Perspective

GREENHOUSE GASES SCIENCE AND TECHNOLOGY

The US Department of Energy's R&D program to reduce greenhouse gas emissions through beneficial uses of carbon dioxide†

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Abstract: As high CO_2-emitting utilities and other industries move toward implementing carbon capture and storage (CCS) technologies to manage greenhouse gas emissions, more and more CO_2 will become available as a resource for multiple applications. CO_2 will be a plentiful potential feedstock (carbon source) for many products, including commercial chemicals, plastics, and improved cement. Unfortunately, CO_2 is a stable compound with a low energy state and does not readily participate in chemical reactions without added energy. Additionally, the supply of CO_2 that may be available as the USA moves toward a carbon-constrained economy far exceeds the current demand for CO_2 as a commodity chemical. Thus, identifying candidate chemistries and economically feasible approaches that utilize large amounts of CO_2 as a feedstock for high-demand products is very challenging.

The United States Department of Energy (DOE), through its National Energy Technology Laboratory (NETL), has an active carbon sequestration program. The goal of the CO_2 Utilization Focus Area is to identify and develop a suite of technologies that can beneficially use CO_2 to produce useful products that can generate revenue to offset capture costs associated with CCS implementation, contribute to CO_2 emissions reductions, and reduce the demand for petroleum based feedstocks and products. Currently, projects being supported fall into the categories of (i) enhanced hydrocarbon recovery, (ii) chemicals production, (iii) mineralization processes for building products, and (iv) plastics production. This perspective discusses the current status of CO_2 use and presents a review of DOE's program to identify and demonstrate uses for captured CO_2.

Keywords: CO_2 mitigation; CO_2 utilization; EOR; chemicals production; mineralization; plastics production

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Introduction

Coal is predicted to continue to dominate power generation for the next 25 years,[1] and since power generation from coal is a significant source of carbon dioxide (CO_2) emissions, the reduction of these emissions is a critical research need. The United States has made a commitment to work toward the long-term reduction of CO_2 emissions, which in the USA originate mainly from the combustion of fossil fuels for energy production, transportation, and industrial processes, with about one third of US anthropogenic CO_2 emissions coming from power plants.[1] The US Department of Energy's (DOE) Carbon Sequestration Program, along with related R&D programs throughout the world, continues to make progress toward the goals of lowering the cost of CO_2 capture and ensuring that the CO_2 can be safely and permanently sequestered in geologic formations in a process know as carbon capture and storage (CCS).[2]

Another potential approach to reduce CO_2 emissions is CO_2 utilization, sometimes referred to as CO_2 reuse or carbon capture and *reuse* (CCR). As carbon capture technology has advanced, the concept of CO_2 utilization has attracted more interest due to its potential not only to reduce emissions but also as a means to generate revenue to offset the cost of capture.[3] It is anticipated that large volumes of CO_2 will be available as fossil-fuel-based power plants and other CO_2-emitters are equipped with CO_2 emissions control technologies to comply with regulatory requirements. While DOE efforts are underway to demonstrate the permanent storage of captured CO_2 through geologic sequestration, the captured CO_2 may also be viewed as an inexpensive raw material with multiple potential beneficial uses.

To explore this potential, DOE, as part of its Carbon Sequestration Program, has created a CO_2 utilization focus area, the goals of which are to identify and develop a suite of technologies that can beneficially use CO_2 and to develop useful products that can (i) offset the cost of capture, (ii) help mitigate CO_2 emissions, and (iii) reduce the demand for petroleum-based products and feedstocks. In sponsoring projects, preference is given to technologies that reduce CO_2 emissions while producing useful products with economic value. Deployment of carbon utilization technologies will require a comprehensive understanding of product markets and energy balances and will require life cycle studies to ensure that a net decrease in CO_2 emissions is associated with implementation of these technologies.[4]

The main objectives of the CO_2 utilization focus area are to:

- Identify promising CO_2 utilization technologies with the potential to produce a product at an economically viable cost.
- Identify technical and commercial barriers to using CO_2 as a raw material and to develop an R&D program to address these issues.
- Improve understanding of constraints on carbon emissions (e.g. a carbon tax) that would make CO_2 utilization technologies economically feasible.
- Assess the global CO_2 reduction and the product market potential that would result from the implementation of CO_2 utilization technologies.

There are many potential benefits to achieving the goals of the CO_2 utilization focus area (Table 1).

Figure 1 illustrates most of the current and potential uses of CO_2. However, many of these uses are

Table 1. Potential benefits from achieving the CO_2 utilization focus area goals.

Provision of a means of generating revenue to offset the cost of CO_2 capture.
Reduced demand for petroleum-based feedstocks and emissions reduction associated with their reduced use.
New uses for waste streams.
Elimination of costs associated with hazardous material handling and disposal by substituting CO_2 for hazardous chemical feedstocks.
Production of green products.
Production of products with enhanced properties (e.g. increased strength, improved durability, reduced weight).
Provision of a basis for claiming carbon credits.
Development of markets for new materials.
Creation of jobs as new processes are implemented.

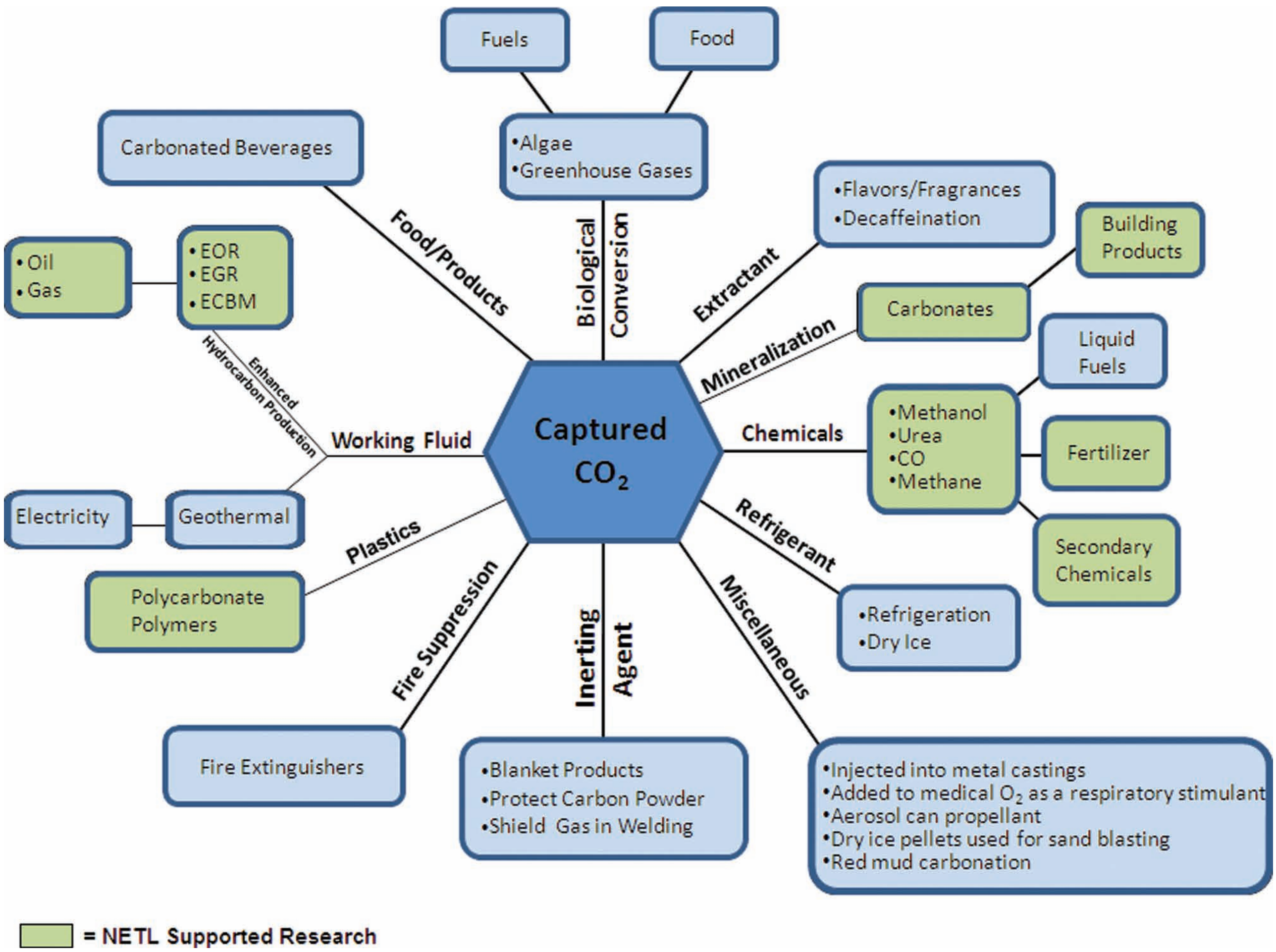

Figure 1. Schematic illustrating the many uses of CO_2.

small and typically emit the CO_2 to the atmosphere during or after use. DOE's priority research areas for CO_2 utilization, highlighted in green in Fig. 1, are (i) CO_2-enhanced hydrocarbon recovery, (ii) chemicals production, (iii) mineralization processes, and (iv) plastics and polymer production. These areas have been identified as opportunities with high potential to use significant volumes of CO_2 and be economically viable.[3] To date, the NETL Carbon Sequestration Program is supporting CO_2-enhanced hydrocarbon recovery Research, Development & Demonstration (RD&D) projects through the Regional Carbon Sequestration Partnership initiative.[5] In the other research areas, DOE is supporting six CO_2 utilization projects valued at $5.9 million. The following is a discussion of the projects sponsored by NETL in the identified priority research areas.

Current supply and demand for CO_2

CO_2 is already a commodity chemical with many and varied uses. The current demand for CO_2 comes largely from the food, oil and gas, and chemical industries. The food industry is the largest user of liquid CO_2, although it may not be used in the form in which it is purchased. A significant portion of this CO_2 is used in food chilling to keep products cool during harvesting, processing, and transport. Some CO_2 is used in producing carbonated beverages, such as soft drinks. For these applications, the ultimate fate of the CO_2 is typically to be emitted to the atmosphere.

The oil and gas industry uses CO_2 to enhance hydrocarbon recovery in mature or depleted fields. Enhanced hydrocarbon recovery typically requires large volumes of CO_2 over an extended period. Using CO_2 to recovery additional oil is considered a mature technology and,

Table 2. Current CO_2 use pattern.

Use	Estimated Usage Mt/y
Enhanced oil recovery	50
Urea (captive use)	120
Food industry (liquid)	8.5
Beverage carbonation	8
Inorganic carbonate/bicarbonate	8
Oil and gas industry non-EOR	3
Other liquid uses	<1
Miscellaneous	<1

for some large oil fields, CO_2 is delivered by a network of dedicated pipelines. CO_2 is sometimes used for formation fracturing in which liquefied CO_2 replaces water or brine as the hydraulic fracturing (fracking) fluid and serves as a carrier of propping agents and/or chemicals. CO_2 has a variety of uses in the chemical industry, including as a raw material for the production of a variety of materials, for inerting and pressurizing, and for cooling. Estimated CO_2 usage is about 200 million metric tons per year (Mt/y). Table 2 and Fig. 2 summarize current CO_2 use patterns.[3]

The current supply of CO_2 comes from a number of sources, the most important of which are:

- A by-product of hydrogen (H_2) and ammonia (NH_3) production (230 million metric tons per year).
- A by-product of ethanol production by fermentation (115 million metric tons per year).
- A by-product of the production of synthetic natural gas (SNG) (1.6 million metric tons per year).
- A by-product of the production of lime and Portland cement (115 million metric tons per year).
- A by-product of landfill operations that produce a gas stream rich in CO_2 and methane (CH_4).
- A by-product of the production of natural gas (135 million metric tons per year).
- An extract from flue gases resulting from the combustion of fossil fuels (2870 million metric tons per year).
- Natural deposits, some of which approach 100% CO_2 purity (50 million metric tons per year).

Values in parentheses are approximate annual amounts of CO_2 available in the USA based on 2010 data.[5] However, it is estimated that of all the anthropogenic CO_2 generated, only 0.5% is captured and used with the rest being released to the atmosphere.[3] Consequently, when considering the potentially large CO_2 supply from fossil-fuel-based power generation and other large point sources, it is apparent that the current demand is relatively small compared to the

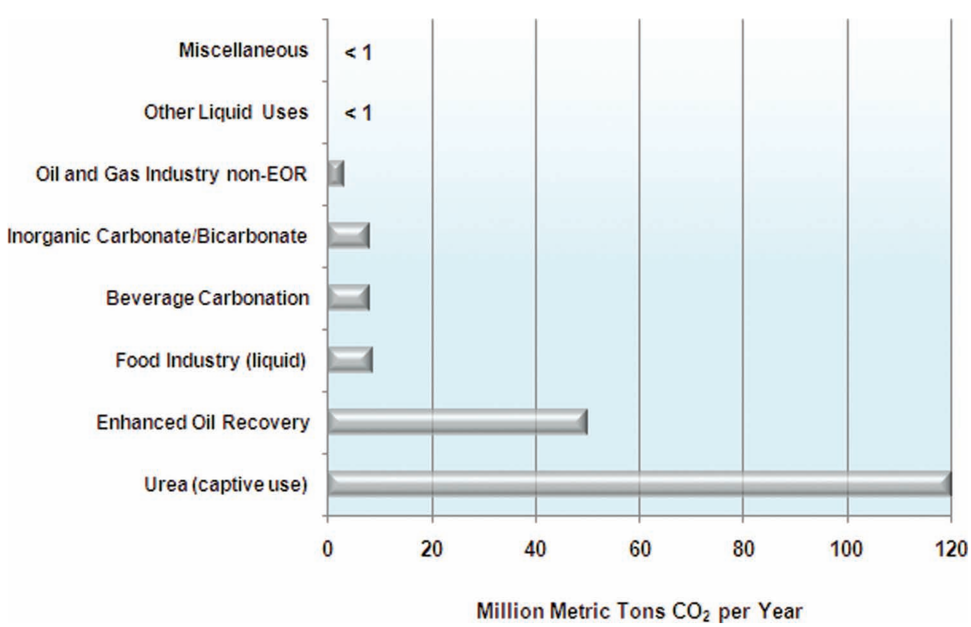

Figure 2. CO_2 consumption for various activities.

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supply that would be available should the USA turn toward a carbon-constrained economy.

CO_2-enhanced hydrocarbon recovery

CO_2-enhanced hydrocarbon recovery embraces enhanced oil recovery (EOR), enhanced gas recovery (EGR), and enhanced coal-bed methane recovery (ECBM), as discussed later.

CO_2-enhanced oil recovery (EOR) and CO_2-enhanced gas recovery (EGR)

CO_2-EOR and CO_2-EGR are techniques in which compressed CO_2 is injected into depleted oil and gas fields to increase production. In the case of CO_2-EOR, the CO_2 tends to dissolve in the oil making it less viscous and easier to extract. Some of the dissolved CO_2 is recovered with the oil at the production wells. Since a cost is associated with obtaining the CO_2 from either a natural or other source, it is common practice to separate the CO_2 from the oil for reinjection. The portion of CO_2 that is not extracted with the oil remains stored in the pore spaces of the reservoir. Therefore, over time CO_2 accumulates in the reservoir in place of the recovered oil.[6,7] EGR involves a similar process except that the CO_2 acts more to displace gas toward production wells rather than to mix with and change the physical properties of the formation gas.

Oil and gas formations offer excellent near-term potential for CO_2 storage because the geologic conditions that trap oil and gas are also conducive to long-term geologic storage of CO_2.[8] CO_2-EOR has been practiced for over 40 years with incremental oil recoveries ranging from 10–15% of the oil in place.[5] DOE's Regional Carbon Sequestration Partnerships (RCSPs) have documented the locations of approximately 143 billion metric tons of prospective storage in oil reservoirs distributed over 29 states and 4 Canadian provinces.[5] The RCSPs are conducting eight small-scale validation phase tests in different geologic formations containing oil and gas (Table 3). Regardless of the injected volumes, formation thickness/characteristics, or depositional environment, all injection test sites successfully injected CO_2 with associated oil production.[9]

The PCO_2R Partnership Zama test in the Alberta Basin is also testing the capability to inject a combination of CO_2 and hydrogen sulfide (H_2S) into a carbonate reservoir and is monitoring the effects on the injection zone, confining system, and produced hydrocarbon quality.

CO_2-enhanced coal-bed methane recovery (ECBM)

CO_2-ECBM production involves injecting CO_2 into a coal seam to displace and produce methane gas. Due to preferential adsorption of CO_2, this has the added

Table 3. Summary of geologic conditions at selected RCSP validation phase field tests injecting CO_2 into oil and gas formations.

RCSP – Geologic Provinces	Injected CO_2 Amount	Storage Formation (Thickness)	Incremental Production
MGSC – Illinois Basin-Loudon Field	40 metric tons	Cypress Sandstone (80 feet)	93 bbl Produced
MGSC – Illinois Basin-Mumford Hills	2850 metric tons	Clore Formation (10–40 feet)	4–8 times increase in current production rate
MGSC – Illinois Basin-Sugar Creek	5850 metric tons	Jackson Sandstone (5–20 feet)	2–3 times increase in current production rate
PCO_2R – Alberta Basin (Zama)	25 400 metric tons	Keg River Formation (400 feet)	25 000 bbl produced
PCO_2R – Williston Basin	400 metric tons	Mission Canyon Formation (14 feet)	242 bbl produced
SECARB – Gulf Coast-Cranfield	627 744 metric tons	Tuscaloosa Formation (90 feet)	NA
SWP – Paradox Basin	630 000 metric tons	Desert Creek and Ismay (200 feet total)	~159 000 bbl produced
SWP – Permian Basin	86 000 metric tons	Cisco-Canyon (213 feet)	Increase from 575 to 2000 bbl/day

benefit of storing a portion of the injected CO_2 by adsorption on the organic-rich surfaces within the coal, which tends to displace the less strongly adsorbed methane.[10,11] The degree to which CO_2 is preferentially adsorbed can vary, with some coals adsorbing several CO_2 molecules for each methane molecule released. CO_2-ECBM has the potential to increase the amount of produced methane to nearly 90% of the gas in place compared to conventional recovery of only 50% by means of reservoir pressure depletion.[10–12] Laboratory investigations, small-scale field tests, and numerical modeling results are encouraging but highlight the need for detailed understanding of both CO_2 sorption under reservoir conditions (to improve estimates of capacity) and the dynamic response of coal to CO_2 sorption (which may either enhance or degrade injectivity). If these issues can be successfully addressed, the potential benefit derived from methane production could provide a strong incentive for the rapid commercial deployment of CO_2 storage in unmineable coal seams.

The potential CO_2 storage capacity in unmineable coal seams in the USA is significant, representing at least decades at the current rate of 3.8 billion metric tons per year of CO_2 emissions from large stationary sources. Although not all unmineable coal deposits have been evaluated, the RCSPs have documented (at the geologic basin level) 60 to 117 billion metric tons of CO_2 storage potential distributed over 21 states and one Canadian province.[5] The RCSPs' estimates include only those coal seams that at present are uneconomic to mine using current technology.

CO_2-enhanced geothermal systems (EGS)

EGS is a novel technology that enables cost effective energy extraction from formations that would otherwise not be suitable as a geothermal energy source.[13] The enhancement comes from using supercritical CO_2 instead of water or brine as the working fluid to recover heat and generate electric power via a supercritical CO_2 turbine. The CO_2 is continuously cycled through the system with additional CO_2 added to replace losses. One case study estimates the potential annual storage at around 100 000 tons of CO_2 for a 10 MW power system.[14] While this is only a rough estimate, it suggests that EGS, if widely deployed, could have the potential to store millions of tons of CO_2 per year. Although EGS technology development is not currently supported by the NETL Carbon Sequestration Program, it is increasingly becoming the central focus for DOE geothermal research support.

Chemicals production

DOE is supporting a number of research efforts to evaluate the technical and economic feasibility of chemically converting CO_2 into a variety of useful chemicals with an emphasis on developing new or expanding existing markets, replacing petroleum-derived feedstocks, and reducing CO_2 emissions. The following is a brief description of the ongoing research efforts currently supported by DOE to evaluate the economics and CO_2 mitigation potential of CO_2 conversion to commodity chemicals.

Production of acrylates

Researchers at Brown University are assessing the viability of CO_2 reduction with ethylene, using low-valent molybdenum as a catalyst, to produce acrylic acid or other valuable acrylate compounds.[15] The environmental advantage of producing acrylates from CO_2 and ethylene has spurred research into the development of catalysts to promote this reaction. A small number of transition metal complexes have shown the ability to catalyze the coupling of CO_2 and ethylene, with molybdenum complexes showing the most promise by forming acrylate hydride complexes. Such complexes appear to offer the prospect of closing the hypothesized catalytic cycle of acrylic acid synthesis. The only thing lacking for closure of this catalyst cycle is reductive formation of an O–H bond. However, the formation of free acrylic acid has yet to be observed for any complex capable of uniting CO_2 and ethylene. Brown researchers will systematically evaluate factors and mechanisms that may impact the kinetics of reductive O-H elimination from acrylate hydride complexes en route to providing a definitive assessment of the potential for acrylic acid production by this technique.

Reduction of CO_2 using low-grade carbon sources

RTI International is conducting experiments to demonstrate the conversion of CO_2 to carbon monoxide (CO) using abundant, low-value carbon sources, such as petroleum coke, sub-bituminous coal, lignite,

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and biomass, as the reductant.[16] The chemistry involved is the reverse Boudouard reaction:

$$CO_2 + C \rightarrow 2CO \quad (1)$$

The same products can be achieved using molecular hydrogen (H_2) as the reductant, but H_2 can only be produced from materials such as natural gas and water, making its use impractical. The production of CO is attractive because it is a feedstock in the production of many important chemicals, including aldehydes, ketones, carboxylic acids, anhydrides, esters, amides, imides, carbonates, and urea. Furthermore, CO is one of the components of synthesis gas which can be used as a feedstock to produce value-added products such as methanol, acetic acid, dimethyl ether, and diesel fuel. A fluidized bed reactor is being used to investigate the technical feasibility of the reaction and to determine reaction rates and catalytic activity for both fossil and biomass sources of carbon. Process simulation and modeling will be used to evaluate various process configurations and to assist in process optimization and estimating process economics.

Production of commodity chemicals from CO_2

The Massachusetts Institute of Technology (MIT) and Siemens Corporation are researching a new process for the synthesis of commodity chemicals from CO_2 in an integrated CO_2 capture and conversion system.[17] This technology can be viewed as a novel chemical sequestration process that produces organic carbonate commodity chemicals from dilute CO_2 recovered from gas streams generated by industrial CO_2 emitters, such as power plants. Organic carbonates have multiple uses, including as intermediates for polycarbonate synthesis, as electrolyte solvents for lithium ion batteries, as organic solvents for paints, and as fuel additives. Organic carbonates can also be substitutes for various toxic chemical reagents.

The basis of this technology is the chemical affinity of electrochemically reduced quinones for CO_2 molecules. This affinity facilitates CO_2 capture from a dilute gas stream through the formation of bis(carbonate) addition products. The technology will exploit the propensity for such nucleophiles to undergo additional reactions with various electrophiles. The reaction product of CO_2 with an electrophilic species will be released on electrochemical oxidation of the bis(carbonate) products. The technology has the potential not only to capture CO_2 from industrial emitters but also to utilize the CO_2 in the captured state as a raw material to produce organic carbonates in an energy efficient process. Efforts include establishing the engineering feasibility of the process and performing life cycle environmental and cost analyses of the overall process.

Conversion of CO_2 to hydrocarbons using photocatalysts

PhosphorTech is pursuing the conversion of CO_2 to hydrocarbons using photocatalysts to recover H_2 from water, similar to the function of chlorophyll in photosynthesis.[18] An ideal photocatalyst has high quantum yield, high sunlight absorption for maximum utilization of solar energy, high hydrocarbon reaction yield for maximum reforming of CO_2, high chemical stability to permit long-term operation without replacing catalyst, and low production cost. Consideration is being given to nanostructures to provide a large surface area for higher reaction rates and higher light absorption efficiency. PhosphorTech is evaluating solution-based processes, nanocrystal synthesis, catalyst evaluation, and reactor design.

Mineralization processes

Carbonate mineralization refers to the conversion of CO_2 to solid inorganic carbonates.[19] Naturally occurring alkaline and alkaline-earth oxides react chemically with CO_2 to produce minerals such as $CaCO_3$ and $MgCO_3$. These minerals are highly stable and can be used in construction materials. Because the cement and concrete industries are energy intensive and contribute substantially to industrial CO_2 emissions, there is great interest in developing manufacturing technologies and methods that are more energy efficient and less carbon intensive. DOE is supporting multiple projects to explore the feasibility of sequestering CO_2 through energy efficient mineralization processes that form stable carbonates.

Improved curing of precast concrete

McGill University is working on the improvement of CO_2 curing of precast concrete to accelerate strength gain, reduce energy consumption, and increase durability, with the key objective being to enhance the CO_2 uptake capacity of concrete during early stage curing.[20] To make the process economically feasible, a self-concentrating absorption technology will be integrated into the curing system to produce a low-cost purified CO_2 source from flue gas.

When concrete is cured using CO_2, the CO_2 is converted to thermodynamically stable calcium carbonate which is embedded in calcium silicate hydrate. Concrete masonry blocks and fiber-cement panels are ideal candidate building products for carbon sequestration, since they are mass produced and require steam curing. This research will examine the possibility of achieving a cost-effective, high performance concrete manufacturing process through a prototype production facility using specially designed chambers called CO_2 claves to replace steam kilns and implement forced-diffusion technology to maximize carbon uptake at a minimal process cost. This process makes precast concrete products stronger, less porous, and more durable. The production cycle is also significantly shortened when CO_2, instead of steam, is used in the curing process.

Substitute for Portland cement in concrete

CCS Materials is testing an energy efficient CO_2-consuming inorganic binder as a substitute for Portland cement in concrete.[21] The process utilizes a binding phase based on carbonation chemistry that does not require pyro-processing. This eliminates the need for large Portland cement kilns, thereby saving a significant amount of energy and reducing CO_2 emissions. Research is focused on reducing energy consumption during the material creation process and increasing carbonation yield. Concrete production consumes approximately 500 trillion British Thermal Units (BTUs) of energy per year and in 2009 produced approximately 30 million metric tons of CO_2.[22] By developing a CO_2-consuming inorganic binder and reducing both the energy required to make concrete and the resultant emissions, this research could facilitate the sequestration of large amounts of CO_2 in construction materials.

Co-generation of carbonate and bicarbonate

Skyonic's SkyMine® CO_2 beneficial use project consists of designing and building a pilot facility to employ new technology for removing CO_2 from industrial waste streams through co-generation of carbonate and bicarbonate materials and converting them to beneficial use. The bicarbonates produced from the mineralization process can be sold and used for a variety of purposes, such as an additive to animal feed and to ponds growing algae. With technology perfected in field laboratory facilities, the first pilot SkyMine® plant will recover CO_2 from a portion of the flue gas from a cement manufacturing facility and will convert approximately 75 000 metric tons of CO_2 per year into beneficial use materials in mineral form. A significant added benefit of the SkyMine® process is its capability to produce high value chemicals by conversion of captured CO_2, while operating at energy efficient conditions, thereby reducing national CO_2 emissions in two ways: by direct mineralization with CO_2 that would otherwise be emitted in flue gas and by avoidance of CO_2 by producing chemicals using a process that is less energy-intensive than conventional commercial processes.

Carbonate mineral building materials

Calera Corporation is developing Carbon Mineralization by Aqueous Precipitation (CMAP) technology that directly mineralizes CO_2 in flue gas to carbonates that can be converted into useful construction materials. An existing CO_2 absorption facility for the project is operational at Moss Landing, California, for capture and mineralization. The project team is completing the detailed design, construction, and operation of a building material production system that at smaller scales has produced carbonate-containing aggregates suitable as construction fill or feedstock for cement production. The building material production system will ultimately be integrated with the absorption facility to demonstrate viable process operation at a significant scale. This project is currently supported with funding from the 2009 American Recovery and Reinvestment Act.

Plastics and polymer production

There are some polymerization reactions which can directly copolymerize CO_2 with other monomers. For example, traditional monomers, such as ethylene oxide and propylene oxide, can be combined with CO_2 to produce polycarbonates such as polyethylene carbonate and polypropylene carbonate. A typical reaction is:[17]

$$nCO_2 + nC_3H_6O \rightarrow [\text{-O-CO-O-}C_3H_6\text{-}]_n \qquad (2)$$

The advantage of this approach is that the CO_2 is copolymerized directly without the necessity of first

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converting it to carbon monoxide or some other reactive species, thus significantly reducing energy requirements. There are many potential uses for polycarbonate plastics, including coatings, plastic bags, and laminates.

Aliphatic polycarbonates production

In collaboration with Albemarle Corporation and Eastman Kodak Co., Novomer is developing a process for converting waste CO_2 into a number of polycarbonate products (plastics) for use in the packaging industry.[23] Novomer's novel catalyst technology enables CO_2 to react with epoxides to create a family of thermoplastic polymers that are up to 50 percent by weight CO_2. The project has the potential to convert CO_2 from an industrial waste stream into a lasting material that can be used in the manufacture of bottles, films, laminates, coatings on food and beverage cans, and in other wood and metal surface applications. Commercial feasibility requires a robust manufacturing process and acceptable product performance and economics. Novomer's research effort is aimed at demonstrating production at commercial scale with an end product that meets customer standards and requirements.

Conclusion

NETL's Carbon Sequestration Program CO_2 Utilization Focus Area is currently pursuing advanced technologies in (i) enhanced hydrocarbon 1recovery, (ii) chemicals production, (iii) mineralization processes, and (iv) plastics and polymer production. DOE's current portfolio for this focus area is a diverse mix of CO_2 utilization projects that concentrate on these areas. Indications are that these areas are among the most promising for making a contribution to reducing CO_2 emissions and offsetting capture costs.

Enhanced hydrocarbon recovery shows great promise for both increasing energy supply and storing large volumes of CO_2. CO_2 has been used to enhance hydrocarbon recovery for decades resulting in an established infrastructure, regulatory framework, and technical knowledge base. With the added benefit of incremental revenues to offset costs, enhanced hydrocarbon recovery has the most potential for early deployment. RD&D efforts for enhanced hydrocarbon recovery are largely being conducted as part of DOE's RCSP initiative.

While CO_2 is a thermodynamically stable molecule, advances in catalysts and alternative reactive pathways may make it feasible to use CO_2 as a feedstock in the production of bulk chemicals. In addition to evaluating the CO_2 mitigation potential of this approach, DOE supported research efforts include evaluating the potential to expand existing markets and identifying substitutes for petroleum-derived feedstocks.

Mineralization processes that use CO_2 to cure concrete and to create inorganic binders as an alternative to Portland cement show promise for consuming CO_2 and reducing energy intensity. Concrete is one of the most widely used construction materials, and the concrete industry is among the largest producers of CO_2 emissions. Consequently, there is great incentive to increase the uptake of CO_2 during production of concrete products and to reduce the energy intensity of cement production and the concrete curing process.

The production of stable plastics through copolymerization to produce polycarbonates using CO_2 requires less energy by eliminating the need for intermediate reactions. Advances in this area have led to at least one process that is approaching commercialization.

Acknowledgement

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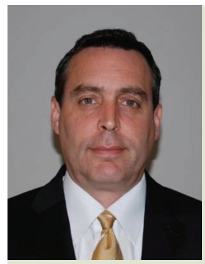

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