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## Integration Publications

## Acknowledgments
Introduction

Based at Princeton University, the Carbon Mitigation Initiative (CMI) is a university-industry partnership sponsored by BP that began in 2000. In 2014, BP renewed CMI’s contract for an additional 5 years, carrying the program forward through 2020.

Administered by the Princeton Environmental Institute, CMI currently includes 14 lead faculty and more than 60 Princeton research staff and students. The program addresses the natural and industrial processes that determine the rate of accumulation of carbon dioxide and other greenhouse gases in the atmosphere and identifies both risks and opportunities posed by the carbon problem. Research teams are organized into three groups: science, technology, and integration.

CMI Science focuses on how terrestrial vegetation and the oceans soak up carbon and thereby determine the fraction of the carbon dioxide (CO₂) emitted into the atmosphere that actually stays there. CMI science features close collaboration with Princeton’s neighbor, the Geophysical Fluid Dynamics Laboratory (GFDL) of the US Department of Commerce. Together CMI and GFDL are improving the understanding of how climate variability and departures from the historical frequency of extreme events, such as heat waves, droughts, and hurricanes, impact business and society. Another initiative is providing simplified models for understanding the movement of ice through narrow straits, which can affect flow and mixing in the ocean.

CMI Technology explores the integration of intermittent renewable energy (wind and solar) into electricity grids, as affected by carbon policy and renewable energy policy—including the evolving roles for energy conversion in conjunction with CO₂ capture and storage. Capture studies include both biological and fossil fuel inputs. Storage studies emphasize leakage pathways and also investigate storage in shales. Work also continues that is directed toward maximizing energy storage in batteries.

CMI Integration introduces new conceptual frameworks that are useful for climate change policy, including efforts to make emerging statistical analyses of extreme events more accessible; improve the risk-assessment framework for the current scientific understanding of sea level rise; and expand discussions of climate change mitigation and adaptation from global-scale intervention to small-scale urban planning and engineering. In addition, there is new work on the limited potential for CO₂ reuse after capture and chemical activation.

Over the course of 2016, CMI continued its extensive engagement with BP executives and staff. Princeton hosted multiple BP visitors, and several CMI principal investigators conducted town halls and met with senior BP officials in London, Houston, Chicago, and Washington DC to provide information about CMI research in climate science and technology and to engage in public policy discussions.

During a ceremony held on the Princeton campus in February 2016, Director of Climate Change and Sustainability Technology Gardiner Hill presented the 2016 CMI Best Paper Award for Posdoctoral Fellows to former fellow Caroline Farrior. Farrior, who worked in
the Pacala lab, was awarded for her paper published in the January 2016 issue of *Science* entitled, “Dominance of the Suppressed: Power-law size structure in tropical forests.” Papers are judged for their quality and impact on the carbon mitigation community.

The 15th annual meeting of the Carbon Mitigation Initiative (CMI) was held on April 13-14, 2016 in London. This is the first time in the 16-year history of CMI that the annual meeting was held somewhere other than the Princeton University campus. Locating the meeting in London facilitated deeper interaction between CMI investigators and European colleagues. Over 60 people attended to hear presentations and take part in discussions about terrestrial and ocean carbon sinks, carbon targets and budgets, carbon dioxide and methane leakage, and post-COP21 perspectives.

The London meeting also featured “side events” throughout the week focused on climate policy, subsurface storage of CO$_2$, methane leakage, climate variability, and battery technology. Attendees included Princeton faculty and students and colleagues from BP, GFDL, five national and international universities, and several environmental non-profit organizations and policy think-tanks.

CMI is pleased to announce two new leaders: Gabriel Vecchi, a new member of the senior faculty in geosciences, and Ian Bourg, an assistant professor of civil environmental engineering. Both also hold appointments at the Princeton Environmental Institute. Vecchi is an expert in hurricanes, and Bourg in clays in soils and geological formations.

As of 2016, CMI has a new Executive Sponsor, Cindy Yeilding, Senior Vice President, BP America.

For more information, visit us at CMI’s website - cmi.princeton.edu - or email us at cmi@princeton.edu.
CMI Science focuses on how terrestrial vegetation and the oceans soak up carbon and thereby determine the fraction of the carbon dioxide (CO$_2$) emitted into the atmosphere that actually stays there. CMI science features close collaboration with Princeton’s neighbor, the Geophysical Fluid Dynamics Laboratory (GFDL) of the US Department of Commerce. Together CMI and GFDL are improving the understanding of how climate variability and departures from the historical frequency of extreme events, such as heat waves, droughts, and hurricanes, impact business and society. Another initiative is providing simplified models for understanding the movement of ice through narrow straits, which can affect flow and mixing in the ocean.

Research Highlights – At a Glance

**Stephen Pacala**: Plants lose water and take up carbon through stomates, and the ability to simulate their behavior under various conditions is an essential part of global climate models. The Pacala group has developed and tested a new hypothesis of stomate regulation that improves upon current models in predicting stomate behavior during drought.

**Jorge Sarmiento**: Modeling studies suggest that the ocean around Antarctica acts as a key sink for atmospheric CO$_2$ and heat, thus mitigating global temperature increases caused by rising levels of CO$_2$. However, ship-based observations needed to understand the processes behind this uptake are scarce in the harsh and remote Southern Ocean, particularly in winter. To combat the data shortage, Jorge Sarmiento is directing the first large-scale deployment of robotic floats equipped with biogeochemical measurement instruments in this region. The project is enabling unprecedented observations of pH, biological productivity, carbon cycling, and phytoplankton dynamics in the Southern Ocean and improving our ability to predict its future.

**François Morel**: The ongoing increase in atmospheric CO$_2$ acidifies the surface ocean. The Morel group has documented highly significant effects of ocean acidification on the bioavailability of essential trace metals such as iron and zinc, which are known to limit the growth of phytoplankton and, hence, the productivity of ecosystems in large areas of the oceans. A newly developed
electrochemical analytical method is the first to show a quantitative correspondence between metal “lability” and rates of biological uptake in natural seawater.

**Michael Bender:** Ice core studies from the Allan Hills Blue Ice Area in Antarctica have yielded ice dating back to 2,000,000 years ago, the oldest ever retrieved. Analysis of ice dating to 1,000,000 years ago suggests that links between climate and CO₂ are similar to those of more recent glacial cycles.

**Howard Stone:** Climate changes involve atmospheric motions, ocean flows, and evolution of ice on land and in the sea. These dynamics are necessarily interrelated; insights into individual processes can help to illuminate poorly understood aspects of global climate dynamics, such as factors affecting the maintenance of sea ice cover in the Arctic basin. Sea ice cover can impact fresh water fluxes, local ecology and ocean circulation. Over the past year, the Stone group has continued to study the physical mechanisms involved in the development of ice bridges in narrow straits and has succeeded in providing simple predictors for the conditions required for the bridge formation and maintenance. The approach accounts for processes on length scales below those normally resolved in climate models.
Modeling Stomatal Regulation Under Drought Conditions

Principal Investigator: Stephen Pacala

At a Glance

Plants lose water and take up carbon through stomates, and the ability to simulate their behavior under various conditions is an essential part of global climate models. The Pacala group has developed and tested a new hypothesis of stomatate regulation that improves upon current models in predicting stomatate behavior during drought.

Research Highlight

Tiny valves on the surfaces of leaves, called stomates (Figure 1.1.), regulate carbon gain and water loss by plants, and are thus linchpins of the global carbon and water cycles. Amazingly, a simple equation regulates stomates worldwide. This equation is backed by enormous empirical data and a 40-year-old evolutionary explanation, and controls carbon gain and water loss in all Earth System models that predict climate. It is one of the most widely accepted paradigms in ecology and has been taught for decades in introductory biology courses worldwide, including Princeton’s.

Figure 1.1. A stomate on the surface of a cucumber leaf.
Nonetheless, neither the simple model nor the evolutionary hypothesis explains observed stomatal closure during drought. Moreover, the 40-year-old evolutionary hypothesis is not consistent with the current understanding of plant competition for water, and does not include recent discoveries about damage to plant hydraulic systems during drought.

The Pacala group developed an alternative hypothesis that includes plant competition and hydraulic damage, such as impaired water flow through xylem. The new hypothesis has the same empirical support as the classical hypothesis under non-drought conditions and also predicts observed stomatal closure during drought.

A statistical test was developed to explicitly separate the classical and new hypotheses, and assembled a global data set that could be used with the test. The results unanimously support the new hypothesis over the classical hypothesis. We have since built the new model of stomatal control into our Earth System Model. Early tests imply improvements in both the carbon and hydrologic cycles, particularly in tropical forests. This work is timely because of recent studies implying that drought has reduced the Amazon carbon sink.

References


Update on the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) Project

Principal Investigator: Jorge Sarmiento

At a Glance

Modeling studies suggest that the ocean around Antarctica acts as a key sink for atmospheric carbon dioxide (CO$_2$) and heat, thus mitigating global temperature increases caused by rising levels of CO$_2$. However, ship-based observations needed to understand the processes behind this uptake are scarce in the harsh and remote Southern Ocean, particularly in winter. To combat the data shortage, Jorge Sarmiento is directing the first large-scale deployment of robotic floats equipped with biogeochemical measurement instruments in this region. The project is enabling unprecedented observations of pH, biological productivity, carbon cycling, and phytoplankton dynamics in the Southern Ocean and improving our ability to predict its future.

Research Highlight

CMI member Jorge Sarmiento directs the National Science Foundation-funded Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project, a multi-institutional effort to observe the poorly sampled ocean around Antarctica and increase our understanding of how it influences Earth’s climate and carbon cycles. CMI-supported modeling studies have indicated that the Southern Ocean is a large sink for atmospheric heat and carbon, as well as an important source of nutrients for low-latitudes, but efforts to observe the region directly are hampered by rough conditions that limit access by conventional research vessels. SOCCOM scientists are working to dramatically increase the number and variety of observations of the Southern Ocean through the world’s first large-scale deployment of biogeochemical (BGC) Argo floats (Figure 1.2.1.) – robotic floats equipped with newly developed biogeochemical sensors to measure pH, nitrate, and oxygen in addition to ocean temperature and salinity. The new observations are giving an unprecedented view of carbon cycling and biological productivity in this important region, and helping us to understand how these processes might change in the future.

Seventy-seven SOCCOM BGC floats (Figure 1.2.2.) are currently operating and have collectively made over 2 million observations in the Southern Ocean. The SOCCOM float data are made freely available to the public in near-real time, and have been incorporated into the global Argo data system used by hundreds of researchers around the world.

Complementing this observational effort, the SOCCOM team has developed model-based tools to study controls on Southern Ocean biogeochemistry and its response to climate change. To better understand the current workings of the Southern Ocean, SOCCOM researchers have assimilated observational data into an ocean model to produce a 3-D, physically realistic estimate of Southern Ocean biogeochemistry (B-SOSE) that is freely available to the oceanographic community. To improve predictions of future climate and carbon cycle changes, planning has been completed for a Southern Ocean Model Intercomparison Project (SOMIP) that will analyze differences among Earth system model forecasts from leading research groups.
Together, SOCCOM data and tools are providing unparalleled insights into the Southern Ocean. Wintertime and under-ice measurements never before available are yielding information on the annual variability of pH and carbonate saturation in the system, net community production, carbon export, air-sea fluxes of CO$_2$ and O$_2$, and bloom dynamics. For example, analyses of the new data have revealed that seasonal changes in CO$_2$ fluxes and nutrient concentrations are much larger than previously estimated from ship-based data, which is biased toward the summer months. This insight has implications for our understanding of the magnitude, timing, and location of Southern Ocean carbon uptake, and also for model development, as current models of ocean biogeochemistry have been tuned to match the earlier, seasonally-biased estimates of carbon and nutrient distributions. These and other early research results, along with SOCCOM technology and methods, will be shared in a special issue of the *Journal of Geophysical Research - Oceans* this spring.

SOCCOM will continue to make progress on observational and modeling goals in the coming year. This September will mark the end of the group’s third cruise season, after which over 90 BGC floats will have been deployed, bringing SOCCOM nearly halfway to its goal of 200 floats deployed within six years. This year will also see SOCCOM float data incorporated into the biogeochemical state estimate and the initiation of SOMIP. Beyond SOCCOM, the team is working with international research partners to expand the SOCCOM network of BGC floats and create a global observing system for ocean health.

Figure 1.2.1. SOCCOM float deployment from the R/V Nathaniel B. Palmer, January 2016. Float 12390 was named “KC Bell” by John Witherspoon Middle School students as part of SOCCOM’s adopt-a-float program. Photo credit: Climate Central.
Figure 1.2.2. SOCCOM float locations and trajectories, February 2017. Red dots are locations of operating floats; blue are inoperative floats. Yellow lines indicate float trajectories since deployment. Credit: SOCCOM.

References


Effects of Ocean Acidification on the Bioavailability of Essential Metals to Marine Phytoplankton

Principal Investigator: François Morel

At a Glance

The ongoing increase in atmospheric carbon dioxide (CO$_2$) acidifies the surface ocean. The Morel group has documented highly significant effects of ocean acidification on the bioavailability of essential trace metals such as iron and zinc, which are known to limit the growth of phytoplankton and, hence, the productivity of ecosystems in large areas of the oceans. A newly developed electrochemical analytical method is the first to show a quantitative correspondence between metal “lability” and rates of biological uptake in natural seawater.

Research Highlight

The acidification (i.e., decreasing pH) of the surface ocean modifies its chemistry and, potentially, the bioavailability of nutrients. The Morel group has conducted both field and laboratory experiments to examine how the bioavailability of essential trace metals to phytoplankton changes over the range of pH values expected to occur in surface seawater over the next century.

The availability of trace metals to marine microorganisms depends on the extent to which they are bound to organic compounds, which in turn depends on ocean acidity. By increasing the organic binding of iron, ocean acidification decreases the bioavailability of one of the most important limiting nutrients in the oceans. For zinc, a metal that affects the assemblage of phytoplankton species that fuel marine food webs, the opposite result—an increase in bioavailability upon acidification—is expected and generally observed. Sometimes, however, a decrease in zinc bioavailability can result from competitive metal binding among organic compounds.

In laboratory experiments, a decrease in pH modified the bioavailability of iron and zinc in a way that was quantitatively consistent with the calculated change in their binding by the weak and strong organic complexing agents in the experimental medium. Extending these results to natural seawater is difficult, however, due to the presence of myriad organic compounds of unknown chemistry and affinity for the metals of interest.

To overcome this difficulty, the Morel group developed an electrochemical method to quantify the effects of acidification on metal availability in natural seawater in the presence of unknown metal-binding compounds. The new method distinguishes between the metal species available for biological uptake by phytoplankton and those that are not. These results will enable future assessments and predictions of how increases in CO$_2$ concentration impact marine ecosystems.

The simplicity of the figure that illustrates these results (Figure 1.3.) belies their novelty and importance: it is the first time that a quantitative correspondence has been shown between chemical measurements of metal “lability” and rates of biological uptake in natural water samples.
Figure 1.3. The concentration of labile Zn (units: pM, or $10^{-12}$ moles per liter) measured by electrochemistry (anodic stripping voltammetry), and the short-term Zn uptake rate by phytoplankton (units: amol per hour per cell, amol = $10^{-18}$ moles) at pH 7.9 and pH 8.3 in coastal seawater.

References


Climate Studies Based on Old Ice from Antarctica

Principal Investigator: Michael Bender

At a Glance

Ice core studies from the Allan Hills Blue Ice Area in Antarctica have yielded ice dating back to 2,000,000 years ago, the oldest ever retrieved. Analysis of ice dating to 1,000,000 years ago suggests that links between climate and carbon dioxide (CO$_2$) are similar to those of more recent glacial cycles.

Research Highlight

Many scientists have looked to characteristics of past climates as one guide to our planet’s future climate. A wide range of “paleoclimate” archives have been studied for this purpose. Of these archives, ice cores drilled through the Greenland and Antarctic ice sheets are unique in that they preserve fossil air that was trapped more or less when the snow fell. Ice core samples have been used to characterize variations in the CO$_2$ concentration of air, among other properties. Through ice core studies, we have a detailed record of atmospheric CO$_2$ variations back to 800,000 years ago. The results show that global climate varies closely with CO$_2$ concentration changes during the ice ages. Heretofore, no older ice had been retrieved. This is a serious limitation, because glacial cycles were different before 800,000 years ago: earlier glacial cycles were less intense and lasted for a shorter time. We want to understand the difference in conditions between earlier ice ages (1,000,000-2,000,000 years ago) and the past 800,000 years.

My colleague John Higgins and I, working with a group from the University of Maine, along with graduate student Yuzhen Yan, have searched for old ice in a previously unexplored Antarctic environment: the Allan Hills Blue Ice Area. Preceding ice core studies have drilled cores where the ice age at the surface is zero, and age increases progressively with depth. In the Allan Hills, the Transantarctic Mountains block the flow of ice to the oceans. They guide old ice from the bottom of the ice sheet to the surface (Figure 1.4). In three expeditions to the Allan Hills over the past six of years, we have recovered ice dating back to 2,000,000.

We have analyzed ice dating to 1,000,000 years ago for CO$_2$, methane (CH$_4$), and other properties. The data suggest that links between climate and CO$_2$ are similar to those of more recent glacial cycles. During the last expedition (austral summer of 2015-2016), we recovered ice as old as 2,000,000 years. To date we have focused on the time-consuming process of dating the ice. Our Maine collaborators have analyzed the isotopic composition of the ice, which turns out to reflect past temperatures of the study region. We will begin making analyses of greenhouse gases (CO$_2$ and CH$_4$) shortly.

Studies of million-year-old ice showed that, at that time, Earth’s climate properties co-varied as during more recent times. For example, the relation between CO$_2$ and Antarctic temperature was the same 1,000,000 years ago as during the larger climate fluctuations of more recent times. With our new samples, we will determine if this pattern holds true further back in time. We will also be able to test the hypothesis that the long-term climate cooling of the last 3,000,000 years ago was a consequence of declining levels of CO$_2$ in air. Overall, this research will contribute to the objective of studying Earth’s past climates to advance our understanding of the response of climate to changing levels of CO$_2$ and other greenhouse gases.
Figure 1.4. Left: A cartoon illustrating ice flow in the Allan Hills, Antarctica. The glacier flows east (solid lines with arrows) but runs up against the Allan Hills of the Transantarctic Mountains, which guides deeply buried old ice to the surface. Credit: Whillans and Cassidy, 1983. Right: A photo looking north. The dark areas to the extreme right side of the photo are the peaks of the Transantarctic Mountains. Note the contrast between (old) blue ice in the upper half of the photo and modern snow in the lower part. Snowmobile for scale. Photo credit: Yuzhen Yan.
Modeling Ice Bridges to Obtain Results Beyond the Resolution of Climate Models

**Principal Investigator:** Howard Stone

**At a Glance**

*Climate changes involve atmospheric motions, ocean flows, and evolution of ice on land and in the sea. These dynamics are necessarily interrelated; insights into individual processes can help to illuminate poorly understood aspects of global climate dynamics, such as factors affecting the maintenance of sea ice cover in the Arctic basin. Sea ice cover can impact fresh water fluxes, local ecology and ocean circulation. Over the past year, the Stone group has continued to study the physical mechanisms involved in the development of ice bridges in narrow straits and has succeeded in providing simple predictors for the conditions required for the bridge formation and maintenance. The approach accounts for processes on length scales below those normally resolved in climate models.*

**Research Highlight**

Ice bridges are stationary, rigid structures composed of sea ice, which are commonly formed in the many straits and channels throughout the Canadian Arctic Archipelago. Under certain conditions, the ice bridges are stable and span the width of the strait, connecting the two neighboring landmasses. These ice bridges appear seasonally and persist for several months, impacting both the local climate and ecology in two significant ways. First, since they are solid structures spanning the strait, they inhibit the flow of sea ice from colder regions into warmer waters. Second, by regulating the motion of ice, they affect the dynamics of flow and mixing in the ocean, thus influencing ocean salinity and regulating the transport of gases and nutrients that are crucial for ecological processes (e.g., the growth of photosynthetic plankton that form the base of marine food chains).

While ice bridges are regularly and predictably observed in the field, the precise mechanical conditions under which they form are not well understood. Improved models for predicting the dynamics of ice bridges would lead to a fuller picture of global changes in sea ice and fill in gaps in common large-scale climate models, which typically fail to resolve dynamics at the scale of a narrow strait. Failure to form an ice bridge during a particular season can, for instance, result in an irrecoverable loss of sea ice through flow into warm oceans and subsequent melting. Since 2015, the Stone group has studied the physical mechanisms involved in the bridge formation process and has succeeded in providing simple predictors for the conditions required for the formation and maintenance of ice bridges.

Although most studies of ice flows implement numerical models, the mechanics community has a long history of developing simplified models for studying flow in narrow geometries. Over the past year, the Stone group has used these techniques to provide a mathematical model that includes the role of mechanical stresses in the ice in response to wind, which is more central to ice bridge formation than other secondary processes such as the rotation of the Earth, or ice melting and freezing; water flow has also been included. This model will provide oceanographers and climate scientists with tools by which to understand the complex dynamics of sea ice, while speaking more broadly to the scientific community on problems of global importance. The group produced a new
theory to predict the flux of ice expected in situations without ice bridges, which agrees well both with field measurements and large-scale computational models. The theory also makes predictions for the critical ice thickness (defined to account for the wind stress, the compressive strength of the ice and the channel width) beyond which the flow becomes entirely arrested, which is also consistent with numerical studies.

Figure 1.5. (A) Map showing the Nares Strait between northwestern Greenland and Ellesmere Island, Canada. The Nares Strait is a site for seasonal ice bridge formation. Credit: Environment Canada, Government of Canada. (B) Satellite image indicating the location of a stable ice bridge in the Nares Strait (from May 25, 2001), marking the boundary between (a) the ice sheet and (b) open water in the strait. Image adapted from: Dumont, D., Y. Gratton, and T. E. Arbetter, 2009. Modeling the dynamics of the North Water Polynya ice bridge. J. Phys. Oceanogr., 39: 1448–1461. (C) The formation of ice bridges depends on the ice thickness $h$, the maximum and minimum widths of the strait $w_{\text{max}}$ and $w_{\text{min}}$, respectively, the wind stress $\tau$ and the compressive strength of the ice $S$. Shaded regions are theoretical predictions, and symbols are numerical results for the flow state as a function of the ice thickness, which includes ice-bridge formation. The conditions for ice bridge formation are more restrictive in simulations than in the theory due to dynamic instabilities of the bridge that arise from a tendency of the ice to continue flowing during incipient stages of bridge formation. (D) Ice velocity as a function of the wind stress in Nares Strait, indicating theoretical predictions for different ice thicknesses (lines) and the field data of Samelson et al. 2006 GRL (symbols), which span a range of thicknesses that is not measured. The sign of $\tau$ denotes the direction of the wind, with positive $\tau$ representing the dominant northerly winds towards the Atlantic Ocean. Concurrent measurements of ice properties and forcing conditions will allow the theory to predict sea ice fluxes through straits.
The Stone group’s current efforts are focused on modeling the process by which the flow becomes arrested, eventually leading to the formation of an ice bridge. Such behavior also arises in other engineering and science problems, such as the flow of granular materials, including soil, in confined geometries, which suggests a broader scope for understanding other physical and geological processes. Additionally, our theory provides a means to calibrate existing models of sea ice dynamics against field observations without the need to run detailed simulations. Thus, our theoretical efforts not only explain a complex geophysical flow phenomenon in straits, but also provide a means to refine the modeling of sea ice in the more general context of Arctic and Antarctic ice flows.

In the future, the group aims to tackle ice accumulation and flow past islands, which are other significant aspects of dynamics in the arctic. A long-term goal is to understand the eventual breakup of ice bridges and dynamics of formation and flow using a model that incorporates processes such as wind forcing, ice melting and water flow.

References


Science Publications


Yau, A.M., M.L. Bender, T. Blunier, and J. Jouzel, 2016. Setting a chronology for the basal ice at Dye-3 and GRIP: Implications


CMI Technology

CMI Technology explores the integration of intermittent renewable energy (wind and solar) into electricity grids, as affected by carbon policy and renewable energy policy—including the evolving roles for energy conversion in conjunction with carbon dioxide (CO$_2$) capture and storage. Capture studies include both biological and fossil fuel inputs. Storage studies emphasize leakage pathways and also investigate storage in shales. Work also continues that is directed toward maximizing energy storage in batteries.

Research Highlights – At a Glance

Michael Celia: In order to have a significant impact on the carbon problem, very large amounts of captured CO$_2$ need to be injected underground, with quantities reaching gigatonnes of CO$_2$ per year by mid-century. The Celia group has developed models for large-scale injection, including pressure responses and associated pressure management schemes, and applied these to realistic injection scenarios in the Illinois Basin of North America, with simulated basin-wide injection rates exceeding 200 Mt CO$_2$/yr. Results indicate that if carbon capture and storage is to be implemented at the scale required to impact the carbon problem, such basin-wide analyses will need to be performed and appropriate management of pressure developed and implemented.

Ian Bourg: The objective of this initiative is to resolve the physics of soil carbon storage. The carbon storage capacity of soils is known to increase significantly with clay content, and in particular with the content in swelling clay minerals (smectites), but the cause of this relationship remains unknown. Using atomistic-level simulation methodologies, the Bourg group was able to model fully flexible clay particles surrounded by water and interacting with dissolved organic compounds. These results will enable more accurate Earth System Model predictions of the soil carbon sink and inform practical strategies for enhancing this important carbon sink.

Daniel Steingart: We are studying a fundamental question in battery research – whether apparently negative and inevitable physical phenomena in an electrochemical cell, such as corrosion and anisotropic growth, can be exploited for benefit. We use various imaging techniques to examine the deposition and removal of plate metals during cell operation and in conditions that emulate practical usage patterns.
Full-scale Basin-wide CO\textsubscript{2} Injection with Pressure Management

Principal Investigator: Michael Celia

At a Glance

In order to have a significant impact on the carbon problem, very large amounts of captured carbon dioxide (CO\textsubscript{2}) need to be injected underground, with quantities reaching gigatonnes of CO\textsubscript{2} per year by mid-century. The Celia group has developed models for large-scale injection, including pressure responses and associated pressure management schemes, and applied these to realistic injection scenarios in the Illinois Basin of North America, with simulated basin-wide injection rates exceeding 200 Mt CO\textsubscript{2}/yr. Results indicate that if carbon capture and storage is to be implemented at the scale required to impact the carbon problem, such basin-wide analyses will need to be performed and appropriate management of pressure developed and implemented.

Research Highlight

The capture and belowground storage of carbon dioxide emissions from power plants and other sources has the potential to mitigate climate change by preventing the release of these emissions into the atmosphere. In order to have any significant impact on the carbon problem, very large amounts of captured CO\textsubscript{2} need to be injected underground, with quantities reaching gigatonnes of CO\textsubscript{2} per year by mid-century. This will require tens to hundreds of millions of tonnes of CO\textsubscript{2} to be injected into a given sedimentary basin.

Earlier research by the Celia group, and others, led to the idea that very large-scale injection of CO\textsubscript{2} may need to be coupled with brine production and other measures to control pressure buildup in the injection formations.\textsuperscript{1-11} To illustrate the impacts of very large-scale injection, a new study simulates pressure buildup in the Illinois Basin associated with injection of CO\textsubscript{2} into the Mount Simon Formation. Figure 2.1.1 shows the increase of pressure associated with injection of close to 200 Mt CO\textsubscript{2}/yr, assuming 54 different on-site injection locations, and using a computational model that includes 11 geological layers and covers approximately 300,000 km\textsuperscript{2}.

The Area of Review (AoR) is defined as the area where, by EPA regulation, pressure increase is sufficient to require site characterization and monitoring. The total AoR for this injection scenario is close to 200,000 km\textsuperscript{2}. Not only is this a large area, but many of the individual injection sites have AoRs that overlap with those from neighboring injection sites, thereby complicating the determination of responsible parties in the event of a leakage event or other problem. In addition, the large pressure build-up has a number of associated risks including possible leakage of brines from the injection formation to shallow drinking water aquifers (this is the basis of the EPA definition for AoR) as well as increased potential for induced seismicity.

One way to reduce pressure build-up, and thereby the AoR, is through the use of brine production wells. Such wells need to be close enough to the injection to have an impact on the pressure response, but far enough away to avoid any early CO\textsubscript{2} breakthrough. If the volume of brine extracted matches the volume of CO\textsubscript{2} injected, then the pressure responses associated with each injection well can be controlled and the pressure build-up is highly localized. A strategy of 100% volume matching reduces the overall AoR from around 200,000 km\textsuperscript{2} to less than 20,000 km\textsuperscript{2} while eliminating overlapping AoRs (Figure 2.1.2.).
Figure 2.1.1. Onsite injection scenario after 50 years of continuous injection without pressure management. Left panel: CO₂ plumes in the injection formation. Right panel: Pressure increase and area of review (AoR, hatched area) in the injection formation. Total AoR is close to 200,000 km². From Bandilla and Celia.

Production of brine carries its own set of challenges, however, related to the use and disposal of the brines. While earlier collaborative work with Lawrence Livermore National Laboratory studied the possible use of heat from produced waters as well as desalination options, these utilization options appear to be limited in the Illinois Basin due to the relatively low temperatures and high salinities. Therefore disposal of the produced water becomes an issue. We have considered reinjection of the produced brines into formations above the injection formation (that is, above the Mount Simon Formation), with fractions ranging from 25% to 100% of the extracted water. In these cases, pressure increases in the overlying formations need to be analyzed and potential AoRs need to be computed for those injection operations.

Also, as in our earlier analysis of the Basal Sandstone formation in western Canada, we considered off-site injection at regional centers, as opposed to on-site injections. This requires pipelines to transport the CO₂ to the best locations for injection, but the result is a smaller and more easily managed pressure response. Even without brine extraction, this strategy reduces the overall AoR by about 30%. Adding brine extraction then allows for much larger reductions in AoR values, similar to the on-site results. The use of regional centers chosen for optimal injection properties also solves the problem of excessive pressure buildup at injection locations where subsurface properties are not conducive to large-scale injection, which happens at several of the on-site locations, affecting approximately 25% of the total CO₂ injected.
Overall, if carbon capture and storage is to be implemented at the scale required to impact the carbon problem, these kinds of basin-wide analyses will need to be performed and appropriate management of pressure developed and implemented.

References


Resolving the Physics of Soil Carbon Storage

Principal Investigator: Ian Bourg

At a Glance

The objective of this initiative is to resolve the physics of soil carbon storage. The carbon storage capacity of soils is known to increase significantly with clay content, and in particular with the content in swelling clay minerals (smectites), but the cause of this relationship remains unknown. Using atomistic-level simulation methodologies, the Bourg group was able to model fully flexible clay particles surrounded by water and interacting with dissolved organic compounds. These results will enable more accurate Earth System Model predictions of the soil carbon sink and inform practical strategies for enhancing this important carbon sink.

Research Highlight

Soil are a vast pool of carbon (2,400 gigatonnes of carbon, integrated from the surface to 2 m depth), roughly three times larger than the atmosphere and 240 times current annual fossil fuel emissions. A 0.4% annual increase in global soil carbon content would, on its own, entirely offset global fossil fuel emissions\(^1\). Conversely, soil carbon losses have historically led to significant anthropogenic carbon dioxide emissions. The US’s Great Plains lost almost 4% of their soil organic carbon over the last 30 years, and decreases of similar or greater magnitude have been estimated for other regions.

The carbon storage capacity of soils is known to correlate with soil clay content, and in particular with the content in swelling clay minerals (smectites), but the cause of this relationship remains unknown. Clay minerals contribute predominantly to the specific surface area and cation exchange capacity of soils, suggesting that organic molecules may become chemically shielded from microbial degradation by attachment to clay surfaces. Clay minerals also strongly influence the hydraulic permeability of porous media, suggesting that they may slow the degradation of soil organic matter by modulating soil microbiology and/or hydrologic permeability.

A key breakthrough in this initiative in 2016 is the ability to model, using atomistic-level simulation methodologies developed by the Bourg group over the last two years, fully flexible clay particles surrounded by water and interacting with dissolved organic compounds. As a first test of this methodology, the group simulated the adsorption of dissolved gases (noble gases, methane, CO\(_2\), or H\(_2\)) on smectite clay particles (Gadikota et al., 2017). These simulations (Figure 2.1.), which solve Newton’s equations of motion for systems of about 100,000 atoms using semi-empirical models of all relevant interatomic interactions, require about two weeks of time on hundreds of parallel processors. The main challenge is to develop models of these interatomic interactions that accurately predict the properties of real clay-water systems, a research area in which the Bourg group is actively involved, in collaboration with synchrotron scientists at two US National Laboratories. The simulations are carried out on the Cori supercomputer of the US Department of Energy, the world’s fifth fastest computer.

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\(^1\) According to Earth System Models, soil carbon content will increase significantly over the 21st century. The magnitude of this increase is poorly known (it may range from 0.01 to 0.15% annually) because of a lack of understanding of the fundamental mechanisms that control the rate of microbial degradation of soil organic matter. A 0.02% annual increase in the global soil carbon content would add 25 GtC to the soils, which is a stabilization “wedge” as defined by Pacala and Socolow (2004).
The results show that clay minerals, despite their well-known hygroscopic nature, have a significant hydrophobic character at the atomistic scale. This local hydrophobicity exists because the random distribution of negatively charged sites (mostly isomorphic substitutions of Al by Mg) in the clay structure gives rise to uncharged “patches” on the clay surface, i.e., localized regions where the clay surface is hydrophobic because it carries no exchangeable cations (Na\(^+\) ions in Figure 2.1). The affinity of different dissolved gases for the clay surface further shows unexpected variations related to the size and shape of the adsorbing molecules and the structuring of interfacial water by the clay surface. Results obtained with dissolved gases and preliminary results obtained with uncharged organic compounds suggest that organic molecules containing aromatic rings and/or heteroatoms (O, N, S) should have a significantly greater tendency to attach to (and become physically shielded by) clay surfaces.

Figure 2.1. Snapshot of a simulation cell containing a stack of smectite clay nanoparticles (1 nm thick clay particles with 0.6 nm thick interlayer nanopores) in contact with a mesopore (0.6 M NaCl solution). Clay structural atoms are shown as red, yellow, pink, green, and white spheres (O, Si, Al, Mg, and H, respectively); water molecules are shown as red and white sticks; Na and Cl ions are shown as dark and light blue spheres; five molecules of a monoatomic gas solute (Ar) are shown as large orange spheres. Each simulation required 35 nanoseconds (35 million time steps) to obtain average equilibrium properties of the system of interest. The clay particles have a negative structural charge that is balanced by exchangeable sodium ions in the interlayer nanopores.

The Bourg group is building upon these simulation methodologies to investigate the mechanisms of soil carbon storage through two research efforts. The first effort (carried out under the auspices of CMI) focuses on developing a fundamental knowledge of the thermodynamics of adsorption of a range of organic molecules representative of soil organic matter on smectite clay minerals. The second effort (supported by the US Department of Energy) focuses on developing new constitutive relationships for the impact of clay minerals on the permeability of soils. The two research efforts are independent (and carried out by different team members), but their results inform each other.
In addition to providing an advanced understanding of carbon cycling in soils, this initiative will enable more accurate representations of the interaction of organic or hydrophobic compounds with clay surfaces in other areas, for example, in basin modeling, CO$_2$-enhanced oil recovery, and the remediation of soils contaminated by organic contaminants. Results on the adsorption of dissolved gases on smectite surfaces shed light on long-standing questions associated with the use of noble gases as tracers of fluid migration in the subsurface.

References


Exploiting Negative Phenomena to Maximize Energy Storage in Batteries

Principal Investigator: Daniel Steingart

At a Glance

We are studying a fundamental question in battery research—whether apparently negative and inevitable physical phenomena in an electrochemical cell, such as corrosion and anisotropic growth, can be exploited for benefit. We use various imaging techniques to examine the deposition and removal of plate metals during cell operation and in conditions that emulate practical usage patterns.

Research Highlight

In our first full year working with the Carbon Mitigation Institute we posed a fundamental question in energy storage research: can apparently inevitable physical outcomes in a cell such as corrosion and anisotropic growth be exploited for benefit rather than suppressed and avoided?

In a closed electrochemical cell, the maximum energy density is achieved when the lightest possible electrochemically active components are paired with the largest possible potential window. While this demands use of a heretofore unrealized fluoride compound as an oxidizing agent, it also requires use of metallic lithium as a reducing agent. Metallic lithium has been used successfully as a primary metal anode for half a century, but its use as a secondary anode has been limited by both the chaotic nature of its redeposition during a charging cycle and the possibility of an explosion when there is an uncontrolled short circuit. Its application as a secondary anode is feasible only where performance requires a minimal safety factor.

Building upon our previous studies of the growth of zinc at potentials beyond the onset of reactant starvation, we have spent the last year establishing the laboratory infrastructure required to examine the deposition and removal of plate metals while the cells are operating (Figure 2.3.). This includes optical microscopy, electrochemical acoustic analysis, and transmission X-ray microscopy.

We have imaged lithium and zinc with all of these methods, and we are beginning our second year with stability analysis of plate metal systems deposited and removed in various regimes that emulate practical usage patterns. We now have further evidence that better utilization of the active material is achieved with asperities that are pre-grown at the correct length scales rather than the flat structures dictated by conventional design.

Although flat structures are easiest to imagine being “predictable,” in actuality the complex competition between nucleation and growth during crystal growth quickly turns a flat surface into a rough structure. Instead, by starting with a rough structure that is “sympathetic” to the length scales natural to a given growth rate, more of a metal anode can be used reliably.

Going forward this year, we want to test the limits of how much of this rough scaffold can be utilized before the effect is no longer present, and what impurities might be leveraged to act as scaffold.
Figure 2.3. 3D reconstruction (left) and 2D image (right) of zinc dendrites that have maximized cycle life and energy density.

References


Technology Publications


CMI Integration introduces new conceptual frameworks that are useful for climate change policy, including efforts to make emerging statistical analyses of extreme events more accessible; improve the risk-assessment framework for the current scientific understanding of sea level rise; and expand discussions of climate change mitigation and adaptation from global-scale intervention to small-scale urban planning and engineering. In addition, there is new work on the limited potential for carbon dioxide (CO$_2$) reuse after capture and chemical activation.

Research Highlights – At a Glance

**Michael Oppenheimer**: Cities are engineered landscapes, and planning and development choices can significantly exacerbate or mitigate the impacts of climate and environmental change. The height of buildings and their spatial configuration influence the urban form and surface texture, which further affect the surface aerodynamic processes, energy use efficiency and emissions. A “smart” engineered urban landscape can reduce heat stress, and improve energy efficiency and air quality.

**Robert Williams, Eric Larson, and Thomas Kreutz**: Collaborating with analysts at NRG Energy, the largest competitive power producer in the US, the Energy Systems Analysis Group (ESAG) launched a new initiative in 2016 to model the prospective evolution of high penetrations of intermittent renewable electricity supplies (iRES – mainly wind and solar photovoltaic) on US grids. Major challenges must be addressed to reach high iRES penetrations cost-effectively. The research seeks to understand and articulate the cost and carbon implications to mid-century of deployment of various grid technologies interacting with alternative electricity and carbon market redesigns.

**Robert Socolow**: The widely discussed carbon mitigation strategy, CO$_2$ capture and use, is often touted as a way to improve the use of fossil fuel carbon. The idea is to make vehicle fuel by chemically reducing the CO$_2$ in the exhaust stream of a fossil fuel power plant, thereby using the carbon extracted with a fossil fuel twice—once for power and once for transport. This reasoning is flawed, because the same carbon benefit can almost always be achieved more straightforwardly and at lower cost by an alternate use of the large amount of low-carbon energy required to make fuel from CO$_2$. Only a high oil price and a high price for electric vehicles can create a domain of competitiveness for CO$_2$ capture and use.
Designing Urban Land Form for Climate and Environmental Co-Benefits

Principal Investigator: Michael Oppenheimer

At a Glance

Cities are engineered landscapes, and planning and development choices can significantly exacerbate or mitigate the impacts of climate and environmental change. The height of buildings and their spatial configuration influence the urban form and surface texture, which further affect the surface aerodynamic processes, energy use efficiency and emissions. A “smart” engineered urban landscape can reduce heat stress, and improve energy efficiency and air quality.

Research Highlight

Heat stress associated with climate change is one of the most serious climate threats to human society. The impact is further amplified for urban populations because of the urban heat island effect—a common phenomenon in which surface temperatures are higher in urban areas than in surrounding rural areas. Cities are also hotspots for carbon dioxide emissions and strong sources of anthropogenic aerosols. Because more than 50% of the world’s population currently lives in cities, and that percentage is projected to increase to 70% by year 2050, there is a pressing need to find effective solutions to cope with the heat and environmental stress.

It is now recognized that in addition to the traditional emphasis on building up the city’s preparedness or resilience, urban planning and adaptation agendas should also include active modification to the urban landscape in the face of climate change.

Figure 3.1.1. Schematic of air turbulence over urban surface.
In 2016, STEP postdoctoral fellow Lei Zhao, with his advisor, Michael Oppenheimer, developed a novel methodology that combined government building footprint dataset, ultra-high resolution imagery from LiDAR, and satellite observations to investigate the impact of surface morphology and texture on urban climate and environment. The results point to robust relationships between urban morphological properties and the efficiency of heat convection from the city’s surface to the lower atmosphere. Specifically, the height of buildings and their spatial configuration are strong determinants of surface aerodynamic roughness, which represents the urban convection efficiency (Figure 3.1.1). Intensified convection helps not only to reduce temperatures but also to disperse air pollutants.

The study has three important implications. First, this work for the first time demonstrates that surface morphology can affect the urban local climate and environment. Further, it advances the scientific understanding of the impacts of complex surfaces on surface aerodynamic processes. In climate models, land surface is usually modeled as a grid of “tiles” that represent surfaces such as vegetated land, glacier, wetland, lake, and urban areas (Figure 3.1.2). For urban tiles, however, surface geometry, representation, and parameterization are still highly simplified. Insights generated from this study will help improve the ability of climate models to accurately quantify the surface energy, momentum and mass transfer between land and the atmosphere over these urban tiles.
Second, the study provides actionable guidance to policy makers on future urban planning and development concerning urban heat mitigation, climate change adaptation and air pollution abatement. Cities are engineered landscapes, and planning and development choices can significantly exacerbate or mitigate the impacts of climate and environmental change. Results from this study point to the possibility of “smart” engineering urban landscapes to reduce heat stress, and improve energy efficiency and air quality.

Third, it bridges a disconnect in the global climate research agenda between large-scale carbon mitigation and local-scale urban engineering. Unlike planetary-scale mitigation strategies, urban engineering has impacts on a much smaller area of land. Cities are functional units of climate mitigation agendas. A reorientation of some of the discussion of climate change mitigation and adaptation from global-scale climate intervention to small-scale urban planning and engineering can motivate local actions by delivering environmental benefits directly and immediately.

References


Understanding Challenges with Intermittent Renewable Electricity Expansion

Principal Investigators: Tom Kreutz, Eric Larson, and Bob Williams

At a Glance

Collaborating with analysts at NRG Energy, the largest competitive power producer in the US, the Energy Systems Analysis Group (ESAG) launched a new initiative in 2016 to model the prospective evolution of high penetrations of intermittent renewable electricity supplies (iRES – mainly wind and solar photovoltaic) on US grids. Major challenges must be addressed to reach high iRES penetrations cost-effectively. The research seeks to understand and articulate the cost and carbon implications to mid-century of deployment of various grid technologies interacting with alternative electricity and carbon market redesigns.

Research Highlight

Incentives from governments around the world have led to rapid growth in iRES while R&D and experience have led to dramatic reductions in their capital costs—trends that are expected to continue. There are at least three major challenges to be understood and addressed to realize high iRES penetrations.

One major challenge is providing electric balancing capacity in the form of backup or storage. This challenge is well-addressed today by natural gas-fired combustion turbine (CT) and combined cycle (GTCC) backup units, together with iRES curtailment whenever iRES exceed demand. However, as iRES grid penetration increases, iRES generation costs will rise despite falling capital costs, because such curtailments will increase rapidly. California might be considered a window to the future of iRES. Under the state’s new 50% Renewable Portfolio Standard (RPS) mandate, iRES is expected to reach 35% of total generation by 2030\(^1\). Figure 3.2.1. illustrates the iRES over-generation problem for California, where future iRES is expected to be dominated by utility-scale solar photovoltaic electricity.

![Figure 3.2.1. Modeled base-case electricity generation for a day in April 2030 for the California independent system operator (CAISO) grid with different RPS requirements and absent new bulk electricity storage. To satisfy the 50% RPS, about 20 GW of PV generation (the over-generation rate, in red) would need to be curtailed at mid-day.](image-url)
High iRES grids dominated by either wind or solar are likely to require high iRES curtailment rates, although for wind, the iRES supply pattern will be less predictable, over-generation will take place at different times of day, and required ramping rates for balancing capacity will typically be faster. Figure 3.2.2. illustrates these features for Texas, which currently has by far the largest wind generating capacity of any US state (18.5 GW): wind power output (a) is typically strongest at night, (b) drops sharply in the morning as load is rising, (c) picks up again in the evening as load begins to drop, and (d) varies significantly day by day (also season by season).

Figure 3.2.2. Seven days of wind power output and electric load for the grid operated by the Electric Reliability Council of Texas (ERCOT). Net system load is calculated as gross load minus wind generation.

In both solar-dominated and wind-dominated iRES cases, the mismatch between iRES and load means that the system operator needs to curtail over-generated iRES at times and to rapidly adjust backup supplies at other times in order to reliably satisfy electricity demand. Grids with high iRES made up of a more balanced mix of solar and wind are likely to have lower curtailment rates, partly because wind and sun may be available at different times.

Curtailments of iRES can also be mitigated by storing over-generated electricity. Bulk electricity storage via batteries over periods longer than a couple of hours is expensive, and pumped hydro storage (PHS) is geographically constrained. However, natural gas-fired compressed air energy storage (CAES) is likely to be less costly than PHS and potentially deployable throughout most of the US. CAES is commercially ready for storage in salt caverns (deployable in wind-rich regions such as Texas and possibly also the Rocky Mountain and northern Great Plains regions) and might be cost-competitive with new CT backup capacity. CAES could be much more widely available via
storage in porous media (expected to be less costly than salt caverns\(^1\)) and mined hard rock—options that have not yet been demonstrated.

A second major challenge to high iRES penetrations is the reduction in carbon dioxide (CO\(_2\)) emissions from balancing capacity that likely will be required to meet long-term carbon-mitigation goals. This can be accomplished via some mix of electricity storage (including natural gas CAES) and Carbon Capture and Storage (CCS). The latter is challenging because of high costs for CCS-integrated balancing capacity units that have to operate at low capacity factors, as will be the case with high iRES grid penetrations. Plausible strategies for addressing this challenge effectively have been proposed\(^7\).

A third major challenge is that increasing penetrations of iRES threaten the effective functioning of wholesale electricity markets, in which the price paid to all generators is set by the operating cost of the marginal unit. Because the operating cost of iRES is close to zero, large iRES penetrations significantly depress the prices paid to all generators, even those that play critical balancing roles and others with desirable features such as low carbon emissions. Continuing traditional short-run marginal cost-based pricing of wholesale electricity in the face of continuing iRES penetrations threatens new investments of any kind needed to maintain a reliable grid, including investments needed to realize deep decarbonization goals. Brouwer, et al.\(^8\) demonstrate how traditional marginal-
cost electricity pricing is increasingly untenable as iRES penetrations grow (Fig. 3.2.3). New policies that adequately reward generators for critical attributes like low-carbon emissions and balancing capabilities are needed to resolve this dilemma.

ESAG continues to build a relationship with analysts at NRG Energy and is working with them to conceptualize a modeling framework for analyzing the impacts that different grid technologies and electricity-market redesigns would have on achieving iRES penetration and carbon-mitigation goals. Models used by others can be loosely classified as capacity expansion, which typically examine impacts of alternative policies on mid-to-long term generation mixes, but without considering economic dispatch competition and associated wholesale-electricity market structures; or unit commitment-dispatch which are typically designed to simulate day-by-day, hour-by-hour economic dispatching for a geographically-specified power grid. Both types of models require large numbers of inputs and considerable computation times, making them unwieldy for exploring multiple scenarios. ESAG seeks to develop a modeling framework that combines essential features of both model types, but maintains sufficient simplicity and nimbleness that alternative technology and policy scenarios can be studied with manageable computation times.

References


5 The only commercial CAES technology involves caverns solution-mined in salt domes, which are available in the Gulf Coast region of Texas. Such caverns could also be created in the bedded salt formations that are available in the Rocky Mountain and Northern Great Plains regions, although creating salt caverns in bedded salt is more challenging. (S. Succar and R.H. Williams, 2008. Compressed Air Energy Storage: Theory, Operation and Applications, a report of the Energy Systems Analysis Group prepared for BP, Princeton Environmental Institute, Princeton University.)

6 The specific capital cost ($/kWe) for a natural gas-fired salt-cavern CAES unit with 10 hours of storage is likely to be no higher than for a new CT, and the natural gas required per kWh is ~2/5 of that required for the CT unit. The latter benefit will be offset to some degree by the cost paid for the IRE that will be stored.


The Limited Domain of Carbon Capture and Use

Principal Investigator: Robert Socolow

At a Glance

The widely discussed carbon mitigation strategy, carbon dioxide (CO₂) capture and use, is often touted as a way to improve the use of fossil fuel carbon. The idea is to make vehicle fuel by chemically reducing the CO₂ in the exhaust stream of a fossil fuel power plant, thereby using the carbon extracted with a fossil fuel twice—once for power and once for transport. This reasoning is flawed, because the same carbon benefit can almost always be achieved more straightforwardly and at lower cost by an alternate use of the large amount of low-carbon energy required to make fuel from CO₂. Only a high oil price and a high price for electric vehicles can create a domain of competitiveness for CO₂ capture and use.

Research Highlight

A leading strategy for combatting climate change is CO₂ capture and storage, or CCS. It is already deployed at a few coal power plants. The CO₂ that results from combustion is captured with chemicals and sent into geological formations deep below ground for long-term storage. Upon hearing about CCS for the first time, laypeople and experts alike ask: If you go to the trouble of capturing CO₂ at power plants, surely there is something better to do with it than to put it underground?

This is such a reasonable question! The strategy that is being sought even has a name: “Carbon Dioxide Capture and Use,” or CCU. Worldwide, chemists are seeking new ways to “activate” CO₂ to make CCU more competitive. This Highlight explores the CCU economy.

Today’s economy and the CCU economy

Figure 3.3. (top panel) shows a simplified representation of today’s fossil-fuel-based energy economy, as well as the CCU economy and two alternatives. In all panels, chemically reduced carbon is removed from the subsurface as fossil fuel (red arrow), oxidized to release the energy that powers the economy (rounded rectangle), and sent to the atmosphere as CO₂ for disposal (blue arrow). The sketch separates today’s economy into two sub-economies, one where energy is used centrally and the other where energy is widely distributed before use.

In the CCU economy (upper-middle panel), the blue and red arrows in the top panel are unchanged, but the passage of carbon through the economy is more complex. CO₂ is captured at a centralized facility after fossil fuel is burned, then chemically reduced to a synthetic fuel in a conversion facility with the help of low-carbon energy (green dashed arrow), and the synthetic fuel is burned at a decentralized energy conversion device (e.g., in a vehicle engine). Thus, there are two power plants: one provides the CO₂ (the “source plant”) and the other enables the conversion of the CO₂ into synthetic fuels (the “CCU-enabling plant”). In a transaction internal to CCU, the source plant pays a “tipping fee” to the conversion facility instead of paying the government a CO₂ emissions tax or paying for CO₂ storage. For specificity, imagine that in the CCU system wind power transforms coal-power-plant exhaust into gasoline. The circle represents the conversion process.

In the second half of 2016, I served on a task force that wrote a report for the US Department of Energy. Entitled “Task Force Report on CO₂ Utilization and Negative Emissions Technologies,” it was submitted to Secretary of Energy, Ernest J. Moniz, on December 13, 2016. It is online at https://energy.gov/seab/downloads/final-report-task-force-co2-utilization, where the task force participants and a DOE “Assessment” of the report are also found. This Highlight explores an issue that was left unresolved in our report. It is a work in progress.
Figure 3.3. Carbon flows in today’s energy system (top) and three future low-carbon energy systems, all of which augment the role of low-carbon energy (dashed green arrow). These alternatives feature Carbon Capture and Use (CCU, upper middle), low-carbon centralized energy (lower middle), and low-carbon distributed energy use (bottom). Chemically reduced carbon is shown with red arrows and CO$_2$ with blue arrows. In the CCU energy system, CO$_2$ is captured at a centralized fossil-fuel-burning facility and transformed back to a hydrocarbon for a second, decentralized use. Not shown is the part of the CCU economy where uses of CO$_2$ do not require its chemical transformation.

In the CCU economy (upper-middle panel), the blue and red arrows in the top panel are unchanged, but the passage of carbon through the economy is more complex. CO$_2$ is captured at a centralized facility after fossil fuel is burned, then chemically reduced to a synthetic fuel in a conversion facility with the help of low-carbon energy (green dashed arrow), and the synthetic fuel is burned at a decentralized energy conversion device (e.g., in a vehicle engine). Thus, there are two power plants: one provides the CO$_2$ (the “source plant”) and the other enables the conversion of the CO$_2$ into synthetic fuels (the “CCU-enabling plant”). In a transaction internal to CCU, the source plant pays a “tipping fee” to the conversion facility instead of paying the government a CO$_2$ emissions tax or paying for CO$_2$ storage. For specificity, imagine that in the CCU system wind power transforms coal-power-plant exhaust into gasoline. The circle represents the conversion process.

3 If the source of CO$_2$ for CCU is a cement or steel plant, rather than a power plant, some of the arguments here are less strong, because substitution of a low-carbon alternative is less straightforward, given that carbon flows are associated not only with energy production but also with the industrial process.
Alas, CCU is a deeply flawed concept, primarily because there are nearly always better ways of using the low-carbon enabling energy.

**Low-carbon enabling energy for CCU** Somewhat more than one unit of enabling energy must be used to convert CO$_2$ (and water) into one unit of high-value energy embedded in carbon-based liquid or gaseous fuel. How else could the enabling energy be used? Two limiting cases are presented in the lower-middle and bottom panels of Figure 3.3., respectively, where low-carbon energy substitutes exclusively for either centralized or distributed uses of fossil energy. Imagine that in the “Low-Carbon Power” system wind power enables the closing down of traditional coal plants, while the gasoline system remains unchanged. And imagine that the “Low-Carbon Vehicle” system is one where wind power enables electric vehicles, while coal power plants keep running.

All three options can become less costly than doing nothing when the CO$_2$ price is high; the case for CCU rests on there being situations where CCU competes favorably with the other options. Comparing the CCU option and the Low-Carbon Vehicle option (bottom panel), there is a breakeven price for electric vehicles above which CCU synthetic fuels are competitive. CCU can prosper only when little progress has been made toward the electrification of vehicles and the use of biomass-derived fuel. Such a world rarely emerges in the low-carbon narratives embedded in today’s scenarios. Rather, the common view is that the electrification of decentralized energy, especially in transport, will flourish when a strong CO$_2$ emissions constraint is imposed; sometimes, only air travel is not electrified by mid-century.

Comparing the CCU option and the Low-Carbon Power option (lower-middle panel), there is another breakeven price, the price of crude oil (and therefore crude-oil-derived vehicle fuels), above which CCU synthetic fuels are competitive. Thus, CCU requires both a high oil price and a high price for electric vehicles. Either constraint can be the one that limits the competitiveness of CCU.\(^4\)

**CO$_2$ capture cost** We cannot neglect the substantial investment required to capture the CO$_2$ at the source plant. In a circumstance particularly favorable to CCU, but surely a niche market, the source power plant has been a CCS plant, and thus has already paid the capture costs, but for some reason its access to storage has ended.

**Delay time** CCU is sometimes presented as a CO$_2$ storage strategy. It is not. An important variable is the delay time: the length of time between the capture event at the source plant and the moment of CO$_2$ emission when the CCU fuel is used. A delay time of several decades or longer can occur in principle, but only if the captured carbon becomes embedded in a long-lived product like a plastic bench or a steel pipe.

**Enhanced oil recovery** The CCU panel of Figure 3.3. represents only uses of CO$_2$ where it is transformed chemically. CO$_2$ chemically unchanged is used in the food system and for cleaning, but by far its largest use is in the oil industry for “enhanced oil recovery (EOR),” where CO$_2$ is injected into old oil fields to promote the extraction of additional oil. Nearly all of the CO$_2$ brought to the oil field for EOR remains there when oil production ceases, trapped in geological formations. EOR today leaves about one carbon atom behind in the oil field for each carbon atom in the produced oil.

\(^4\) In a highly idealized schematic model, CCU must be less expensive than both (crude-oil fuel minus coal power) and (electric vehicles minus wind power).
EOR could be modified so that much more carbon is left behind. To the disappointment of the many champions of CO$_2$ reuse as a pathway to hydrocarbons, EOR may be the only climate-significant version of CCU.

**Acknowledgments**

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Integration Publications


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