Integrated Electrochemical Processes for CO₂ Capture and Conversion to Commodity Chemicals

Background

The Department of Energy’s (DOE) Carbon Storage Program encompasses five Technology Areas: (1) Geologic Storage and Simulation and Risk Assessment (GSRA), (2) Monitoring, Verification, Accounting and Assessment (MVAA), (3) Carbon Dioxide (CO₂) Use and Re-Use, (4) Regional Carbon Sequestration Partnerships (RCSP), and (5) Focus Areas for Sequestration Science. The first three Technology Areas comprise the Core Research and Development (R&D), which includes studies ranging from applied laboratory to pilot-scale research focused on developing new technologies and systems for greenhouse gas (GHG) mitigation through carbon storage. This project is part of the Core R&D CO₂ Use and Re-use Technology Area and focuses on developing pathways and novel approaches for reducing CO₂ emissions in areas where geologic storage may not be an optimal solution. Carbon dioxide use and re-use applications could generate significant benefits through the capture or conversion of CO₂ to useful products such as fuels, chemicals, or plastics. Revenue generated from these applications could offset a portion of the CO₂ capture cost. The program’s R&D strategy includes adapting and applying existing technologies that can be utilized in the next five years, while concurrently developing innovative and advanced technologies that will be deployed in the decade beyond.

The area of CO₂ use and re-use for carbon storage is relatively new and less well-known compared to other storage approaches, such as geologic storage. Many challenges exist for achieving successful CO₂ use and re-use, including the development of technologies capable of economically fixing CO₂ in stable products for indirect storage. More exploratory technological investigations are needed to discover new applications and reactions. Each CO₂ use and re-use technology approach has a specific application, advantages over others, and challenges that are the focus of existing and future research. Technologies being developed will work towards meeting carbon storage programmatic goals; and these technologies may provide coal-based electric power generating facilities and other industrial CO₂ emitters additional tools to manage CO₂ emissions. This project is investigating an electrochemical process that chemically stores CO₂ by using it in the creation of organic carbonate chemicals. This novel approach to capturing and converting CO₂ into commodity chemicals could reduce the burden on CO₂ storage sites, provide a means to reduce anthropogenic CO₂ emissions, and provide an inexpensive method for producing useful materials from CO₂.
Researchers at the Massachusetts Institute of Technology (MIT) and Siemens are investigating the feasibility of integrating CO\(_2\) from emission sources (power plants, manufacturing facilities, cement plants, or fertilizer facilities) into a chemical reaction process that creates organic carbonate commodity chemicals for later use. The researchers also are designing electrochemical processes which allow for multi-stage, continuous capture of CO\(_2\) followed by organic carbonate synthesis using organocatalysts. They are conducting multiple lifecycle analyses of the electrochemical process and commodity chemicals synthesized during chemical CO\(_2\) storage process (Figure 1). The basis of this technology is the chemical affinity of electrochemically active carriers for CO\(_2\) molecules. These carriers facilitate the effective capture of CO\(_2\) from a dilute gas stream (effluents from CO\(_2\) emitters) through the formation of chemically activated species. The proposed technology exploits the characteristics of these activated species to undergo chemical reaction with various reagents to yield commodity chemicals. The technology has the potential to not only capture CO\(_2\) from industrial carbon emitters but also to utilize the CO\(_2\) in the activated state as a raw material to produce useful commodity chemicals in an energy efficient process.

**Project Description**

The goal of the project is to chemically store CO\(_2\) by the creation of organic carbonate commodity chemicals and to develop various models to evaluate reactivity, environmental lifecycle analysis, and economic parameters. This project is a laboratory/process engineering study with the following three main focus areas:

- **Scientific assessment of the integrated chemical storage process:** The proposed technology allows for the capture of CO\(_2\) and its chemical storage in commodity chemicals. The initial study examines the synthesis of organic carbonates from CO\(_2\). As research progresses, more complex organic carbonate molecules are being synthesized using electrophiles (reagents attracted to electrons that participate in a chemical reaction by accepting an electron pair in order to bond to a nucleophile) in combination with CO\(_2\).

- **Engineering assessment of the integrated chemical storage process:** A multi-stage, continuous function electrochemical cell will be designed and utilized to allow for the synthesis of organic carbonate commodity chemicals and the chemical storage of CO\(_2\) (Figure 2). A process model also is being developed to illustrate operating parameters and power usage demands of the electrochemical cell. Numerical and fluid dynamic simulations will supplement the process model.

- **Lifecycle analyses of the integrated chemical storage process:** Evaluations of the environmental and economic performance for each CO\(_2\) utilization pathway, consisting of the CO\(_2\) source, the CO\(_2\) capture and conversion process to commodity chemicals, and the potential industrial application of the carbon-utilization model, are being considered. Several alternative pathways leading to commercially viable and desirable commodity chemicals will also be considered.

**Accomplishments**

The following accomplishments were achieved as part of the overall goal to create organic carbonate commodity chemicals:

- Discovered that electrophilic bromine sources are effective catalysts for conversion of CO\(_2\) and epoxides or olefins into cyclic carbonates, which are valuable commodity chemicals. This demonstrates that this method is capable of synthesizing organic carbonates from CO\(_2\).

- Discovered a novel mechanism of epoxide activation as part of the assessment of the integrated chemical storage process. The impact of this discovery may be very broad.

- Determined through an engineering assessment, of the chemical process, that continuous processing is superior to batch processing and is likely to be the preferred approach in the majority of CO\(_2\) conversion methods.

**Goals/Objectives**

**Figure 1:** Schematic diagram of the integrated process to capture CO\(_2\) and utilize it as a raw material to produce useful commodity chemicals in an energy efficient manner.

**Figure 2:** Image of the continuous reactor used as part of the assessment of the integrated chemical storage process.

**Benefits**

This chemical storage of CO\(_2\) helps to minimize CO\(_2\) emissions and supplement geologic CO\(_2\) storage, particularly in areas where such storage might not be a viable option. This technology has the potential to not only capture CO\(_2\) from industrial carbon emitters but also to utilize the CO\(_2\) in the activated state as a raw material to produce useful commodity chemicals in an energy efficient process. The added value of this research includes integrated, CO\(_2\) capture and chemical storage processes; production of various commodity chemicals depending on the reagents used to react with the activated species; and minimal energy requirements. This technology contributes to the Carbon Storage Program’s effort of developing cost effective methods for CO\(_2\) use and re-use, as a viable alternative to geologic carbon storage.