CO_2 storage prospects. www.uwyo.edu/uw/news/2013/04/uw-researchers-lithium-discovery-could-boost-CO_2-storage-prospects.html

US Department of Energy, Office of Fossil Energy (2016). Energy department selects projects to demonstrate feasibility of producing usable water from CO_2 storage sites. energy.gov/fe/articles/energy-department-selects-projects-demonstrate-feasibility-producing-usable-water-CO_2

Bioenergy with CCS

IEA Bioenergy Annual Outlook 2015.

EIA Annual Outlook 2015.

Biomass Power Association website.

United States Department of Energy website.

Non-Geologic Uses of CO_2 – Food and Beverage

IHS Chemical Economics Handbook 2015.

American Beverage Association website.

McGraw Hill Encyclopedia of Science and Technology 1997.

www.dryiceinfo.com.

Power Engineering Magazine September 2000.

Private communication with AES Executives.

Non-Geologic Uses of CO_2 – Inorganic Chemicals

Metz, B. et al. eds., IPCC (2005): IPCC Special Report on Carbon Dioxide Capture and Storage, Chapter 7. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, 442pp and references therein.

O'Connor, W.K., D.C. Dahlin, G.E. Rush, S.J. Gedermann, L.R. Penner, D.N. Nilsen (2005). Aqueous mineral carbonation, Final Report, DOE/ARC-TR-04-002.

Carbon Sequestration Leadership Forum (2013), Final Phase II Report by the CSLF Task Force on CO_2 Utilization Options, www.cslforum.org/publications/documents/CO2UtilizationOptions_Phase2FinalReport.pdf

See ASTM C 266: Time of setting of hydraulic-cement paste by Gillmore needles, AASHTO T 131 and ASTM C 191: Time of setting of hydraulic cement by Vicat needle.

ASTM C150: Standard specification for Portland Cement.
www.ieaghg.org/rdd/gmap/project_specific.php?project_id=40
U.S. Geological Survey, 2009, Cement & construction sand and gravel statistics.
U.S. Geological Survey (2009a), Construction sand and gravel statistics, in Kelly, T.D., and Matos, G.R., comps., Historical statistics for mineral and material commodities in the United States: U.S. Geological Survey Data Series 140, available online at pubs.usgs.gov/ds/2005/140/.
U.S. Geological Survey (2009b), Cement statistics, in Kelly, T.D., and Matos, G.R., comps., Historical statistics for mineral and material commodities in the United States: U.S. Geological Survey Data Series 140, available online at pubs.usgs.gov/ds/2005/140/.

Non-Geologic Uses of CO_2 – Organic & Specialty Chemicals/Plastics & Polymers/Fuels

Ampelli C; Perathoner S; Centi G. CO_2 utilization: an enabling element to move to a resource- and energy-efficient chemical and fuel production. Phil. Trans. R. Soc. A 2015, 373, 20140177.
Aresta, M.; Quaranta, E. Carbon Dioxide: A Substitute for Phosgene. Chemtech, 1997, 27 (3), 32-40.
Centi, G.; Perathoner. S. Opportunities and prospects in the chemical recycling of carbon dioxide to fuels. Catalysis Today, 2009, 148, 191–205.
CRI. 2015. CRI's plant in Iceland for conversion of CO_2 by catalytic hydrogenation to methanol: carbonrecycling.is/projects-1/.
Dai, C.Y., A.F. Zhang, K.K. Hou, M. Liu, C.S. Song and X.W. Guo. Synthesis of Hollow Nanocubes and Macroporous Monoliths of Silicalite-1 by Alkaline Treatment. Chemistry of Materials, 2013, 25 (21), 4197-4205.
Dai, C.Y., A.F. Zhang, M. Liu, J.J. Li, F.Y. Song, C.S. Song* and X.W. Guo*. Facile One-step Synthesis of Hierarchical Porous Carbon Monoliths as Superior Support of Fe-based Catalyst for CO_2 Hydrogenation. RSC Advances, 2016, 6, 10831-10836.
EPA. 2009. www.epa.gov/ttn/oarpg/t1/fact_sheets/voc_exemp01011309.pdf
Eramo, M. Technip's *Inaugural Ethylene Forum*, November 5, 2013. http://media.corporate-ir.net/media_files/IROL/11/110877/05_Global_Ethylene_Market_Outlook_Eramo.pdf
European firms seek to convert early gains into market opportunities. Chem. Eng. News, 2013, 91, 20-21.
FONA. 2014. Technologies for Sustainability and Climate Protection Chemical Processes and Uses of CO_2. Federal Ministry of Education and Research, Bonn, 2014.
Jiang, X., N. Koizumi, X.W. Guo and C.S. Song.* Bimetallic Pd-Cu Catalysts for Selective CO_2 Hydrogenation to Methanol. Applied Catalysis B: Environmental, 2015, 170–171, 173–185.
Josef, D. 2014. www.slideshare.net/JosefDavid/global-CO2-2014
Koizumi, N., X. Jiang, J. Kugai, and C.S. Song. Effects of Mesoporous Silica Supports and Alkaline Promoters on Activity of Pd Catalysts in CO_2 Hydrogenation for Methanol Synthesis. Catalysis Today, 2012, 194, 16-24.
Li, Y.W.; Chan, S.H.; Sun, Q. Heterogeneous catalytic conversion of CO_2: a comprehensive theoretical review. Nanoscale, 2015, 7, 8663-8683.

Ma, X.L., X.X. Wang, and C.S. Song. "Molecular Basket" Sorbents for Separation of CO_2 and H_2S from Various Gas Streams. Journal of American Chemical Society, 2009, 131 (16), 5777–5783.

McSpadden, K. 2015. fortune.com/2015/04/28/audi-just-invented-fuel-made-from-CO2-and-water/

Nie, X.W., H.Z. Wang, M.J. Janik, X.W. Guo* and C.S. Song*. Computational Investigation of Fe-Cu Bimetallic Catalysts for CO_2 Hydrogenation. Journal of Physical Chemistry C, 2016, 120 (17), 9364–9373.

NPK. 2015. npk101.wordpress.com/category/nitrogenous-fertilizers/

Ondrey, G. BASF INAUGURATES WORLD-SCALE ACRYLIC ACID COMPLEX IN BRAZIL. CHEM. ENG. NEWS, June 20, 2015.

Quadrelli, E.A.; Fussler, C. Solutions for a Circular Carbon Economy. Briefing Paper. CPE Lyon, April 2015.

Quadrelli, EA; Centi, G.; Duplan, JL; Perathoner. S. Carbon Dioxide Recycling: Emerging Large-Scale Technologies with Industrial Potential. ChemSusChem 2011, 4 (9), 1194-1215.

Sadat, W.I.A.; Archer, L.A. The O2-assisted Al/CO_2 electrochemical cell: A system for CO_2 capture/conversion and electrical power generation. Sci. Adv. 2016, 2, e1600968, July 20, 2016.

Satthawong, R., N. Koizumi, C.S. Song*, and P. Prasassarakich. Comparative Study on CO_2 Hydrogenation to Higher Hydrocarbons over Fe-Based Bimetallic Catalysts. Topics in Catalysis, 2014, 57, 588–594.

Satthawong, R., N. Koizumi, C.S. Song*, and P. Prasassarakich. Light Olefin Synthesis from CO_2 Hydrogenation over K-Promoted Fe-Co Bimetallic Catalysts. Catalysis Today, 2015, 251, 34-40.

Satthawong, R., N. Koizumi, C.S. Song, and P. Prasassarakich. Bimetallic Fe-Co Catalysts for CO_2 Hydrogenation to Higher Hydrocarbons. Journal of CO_2 Utilization, 2013, 3-4, 102-106.

Scott, A. Carbon Dioxide-To-Chemical Processes Poised for Commercialization. Chem. Eng. News, 2013, 91, 20-21.

Song, C.S., A. M. Gaffney, and K. Fujimoto. CO_2 Conversion and Utilization. American Chemical Society, Washington DC, ACS Symposium Series, Vol. 809, 2002, 420 pp.

Song, C.S.; Pan, W. Tri-reforming of Methane: A Novel Concept for Catalytic Production of Industrially Useful Synthesis Gas with Desired H_2/CO Ratios. Catalysis Today, 2004, 98 (4), 463-484.

Song, C.S. Global Challenges and Strategies for Control, Conversion and Utilization of CO_2 for Sustainable Development Involving Energy, Catalysis, Adsorption and Chemical Processing. Catalysis Today, 2006, 115, 2–32.

Wang X.X, V. Schwartz, J. C. Clark, X.L. Ma, S. Overbury, X.C. Xu, C.S. Song. Infrared Study of CO_2 Sorption over "Molecular Basket" Sorbent Consisting of Polyethylenimine-Modified Mesoporous Molecular Sieve. Journal of Physical Chemistry C, 2009, *113* (17), 7260–7268.

Wang, W., S.P. Wang, X.B. Ma and J.L. Gong. Recent advances in catalytic hydrogenation of carbon dioxide. Chem. Soc. Rev., 2011, 40, 3703-3727.

Wang, X.X. and C.S. Song. Temperature-Programmed Desorption of CO_2 from Molecular Basket Sorbents Consisting of SBA-15 with Different Loadings of Polyethylenimine. Catalysis Today, 2012, 194, 44-52.

Non-Geologic Uses of CO_2 – Fuels

www.eia.gov/forecasts/ieo/liquid_fuels.cfm.
energy.gov/sites/prod/files/2016/03/f30/mypp_beto_march2016_2.pdf.
www.usea.org/sites/default/files/042015_Microalgae%20removal%20of%20CO2%20from%20flue%20gas_ccc250.pdf.
pubs.acs.org/doi/abs/10.1021/acs.iecr.5b03277.
energy.gov/eere/bioenergy/algal-biofuels.
algaebiomass.org/resource-center/abo-resources/algae-map/.
www.usea.org/sites/default/files/042015_Microalgae%20removal%20of%20CO2%20from%20flue%20gas_ccc250.pdf.
energy.gov/eere/bioenergy/related-links-0.
energy.gov/eere/bioenergy/algal-integrated-biorefineries.
algaebiomass.org/blog/8938/the-new-2015-algae-industry-project-book/.
www.algenol.com/sites/default/files/press_releases/Production%20and%20Jobs%20Press%20Release%2003.08.2013.pdf.
www.duke-energy.com/environment/carbon-capture-and-storage.asp.
www.lanzatech.com/arcelormittal-lanzatech-primetals-technologies-announce-partnership-construct-breakthrough-e87m-biofuel-production-facility/.
www.netl.doe.gov/research/coal/project-information/proj?k=FE0026490.
www.srpnet.com/newsroom/releases/032116.aspx.
www.nesteoil.com/default.asp?path=1,41,540,17988,7906,24191.
msbusiness.com/blog/2014/11/14/bioplastics-maker-opens-business-east-mississippi/ .
www.accelergy.com/technology_cbtl.html.
www.algaeindustrymagazine.com/accelergy-partners-with-yankuang-for-algae-farm-at-coal-to-liquids-plant-in-china/.
www.biofuelsdigest.com/bdigest/2014/10/01/state-of-the-algae-industry-10-top-level-commercial-leaders-look-at-the-path-to-scale/.
solarfuelshub.org/.
arpa-e.energy.gov/?q=slick-sheet-project/converting-CO2-fuel-and-chemicals.
energy.gov/sites/prod/files/2014/09/f18/algal_biofuels_factsheet.pdf.
www.epa.gov/sites/production/files/2015-08/documents/algenol-determination-ltr-2014-12-4.pdf.
www.jouleunlimited.com/epa/OAR-16-000-5822_Joule_Petition_Response.pdf.
www.epa.gov/otaq/fuels/renewablefuels/new-pathways/approved-pathways.htm.
www.theguardian.com/environment/2014/apr/02/ecover-algae-laundry-liquid-palm-oil
cbmjournal.springeropen.com/articles/10.1186/s13021-015-0040-7.
algaebiomass.org/wp-content/gallery/2012-algae-biomass-summit/2016/05/Algae-Biomass-Organization-FE-Carbon-Use-Reuse-RFI-Comments-FINAL-4_25_16.pdf.
U.S. DOE 2010. National Algal Biofuels Technology Roadmap. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program.
pubs.acs.org/doi/abs/10.1021/es304135b.
www.algenol.com.
bioenergykdf.net/billionton2016/overview.

energy.gov/sites/prod/files/2016/03/f30/mypp_beto_march2016_2.pdf.
bioenergykdf.net/billionton2016/overview.
www.algenol.com.
www1.eere.energy.gov/bioenergy/pdfs/algal_biofuels_roadmap.pdf.
www.nap.edu/read/13105/chapter/8#274.
digitalcommons.pace.edu/cgi/viewcontent.cgi?article=1945&context=lawfaculty.
www.argusmedia.com/~/media/files/pdfs/samples/argus-americas-biofuels.pdf/?la=en
www.argusmedia.com/~/media/files/pdfs/white-paper/california-environmental-markets.pdf/?la=en.
www.afdc.energy.gov/laws/10515.
www.rd.usda.gov/programs-services/biorefinery-renewable-chemical-and-biobased-product-manufacturing-assistance.
www.gao.gov/products/GAO-15-674.
onlinelibrary.wiley.com/doi/10.1002/bbb.1505/references.
www.bio.org/sites/default/files/Position_Carbon_Footprint_PCF.pdf.
www.biopreferred.gov/BioPreferred/.
www.biopreferred.gov/BPResources/files/WhyBiobased.pdf.
onlinelibrary.wiley.com/doi/10.1111/j.1530-9290.2012.00468.x/abstract.
www.coca-colacompany.com/stories/plantbottle-benefits.
42 U.S.C. § 7545(o).
H.R. 2454, Section 722(b)(9).

Non-Geologic Uses of CO_2 – Agricultural Fertilizers

Agricultural prices, National Agricultural Statistics Service. USDA, May 2, 2016.
The future of forests: Emissions from Tropical Deforestation, with and without a carbon price, 2016-2050. Jonah Busch, Jens Engelmann. Center for Global Development. Washington D.C. August 2015.
Frank Brentrup, Christian Palliere. Energy efficiency and greenhouse gas emissions in European nitrogen fertilizer production and use. Belgium, EU. 2008.
Robert Sanders. Fertilizer use responsible for increase in nitrous oxide in atmosphere. UC Berkeley. April 2012.
Carbon Works Inc. Arcadia, FL. 34265 USA 2013.
Fertilizer efficiency and plant health with carbon boost. FB Sciences Inc. Collierville TN 38017 and Norfolk, VA. Feb. 2015.
2015 Key World Energy Statistics International Energy Agency. Paris, France. 2015.

CO_2 Utilization Technologies in China

British Petroleum. (2012). BP statistical review of world energy.
Buscheck, T. A., Geochemical, H., & Bielicki, J. M. (2016).*Reducing Energy's Footprint by Producing Water and Storing CO_2.* CORNERSTONE MAG. Retrieved at http://cornerstonemag.net/reducing-energys-footprint-by-producing-water-and-storing-CO2/

Li, Q., Wei, Y. N., Liu, G., & Lin, Q. (2014). Combination of CO 2 geological storage with deep saline water recovery in western China: insights from numerical analyses. *Applied Energy*, *116*, 101-110.

The Administrative Center for China's Agenda 21 (ACCA21). (2015). *A report on CO_2 utilization technologies assessment in China*.

Chapter F

Administrative Center for China's Agenda 21 (2014). China's CO_2 Utilization Technology Review, Science Press.

Carbon XPrize. carbon.xprize.org

Code of Federal Regulations (2016). Title 40, Part 60 – Standards of Performance for New Stationary Sources, section 60.5555(g).

Conference of the Parties to the United Nations Framework Convention on Climate Change, Twenty-First Session (2015). Durban Platform for Enhanced Action (decision 1/CP.17), Adoption of a protocol, another legal instrument, or an agreed outcome with legal force under the Convention applicable to all Parties, Adoption of the Paris Agreement, draft decision -/CP.21, Annex, Paris Agreement, Art. 2, sec. 1(a). unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf and unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

Cornerstone Magazine (2015). Finding Opportunities for CCUS in China's Industrial Clusters, Tables 1, 3. cornerstonemag.net/finding-opportunities-for-ccus-in-chinas-industrial-clusters/

Denbury Onshore, LLC (2015). Petition for Reconsideration of 40 C.F.R. § 65.5860(f)(2) and Expedited Stay Pending Reconsideration. In the Matter of: Carbon Pollution Emission Guidelines for Existing Stationary Sources – Electric Utility Generating Units, before the U.S. Environmental Protection Agency, Docket # EPA-HQ-OAR-2013-0602.

GHG Daily Monitor (2016). Achieving Paris Agreement Goals Requires CCUS, Groups Say, GHG Daily Monitor, Vol. 1, No. 74. www.exchangemonitor.com/publication/ghg-daily-monitor/achieving-paris-agreement-goals-requires-ccus-groups-say/

Global Carbon Capture and Storage Institute (2015). CCS Status Report, GCCSI. hub.globalccsinstitute.com/sites/default/files/publications/196843/global-status-ccs-2015-summary.pdf

Interagency Task Force on Carbon Capture and Storage (2010). Final Report. energy.gov/sites/prod/files/2013/04/f0/CCSTaskForceReport2010_0.pdf

Intergovernmental Panel on Climate Change (2014). Climate Change 2014, Synthesis Report, p. 23. //ar5-syr.ipcc.ch/ipcc/ipcc/resources/pdf/IPCC_SynthesisReport.pdf

International Energy Agency (2013). Technology Roadmap, Carbon Capture and Storage. www.iea.org/publications/freepublications/publication/TechnologyRoadmapCarbonCaptureandStorage.pdf

International Energy Agency (2014). CCS 2014: What Lies in Store for CCS, Insight Series 2014. www.iea.org/publications/insights/insightpublications/Insight_CCS2014_FINAL.pdf

Kevin Connors 2013. Presentation: IOGCC task force report, www.netl.doe.gov/File%20Library/events/2013/carbon%20storage/8-20-Kevin-Connors-DOE-CCS-R-D-Meeting-08212013.pdf

MIT 2016. Carbon capture & sequestration technologies, Illinois Industrial carbon capture and storage fact sheet: Carbon dioxide capture and storage project, sequestration.mit.edu/tools/projects/illinois_industrial_ccs.html

National Coal Council (2015). Fossil Forward: Revitalizing CCS, Bringing Scale and Speed to CCS Deployment. www.nationalcoalcouncil.org/studies/2015/Fossil-Forward-Revitalizing-CCS-NCC-Approved-Study.pdf

Oxy Denver Unit CO_2 Subpart RR Monitoring, Reporting and Verification Plan (2015). www.epa.gov/sites/production/files/2015-12/documents/denver_unit_mrv_plan.pdf

The Global CO_2 Initiative. //www.CO_2.sciences.org#top

U.S. Energy Information Administration (2016). "How Much of U.S. Carbon Dioxide Emissions Are Associated with Electricity Generation?" www.eia.gov/tools/faqs/faq.cfm?id=77&t=11

U.S. Environmental Protection Agency (2015). Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units, 80 Fed. Reg. 64662, 64884. www.gpo.gov/fdsys/pkg/FR-2015-10-23/pdf/2015-22842.pdf

U.S. Environmental Protection Agency (2011). PSD and Title V Permitting Guidance for Greenhouse Gases, EPA-457/B-11/001, Pages 36, 43. www.epa.gov/sites/production/files/2015-12/documents/ghgpermittingguidance.pdf

U.S. Environmental Protection Agency (2015). Standards of Performance for Greenhouse Gas Emissions from New, Modified, and Reconstructed Stationary Sources: Electric Utility Generating Units, 80 Fed. Reg. 64510, 64581. www.gpo.gov/fdsys/pkg/FR-2015-10-23/pdf/2015-22837.pdf

Utility Air Regulatory Group v. EPA, 134 S. Ct. 2427 (2014).

Vello Kuuskraa et al. (2013). CO_2 Utilization from 'Next Generation' CO_2 Enhanced Oil Recovery Technology, Energy Procedia, Elsevier. www.adv-res.com/pdf/CO_2%20Utilization%20from%20_Next%20Generation_%20CO_2%20Enhanced%20Oil%20Recovery%20Technology.pdf

Wikipedia (2016). Life-cycle assessments. en.wikipedia.org/wiki/Life-cycle assessment

Appendices

Appendix 1. CO_2-EOR Major Players

The CO_2-EOR industry is dominated by three major players – Occidental Petroleum, Kinder Morgan and Denbury Resources. These three companies account for nearly 70% of current CO_2-EOR liquids (oil and natural gas liquids-NGLs) production, with numerous companies, large and small, providing the remaining volumes.

Occidental Petroleum, operating its CO_2-EOR business as Oxy Permian, produces 120,000 barrels per day (B/D) gross (104,000 B/D net) crude oil and NGLs from use of CO_2 in 33 EOR projects. Oxy Permian also operates 1,900 miles of CO_2 pipelines with 2.4 Bcfd (46 MMmt/yr) of capacity. The company expects significant additional oil production from new CO_2-EOR projects, such as at North and South Hobbs (Lea County, New Mexico) and from pursuit of ROZ resources at Wasson, Hobbs and other oilfields. Oxy Permian's strategies for CO_2-EOR include an investment of $500 million in 2016 and "establishing major growth programs in EOR with game changing technologies."

Kinder Morgan, with 80,000 B/D (gross) of crude oil and NGLs production from CO_2–EOR, is today the operator of the pioneering SACROC CO_2 flood, having revitalized this project with new investments and improved technology. Kinder Morgan has set forth an ambitious $4.1 billion, 10 year program for its CO_2 E&P and its CO_2 S&T business units. A notable CO_2-EOR effort is Kinder Morgan's recently started ROZ project at Tall Cotton (Gaines, County, Texas) in the San Andres ROZ "fairway", a "greenfield" CO_2-EOR project outside the structural close of any oil field.

Denbury Resources with 55,000 B/D gross (41,000 B/D net) of oil production from use of CO_2 has recently built two long distance, large capacity CO_2 pipelines – the 320 mile, 24-inch Green Pipeline along the Gulf Coast of Louisiana and Texas and the 230 mile, 20-inch Greencore Pipeline in Wyoming and Montana. Along with its extensive CO_2 pipeline systems, Denbury currently injects 700 MMcfd (13 MMmt/yr) of natural CO_2 production plus 70 MMcfd of CO_2 captured from industrial plants (the Air Products hydrogen plant and the PCS nitrogen plant). Denbury has announced plans to initiate several new CO_2-EOR projects – at Conroe, Webster and Thompson along the Gulf Coast and at the Cedar Creek Anticline in Montana.

Appendix 2. U.S. Regional CO_2 Utilization/Storage and Oil Recovery Potential

The CO_2 Utilization/Storage and Oil Recovery Potential of Nine Lower 48 Onshore Regions

	Region	Oil Reservoirs Favorable For CO2-EOR	CO2 Demand (MMmt)				Oil Recovery (Billion Bbls)			
			Technical		Economic [4]		Technical		Economic [4]	
			SOA	"Next Generation"	SOA	"Next Generation"	SOA	"Next Generation"	SOA	"Next Generation"
1	Appalachia	103	520	1,160	10	290	1.1	3.4	*	1.3
2	California	89	1,340	2,320	480	1,760	3.1	7.9	1.2	6.7
3	East/Central Texas	193	4,120	6,040	2,120	3,620	11.1	20.9	5.9	13.5
4	Michigan/Illinois	148	660	1,050	330	570	1.8	3.0	1.1	1.8
5	Mid-Continent [1]	183	4,220	6,530	2,120	3,270	12.9	22.5	6.6	12.0
6	Permian Basin [2]	217	6,070	8,620	2,690	4,750	13.6	24.0	6.4	14.6
7	Rockies [3]	146	1,930	2,790	710	1,270	4.5	9.7	1.9	4.7
8	Gulf Coast	209	2,590	3,390	290	1,440	5.4	10.1	0.9	4.8
9	Williston	86	820	1,150	130	360	2.1	4.0	0.3	1.3
Total		**1,374**	**22,270**	**33,050**	**8,880**	**17,330**	**55.6**	**105.5**	**24.3**	**60.7**

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[1] Includes 0.1 billion barrels already produced or proved with CO2-EOR.

[2] Includes 2.2 billion barrels already produced or proved with CO2-EOR.

[3] Includes 0.3 billion barrels already produced or proved with CO2-EOR.

[4] Evaluated using an oil price of $85/B, a CO2 cost of $40/mt and a 20% ROR, before tax.

Source: Advanced Resources International

Appendix 3. Reports of The National Coal Council
June 1986 – August 2016

June 1986	Coal Conversion
	Clean Coal Technologies
	Interstate Transmission of Electricity
	Report on Industrial Boiler New Source Performance Standards
June 1987	Reserve Data Base: Report of The National Coal Council
	Improving International Competitiveness of U.S. Coal and Coal Technologies
Nov. 1988	Innovative Clean Coal Technology Deployment
Dec. 1988	Use of Coal in Industrial Commercial, Residential & Transportation Sectors
June 1990	Industrial Use of Coal and Clean Coal Technology – Addendum Report
	The Long Range Role of Coal in the Future Energy Strategy of the United States
Jan. 1992	The Near Term Role for Coal in the Future Energy Strategy of the United States
	Improving Coal's Image: A National Energy Strategy Imperative
May 1992	Special Report on Externalities
Feb. 1993	Role of U.S. Coal in Energy, the Economy& the Environment
	A Synopsis of NCC Reports (1986 – 2003)
Nov. 1993	The Export of U.S. Coal and Coal Technology
Feb. 1994	Clean Coal Technology for Sustainable Development
May 1995	Critical Review of Efficient & Environmentally Sound Coal Utilization Technology
Nov. 1995	The Implications for Coal Markets of Utility Deregulation & Restructuring
Feb. 1997	Vision 2020: The Role of Coal in U.S. Energy Strategy
Oct. 1997	Clean Air Act Rules, Climate Change & Restructuring of the Electricity Industry
Nov. 1998	Coal's Role in Achieving Economic Growth and Environmental Stability
May 2000	Research & Development Needs for the Sequestration of Carbon Dioxide
May 2001	Increasing Coal-Fired Generation Through 2010: Challenges and Opportunities
May 2003	Coal-Related Greenhouse Gas Management Issues
Nov. 2004	Opportunities to Expedite the Construction of New Coal-Based Power Plants
March 2006	Coal: America's Energy Future (Volumes I & II)
June 2007	Technologies to Reduce or Capture and Store Carbon Dioxide Emissions
May 2008	The Urgency of Sustainable Coal
Dec. 2009	Low Carbon Coal: Meeting U.S. Energy, Employment & Carbon Dioxide Emission Goals with 21st Century Technologies
March 2011	Expediting CCS Development: Challenges and Opportunities
June 2012	Harnessing Coal's Carbon Content to Advance the Economy, Environment & Energy Security

May 2014	Reliable & Resilient: The Value of Our Existing Coal Fleet
January 2015	Fossil Forward – Revitalizing CCS: Bringing Scale & Speed to CCS Deployment
Nov. 2015	Leveling the Playing Field: Policy Parity for CCS Technologies
August 2016	CO_2 Building Blocks: Assessing CO_2 Utilization Options

Reports can be found on the NCC web site at www.NationalCoalCouncil.org

Appendix 4. NCC Member Roster - 2016

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