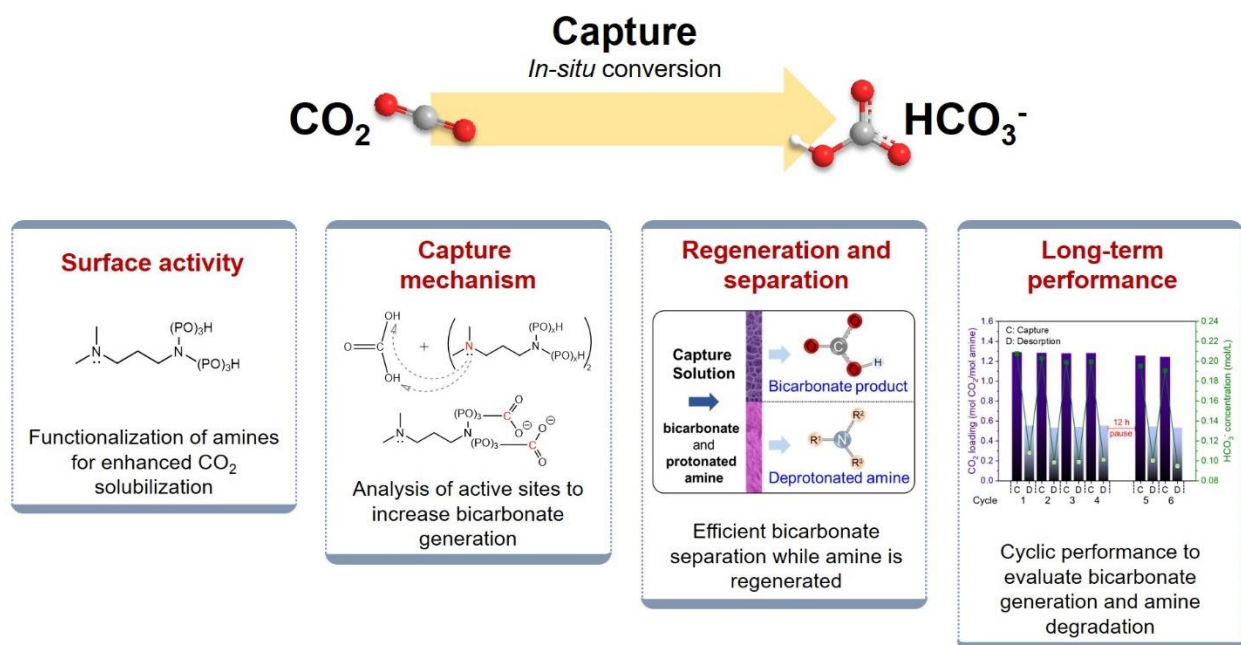


Overview

Our research group is an interdisciplinary platform for fundamental and applied research on sustainable energy ecosystems, including subsurface energy resources and carbon capture, utilization, and storage (CCUS). In this page, three projects are highlighted among other projects within the IAP, aiming to address techno-economic-environmental challenges in carbon management.



1. CO₂ Capture as Bicarbonate

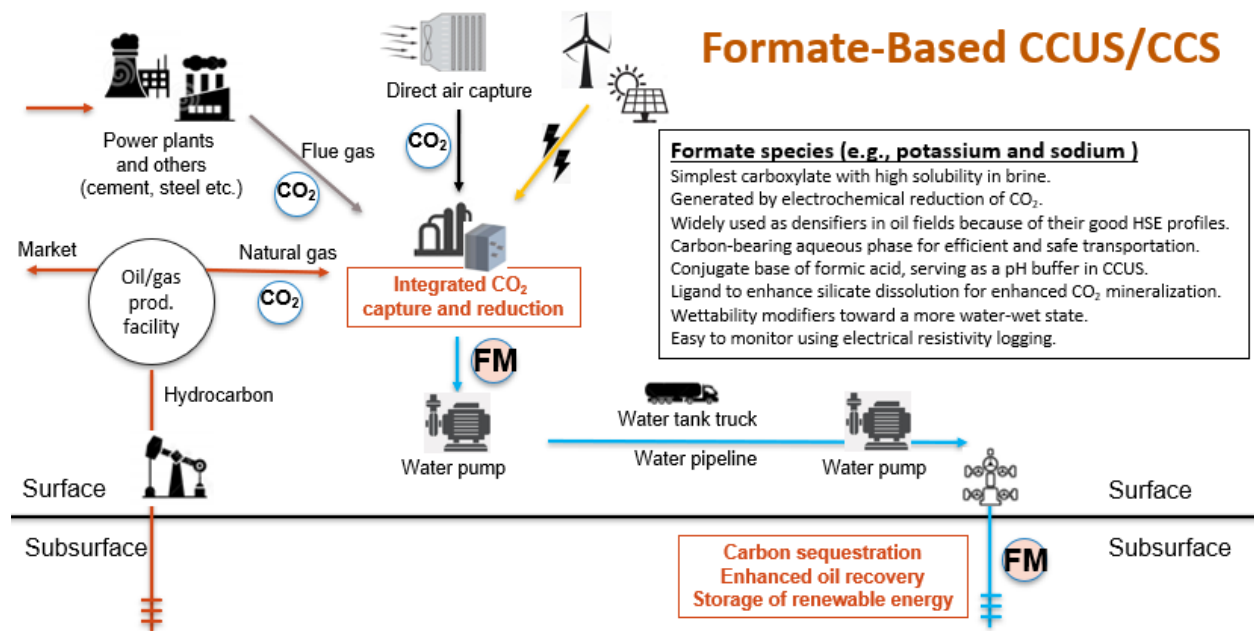


As part of CCUS, amine-based post-combustion capture has been commercially used, but it is energy-intensive to strip the CO₂ captured by conventional amine solutions as carbamates while regenerating the amine solvent by heating it to a high temperature (e.g., 120 – 180°C). The regeneration step accounts for a large fraction of the total operating cost. Also, the traditional method of CO₂ “catch-and-release” is unnecessary when the downstream processes in carbon management do not require CO₂ as a carbon carrier. Many green chemicals can be generated from bicarbonate in aqueous media at lower costs and carbon intensity than from CO₂.

This project is to evaluate CO₂ capture as bicarbonate, aiming to improve the overall efficiency of carbon management by not using CO₂ as a carbon carrier. Two main components of the research are i) CO₂ capture as bicarbonate using a novel class of surface-active tertiary amines

and ii) the bicarbonate separation and amine regeneration in a single step. The overall objective of this research is to examine the energy efficiency of the bicarbonate pathway in comparison to the conventional CO₂ stripping process that is enabled and thus burdened by the need for temperature swings.

2. Formate Species as Carbon/Hydrogen Carriers



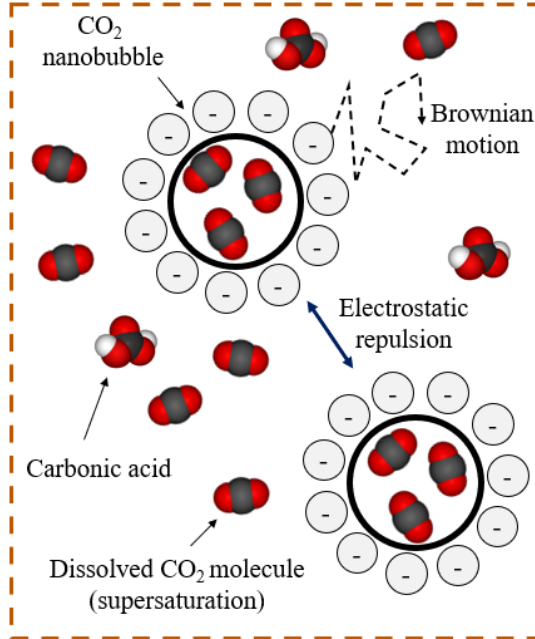
Conventional CCUS uses CO₂ as a carbon carrier, which possesses various drawbacks related to its physical properties, such as low carbon density at low to moderate pressure, low mass density, low viscosity, immiscibility with water, and corrosivity. The potential risk of CO₂ leakage from subsurface storage sites by the buoyancy-driven upward flux must be carefully monitored and controlled for decades. Also, the significant costs associated with CO₂ capture, compression, transportation, and recycling after CO₂ breakthrough at production wells are practically important factors for subsurface CO₂ storage at scale.

Alkali formates can be used as an alternative to CO₂ as a carbon carrier for geological storage that addresses the techno-environmental concerns mentioned above. Contrary to CO₂, formate species (e.g., sodium and potassium) are highly soluble in brine with a carbon density of up to 18 mol/L (comparable to >12 MPa compressed CO₂) even at standard conditions. In addition, they have been used as densifiers for drilling fluids in oil fields because of their health-safety-environmental profiles. Since formate species are stable under typical conditions of subsurface carbon storage, the formate-based carbon storage is analogous to, but more reliable than the solubility trapping mechanism of CO₂ without involving less secure mechanisms, such as structural and capillary trapping. Moreover, aqueous formate solutions can be used as pH buffers in combination with or after CO₂ injection, enabling geochemical control over the geological

sealing integrity of CO₂ storage sites. Also, formate species have been studied as wettability modifiers on carbonate rocks leading to potential applications for enhanced oil recovery (EOR).

This research project is to investigate the potential of an efficient and reliable geological carbon sequestration strategy using aqueous formate solution as a carbon carrier for CCUS. Although carbon storage in aquifers is the ultimate goal, injection of aqueous formate solution into an oil reservoir is also studied as an economically viable option for carbon storage without solely relying on the carbon tax credit. Such revenue sources from enhanced oil production can provide the time and resources to further optimize this technology which will facilitate the transition from increased oil production to low-cost, secure carbon sequestration. An aqueous formate solution with a moderate carbon density of 10 mol/L is equivalent to dissolving 70 kg of CO₂ per barrel of brine. This is approximately 250 times the CO₂ solubility in brine at standard conditions. If formate-based carbon storage was deployed by utilizing the produced water in oil fields in the lower 48 states, which amounts to at least 40 billion barrels per year, 2.8 G tonnes of CO₂ equivalent carbon per year can be stored with the existing water-disposal sites and facilities.

3. Aqueous Nanobubble Dispersion of CO₂



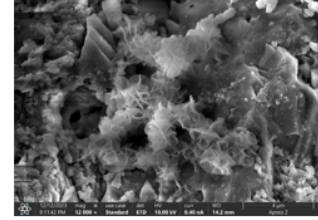
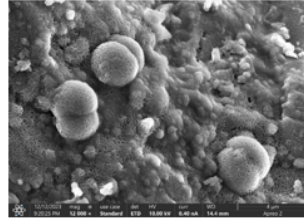
Physical Properties

More than 50% greater amount of CO₂ than the inherent solubility of CO₂ in brine
Majority of CO₂ present as molecule dispersion (supersaturation) in aqueous phase
No risk of nano-size bubbles being trapped in pores.
Substantially reduced buoyant forces in comparison to a bulk CO₂ phase.
Transport of CO₂ as part of ordinary aqueous-phase flow.

Application 1 - Enhanced Oil Recovery

Successfully tested for conventional and tight oil recovery at lab scale.
Greater oil recovery at breakthrough in comparison to water flooding and carbonated water flooding.

Application 2 - CO₂ Mineralization



Carbonate minerals, such as vaterite (left) and hydromagnesite (right), were observed as secondary minerals when aqueous CO₂-nanobubble dispersion was used for CO₂ mineralization with basalt rock samples at lab scale.

Carbonated water has been used as a CO₂ injection method for EOR and geological carbon sequestration. It recently attracted attention particularly because carbonated water may accelerate the eventual mineralization of CO₂ without needing the CO₂ dissolution step, for example, in (ultra)mafic formations (e.g., basalt). An obvious shortcoming of using carbonated water is that the carbon density in carbonated water (i.e., CO₂ solubility) is much smaller than pure CO₂ at injection conditions (i.e., supercritical CO₂), and the CO₂ solubility decreases with salinity and temperature. An estimation based on CarbFix's CO₂ mineralization project is that 22 tonnes of water was required to capture 1 tonne of pure CO₂ for storage; that is, the carbon density was approximately 1 mol/L, a common level of CO₂ solubility in water.

It is possible to increase the CO₂ content in water beyond carbonated water by generating nanobubbles of CO₂ dispersed in water. Aqueous nanobubble dispersion refers to a state in which nano-scale bubbles of water-immiscible gaseous species are dispersed in the external water phase that is supersaturated by the gaseous species. Nanobubble dispersions have been applied in various industries, such as agriculture and wastewater treatment, with the ability to contain a large amount of gas. Kinetically stable nanobubbles at atmospheric pressure in an open system have been reported because of extremely small buoyant forces, repulsive forces among negatively charged surfaces of nanobubbles, and the supersaturated water suppressing Ostwald ripening. However, the previous studies on nanobubble dispersions are focused on an open system near atmospheric pressure. We have uniquely studied the fundamentals of nanobubble dispersions for subsurface applications including geological CO₂ sequestration and CO₂ EOR.