CMI

Carbon Mitigation Initiative

2012

ANNUAL REPORT

2012 ANNUAL REPORT CARBON MITIGATION INITIATIVE

Carbon Science

Low Carbon Energy

Fluids & Energy

Policy & Integration

PRINCETON UNIVERSITY

Carbon Mitigation Initiative

Annual Report 2012

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CMI – Carbon Mitigation Initiative on the web
http://cmi.princeton.edu

CMI Overview

The Carbon Mitigation Initiative (CMI) at Princeton University is a university-industry partnership sponsored by BP. The goal of the project is to find solutions to the carbon and climate problem that are safe, effective, and affordable. Now entering our 13th year, our researchers are speeding progress in the areas of low-carbon energy, carbon storage, carbon science, and carbon policy.

The Carbon Science Group collects data from the oceans, the atmosphere, ice cores, and the land biosphere to study how natural sources and sinks of carbon have varied in recent and ancient times, and how they will respond to future climatic change.

The Fluids & Energy Group studies potential risks of injecting CO_2 underground for permanent storage. Models of subsurface CO_2 behavior coupled with laboratory studies and field tests are helping the group evaluate that risk.

The Low-Carbon Energy Group studies the production of power and fuels from fossil fuels with CO_2 capture, biomass as an energy source on its own and combined with fossil fuels, wind power, and batteries for power and storage.

The Policy & Integration Group synthesizes research discoveries and explores the policy implications of carbon mitigation strategies. It also works to communicate issues of carbon and climate to industry, government, NGO's, and the general public.

Led by CMI Co-Directors Stephen Pacala and Robert Socolow, the group has grown to include over 70 researchers who have published over 700 peer-reviewed articles. Together we are building a comprehensive view of the challenges of carbon mitigation - and how they can be overcome.

For more information, visit us at CMI's website - http://cmi.princeton.edu - or email us at cmi@princeton.edu.

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Executive Summary

After an infusion of new faculty in 2011, CMI has an even stronger program with new areas of research that complement established efforts.

Carbon Science

The Carbon Science Group continues to improve estimates of past and future terrestrial and oceanic carbon sinks and to assess impacts of climate change.

The group's newest work on the land sink is helping unravel complicated controls on forest growth, and suggests that the "fertilization sink" caused by increasing carbon dioxide (CO_2) should continue into the future. A steep increase in terrestrial carbon storage in the late 1980s has been confirmed, and the location of the sinks identified. Also this year, a study of volcanic influence on estimates of carbon sink variability shows sinks are not decreasing as suggested by studies in the literature.

In the ocean, a new instrument developed over the course of the CMI program is providing fast and accurate measurements of dissolved carbon dioxide at the sea surface and is expected to be widely adopted. New work on ocean acidification highlights possible impacts of CO_2 rise on global primary production, and research on impacts predicts significant changes in fish size and habitat with climate change.

Looking into the ancient past, groundbreaking paleoclimate work is extending the ice record back further than previously thought possible. Looking toward the future, a new focus added in 2012 will harness the power of high-resolution climate models to predict changes in climate variability and impacts over the next 25 to 50 years.

Low-Carbon Energy

In 2012, the Capture program of the Low-Carbon Energy Group continued its focus on the potential of CO_2 enhanced oil recovery (EOR) to improve the economics of carbon capture and storage (CCS). The group participated in a National Coal Council study for US Energy Secretary Steven Chu on CCS-EOR strategies for coal-energy conversion plants, providing economic analysis of all systems studied. The researchers also developed a new proposal to subsidize carbon capture projects by using revenues from oil recovered using captured CO_2, and completed a study on the relative economic and climate benefits of CO_2 EOR versus "CO_2 activation" (using CO_2 and low-carbon hydrogen to make synthetic fuels). New projects have been initiated with the National Renewable Energy Technology Laboratory, including development of a strategy to produce synthetic jet fuel from coal and biomass in the Ohio Valley, and collaborations with Italian and Chinese colleagues remain strong and productive.

The Energy Storage program continued to explore factors that impact lithium-ion battery performance and began exploring the benefits of lithium iron phosphate batteries. The researchers also developed a new approach to studying battery characteristics by examining properties in the frequency domain.

Fluids & Energy

This year the Fluids & Energy Group continued its focus on large-scale models of CO_2 injection, a high point being the publication of a textbook on modeling techniques for the CCS community. At the injection scale, the in-house *Dynaflow* geomechanical model is now being applied to study physical stresses accompanying CO_2 injection at BP's In Salah site. The Vertical Interference Test, a technique for estimating wellbore permeability proposed by Princeton and being applied by BP and Schlumberger, is providing estimates of well cement permeabilities in the field.

Faculty who joined the Group in 2011 are pursuing bench-scale experiments and molecular-scale modeling that are providing fundamental insights into below-ground behavior of CO_2. New experimental studies are shedding light on fundamental fluid flow processes, such as viscous fingering, with applications for CO_2 storage and enhanced oil recovery. An expanding molecular-based simulation program is exploring the formation of CO_2 and methane hydrates, as well as properties of CO_2-salt-water mixtures in the subsurface.

Policy & Integration

A hallmark of CMI is its efforts to break down barriers to progress in carbon and climate policy. A major focus of the group in 2012 was re-invigorating the carbon and climate discussion by emphasizing climate change as a risk-management issue. Policy & Integration researchers contributed to a number of policy-relevant articles, encouraging the environmental community to acknowledge some of the "hard truths" of climate change and also working to educate policymakers about the risks of climate change and sea-level rise.

The program also continued to explore both the benefits and challenges of mitigation options. Co-Director Robert Socolow continued his collaboration with Michael Desmond of BP probing the feasibility of carbon dioxide removal from the atmosphere, and was a driving force behind a special fee-free issue of Climatic Change devoted to the topic. Other research on mitigation included the advantages and proliferation risk of small modular nuclear reactors and an innovative thesis on the rise of the Chinese wind energy industry.

On the outreach front, the "stabilization wedges concept" continues to be a popular tool in the classroom and the media, and the group is enhancing an open-source toolbox for developing energy-economics models, with a particular focus on India. Climate Central, a non-profit climate journalism group in Princeton, continues to be a valued partner in educating the public about climate change, its impacts, and options for mitigation.

Developments at Princeton

New external programs at Princeton will also complement CMI's research and teaching. First, CMI will benefit from the burgeoning program in the fundamental physics and chemistry of solar energy and other renewable energy and energy-efficiency strategies at the newly established Andlinger Center for Energy and Environment in the School of Engineering and Applied Science. Although the physical center will first be completed in 2015, the Center is already supporting interdisciplinary research, courses, and seminars on energy issues.

Another potential partner on the horizon for CMI would be a proposed National Science Foundation Science & Technology Center to be housed at Princeton, the Center for Southern Ocean Biogeochemical Observations and Modeling (C-SOBOM). Led by the Carbon Science Group's Jorge Sarmiento, the Center has passed through two rounds of evaluation and is awaiting word on the final award - if funded, this Center would revolutionize understanding of the Southern Ocean and its role as a carbon sink.

Personnel News

There is also news to report regarding CMI participants. In May 2012, Pablo Debenedetti of the Fluids & Energy Group was elected a member the National Academy of Sciences, one of the highest honors that a scientist can receive.

In September 2012, after nearly 5 years of gracious and dedicated service to CMI, Dr. Pascale Maloof Poussart assumed a new position in the office of the Dean of the College, with responsibility for the undergraduate research experience. Dr. Holly Welles now assumes many of Poussart's responsibilities, while continuing in her position of Manager of Communications and Outreach for the Princeton Environmental Institute, of which CMI is a part.

This report is a summary of progress for the year 2012 - previous reports, including a review of our first decade, are available at http:/cmi.princeton.edu. With new staff and new opportunities on campus, CMI is looking forward to even more productive years ahead.

Carbon Science Group

The **Carbon Science Group** uses both observational data and models to improve understanding of carbon sinks and predict the impact of climate change on the carbon cycle. The PI's of the Science Group are **Steve Pacala** and **Lars Hedin** of the Department of Ecology and Evolutionary Biology, and **Michael Bender, David Medvigy, Francois Morel** and **Jorge Sarmiento** from the Department of Geosciences.

Exciting developments in 2012 include a new BP-sponsored program on near-term climate variability, breakthroughs in our understanding of the CO_2 fertilization sink, and a potential world-class observing and modeling center for the Southern Ocean to be housed at Princeton.

Highlights

New Initiatives

- A new BP-sponsored initiative will build the Carbon Science Group's capacity to analyze, predict, and attribute changes in climate over the next 25 years.

- The Sarmiento group prepared a large proposal for the National Science Foundation to form a Center for Southern Ocean Biogeochemical Observations and Modeling.

Controls on the Terrestrial Carbon Sink

- A new analysis shows that, in the absence of a historical CO_2 fertilization sink, the concentration of atmospheric CO_2 would have been 80% greater than observed, and warming would have been 40% larger.

- New models are explaining how nutrient limitation and nitrogen fixation affect CO_2 fertilization, and predict that CO_2 enhancement of the terrestrial carbon sink will continue.

Quantifying the Ocean Carbon Sink

- A new set of climate models indicates that the Southern Ocean south of 30°S took up 71 ± 24% of the excess heat and 43 ± 3% of anthropogenic carbon over the period 1861 to 2005.

- A new instrument for continuous, high precision measurements of the dissolved inorganic carbon concentration (DIC) of surface seawater has been deployed and validated.

New Modeling Tools

- Simulation of ocean carbon cycling has been enhanced by a new model of bacterial cycling for global circulation models.

- A new model explains how drought leads to tree mortality, which has been one of the largest sources of uncertainty in the carbon cycle.

- A new model of fire in terrestrial systems is the first to effectively separate natural and anthropogenic fires at global scales.

Climate Change Impacts

- Ocean acidification may decrease the fixation of nitrogen in the open ocean by decreasing the bioavailability of iron to nitrogen-fixing organisms.

- New model studies predict a 20% reduction in fish size and likely tuna habitat reduction due to climate change and ocean warming.

Long-Term Climate Variability

- Trends in the airborne fraction of anthropogenic CO_2 are shown to be within the noise level when accounting for the decadal-scale influence of explosive volcanic eruptions, indicating that natural sinks are not decreasing as previous studies have found.

- Million year-old ice from Antarctica is extending the ice core record of climate, and researchers are looking for even older ice.

New Initiatives

Program on near-term climate variability

To help anticipate the risks of near-term climate change, in 2012 BP agreed to sponsor a new research program at Princeton entitled "*Climate Variability Over the Next 25 Years.*" Headed by Steve Pacala and Elena Shevliakova, the program will involve collaborative research among BP, CMI, GFDL and the BP-sponsored team at Imperial College (IC). The researchers will use high-resolution climate models to predict climate variability, changes in climate variability and impacts of climate variability over the next quarter century. These studies will include hydrologic variability (i.e. rainfall, evapotranspiration, soil moisture, drought, river flow and flooding) and variability in natural and agricultural ecosystems (i.e. crop, biofuels, and forest production, carbon storage by ecosystems and carbon offsets, including effects of drought-induced fire). The first postdoc has been hired for this project and an offer has been extended to a second.

Proposed Center for Southern Ocean Biogeochemical Observations and Modeling

In the past 20 years, observational analysis and model simulations have transformed our understanding of the Southern Ocean, suggesting that the Ocean south of 30°S, occupying just 30% of the surface area, has profound influence on the Earth's climate and ecosystems. The model studies underlying these results, however, are highly controversial and observational data is sparse in comparison to other areas of the world's oceans.

To address this critical gap in understanding, the Sarmiento group has been involved in a major proposal for the National Science Foundation to form a Center for Southern Ocean Biogeochemical Observations and Modeling (C-SOBOM). If successful, the Center's observations team will deploy over a hundred autonomous floats with biogeochemical sensors to gather data and provide unprecedented observations of the Southern Ocean, while the modeling team develops metrics to test and improve computer simulations of this region. The proposed center would involve researchers from Princeton, Scripps Institution of Oceanography, the University of Arizona, Rutgers, the University of Washington, the Monterey Bay Aquarium Research Institute, and both U.S. and international collaborators – Center awards will be announced in April 2013.

Controls on the Terrestrial Carbon Sink

The **Pacala, Medvigy, Hedin, and Sarmiento** groups are working to understand whether forest storage of carbon will be enhanced by increasing CO_2 levels, what might limit "CO_2 fertilization," and the history and future of this component of the terrestrial carbon sink.

History of the terrestrial sink

The most important accomplishment of the Pacala climate modeling group in 2012 was an analysis of the value of the historical carbon sink in slowing the rise of atmospheric CO_2 and warming. During 2012, Elena Shevliakova and Sergei Malyshev participated in development, evaluation, and analysis of the GFDL comprehensive Earth System Models ESM2M and ESM2G. In collaboration with the GFDL and CMI scientists, they explored interactions between historic land use and increased atmospheric CO_2 concentrations and their implications for carbon cycle and climate. The researchers estimated for the first time that in the absence of historical CO_2 fertilization, the concentration of atmospheric CO_2 would have been 80% greater than observed, and the warming would have been 40% larger than observed. This work will appear in *Proceedings of the National Academy of Sciences* in 2013.

Nutrient limitation and the CO_2 fertilization sink

Because elevated CO_2 generally increases photosynthetic production, enhanced forest growth could scrub anthropogenic CO_2 from the atmosphere and provide a negative feedback on climate change. It is commonly suggested that enhancement of the land sink by CO_2 fertilization should be limited by the availability of nitrogen, yet forest free-air CO_2 enhancement experiments (FACE) have shown continued CO_2 fertilization despite nitrogen limitation

Ray Dybzinski and Caroline Farrior have developed a new forest model that includes a previously unrecognized mechanism and explains the continuing CO_2 fertilization in the FACE experiments. In their simulations, carbon allocation patterns are determined by competition. Enhanced carbon fixation under elevated CO_2 resulted in elevated wood growth and height, but constant fractional allocation to wood, constant allocation to leaves, and elevated fractional and absolute fine root growth. This is positive news for carbon mitigation, as the new model predicts that the CO_2 fertilization component of the land sink will continue for decades. The researchers are working to implement this model in the GFDL land model, LM3 to improve predictions of carbon cycling.

In a related collaboration with Steve Pacala, Ensheng Weng of the U.S. Forest Service developed a working version of a new model of the terrestrial biosphere and has written a manuscript that will be submitted soon. This model has a revolutionary structure, in that it models realistic competition among plant types and so should be able to predict the CO_2 fertilization effects described above.

CO_2 fertilization of recovering tropical forests

The Hedin/ Medvigy group is also focusing on understanding the competitive processes that affect the forest carbon sink, specifically the role of changes in resource availability and competitive dynamics among individuals following disturbances in the tropics. Tropical forests contribute a significant portion of the land carbon sink, but their future ability to sequester CO_2 likely depends on how nutrients interact with forest recovery from cutting, agricultural land use, or natural disturbances. Recent observations place particular importance on this as yet unresolved interaction; first, it is becoming clear that a large fraction of tropical forests worldwide are recovering from some form of disturbance. Second, there is increasing evidence for exceptionally strong constraints by nutrients on carbon accumulation, but only at specific "bottleneck" periods during forest recovery. Third, results from models and empirical studies imply that nitrogen fixing trees may act to alleviate nitrogen limitation on plant growth during particular periods of forest recovery.

Although existing models of the tropical land carbon sink are exceptionally sensitive to potential interactions between carbon recovery and nutrient cycles, they have not been constructed to resolve some of the spatial and temporal scales that are fundamental to nutrient-driven processes. To address this problem, Jennifer Levy has developed a new framework for understanding nutrient cycling on the level of individual trees, and has successfully incorporated this framework into a terrestrial biosphere model, the Ecosystem Demography model 2 (ED2).

Unlike conventional ecosystem models, ED2 resolves (1) heterogeneity in resource environments and (2) resource competition between trees of different sizes and functional types. Because of these two factors, it is possible to scale understanding of nitrogen fixation and nutrient limitation from individual trees to ecosystem-level properties. Furthermore, because field studies often measure properties of individual trees, there is a wealth of data that can be used to challenge and evaluate the new model. The researchers are currently using measurements of nitrogen fixation and the results of nutrient fertilization experiments for this purpose. The resulting validated model will be an important tool for assessing the capacity of tropical forests to act as carbon sinks.

The Medvigy and Hedin labs are in the process of expanding this model by adding a phosphorus algorithm to enable simulation of carbon, nitrogen, and phosphorus interactions. Once this algorithm is ready, it will be easily transferrable into LM3 and other similar models in use Princeton.

North-South variation of nitrogen fixation and terrestrial carbon uptake

This year Duncan Menge used forest inventory data from the USA and Mexico to show that nitrogen-fixing plants comprise ~10% of trees south of 35 degrees latitude but only ~1% of trees north of 35 degrees. Furthermore, the dominant type of nitrogen-fixing tree switches at this same threshold. Menge's research also showed that this transition from 10% to 1% can be explained by a concomitant transition in the nitrogen-fixing "strategy," from rapid tuning of nitrogen fixation in the south to slow or no tuning in the north. The dominant types in the north versus south are thought to have these different strategies, lending support to the hypothesis that these different strategies explain the transition. This is important for climate change because plants that tune nitrogen fixation rapidly (the southern type) remove more carbon dioxide from the atmosphere, whereas plants that do not tune nitrogen fixation (the northern type) remove less carbon dioxide.

Understanding temporal shifts in terrestrial uptake of atmospheric CO_2

In 2011, Jorge Sarmiento and colleagues reported that an abrupt shift in the net land carbon sink, estimated as the residual between fossil fuel emissions, the growth rate of atmospheric CO_2 at Mauna Loa, and modeled ocean carbon uptake, occurred in the late 1980s. The land carbon uptake appears to have remained relatively constant for three decades and to have increased rapidly after 1988/1989.

In collaboration with researchers at UCLA, NASA and the Medvigy group as part of a study supported by a NASA Carbon Cycle Science grant, this year the Sarmiento group analyzed a suite of simulations of primary productivity from the terrestrial biogeochemical model CASA and upscaled FluxNet data to identify independently regions/ecosystems in which carbon uptake is consistent with the timing and magnitude of carbon sinks derived from previous studies. Results show that globally, the net primary productivity (NPP) increased by about 1 Pg C/yr (or 1 billion metric tons of carbon per year) after 1989. The gross primary productivity also increased of approximately 2 Pg C/yr at the same time. These estimates are consistent with the shift in net land carbon uptake detected in previous work. Results further suggest that three key regions are contributing to the abrupt increase in productivity in the late 1980s: Northern Eurasia, Tropical Africa and Tropical South America (see Figure 1).

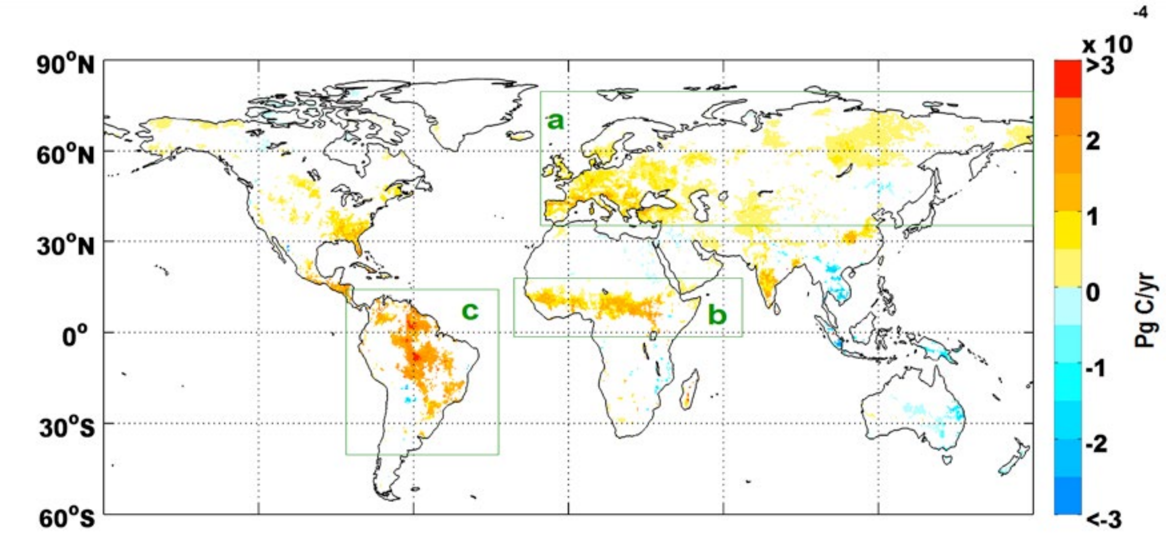

Figure 1: NPP differences between 1990-2008 and 1982-1989. The NPP is estimated using the terrestrial biogeochemical model CASA. Only significant differences are shown (t-test, 5% critical level). The green rectangles are highlighting three regions exhibiting a very strong signal: a) Northern Eurasia, b) Tropical Africa and c) Tropical South America.

The group found that these changes may be climate-constrained. Results showed that the productivity changes observed in the three regions seem influenced by different climatic factors: a) warming in Northern Eurasia (from late 1980s onwards), b) increased precipitation in Tropical Africa (from late 1980s/early 1990s onwards) and c) increased solar radiation over Tropical South America (from mid-1990s onwards).

Claudie Beaulieu in the Sarmiento group is currently analyzing additional CASA simulations to study sensitivity of the results to different forcing data sets. Furthermore, the group is analyzing net ecosystem exchange runs to verify whether the key regions have actually gained carbon or if this increase is due to changes in respiration.

Quantifying the Ocean Carbon Sink

The **Sarmiento** and **Bender** groups use observations and modeling to study the role of the ocean in the carbon cycle and gain insight into history and future of the ocean carbon sink.

Understanding the Southern Ocean's impact on carbon and climate

As part of their NSF proposal (see "New Initiatives" above), the Sarmiento group carried out a CMI analysis focusing on oceanic heat and carbon uptake in a new set of 19 IPCC-class climate models over the period 1861 to 2005. The model intercomparison study shows that 71 ± 24% of the excess heat and 43 ± 3% of anthropogenic carbon is entering the Southern Ocean south of 30°S (Figure 2), although the Southern Ocean only covers 30% of the global ocean surface area. Overall, multi-model variability in CO_2 uptake remains largest over the Southern Ocean, but the multi-model spread is significantly reduced compared to earlier generation models.

Moving forward, the group plans to investigate the response of the Southern Ocean carbon cycle to changing Southern Ocean winds in response to changes in stratospheric ozone levels and greenhouse gas concentrations.

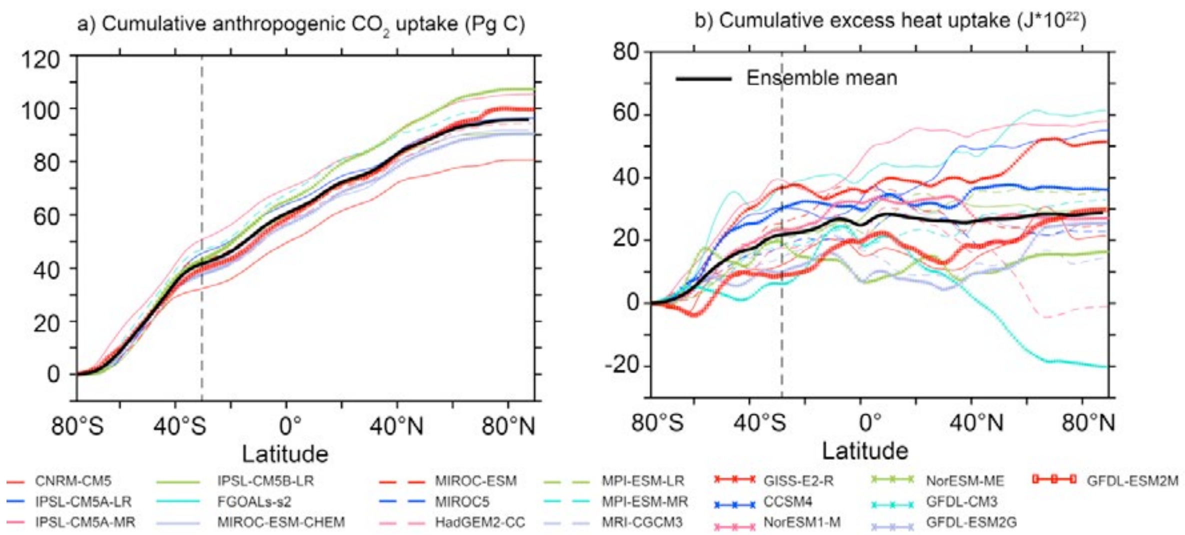

Figure 2: Oceanic uptake of anthropogenic CO_2 and excess heat in CMIP5 models. (a) Cumulative oceanic CO_2 uptake in year 1995 (represented by mean of period 1986 to 2005) and integrated from 90°S to 90°N such that the vertical scale from 0 at 90°S to the total uptake at 90°N. (b) Same as (a), but for excess heat.

Impacts of ocean acidification on phytoplankton

A third of the anthropogenic CO_2 released to the atmosphere dissolves into the surface ocean, reducing its pH. What effects this ocean acidification will have on the ocean biota is a focus of research in the Morel group. Among the manifold potential effects of ocean acidification is a change in the cycling of nitrogen, the principal limiting nutrient for marine ecosystems.

The major input of "new" nitrogen in the open ocean is through nitrogen fixation, which is effected by a few species of cyanobacteria. In experiments with the dominant nitrogen-fixing species, *Trichodesmium* (Figure 3), Morel and colleagues demonstrated that lowering pH decreases both Fe uptake and, independently, the efficiency of N_2-fixation. Because the nitrogenase enzyme, which catalyzes the reduction of N_2 to NH_4+, contains a very large number of iron atoms, and N_2 fixing organisms thrive in regions where iron is scarce, these two effects may act synergistically to decrease the input of new nitrogen to marine ecosystems and impact global productivity.

Measuring dissolved CO_2 in the ocean

To help quantify the fluxes of carbon into and out of the surface ocean, Michael Bender and colleagues have developed a new instrument for continuous, high precision measurements of the dissolved inorganic carbon concentration (DIC) of surface seawater. The DIC instrument achieves high precision using a method called isotope dilution, which allows concentrations to be determined by an isotope ratio measurement that is much easier and more accurate that the normal concentration measurements.

During 2012, the instrument was validated and successfully deployed on 3 cruises. It has since been modified, using a so-called "doublespike" technique, in a way that achieves higher precision while at the same time greatly simplifying the implementation. During the coming year, the group will use this instrument to characterize DIC on cruises in the Southern Ocean and the Arctic Ocean. Other groups have expressed interest in copying this instrument. The researchers expect that it will be widely used for measurements along cruise tracks of oceanographic ships, both to characterize the invasion of fossil fuel CO_2 into ocean surface waters and to track the seasonal imprint on DIC of the annual cycle of biological activity.

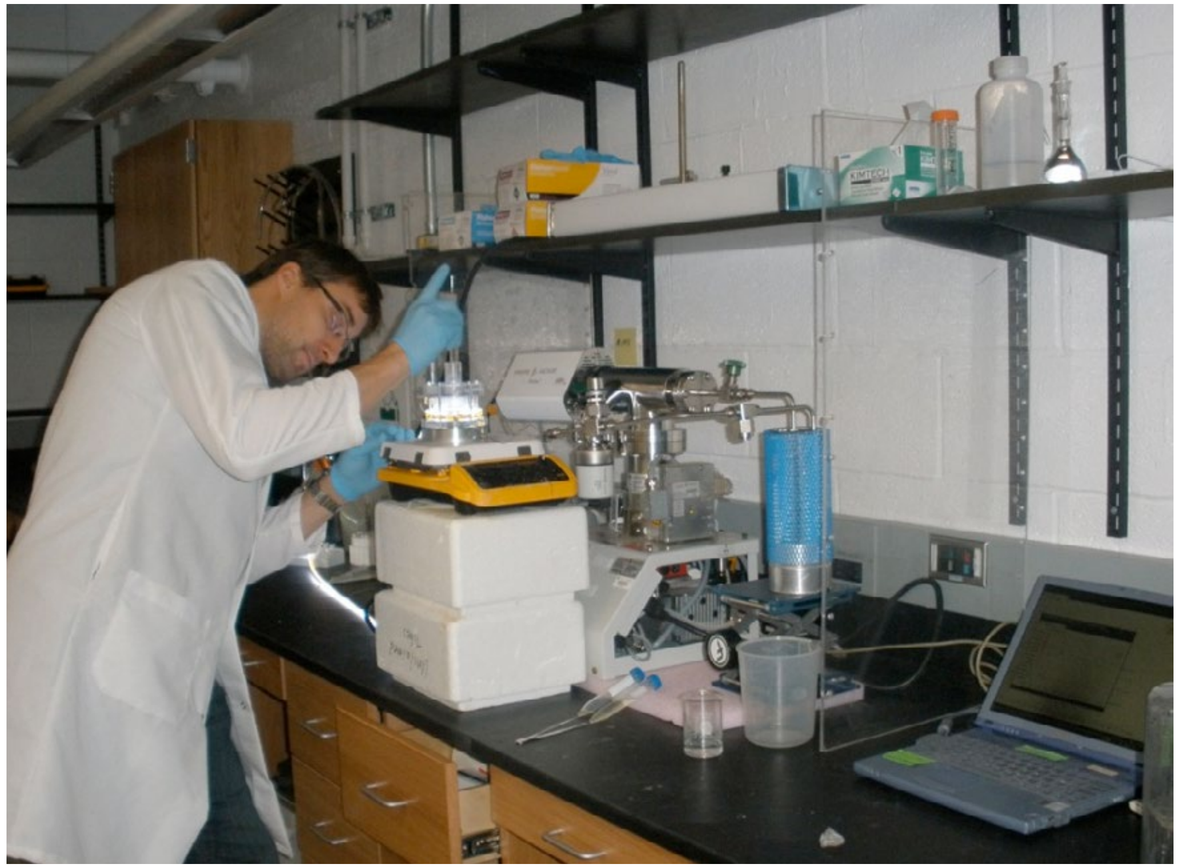

Figure 3: Postdoc Sven Kranz performing an experiment with phytoplankton using a Membrane Inlet Mass Spectrometer.

New Modeling Tools

Since CMI's inception, the Carbon Science Group has worked on developing new tools to improve modeling of the carbon cycle. This year the **Pacala and Sarmiento** groups have developed new approaches to the impacts of drought and forest fires, as well as carbon cycling in the ocean.

Linking drought and tree mortality

Adam Wolf is developing models and observations that link the water cycle, and particularly drought, to the carbon cycle, particularly mortality. Wolf has developed a unique observation system that monitors the biosphere (including microclimate and tree physiology) and reports these data in real time over cellular networks using electronics designed in-house. These observations help constrain a key uncertainty in the model depiction of plant physiology, namely the sensitivity of leaf photosynthesis and evaporation to drought among diverse species. Together, this work aims to identify which species gain and which species lose in a changing climate, and what impacts these demographic shifts will have on the global carbon cycle.

Better depiction of fire in land models

Vegetation fire is a significant contributor of greenhouse gases and other compounds that affect the climate, especially in tropical nations. Sam Rabin and Elena Shevliakova are working on a model of vegetation fire that will simulate the amount of burning on different vegetation types around the world — especially on human-managed lands — for inclusion in a global climate and vegetation model. This separation of fire types, thus far unique in the fire modeling literature, will help the research community better understand how interventions might be undertaken to reduce the impact of fire on the climate. In 2012, the researchers helped develop and publish details of a method that revealed, based on maps of land cover and satellite-observed burned area, how the timing of fire activity within a year differs between agricultural and non-agricultural lands. Development of advanced methods that allow more accurate estimation of the amount of burning on cropland, pasture, and other lands is under way.

An improved model of bacterial cycling in the ocean

Sinking organic particles composed of detrital materials including dead phytoplankton and zooplankton fecal pellets are one of the main ways carbon is transported to the deep ocean as part of the biological pump. Most sinking particles are remineralized, transformed from organic carbon to CO_2, in the mesopelagic zone (150 to 1000 m depth) due to the metabolic activity of heterotrophic bacteria. The Sarmiento group has developed a model to better understand the mechanisms connecting heterotrophic bacteria with these sinking particles in the mesopelagic zone. The 1-dimensional idealized model of a sinking particle includes free-living and attached heterotrophic bacteria, particulate and dissolved organic matter, extracellular enzyme, and hydrolysate. In the past year, a major development in the project has been to add quorum sensing, a signaling system used by bacteria to assess population density, to regulate extracellular enzyme production and particle detachment rates to the model. This new parameterization has dramatically improved the model predictions of carbon flux at the Bermuda Atlantic Time Series station, which is located in the North Atlantic subtropical gyre.

One of the benefits of this model is that it can be integrated with the dynamics of existing models, i.e. the Martin Curve and the ballast model, currently used in IPCC-class models to predict particle attenuation in the deep ocean. The ultimate goal of this project is to improve predictions of the effects of future climate change on carbon sequestration in the ocean.

Model development is nearing completion so the next phase will be to conduct sensitivity studies of key parameters and implement the model in geographic locations with different environmental characteristics.

Climate Change Impacts

The **Sarmiento** group studies the impacts of anthropogenic CO_2 emissions and climate change on ocean chemistry and sea life.

Impact of climate change and ocean warming on fish body size

Changes in temperature, oxygen content, and other ocean biogeochemical properties also directly affect the ecophysiology of marine water-breathing organisms. Previous studies suggest that the most prominent biological responses are changes in distribution, phenology, and productivity. Both theory and empirical observations also support the hypothesis that warming and reduced oxygen will reduce body size of marine fishes. However, the extent to which such changes would exacerbate the impacts of climate and ocean changes on global marine ecosystems remains unexplored.

In collaboration with researchers at the University of British Columbia, the Sarmiento group employed a model to examine the integrated biological responses of over 600 species of marine fishes due to changes in distribution, abundance and body size. The model has an explicit representation of ecophysiology, dispersal, distribution, and population dynamics. The model results show that assemblage-averaged maximum body weight is expected to shrink by 14–24% globally from 2000 to 2050 in a warmer less oxygenated ocean under a high-emission scenario (Figure 4). About half of this shrinkage is due to change in distribution and abundance, the remainder to changes in physiology. The tropical and intermediate latitudinal areas will be heavily impacted, with an average reduction of more than 20%. The results of this study provide a new dimension to understanding the integrated impacts of climate change on marine ecosystems.

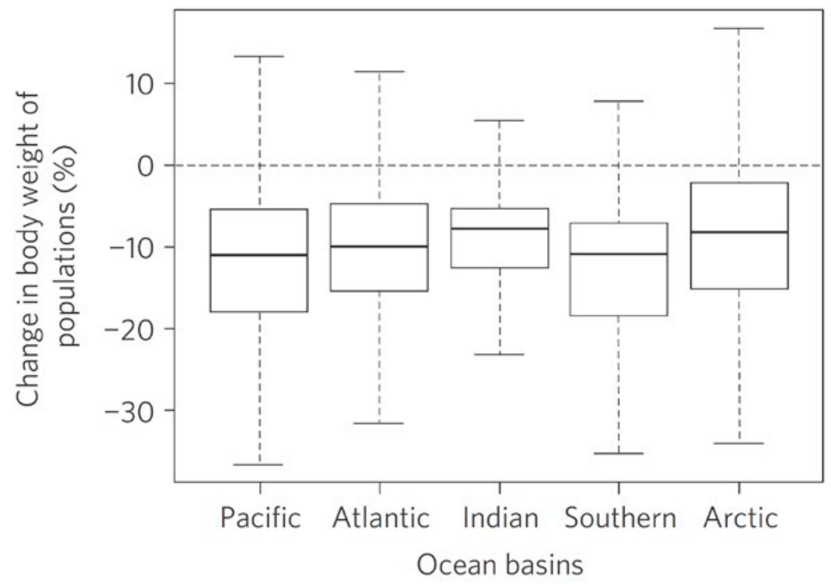

Figure 4: Change in individual-level body size of fishes in different ocean basins from 2000 (averages of 1991-2010) to 2050 (averages of 2041-2060). The thick black lines represent median values, the upper and lower boundaries of the box represents 75 and 25 percentiles and the vertical dotted lines represent upper and lower limits.

Impact of oceanic O_2, CO_2, and temperature changes on tuna habitats

Predicting the effects of climate change on habitat utilization in the ocean environment requires identification of underlying physiological mechanisms influenced by environmental conditions. Hemoglobin-oxygenation is hypothesized to be one of these underlying mechanisms. Oxygen extraction from seawater and delivery to tissues, a fundamental process which depends on hemoglobin, is a necessity for tuna survival, as the globe-traveling fish utilize many different regions and depths in the ocean while foraging for food.

All of the environmental factors associated with hemoglobin-oxygenation are predicted to change in the future: temperature is predicted to increase with climate change, oxygen is predicted to decrease as increases in temperature cause water column stratification to increase, and carbon dioxide is predicted to increase with ocean acidification. It is hypothesized that these changes will result in habitat compression for tuna, but the magnitude and biogeography of the compression will be different among the species of tuna. The Sarmiento group is using the P50 depth, the depth at which 50% of hemoglobin is oxygenated, as the threshold restricting tuna habitat utilization in global datasets and IPCC-class earth system model results. Preliminary results from two earth system models indicate that future climate change will have neutral to negative impacts on the habitat size of Thunnus albacares, the yellowfin tuna, by 2100.

The plan for the next year is to evaluate seven additional IPCC-class earth system models. There are many variations in how the physics, chemistry, and biology of an earth system model is constructed and also differences in the parameterizations selected for each model, all of which contribute to uncertainty in the results. For this reason, it is important to use multiple earth system models to account for the uncertainty resulting from different model formulations. The analysis will also be expanded to include all the tuna species in the genus Thunnus.

Natural Climate Variability

The **Sarmiento** and **Bender** groups examine climate change in the context of long-term natural variability. Sarmiento and colleagues are working to separate anthropogenic signatures on atmospheric carbon from the background noise of natural events, while the Bender group looks to ancient sea ice to better understand the carbon cycle.

Atmospheric CO_2 response to volcanic eruptions

In previous work, the Sarmiento group has shown that tropical volcanic eruptions are one of the most important natural factors that significantly impact the climate system and the carbon cycle on annual to multi-decadal time scales. The three largest explosive volcanic eruptions in the last 50 years – Agung, El Chichón, and Pinatubo – occurred in spring-summer in conjunction with El Niño events and left distinct negative signals in the observational temperature and CO_2 records. However, confounding factors such as seasonal variability and El Niño-Southern Oscillation (ENSO) may obscure the forcing-response relationship.

In this study, Thomas Frölicher in the Sarmiento group determined for the first time the extent to which initial conditions, i.e. season and phase of the ENSO, and internal variability influence the coupled climate and carbon cycle response to volcanic forcing, and how this affects estimates of the

terrestrial and ocean carbon sinks. Ensemble simulations with the Earth System Model CSM1.4-carbon predict that the atmospheric response is ~60% larger when a volcanic eruption occurs during El Niño and in winter than during La Niña conditions (Figure 5). The simulations suggest that the Pinatubo eruptions contributed 11 ± 6% to the 25 Pg terrestrial carbon sink inferred over the decade 1990-1999 and -2 ± 1% to the 22 Pg oceanic carbon sink.

Recent studies have indicated a possible positive trend in the airborne anthropogenic CO_2 fraction, suggesting a worrying decrease in the efficiency of the ocean and land carbon sinks. In contrast to these claims, this study indicates that accounting for the decadal-scale influence of explosive volcanism and related uncertainties removes the positive trend in the airborne fraction of anthropogenic carbon. The results highlight the importance of considering the role of natural variability in the carbon cycle for interpretation of observations and for data-model intercomparison.

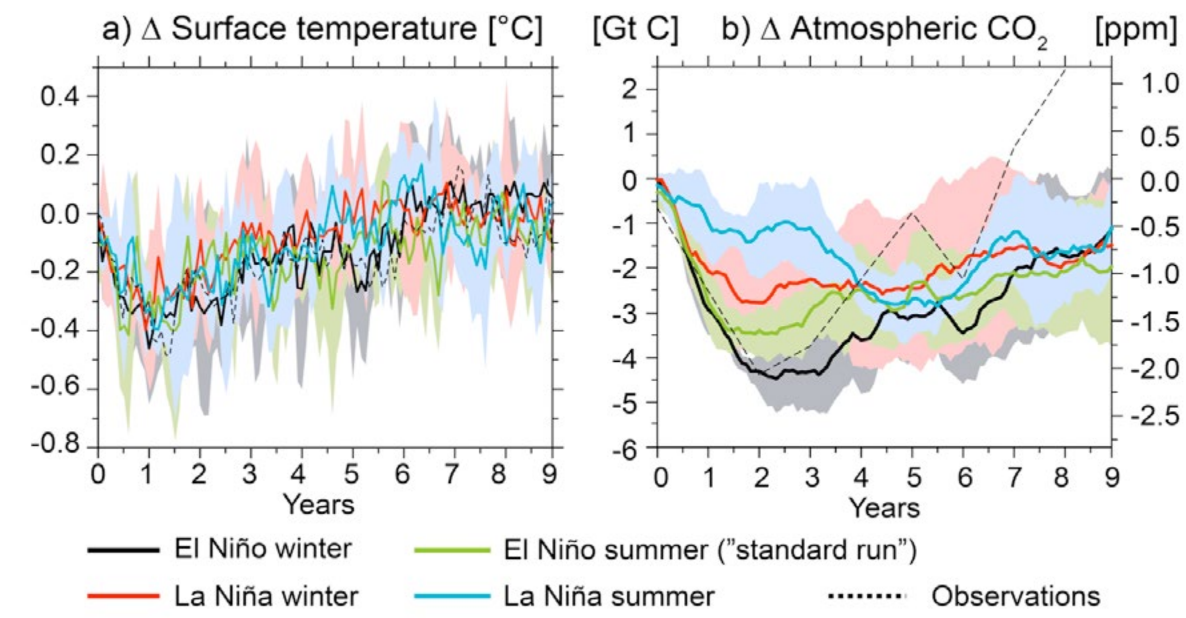

Figure 5: Temporal evolution of global ensemble monthly mean differences in (a) atmospheric surface temperature and (b) atmospheric CO_2. The eruptions started in El Niño winter (black), La Niña winter (red), El Niño summer (green) and La Niña summer (blue) conditions. Shadings indicate one standard deviation confidence interval of the ensemble simulations. Dashed black lines indicate observation-derived temperature and atmospheric CO2 changes after the Mt. Pinatubo eruption (the calculation of the observation-derived atmospheric CO2 changes must be viewed as a tentative attempt - Frölicher et al. 2013).

Extending the record of ancient CO_2 levels

The deepest ice cores yet drilled, targeted to encompass the longest possible continuous records, end at ice 800,000 years old. To extend this record, Michael Bender and colleagues have been searching Antarctic sites where, because of complex glacier flows influenced by the Transantarctic Mountains, older ice may be present near the surface (Figure 6). In the Allan Hills, the researchers have discovered million year old ice that will enable Bender's group to extend back ice core records of CO_2 and climate beyond the oldest ice otherwise available. The team plans to do additional prospecting for even older ice in the region. The hope is that this work will yield ice that can be used to extend the climate record back into the "40 k world" of shorter, less intense climate cycles that prevailed from about 2.5-1 million years ago.

Bender has also written a book, *Paleoclimate*, to be published by Princeton University Press in 2013. The book covers natural climate change and CO_2's role in climate throughout geologic time.

Figure 6: Camp and ice core drill (on sled) in the Allan Hills where the Bender team is seeking even more ancient ice.

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Low Carbon Energy Group

The **Low Carbon Energy Group** consists of two programs – the Capture effort carried out by **Bob Williams** with colleagues **Tom Kreutz** and **Eric Larson**, and the Energy Storage program led by **Craig Arnold**. The Capture group focuses on carbon capture from large-scale fossil fuel and biomass sources, including electric and synfuels plants. The Energy Storage group seeks improved strategies for energy storage that are compatible with renewable energy sources.

Highlights for 2012 include participation in a National Coal Council study of CCS for coal via enhanced oil recovery requested by US Energy Secretary Steven Chu, a new study of CO_2 "activation" to make low-carbon synthetic transportation fuels, and a study that suggests lithium iron phosphate batteries have the potential to significantly reduce system costs for off-grid renewables.

Highlights

Enhanced Oil Recovery (EOR) for Early Applications of CO_2 Capture Technologies

- The Capture group played a leading role in a study prepared by the National Coal Council for Energy Secretary Chu on CO_2 EOR applications of capture technologies; a major Capture group contribution is the finding that synfuel plants and plants making synfuels + electricity as a major coproduct are likely to be competitive even in distant EOR markets if an adequate CO_2 pipeline network is in place.

- In studying the relative profitabilities of coal/biomass plants making diesel and gasoline synfuels and plants coproducing such synfuels plus electricity, it was found that coproduction plants are almost always more profitable.

- A public policy proposal is being developed to use federal tax revenues from new crude oil production via CO_2 EOR and synfuel production to help finance several early plants that sell captured CO_2 for EOR - as a subsidy mechanism for capture technology cost reduction through experience (learning by doing) that would not aggravate the federal deficit.

Studies for the National Energy Technology Laboratory (NETL)

- NETL-supported studies were completed of coproduction of electricity and light olefins from coal and from coal/biomass and coproduction of electricity and ammonia from coal.

- A new one-year project supported by NETL will identify coal/biomass strategies for making synthetic jet fuel in the Ohio River Valley.

CO_2 Activation

- An analytical framework has been developed for investigating the climate-mitigation implications and economics of a strategy termed "CO_2 activation," in which low-carbon H_2 and fossil CO_2 are combined to make synthetic liquid transportation fuels.

China Activities

- Publication of *The Global Energy Assessment: Toward a Sustainable Future,* the Fossil Energy Chapter of which was co-authored by Princeton and Tsinghua University researchers.

- Contributions to the ongoing NETL project on making low-carbon jet fuel by a visiting scientist from SINOPEC's Research Institute for Petroleum Processing in Beijing.

- Participation in meetings convened by the Shenhua Corporation (the world's largest coal company) to discuss creation of a Strategic Research Institute (SRI) and a new magazine (*Cornerstone*) for the World Coal Association that will communicate hopeful coal strategies to world leaders in the public and private sectors.

Italian Collaborations

- Collaborations with researchers at the Energy Conversion Systems Group at Politecnico di Milano and Politecnico di Torino led to the publication of several papers.

Energy Storage Technologies

- Multiple competing mechanisms were identified that gradually increase mechanical stress and the rate of cell degradation in lithium-ion cells over time.
- Higher levels of mechanical stress were found to accelerate the rate of capacity fade in lithium-ion cells, highlighting the importance of stress management in these cells.
- A study of the fundamental transport properties of lithium-ion battery separators is the first step in developing separators that can sustain deformation without inhibiting battery performance.
- The dependence of battery charge and discharge efficiency is modeled and experimentally verified in lithium-ion batteries.
- Lithium iron phosphate batteries are shown to have much better longevity and charge acceptance than lithium cobalt oxide, lithium nickel manganese cobalt oxide, and lead-acid batteries when aged with a variable power profile typical of an off-grid wind system.
- Energy storage used in complex variable power systems, like renewable energy and electric vehicle applications, is modeled in the frequency domain to provide a better metric for characterizing and designing hybrid storage systems.

Low Carbon Energy

Enhanced Oil Recovery Applications of CO_2 Capture Technologies

During 2012 Williams investigated prospects for early deployment of CO_2 capture technologies for which storage is carried out in conjunction with CO_2 enhanced oil recovery (CO_2 EOR). In so-called miscible flooding, injected CO_2 dissolves in oil, reducing its viscosity and facilitating oil flow to the well bore. When the crude oil is recovered, the CO_2 released from the oil is captured and re-injected to extract more oil. After repeated CO_2 recycle, nearly all of the purchased CO_2 ends up being stored in the reservoir from which the crude oil is recovered.

Two of the CO_2 EOR-related projects gave focused attention to the relative economics of alternative CO_2 capture technologies for mature technologies—so-called N^{th}-of-a-kind (NOAK) plants. The third explores an innovative subsidy mechanism for capture technology cost reduction from first-of-a-kind (FOAK) cost levels through experience (learning by doing) in CO_2 EOR applications.

NCC Study of CO_2 Capture for coal energy conversion and storage via EOR

In October 2011 Energy Secretary Chu asked the National Coal Council (NCC) to prepare for him a report on CCS for coal via CO_2 EOR. The NCC invited Williams to participate in this study, and he was given the lead responsibility for the report's analyses of synfuels and synfuels/electricity coproduction, and analyses comparing the economics of all capture options. Williams persuaded the NCC study team to consider natural gas as well as coal in considering synfuels and coproduction systems and to consider co-processing modest biomass amounts (< 10% on an energy basis) with both feedstocks in early-mover projects.

Important findings of the NCC report based on Williams' internal rate of return on equity (IRRE) analyses for NOAK versions of present-day technologies are (for an assumed oil price of $90/bbl and no price on greenhouse gas emissions):

- The only power-only option offering attractive an IRRE is a post-combustion capture retrofit for an existing coal power plant when such a system is located near a CO_2 EOR site.
- Synfuel and coproduction plants located practically anywhere in the US could compete in CO_2 EOR markets (even distant markets) if an adequate CO_2 pipeline infrastructure were in place.

The latter led the NCC study group to its major finding that it is technically and economically feasible to increase US crude oil production via EOR using CO_2 captured at coal plants from the current level of 280,000 bbls/day to 3,600,000 bbls/day by 2035.

The NCC study stressed the strategic importance of deploying first-of-a-kind (FOAK) projects for promising capture technologies as needed first steps toward realization of the identified opportunities. However, because FOAK capture projects are already going forward for pre-combustion, post-combustion, and oxycombustion capture technologies, the only new FOAK project recommended by the NCC study is for a plant selling CO_2 for EOR that coproduces synthetic transportation fuels and electricity based on coprocessing a modest amount of biomass with coal. The NCC study argued that the coal industry and the Energy Secretary should work together to find a way whereby such a plant could be financed, built, and demonstrated at commercial scale.

Recycle vs. coproduction system configurations for providing synfuels

The Capture group has previously analyzed synthetic fuels production for NOAK plants based on both: (a) the Fischer-Tropsch liquids (FTL) process to produce diesel fuel and gasoline from coal (CTL) and from coal/biomass (CBTL), and (b) the methanol to gasoline (MTG) process to produce gasoline from coal (CTG) and from coal/biomass (CBTG) via methanol as an intermediate product. System configurations that recycle unconverted syngas to maximize liquid fuel output were analyzed, as well as system configurations that provide electricity as a major coproduct.

During 2012 Williams extended these analyses to CO_2 EOR applications for synfuel options involving CO_2 capture, to explore relative profitabilities of recycle and coproduction configurations. The expectation when the work started was that at sufficiently high oil prices recycle will be the more profitable; the analysis is aimed at identifying breakeven oil prices for both FTL and MTG systems, and for both coal only and coal/biomass options.

When only coal is a feedstock: When only coal is the feedstock, it makes sense to consider plants of equal capital cost in comparing recycle and coproduction configurations. For FTL it was found that recycle is more profitable than coproduction at crude oil prices higher than about $100/bbl (with no price on GHG emissions)—but also that profitabilities are comparable over a wide range of oil prices (e.g., $80 to $120/bbl). In contrast, for MTG there is no oil price at which coproduction is more profitable than recycle.

When biomass is coprocessed with coal: Because biomass is typically more expensive than coal, coprocessing biomass can be cost-effective only under a carbon mitigation policy. It makes sense to compare systems with equal inputs of scarce biomass and offering equal carbon-mitigation benefits as measured by the greenhouse gas emissions index (GHGI)[1]. Here IRRE values are estimated for two FTL options and two MTG options that coprocess enough biomass to reduce GHGI to 0.17, assuming a $50/t GHG emissions price - see Table 1. The modeled biomass is switchgrass, the growing of which does not require good cropland.

For MTG systems, recycle is more profitable than coproduction for crude oil prices greater than about $80/bbl. For FTL systems, coproduction is always more profitable. This finding arises from the greater percentage of feedstock carbon stored as CO_2 for coproduction (65% vs 54%). The corresponding greater negative CO_2 emissions from photosynthetic CO_2 storage implies a smaller biomass input percentage (24% vs 38%) to realize the targeted GHGI, which in turn implies a lower average feedstock cost. Also, coproduction enjoys scale economy benefits as a result of the assumed equal biomass rates for recycle and coproduction. The FTL finding is especially important in light of the greater need for diesel than for gasoline - which implies that much more FTL capacity than MTG capacity is likely to be built. Table 1 presents IRRE values for these four coal/biomass options when the crude oil price is $90/bbl.

1 Invented by the Capture group, GHGI is a carbon mitigation metric defined as a system's total GHG emissions divided by the GHG emissions for the conventional fossil energy displaced; the latter are assumed to be the equivalent crude oil-derived liquid fuels and electricity from new supercritical coal plants that vent CO2.

Table 1: Comparing Alternative Coal/Biomass Coprocessing Options
(for all options: GHGI = 0.17; biomass consumption rate = 1 x 106 t/y;
$50/t GHG emissions price; $90/bbl crude oil price; coal price = $2.5/GJ; biomass price = $5.0/GJ)

Technology	Output Capacities		% of feedstock C captured/stored as CO_2 (106 t/y of CO_2 stored)	Estimated capital cost for NOAK plant, $106	IRRE (%/year)
	bbls/day gasoline equivalent	MWe of electricity (% of energy output)			
CBTL recycle (38% biomass)	12,730	64.3 (8.0)	53 (2.3)	1860	15.7
CBTL coproduction (24% biomass)	14,270	341 (29)	65 (4.5)	2500	18.9
CBTG recycle (39% biomass)	13,770	12.3 (1.5)	53 (2.3)	1800	19.9
CBTG coproduction (24% biomass)	14,790	337 (28)	65 (4.4)	2750	19.0

CO_2 capture technology cost buydown

Because, in the absence of a price on GHG emissions, required levels of subsidy for launching CO_2 capture technologies in the market are likely to be so high that it would not be feasible to use general federal funds (GFF) to fill the "cost gap," Williams has been exploring an innovative strategy for government support of early launch of CO_2 capture technologies for systems that sell CO_2 into enhanced oil recovery (EOR) markets. The strategy involves using federal tax revenues from new crude oil production via CO_2 EOR and synfuel production to help finance (via competitively-bid grants proportional to the captured CO_2 amount) early plants selling captured CO_2 for EOR. The aim is capture technology cost "buydown"—i.e., cost reduction through experience ("learning by doing").

Table 2: Some Features of Alternative Energy Conversion Systems

Technology	Output Capacities		% of feedstock C captured/stored as CO_2 (10^6 t/y of CO_2 stored; tCO_2 stored/MWh_e)	Estimated capital for NOAK plant, $\$10^6$	GHGI
	bbls/day gasoline equivalent	MW_e of electricity (% of energy output)			
NGCC with CO_2 vented	0	555 (100)	0 (0; 0)	398	0.57
Power only system with capture of CO_2 and its sale for EOR					
NGCC	0	474 (100)	90 (1.4; 0.38)	713	0.20
Fossil fuel/biomass coproduction systems with capture of CO_2 and its sale for EOR					
GBTL (7% biomass)	10,620	409 (41)	47 (1.5; 0.45)	1450	0.50
CBTG (5% biomass)	14,790	317 (27)	64 (4.2; 1.69)	2500	0.50

The Capture group has focused on estimating NOAK costs for energy conversion systems. For this CO_2 capture technology cost buydown analysis, it is assumed that: (a) FOAK costs for capital and operation and maintenance (O&M) costs for new technology are 2.0 X NOAK[2] costs (b) capital and O&M costs decline with experience at the same rate as the learning-by-doing (LBD) rate for SO_2 scrubbers (11% for each cumulative doubling of production), and (c) the subsidy must be large enough to reduce the cost of generating electricity to that for a natural gas combined cycle power plant venting CO_2, currently the technology of choice for new power plants in the United States. To the extent possible, subsidies would be financed with the new federal revenue streams associated with new domestic liquid production. Required subsidies in excess of what can be provided by these new federal revenue streams would be paid for out of GFF.

The analysis is being carried out for four systems that make only electricity and four systems that coproduce transportation fuels and electricity. Findings are presented here for one of the power options (NGCC: a natural gas combined cycle plant) and for two coproduction options that coprocess biomass (an FTL system for natural gas/biomass and an MTG system for coal/biomass—see Table 2). It is assumed that the FTL plant is located at the natural gas wellhead but that the MTG and NGCC plants are located at average power-plant sites. The coproduction systems investigated were designed with just enough biomass (7% in the natural gas-based FTL case and 5% in the coal-based MTG case) to realize GHGI = 0.50.

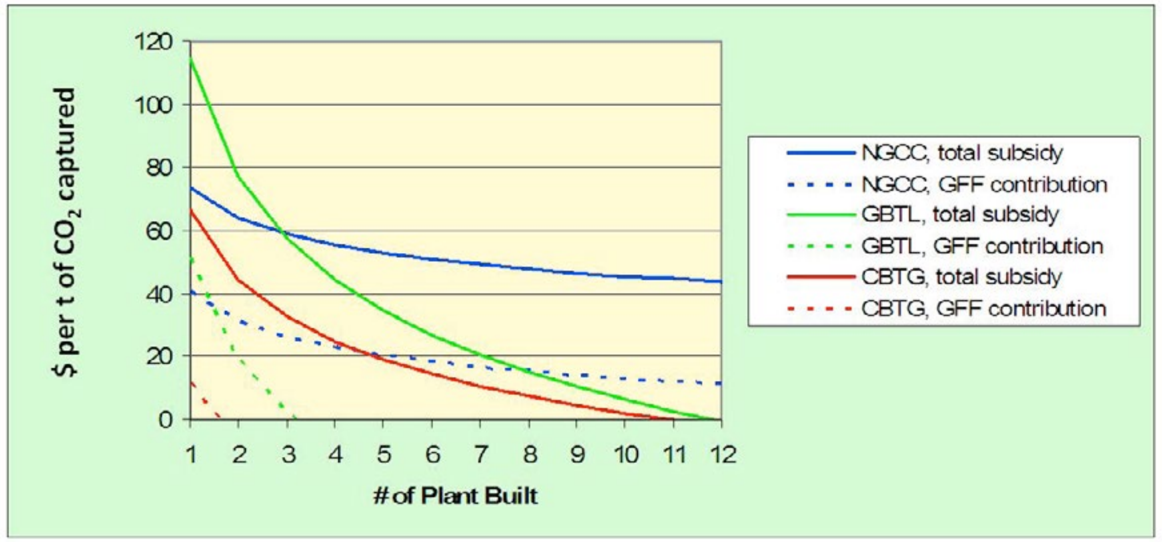

Figure 7: Buydown subsidy required as a function of # of plants built for the three energy conversion systems with CCS listed in Table 2 that sell captured CO_2 into the EOR market when the crude oil price is $90/bbl. GFF are general federal funds that would be needed as part of the subsidy, above and beyond the level of new federal tax revenues that would be generated by operation of the plants.
The assumed fuel prices are $2.5/GJ for coal, $5.4/GJ for natural gas used at natural gas combined cycle (NGCC) power plant, and $3.5/GJ for natural gas used in the natural gas wellhead-sited FTL plant. The assumed plant-gate CO_2 price is:
= $30/t [0.444*(crude oil price in $/bbl) – ($CO_2$ transport cost = $10/t)], which can be considered as representing nearby EOR opportunities

For NGCC the required subsidy declines slowly with the cumulative number of plants built (see Figure 7); the Nth (59th) plant still requires a $30/t$CO_2$ subsidy, and GFF contributions to the subsidy are needed until after 44 plants have been built. In sharp contrast, for the coproduction options the required subsidy declines rapidly. No subsidy is required for the 12th plant, and GFF subsidy contributions are needed only for the first CBTG plant and the first three GBTL plants. Moreover, new federal revenues (net of required subsidies) from domestic liquid production for the first 12 plants amounts to $17 billion for CBTG and $2.6 billion for GBTL. This suggests that market launch for both coproduction technologies and the associated biomass supply logistics technologies can be accomplished in the absence of a price on GHG emissions. Moreover, this can be done in a way that contributes significantly to federal deficit reduction rather than to its buildup, despite huge subsidies for early projects (e.g., $1.8 billion for the first FTL project and $2.9 billion for the first MTG project).

2 This is the actual ratio of FOAK to NOAK costs for the Edwardsport IGCC plant being built by Duke Energy in Indiana.

Studies for the National Energy Technology Laboratory

Coproduction of chemicals and electricity

In October 2010 the Capture group was awarded a grant from the National Energy Technology Laboratory (NETL) to investigate *Energy, Environmental, and Economic Analyses of Design Concepts for the Co-Production of Fuels and Chemicals with Electricity via Co-Gasification of Coal and Biomass.* Led by Larson, the early research program explored the coproduction of gasoline and electricity via co-gasification of coal and biomass in a single oxygen-blown entrained-flow gasifier.

The NETL grant co-supported additional work (beyond what was reported last year) that is described here: research on the co-production of electricity and bulk chemicals – ethylene/propylene and ammonia. This analytical extension is aimed at understanding implications for carbon mitigation and economics of systems providing, as coproducts of electricity, liquids that have higher market values than transportation fuels.

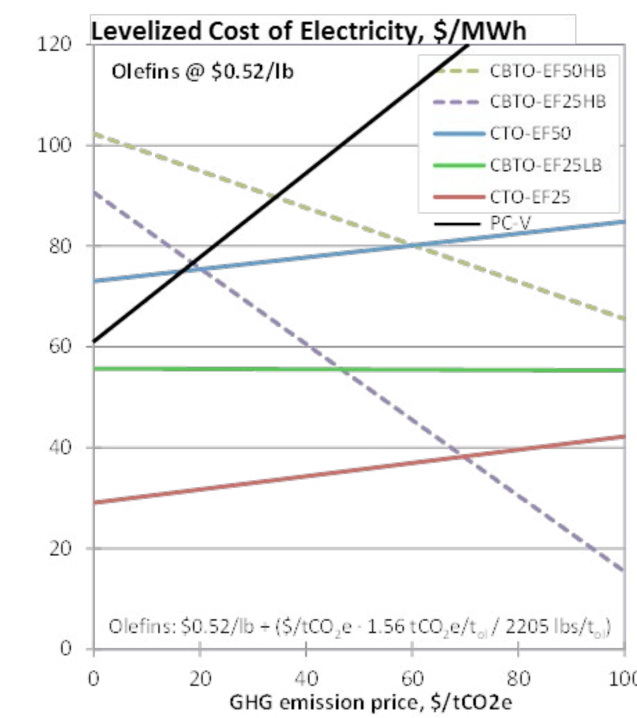

Figure 8. LCOE (in 2007$ per MWh) versus green-house gas emissions price for a new supercritical pulverized coal plant venting CO_2 (PC-V) and five electricity/olefins coproduction options.

Co-producing light olefins and electricity

In the coproduction of light olefins and electricity, coal and torrefied biomass are first co-gasified in a dry-feed, entrained-flow gasifier. The synthesis gas from the gasifier is then converted to methanol, and the methanol is subsequently processed through a commercially-available methanol-to-olefins synthesis reactor. Both coal to olefins (CTO) and coal/biomass to olefins (CBTO) options were analyzed. Process configurations with different biomass feed percentages [HB = high (30%) biomass; LB = low (5%) biomass] and electricity output percentages (EF25 = 25% electricity; EF50 = 50% electricity) were simulated using Aspen Plus software.

Figure 8 shows some of economic findings (in $2007) from an electricity generator's perspective. The figure shows that the options providing a 25% electricity fraction outperform the options for which electricity accounts for 50% of energy output. Moreover, the levelized cost of electricity (LCOE) for both CTO-EF25 (GHGI = 0.41) and CBTO-EF25LB with 5% biomass (GHGI = 0.30) are lower than for a new supercritical coal plant with CO_2 vented (PC-V, with GHGI = 1.00) at all GHG emissions prices. For CBTO-EF25HB, which has a strong negative GHG emission rate (GHGI = - 0.32), a GHG emissions price of only \$20/t CO_2e is needed in order to offer the same LCOE as PC-V. The negative GHGI arises from the assumption that carbon in the olefins is sequestered permanently when products made from them are land-filled at the end of their lives.

Co-producing ammonia and electricity

Because neither electricity nor ammonia contain carbon, it is possible in a system with CCS to achieve near complete decarbonization for such systems without biomass. For this reason, only coal inputs were considered for the ammonia/electricity coproduction analyses. Two sets of coproduction cases were analyzed: one considered steady-state plant operation and a second examined potential impacts of diurnally-varying production rates aimed at exploiting higher electricity values during peak electricity demand periods.

In contrast to the findings for coproducing olefins and power, it was found that LCOE values for the steady-state ammonia-electricity coproduction cases are higher than those for PC-V plants, even assuming prices for natural gas and hence values for the ammonia (since the primary feedstock for commercial ammonia production today is natural gas) that are far higher than prices prevailing today in the U.S. and even when assuming a \$100/t tCO_2e greenhouse gas emissions price.

In process simulations for plants designed to be able to vary the electricity/ammonia output ratio (producing more power when electricity is highly valued) various practical challenges were ignored—such as those associated with rapid up-and-down ramping of plant components, efficiency penalties that might occur with such ramping, and long-term maintenance and equipment fatigue issues with repeated cycling. It was found, nonetheless, that the internal rates of return for co-production were not sufficient to make this alternative plant design and operating strategy an economically viable one.

NETL-2: Co-production of jet fuel and electricity in the Ohio River Valley

In late 2012, the Capture group launched a new one-year project with co-support from a new grant from the National Energy Technology Laboratory. The goal of this work, which is still in its early stages, is to identify coal/biomass-to-liquid (CBTL) system implementation strategies for the Ohio River Valley that might increase the viability of constructing and operating such plants there in the next 5 to 10 years. The emphasis is on assessing technical and economic viability of alternative plant designs for producing primarily synthetic jet fuel that, when blended 50:50 with conventional jet fuel, will meet or beat current and potential future regulatory requirements.

Tom Kreutz is leading the design and simulation of process configurations that will include separate coal and biomass gasifiers feeding syngas to cobalt-catalyzed Fischer-Tropsch synthesis reactors. The latter produce primarily heavy paraffins that are hydrocracked and refined to aviation fuel. Designs that co-produce different levels of electricity will be assessed, and plant designs with different biomass/coal input ratios will be analyzed. Byproduct CO_2 will be captured and sold for use in enhanced oil recovery (EOR), resulting in the carbon ultimately being stored permanently underground.

The Capture group is collaborating in this project with engineers at Booz Allen Hamilton, who are contributing feedstock supply analysis and detailed lifecycle greenhouse gas accounting to complement detailed process design/simulation that will be carried out by the Capture group. The work is benefiting from a one-year visit to Princeton by Dr. Qiang Li, whose home institution is Sinopec's Research Institute of Petroleum Processing in Beijing.

CO_2 Activation

Working with Robert Socolow, **Tom Kreutz** has developed an analytical framework for investigating the economics and climate mitigation implications of making transportation fuels from CO_2, termed "CO_2 activation" (CCA). The research has focused on a prototypical system that combines low carbon H_2 (i.e. H_2 produced from renewable or nuclear energy sources) and CO_2 to make synthetic liquid transportation fuels via the reverse water gas shift reaction followed by Fischer-Tropsch synthesis. Detailed simulations of thermodynamic performance have been carried out as a basis for economic analysis.

Kreutz found that high oil prices favor CCA over the two alternatives: CO_2 venting [Vent (BAU)] and CCS (Figure 9). At low CO_2 emissions prices (below the price P* needed to induce CCS), CCA mitigates GHG emissions by capturing CO_2 en route to the atmosphere and re-using the carbon to make synthetic transport fuels. In this way the carbon is "used twice" before entering the atmosphere as CO_2. This climate benefit is reflected in Figure 9 by a breakeven oil price (BEOP) between CCA and Vent (BAU) which falls with increasing CO_2 price; in other words, a rising carbon tax makes CCA increasingly competitive. At CO_2 emissions prices above P*, however, the BEOP for CCA becomes flat; compared to the alternative option, CCS, CCA provides no benefit to the climate.

CO_2 EOR is much less expensive than CCA, which requires costly capital equipment and vast quantities of low carbon H_2. As a result, the oil prices required for profitable CO_2 EOR (blue lines) are much lower than those needed to induce CCA (black lines), and thus CO_2 EOR is the economically preferred method of "converting" CO_2 to transportation fuels. The climate benefits of CCA and CO_2 EOR are also quite similar.

This work confirms a key result from a previous paper by Kreutz (presented in 2010 at the 10th International Conference on Greenhouse Gas Control Technologies), that CCA does not significantly reduce CO_2 emissions when CCS at power plants is an economically viable option for CO_2 disposal. Moreover, the present analysis shows that, if CO_2 EOR is available as an option for providing additional liquid fuels, EOR will be far more profitable than CCA while providing roughly comparable carbon mitigation benefits.

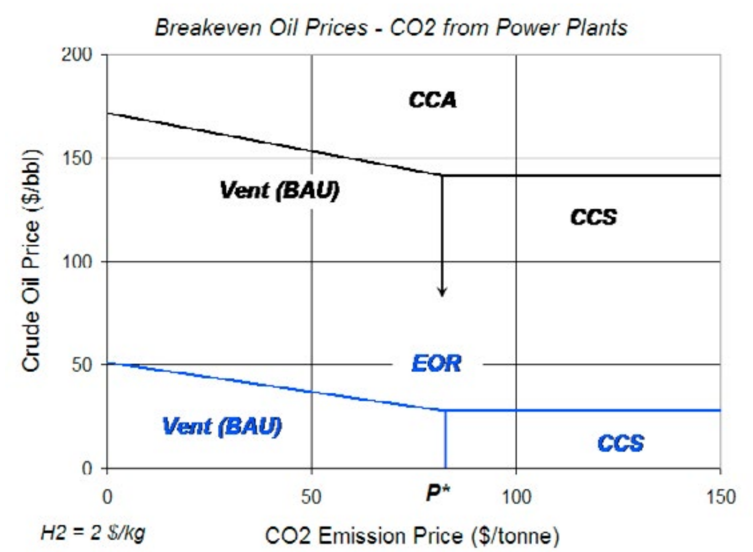

Figure 9: The parameter space shown here and described in the text is divided into segments, in each of which the indicated option is the most profitable investment opportunity. The set of blue lines are applicable wherever CO_2 EOR is an available opportunity; the black lines apply when CO_2 EOR is not an option and CO_2 activation (CCA) is favored.

China Activities

The China-related activities of the Capture group are expanding. Collaborations with Chinese colleagues are especially important in light of the high level of interest in China in coproduction technologies that are the focus of much of the Capture group's recent work. The coal chemical process industry in China has extensive experience with modern coal gasification technologies (more than all the rest of the world combined), and there is much interest in extending this industrial experience from niche chemicals markets to the much larger fuels and electricity markets that require very similar energy conversion technologies.

Zheng Li. A highlight of the Capture group's long-term collaboration with Zheng Li at Tsinghua University was the publication in the fall of 2012 by Cambridge University Press of the *Global Energy Assessment: Toward a Sustainable Future* - an 1865 page (5 kg!), 25-chapter IPCC-style study involving several hundred authors and reviewers globally. The GEA describes technologies and strategies for addressing the major societal challenges related to energy. It is anticipated that the GEA will be regarded as "essential reading" for public- and private-sector decision makers worldwide who are interested in advancing energy toward sustainable development goals.

Eric Larson and Prof. Zheng Li were the Co-Convening Lead Authors for the Fossil Energy Chapter of this report. Williams was a Lead Author, and Guangjian Liu was one of the contributing authors. The Fossil Energy chapter highlights the importance of co-processing coal and biomass with CCS and natural gas and biomass with CCS for meeting sustainability goals. In addition Larson was a Lead Author of the Renewable Energy Chapter for which he made contributions relating to biomass.

Guangjian Liu. The collaboration with Guangjian Liu, established when he was a post-doc with the Capture group during 2008-2010, has been sustained since he returned to Beijing to a faculty position at the North China Electric Power University (NCEPU).

During 2012 the continuing collaboration with Prof. Liu included i) research on olefin/electricity coproduction systems (described above), ii) Williams' visiting NCEPU in October 2012 as part of the continuation of the Capture group's participation in the Coal Conversion and Utilization Research and Education Project led by NCEPU (see 2011 CMI annual report), and iii) Liu's contributions to a new undergraduate engineering course at Princeton, "The Energy-Water Nexus," taught by Larson.

Dr. Qiang Li. Dr. Xiangbo Guo, a scientist at SINOPEC's Research Institute for Petroleum Processing (RIPP) in Beijing, spent calendar year 2010 as a visiting research fellow with the Capture group, where he contributed his understanding of refining processes to the Capture group's coal/biomass-to-liquids work.

In 2012, Dr. Guo introduced the Capture group to his colleague Dr. Qiang Li, who had recently been awarded the same prestigious award by SINOPEC that allows him to spend a sabbatical year at a U.S. university. The Group invited Dr. Li to Princeton, and he is making contributions to the ongoing Capture group project on the production of low-carbon jet fuel from coal and biomass.

Advising Shenhua. Williams was invited by the Shenhua Corporation (the world's largest coal company) to a brainstorming session in Chicago in July 2012 as well as to a followup meeting in Beijing in October 2012 to discuss two initiatives that Shenhua Chairman Xiwu Zhang is pursuing in his new capacity as Chairman of the World Coal Association - creation for the WCA of: (a) a Strategic Research Institute (SRI) for coal that will deal with strategies for the future of coal worldwide, and (b) a new *Cornerstone* magazine that aims to communicate hopeful strategies to world leaders in the public and private sectors who are interested in coal issues.

In these meetings Williams stressed the strategic importance for coal of strategies such as those articulated in the *Global Energy Assessment* that would enable coal to make important contributions to sustainable development goals for global society. Subsequently, Williams recommended a strong candidate for editor of *Cornerstone*, who was hired for that position.

Italian Collaborations

In 2012 the Capture group continued its longstanding collaboration with the Energy Conversion Systems Group at Politecnico di Milano (POLIMI). The research used the novel bottoming cycle optimization methodology of Prof. Emanuele Martelli (former Capture group visiting researcher) to re-analyze and understand more deeply the efficiencies of advanced energy conversion facilities that produce both electricity and liquid fuels. By generating both theoretically optimal and more realistic (i.e., economically viable) plant configurations for waste heat recovery, Martelli's software provides important context for previous Capture group work, highlighting the difference between sub-optimal designs versus fundamental concessions necessary for improved operability and economics.

The research of Dr. Andrea Lanzini (in residence with the Capture group in 2010 as a Fulbright scholar and currently a researcher at Politecnico di Torino) on solid oxide fuel cells and fuel cell/gas turbine (FCGT) hybrids was the focus of another Italian collaboration. Lanzini applied the Capture group's systems analysis methodologies to advanced power plants, coupling coal gasification with FCGT hybrids, focusing on strategies for "methanating" synthesis gas upstream of the SOFC in order to improve overall conversion efficiency and reduce plant costs.

Energy Storage Technologies

Energy storage is playing an increasingly important role throughout the energy infrastructure, from powering hybrid and electric vehicles to offsetting the inherent intermittency of renewable energy generation. Unlike batteries for electronic devices, which can be charged using a pre-determined protocol simply by plugging them into the wall, many of these applications are characterized by highly variable charge and demand profiles. The **Energy Storage Group** headed by **Craig Arnold** is working to characterize how such variability in charging powers affects battery behavior in order to improve overall system efficiency and lifespan.

Impacts of stress in lithium-ion cells

This year, the Energy Storage group has identified several sources of mechanical stress within lithium-ion cells and investigated the impacts of this stress on battery life and performance, identifying several potential areas for improvement.

Stress evolution in Li+ cells. Lithium-ion cells typically operate under some level of compression applied by a rigid constraint, for example a cylinder battery cell. The level of initial stress is fixed by the manufacturer, but this stress is not constant over the life of the cell owing to electrode expansion during charging/discharging as well as other effects. Knowledge of the stress evolution over the cell's entire useful life is important for understanding and predicting battery cell degradation, which is heavily influenced by stress state.

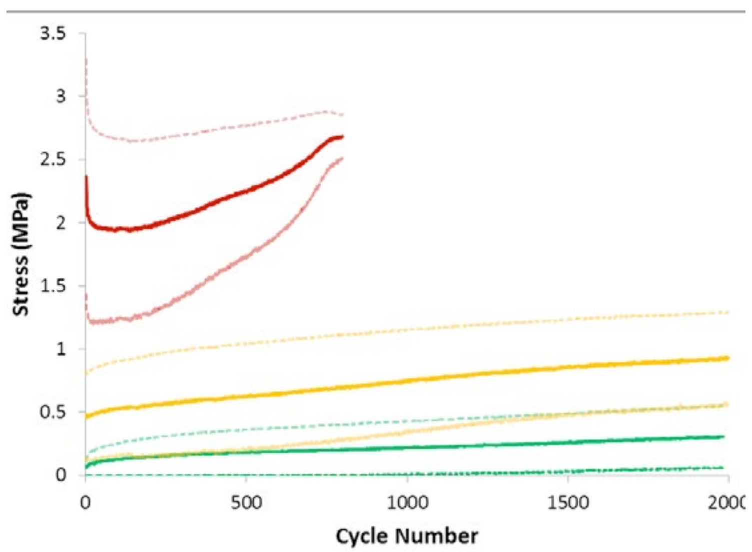

Figure 10: Stress evolution of lithium-ion cells with different initial stack pressures shows as a function of cycle number long term trend of increasing mechanical stress.

Mechanical stress evolution was found to be a function of three competing mechanisms: viscoelastic stress relaxation of the polymeric battery components, volumetric changes of the battery active material due to lithiation, and growth of the SEI (a solid film produced by side reactions). The relative importance of these mechanisms were found to change depending on the initially applied stack pressure, with viscoelastic stress relaxation becoming a more dominant mechanism with increasing levels of stress. At long time scales, SEI growth became a dominant mechanism, increasing stress in all cells. (Figure 10) Future plans include development of more mechanically robust cells through improvements in materials selection and design.

Effects of stress on capacity fade. It is well known that mechanical stress (on the order of hundreds of MPa) that builds up within the electrode particles as a result of particle expansion during lithiation is linked to capacity degradation through particle failure. However, little attention has been given to the relatively modest pressures (tenths of MPa) that are applied to the entire cell during manufacturing and that build up during normal operation. It is commonly believed that these modest pressures have no negative effects on cell operation. However, due to the nature of the soft materials employed in some of the battery components such as the separator, these applied stress levels can result in major deformations over time which could potentially impact battery degradation over the lifetime of a cell.

Arnold and colleagues investigated the effect of applied stack pressure on the electrochemical performance and capacity retention characteristics of lithium-ion batteries. It was found that higher levels of stack stress resulted in higher rates of capacity fade. However, it was also shown that very small amounts of stress (on the order of hundredths of MPa) are beneficial to capacity retention through the prevention of electrode layer delamination. Upon disassembly of the cells it was discovered that growth of a surface film on the electrodes had occurred in the stressed cells, with highly stressed cells showing more film growth. This coupling between stress and chemistry had not been anticipated and will be a subject of future investigation.

Effects of stress on ion transport. High power battery operation requires very fast transport of lithium-ions through a liquid phase electrolyte between anode and cathode of a battery cell. In a real cell, this liquid phase is contained in a porous polymeric separator which is placed between the two electrodes to keep them from coming into contact and creating a short circuit. During battery manufacturing and operation, applied stresses build up which result in compression of the separator, which is relatively compliant compared to the battery electrodes. This separator deformation results in pore closure which ultimately restricts ion transport between the battery electrodes. Knowledge of how the impedance associated with this transport restriction varies with deformation is critical for predicting performance in high power cells.

Arnold's group measured the impedance as a function of deformation of commercial separators by compressing a pouch cell containing separator wetted in electrolyte but no active battery material while simultaneously measuring impedance. Wet-manufactured, dry-manufactured, monolayer, trilayer, polypropylene, and polyethylene separators were tested. A relationship between deformation and impedance using the Bruggeman tortuosity-porosity relationship was derived and verified by curve fitting experimental data (Figure 11). Using the derived relationship the empirical Bruggeman parameters could be determined by curve fitting the experimental data, yielding fundamental information about transport in the separators. Future work will focus on development of separators that can sustain deformation without restricting transport.

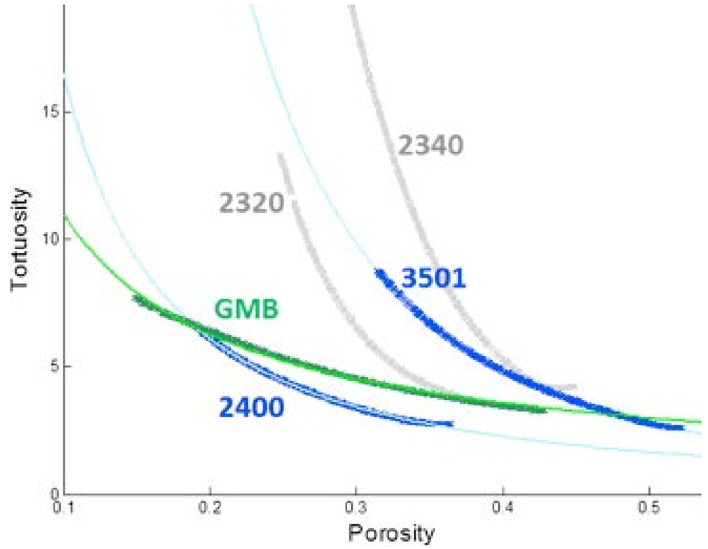

Figure 11: Curve fits of tortuosity vs. porosity for different lithium-ion battery separators used to determine both Bruggeman parameters.

Modeling the rate dependence of charge storage

The variability of wind, solar and other similar power sources necessarily means that batteries in these systems are charged over a range of different powers. Discharge efficiency is known to have a dependence on the discharge power; in Krieger and Arnold (2012) a similar effect on charge efficiency is modeled and experimentally confirmed for charging power. Both models have been expanded to account for an additional limitation to battery capacity as power increases: significant undercharging and underdischarging due to voltage limitations. As power increases, the charging voltage is offset higher and discharging voltage offset lower, leading to premature voltage cutoffs; this effect is more pronounced on charging due to the non-symmetric shape of the voltage curves. (see Figure 12) Energy-power relationships in battery charging and discharging are therefore found to be highly dependent on both the efficiency of charging and voltage limitations at any given power, which must be taken into account when designing battery systems operating over a variable range of powers.

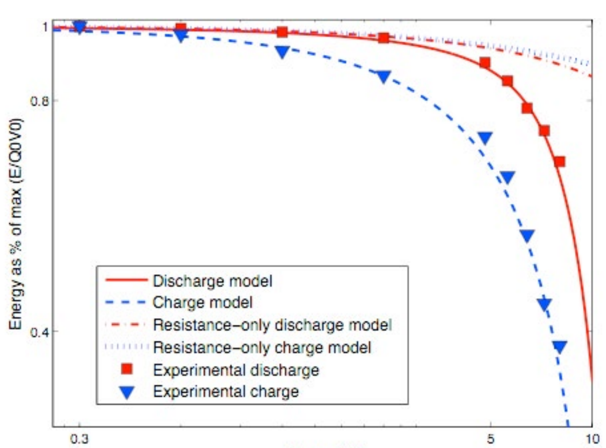

Figure 12: Model for undercharge and underdischarge using experimentally determined value for Q(P) as compared to models without undercharge and underdischarge. The experimental results are dominated by undercharge and underdischarge.

Battery degradation in off-grid renewable applications

The stresses of highly variable and incomplete charging in off-grid renewable energy systems result in rapid degradation of the lead-acid batteries typically used for these electrification projects, incurring large replacement costs over the lifetime of the system. To identify more promising energy storage technologies, Arnold and colleagues compared aging rates and mechanisms among constant-charge and wind-charged lead-acid, lithium cobalt oxide (LCO), LCO-lithium nickel manganese cobalt oxide composite, and lithium iron phosphate batteries.

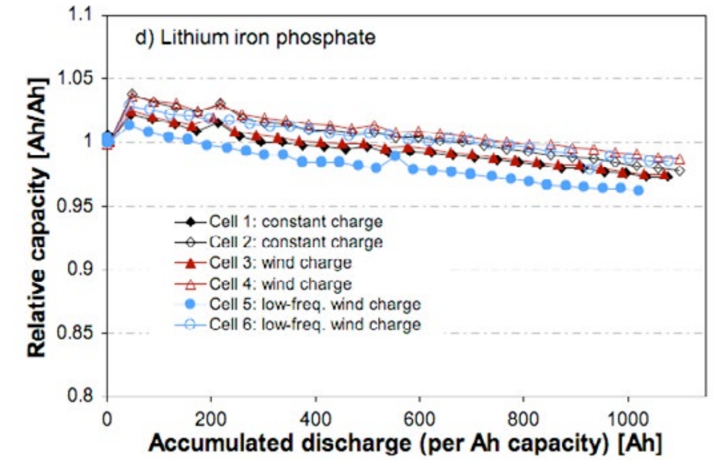

Figure 13: Capacity fade in constant-charged, wind-charged, and low frequency wind-charged lithium iron phosphate cells.

Accelerated aging studies conducted over the course of a year find that while constant-charged lead-acid batteries last longer than wind-charged cells, lithium cobalt oxide cells last longer under variable and incomplete charging conditions than constant charging, and lithium iron phosphate cells show only 1-3% degradation under all charging protocols. While these last cells are more expensive per installed kWh than the lead-acid cells, their consistently good power and voltage performance and ability to withstand deep discharge and incomplete charging allow the systems to be sized smaller. Combined with their long lifespan in variable power conditions, these results suggest significant potential for lithium iron phosphate batteries to reduce system lifetime costs for off-grid renewables.

A frequency-based model for energy storage

Variable power energy storage requirements may be best met by a suite of energy storage technologies instead of a single device. Applications like electric vehicles require both slow delivery of energy and rapid absorption of power during regenerative braking. Variable powers, as seen in the previously described projects, affect the efficiency and lifespan of energy storage devices to different degrees. Batteries may be better at providing bulk storage, whereas ultracapacitors are good at handling high-power bursts. The metrics to understand these complex systems are limited, however. Energy storage devices may be characterized by energy or power density, or discharge time.

Arnold and colleagues are working instead to re-frame energy storage in the frequency domain. In systems where power supply demand has both rapidly changing and slowly changing components, this power profile can be translated into the frequency domain to quantify the energy contained in high, medium or low frequency oscillations. Energy storage devices are also classified by their ideal frequency range – e.g. high frequency for ultracapacitors, low for compressed air energy storage. Frequency analysis is performed using wavelet transforms, which can accommodate the non-stationarity characteristic of many of these systems. This classification of energy storage systems in the frequency domain allows for improved understanding of complex and hybrid systems.

Low Carbon Energy Publications

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Martelli, E., T. G. Kreutz, M. Gatti, P. Chiesa and S. Consonni. "Numerical Optimization of Steam Cycles and Steam Generators Designs for Coal to FT Plants." Accepted for publication in the *Chemical Engineering Research and Design*, Jan. 2013.

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Williams, R. H. "Carbon Mitigation and Economics for Energy Conversion When CO_2 is Stored via Enhanced Oil Recovery." *Proceedings of the 11th International Conference on Greenhouse Gas Control Technologies* (GHGT-11), November 18-21, 2011, Kyoto, Japan

Williams, R.H. (Convening Lead Author), "Linking CO_2 from Synfuel and Coproduction." Chapter 6. In: National Coal Council, 2012: *Harnessing Coal's Carbon Content to Advance the Economy, Environment, and Energy Security.* A report prepared for Energy Secretary Chu, Washington, DC, June 22, 2012.

Williams, R.H. (Lead Author with several others), "Carbon Capture in Coal Power Generation and Coal-Based Alternative Fuels Production Systems." In: National Coal Council, 2012, Chapter 3: H*arnessing Coal's Carbon Content to Advance the Economy, Environment, and Energy Security,* a report prepared for Energy Secretary Chu, Washington, DC, June 22, 2012.

Low Carbon Energy

Fluids & Energy Group

The **Fluids & Energy Group** (formerly the Storage Group) investigates challenges of storing CO_2 below ground. The researchers use computer simulations, field studies, and laboratory experiments to study processes at molecular to basin scales. The PI's of the Group are **Michael Celia** and **Jean Prévost** of Civil and Environmental Engineering, **Pablo Debenedetti** and **Thanos Panagiotopoulos** of Chemical and Biological Engineering, **Howard Stone** (Mechanical and Aerospace Engineering), and **Jeroen Tromp** (Geosciences and Applied and Computational Mathematics).

Innovative research this year has found a possible synergy between carbon capture and storage and geothermal energy, provided insights into suppression of viscous fingering in sub-surface fluids, and produced ground-breaking molecular simulations of methane hydrate formation.

Highlights

Field Investigations

- Vertical Interference Tests to infer effective permeability of cement outside of casing continue to give estimates several orders of magnitude larger than expected from intact cement.

Simulations of CO_2 Storage

- Multi-scale models of underground CO_2 storage continue to be developed and applied to a wide range of practical, large-scale problems, including two-phase flow dynamics, capillary effects, large-scale dissolution, and leakage along faults and old wells.
- Research on Carbon Capture, Utilization, and Storage (CCUS) and geothermal systems shows that produced brines may have an important role in heat extraction and that captured CO_2 might be used in pressure support for geothermal production.
- A *Dynaflow* simulation suggests that injecting CO_2 at cold temperatures may lead to caprock fracturing.

Bench-Scale Investigations

- An experimental study suggests that varying permeability gradients can suppress viscous fingering, a finding with implications for enhanced oil recovery.
- A physical model of leakage of buoyant material shows good agreement with theoretical predictions.

Pore-Scale Modeling

- Pore-scale modeling studies are providing insight into geochemical reactions and phase trapping in CO_2 storage reservoirs.
- For the first time in a molecular simulation, methane hydrates have been formed in the absence of an interface.
- Simulations suggest that phase partitioning and interfacial properties of CO_2-water-salt systems can be predicted with moderate accuracy using existing atomistic models, but point to the need for improved force fields.

Field Investigations

One of the fruits of the partnership between CMI and BP has been the development of a technique called a “Vertical Interference Test” (VIT) to assess the effective permeability of existing wells. This test appears to be a very valuable field tool to estimate in situ permeability along existing wells.

Evaluation of well integrity

Both BP (through collaboration with Walter Crow) and Schlumberger (through collaboration with Princeton alumnus Andrew Duguid) have used Vertical Interference Tests to determine, in situ, the effective permeability of materials (mostly cements) outside of well casings. In 2012, the Celia group has continued collaborations with Andrew Duguid at Schlumberger (Andrew is a PhD alumnus of the CMI program) to analyze data from Vertical Interference Tests. The three most recent tests gave permeability estimates between about 1 milliDarcy and about 200milliDarcy. These fall within the range of other earlier measurements, and are several orders of magnitude larger than permeability of cement plugs retrieved from these locations. The latter observation points to annular flows as dominant along the boreholes.

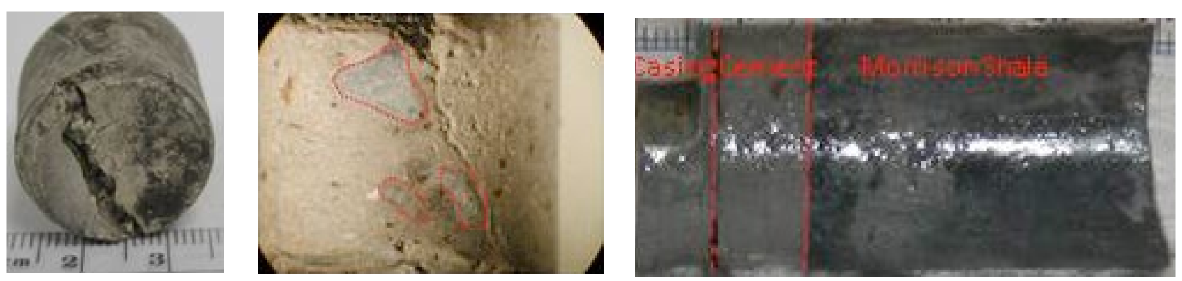

Figure 14: Examples of images from wellbore analysis: Left: Sample showing ~3 mm channel; Center: Sample showing shale fragments in the cement; Right: Side-wall core showing casing, cement, and shale. Figures from Duguid et al. (2012).

Large-Scale Simulations of CO_2 Storage

Since the founding of CMI, the **Celia** group has developed a hierarchy of analytical, semi-analytical, and numerical models that allow simulation of CO_2 injection and leakage, with a particular focus on leakage along old wells. Geared toward quantitative estimation of leakage on large scales, the group’s methods are very efficient and allow for simulations that include hundreds to thousands of leaky wells across many layers of geological formations.

Large-scale model development

This year, Michael Celia and colleagues continued to develop their models and apply them to a number of potential injection sites. These models now predict pressure buildup in the formation, movement of both CO_2 and brine within the injection formation and across confining units into other formations, capillary trapping of CO_2, and dissolution of CO_2 into the brine phase (that is, solubility trapping – see Figure 15 for an example). In 2012, studies examined the impact of different modeling choices on practical simulations of CO_2 fate and transport and the limitations of the Vertical Equilibrium (VE) assumption. A range of models, including the VE models, were also applied to several sedimentary basins that have practical importance, including the Illinois Basin, the Michigan Basin, and the Alberta Basin, as well as the Basal Aquifer of central North America. These simulations have focused on very large-scale systems at scales of injection that can have an impact on the climate problem.

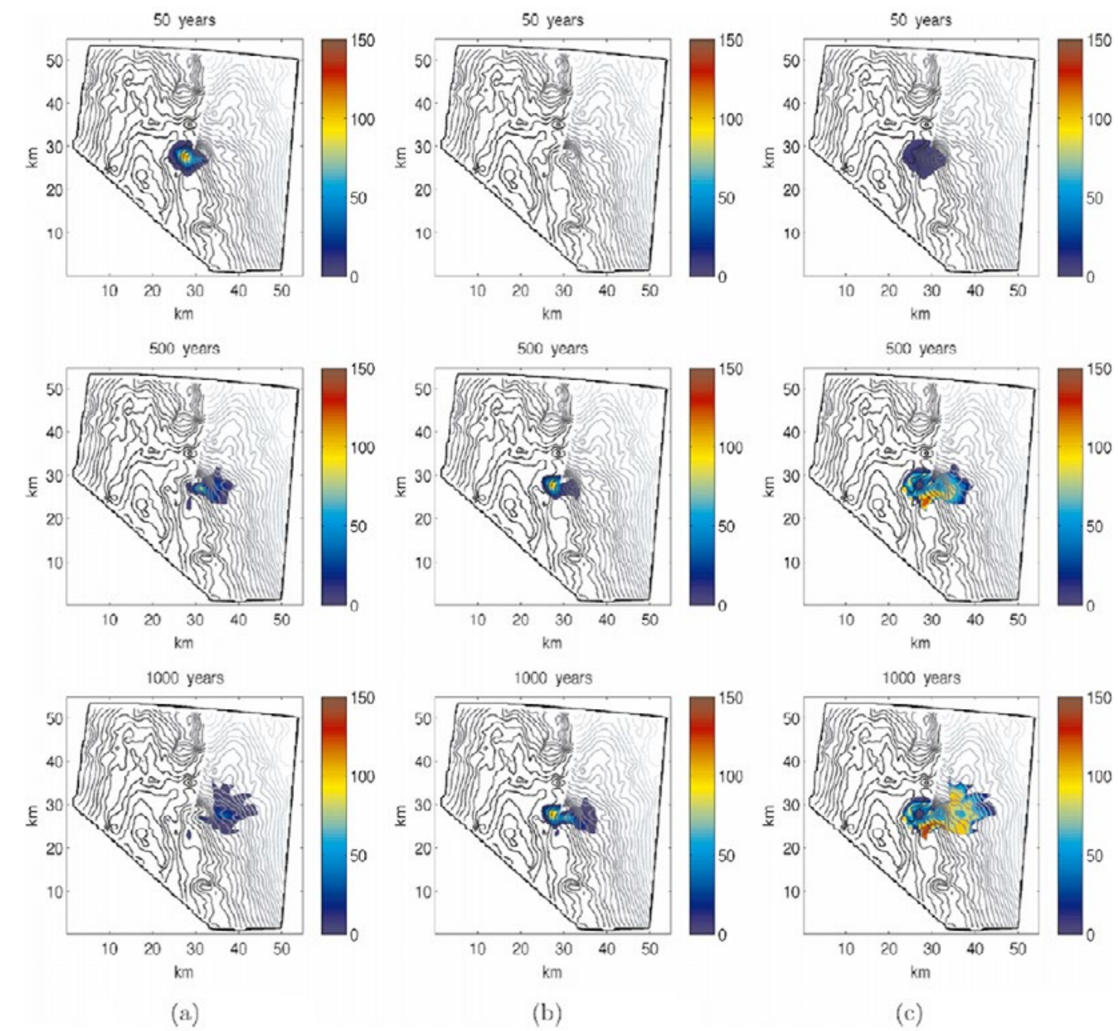

Figure 15: Model results of post-injection CO_2 migration in the Johanson formation off the coast of Norway. Shown are thickness, in meters, of (a) mobile CO_2, (b) residual CO_2, and (c) dissolved CO_2 at 50, 500, and 1000 years. Results were generated using our Vertical Equilibrium model that includes capillary trapping and convective mixing. Figure from Gasda et al. (2012a).

The researchers have also developed a model which eliminates the Vertical Equilibrium assumption while still maintaining its essential computational efficiency – that model is based on dynamic reconstruction of the vertical pressure and saturation profiles, in the context of multi-scale modeling. Development of VE models in the context of multi-scale analysis allows this extension – the idea is described in detail in their recent textbook, *Geological Storage of CO_2: Modeling Approaches for Large-scale Simulation*. The team is also developing a macro-scale percolation model with collaborators at Lawrence Berkeley National Laboratory. Collectively this suite of modeling approaches gives the group substantial flexibility in modeling different aspects of the CO_2 problem.

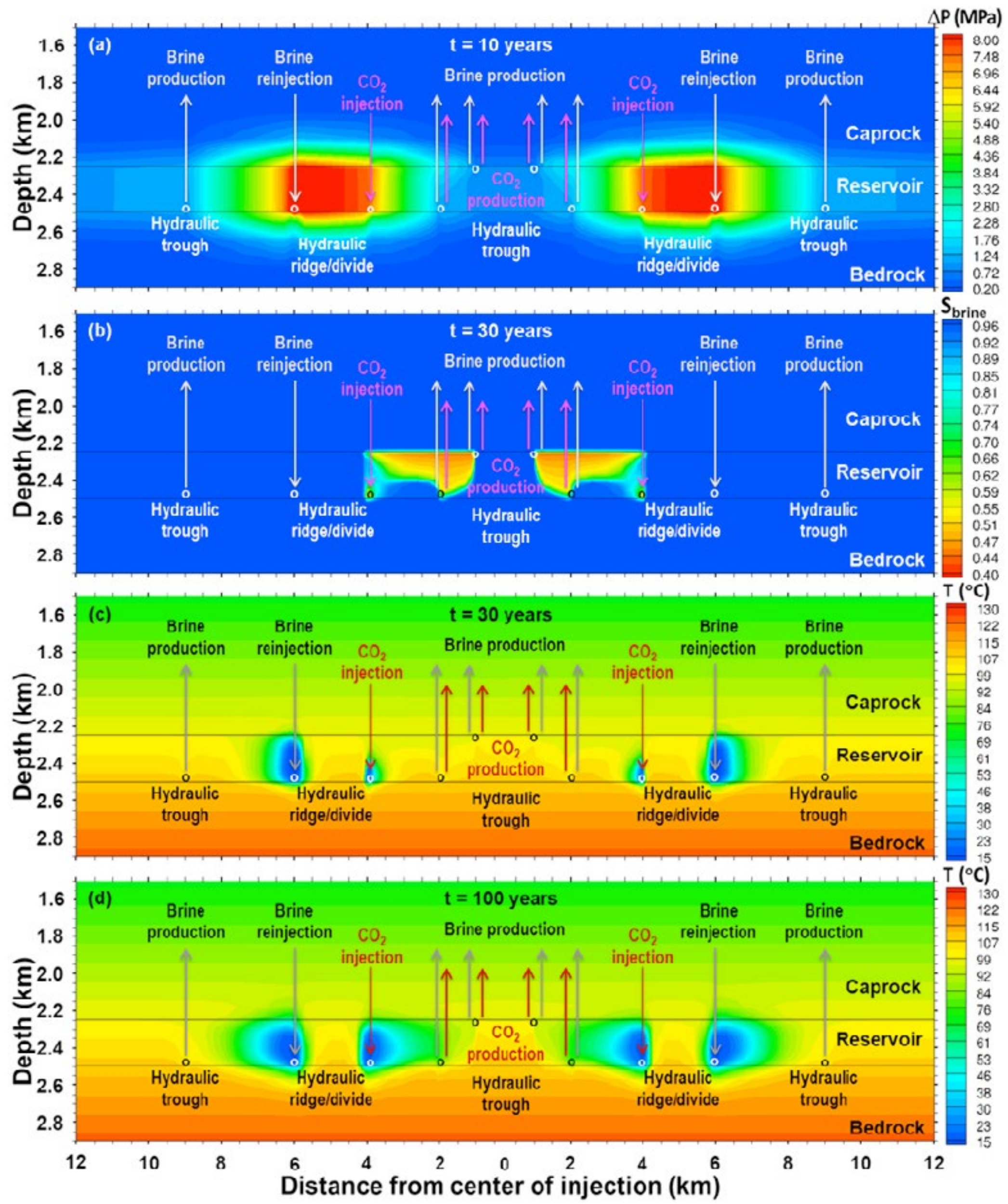

Figure 16: Five-ring pattern of horizontal wells for a reservoir with bottom depth of 2.5 km. (a) Overpressure at 10 years, (b) Brine saturation at 30 years, (c,d) Temperature at 30 and 100 years. Figure from Buscheck et al. (2013).

Active reservoir management and CO_2 utilization

Celia and colleagues also apply their models to consider ways to make carbon capture and storage more effective and economical. In a study of the potential advantages of brine production at CCS sites for the purpose of pressure control, the researchers found that brine production reduced pressure build-up at the CO_2 injection well, thus substantially reducing the Area of Review for given injections as well as the risk of leakage, while possibly enabling higher injectivity.

They have also looked more broadly at possible CO_2 utilization, in the context of Carbon Capture, Utilization, and Storage (CCUS). While produced brines can provide some benefits in terms of water usage, a potentially more important use is associated with heat extraction and the use of CO_2 in pressure support for geothermal production. In conjunction with collaborators at the Lawrence Livermore National Laboratory, they have investigated how a CO_2 injection operation could be integrated into a large-scale geothermal production system (Figure 16). As opposed to earlier studies, CO_2 is not used as the heat-carrying fluid, but instead the injection is used in a pressure support role and the resident hot brines are produced as the working fluid. Eventual CO_2 breakthrough in allowed and is accounted for in the overall analysis. The system may be promising in regions of the country with existing geothermal capacity.

Dynaflow: Injection-Scale Simulations

The **Prévost** group develops simulation tools that capture the effects of coupling between fluid flow, thermal and geomechanical effects. Since the inception of CMI, the group's Dynaflow model, which offers a modular, hierarchical approach for multiphysics simulations, has been adapted to simulate aquifer geochemistry and multiphase flow as well as to predict physical stresses induced by CO_2 injection. The model has recently been applied to study CO_2 injection impacts at BP's In Salah facility in Algeria.

Predicting length of fractures in caprock

The Dynaflow model has unique capabilities to simulate fluid flow fully coupled with thermal and geomechanical effects, allowing prediction of the stresses induced in the caprock by continuous injection of CO_2 in an aquifer. This year, the researchers showed that the temperature of injected CO_2 significantly affects these stresses. Particularly when CO_2 is injected at temperature 40-50°C below the ambient temperature, the stresses in the caprock become tensile and may overcome the tensile strength, causing fracturing of the caprock.

The initial length of fractures is relatively small. However, the team found that the fractures will propagate driven by the high fluid pressure in the aquifer. In collaboration with Howard Stone, Prévost and colleagues have developed an analytical model capable of predicting the resulting fracture length based on the pressure and stress data calculated by Dynaflow. They estimate the length of a hypothetical fracture at the In Salah site to be of the order of 25 – 35 m within 10 years after fracture initiation (Figure 17). On such a length scale there is a risk that a fracture may connect to a leaky fault and become a pathway for CO_2 leakage.

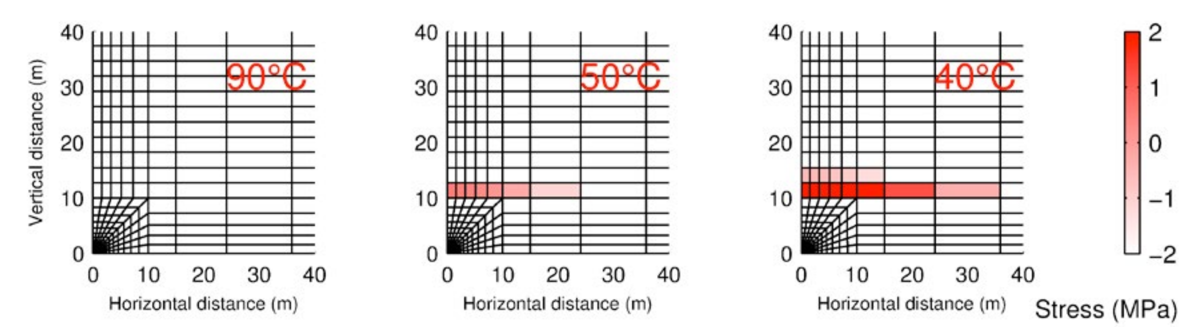

Figure 17. Effects of injection temperature on the longitudinal stresses in the caprock. Effective horizontal stresses in the aquifer and caprock around the injection well after 10 years of continuous injection of CO_2 at 90°C, 50°C and 40°C. (Ambient initial temperature=50°C; positive values correspond to tensile stresses.)

If a CO_2-brine mixture migrates upward, it reaches regions where the pressure and temperature are lower than that of the critical state. Therefore, the migrating mixture may start boiling. Current work is focused on implementing a flash calculations module for the CO_2-water system. Including such a module in Dynaflow will allow the modeling of the flow of the boiling mixture.

Bench-scale Experiments

Predicting the fate of CO_2 injected underground for carbon storage or enhanced oil recovery requires understanding physical processes associated with the underground rearrangement of a buoyant material. This raises new questions regarding multiphase flows in porous media, which the **Stone** group is investigating with a combination of bench-scale laboratory experiments and theory.

Inhibiting viscous fingering

In 2012, Howard Stone and colleagues completed an important study of viscous fingering in the presence of gradients of permeability in the direction of flow. The results were published in *Nature Physics* and also highlighted in *Physics Today.*

Using a modified Hele-Shaw cell, an experimental apparatus composed of two plates that are conventionally parallel, the team led by Talal Al-Housseiny simulated the displacement of a more viscous fluid by a less viscous fluid (analogous to water displacing oil) in a tapered channel. The researchers demonstrated that, though such an interface between these fluids is always unstable between parallel plates, a contracting geometry can stabilize the interface and allow the less-viscous fluid to "sweep" the more-viscous fluid more efficiently. Their results have implications for sweeping contaminants from sensors and cleaning of measuring devices used in applications, and also for enhanced oil recovery. The study suggests that to increase oil recovery in oil-wet reservoirs, injection and production wells might be positioned such that the sweep flow is driven in the direction of decreasing permeability or decreasing grain size to minimize viscous fingering and fluid breakthrough.

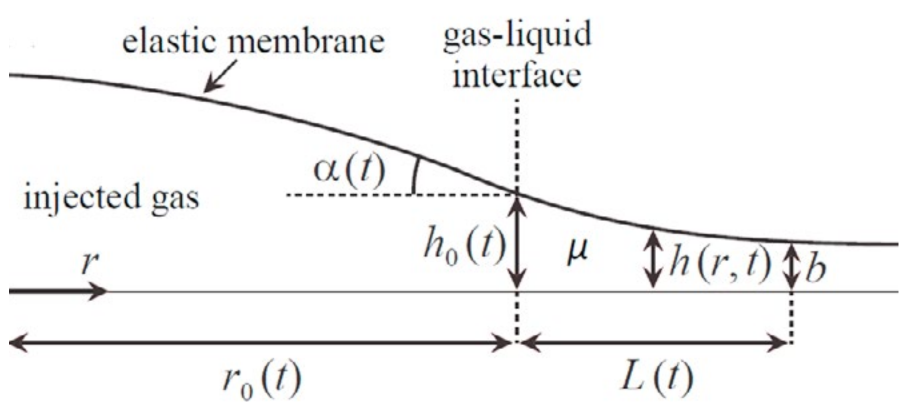

Figure 18. Schematic illustrating the injection of gas below a deformable boundary initially separated by a thin liquid film from a solid impermeable substrate. The injected gas pushes the liquid forward in the form of a plug while simultaneously deforming the upper surface.

Two-phase injection in deformable systems

Recent experimental work in the physics community has shown that the presence of an elastic boundary can also facilitate the suppression of viscous fingering. Since real materials in nature can deform when stressed, as in the case of two-phase injection processes, the Stone group has examined this phenomenon by studying fluid displacement underneath a flexible membrane. The researchers analyzed this two-phase flow and demonstrated how the deflection of the membrane and surface tension at the gas-liquid interface provide the mechanism of suppression (Figure 18), and also determined the corresponding critical conditions.

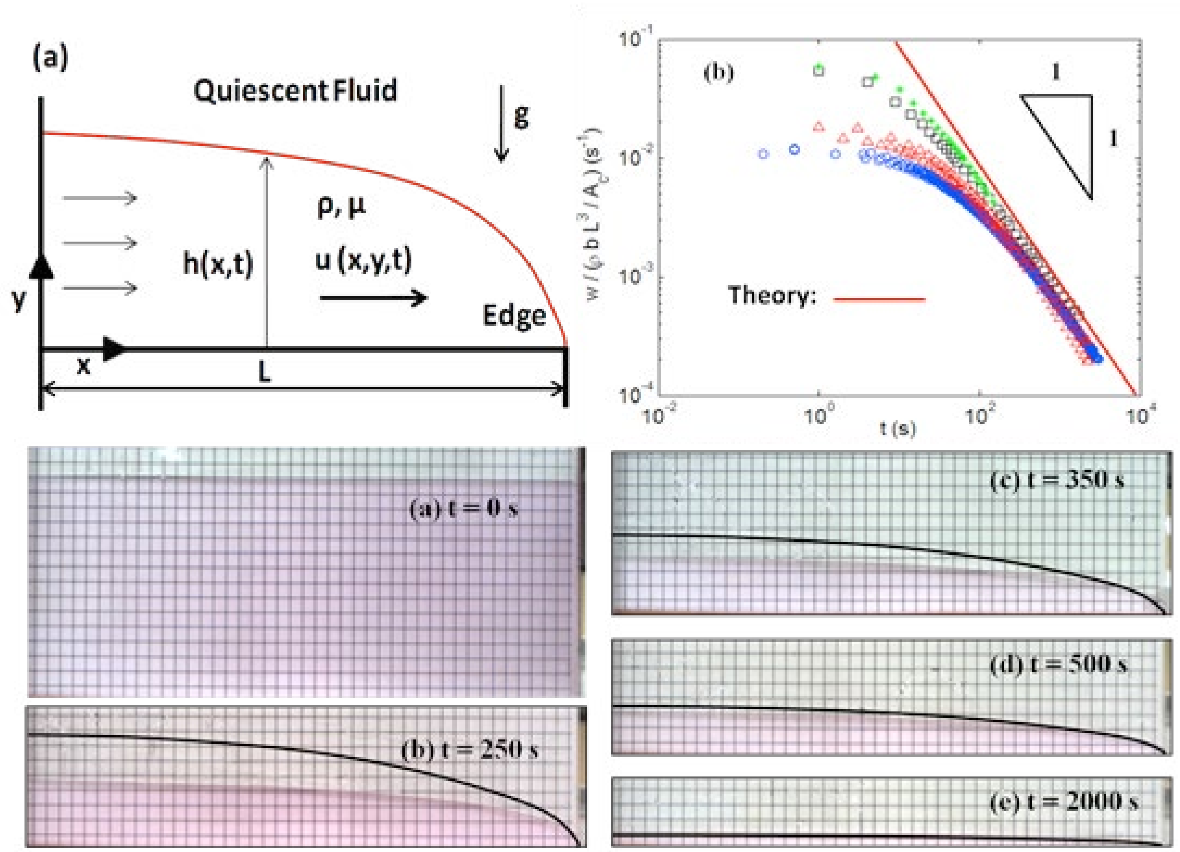

Figure 19: Top: a) Sketch of a gravity current draining from the edge of a model porous medium. (b) Comparison of the experimental results and the theoretical predictions for drainage from uniform Hele-Shaw cells. Experimental results: rescaled liquid mass remaining in a Hele-Shaw cell versus time. The solid line is the prediction (2.5) from the theoretical study, with no fitting parameters. The typical value of gap thickness b in the experiments is 5 mm.

Bottom: Images of a gravity current draining from a uniform Hele-Shaw cell, with comparisons between the experimental results and theoretical predictions (solid curve) for the shape, at various times: (a) t D 0 s; (b) t D 250 s; (c) t D 350 s; (d) t D 500 s; (e) t D 2000 s. In the late period, the self-similar solutions are seen to agree well with the experimental data. The liquid is pure glycerol, which is leaking from the right-hand edge of the cell after removal of a barrier. The grid has markings 1 cm apart.

Fluid escape from a reservoir

Studies of underground CO_2 storage require some understanding of possible failure modes, and the temporal and spatial rearrangements of the buoyant material in such cases. In order to describe fluid drainage behavior from porous media, Stone and colleagues have examined the fundamental problem of drainage from an edge, the extreme case when the vertical leakage pathway becomes infinitely permeable. Previous studies have only been theoretical, but this study used both theory and laboratory experiments in uniform Hele-Shaw cells and V-shaped cells to model gravity currents in both homogeneous reservoirs and those with varying permeability and porosity. In each case, a self-similar solution for the shape of these gravity currents was found and the mass remaining in the system is governed by power-law behavior. Measured profile shapes and the mass remaining in the cells agree well with model predictions (Figure 19). The study provides new insights into drainage processes that may occur in a variety of natural and industrial activities, including the geological storage of carbon dioxide.

Pore-Scale Models

In 2012, the **Celia** group continued to use pore-scale models to study additional issues relevant to CO_2 storage, investigating geochemically reactive systems, trapping, and hysteresis. The geochemical modeling work includes explicit modeling of both precipitation and dissolution, with the associated changes in porosity and permeability tracked as the reactions proceed. The researchers also identify conditions under which unique relationships between porosity and permeability should be expected.

Pore-scale models also provide new insights into how nonwetting fluids are trapped in porous media, including underlying mechanisms and the extent to which continuum-scale trapping functions are hysteretic or path-dependent. The hysteretic nature of all multi-phase constitutive functions can be carried from the small scale to the large scale; a study published this year shows how this can be done for Vertical Equilibrium models, and the conditions under which hysteresis may be important at the large scale.

Molecular Modeling

In 2010, a molecular modeling program was initiated within the Fluids & Energy Group. Pablo **Debenedetti,** Athanassios **Panagiotopoulos**, and Jeroen **Tromp** use molecular simulations to provide new insights into the behavior of CO_2 and methane in subsurface environments.

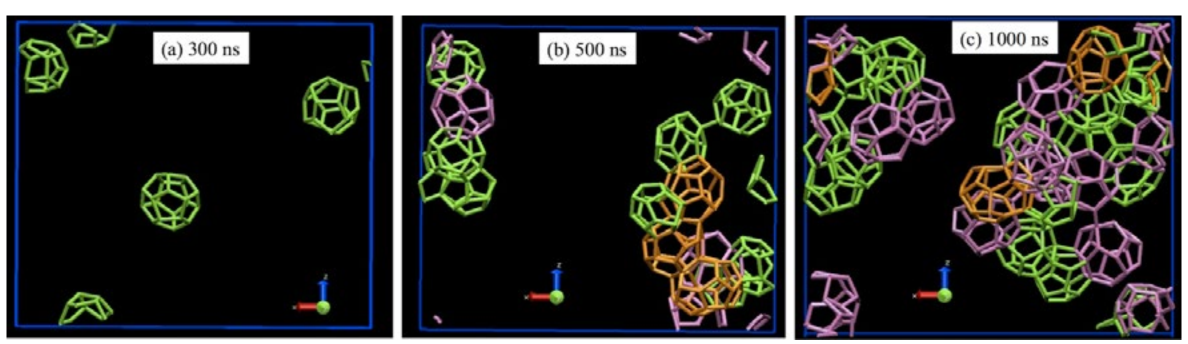

Figure 20: Snapshots depicting the formation of cages during the course of a molecular dynamics simulation of homogeneous nucleation of methane hydrate in water. For clarity, only the water molecules forming the cages are shown ("disordered" water and methane not shown). The cage color code is 5^{12} (green), $5^{12}6^2$ (purple), $5^{12}6^3$ (orange).

Molecular simulation of hydrate melting and formation

The Debenedetti group is using state-of-the-art molecular modeling tools to gain insights into the mechanisms and rates of melting and formation of carbon dioxide and methane hydrates, as well as on their thermodynamic stability across broad ranges of temperature, pressure and salinity. The studies are relevant to CO_2 sequestration (either in the solid form as a hydrate, or as pool of liquid CO_2 below a cap of its hydrate), gas storage and transportation, climate change, and ocean stability.

In 2012, the Debenedetti team performed microsecond-long molecular dynamics simulations of homogeneous nucleation of methane hydrate in bulk water, the first time that such nucleation had been simulated in the absence of an interface. The calculations yielded novel insights into the nucleation mechanism, such as the transient appearance of $5^{12}6^3$ (twelve pentagons and 3 hexagons per cage) and $5^{12}6^4$ cages (twelve pentagons and four hexagons), which are not found in structure I (sI) hydrates; and the aggregation of sub-critical clusters over time scales spanning hundreds of nanoseconds (Figure 20).

The solid phase present at the end of microsecond-long simulations lacks long-range order, however, and is characterized by a ratio of large ($5^{12}6^2$)-to-small (5^{12}) cages that is significantly smaller than observed experimentally in sI crystals (ca. 1 vs. 3). This indicates that long molecular dynamics simulations, though valuable for providing phenomenological insight into nucleation and melting mechanisms, need to be supplemented by path-sampling techniques in order to yield quantitative information on actual rates of hydrate formation. The implementation of such path-sampling simulations is the focus of our ongoing work, which is being done in collaboration with Athanassios Panagiotopoulos (see next section).

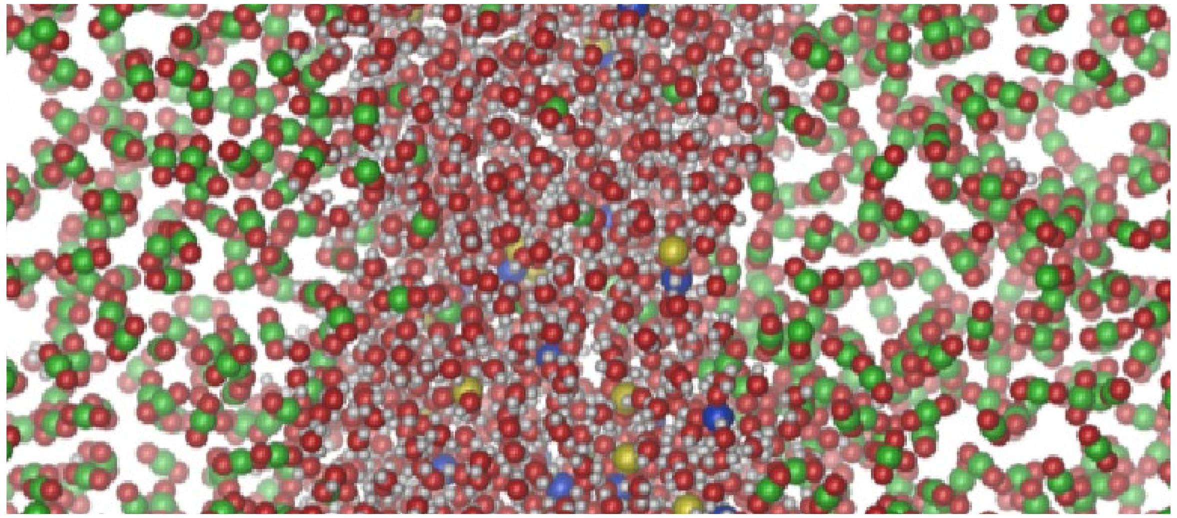

Figure 21: A snapshot from interfacial molecular dynamics simulations of the CO_2-H_2O-NaCl system. Na^+ (blue), Cl^- (yellow), C (green), H (white) and O (red) atoms are shown explicitly.

Molecular modeling of CO_2 capture and storage

In October 2011, a project was initiated within the Fluids & Energy group to develop molecular-based computational tools for predicting fundamental physicochemical characteristics required for understanding and rational design of CO_2 separation processes and long-term CO_2 storage in geological formations. This ongoing research is a collaboration between Athanassios Panagiotopoulos and Pablo Debenedetti, and Jeroen Tromp.

In the past year, the main focus of the project has been the use of atomistic simulations to obtain the phase behavior and interfacial tension of CO_2-H_2O-NaCl mixtures over a broad temperature and pressure range. The researchers demonstrated the applicability of interfacial molecular dynamics methods to the systems and properties of interest. Within the range of the temperature, pressure, salt concentration and system size in our study, they find no NaCl in the CO_2-rich phase at phase coexistence. The work also highlighted the limitations of the existing force fields with fixed-charged, additive pair interactions in predicting phase equilibrium and interfacial properties of the mixtures of interest, suggesting an urgent research need for their improvement.

A PhD student in Chemical and Biological Engineering, Arun Prabhu, was recruited in January of 2012 to work jointly with Professors Debenedetti and Panagiotopoulos in the general area of the CMI project. Arun's initial studies have focused on hydrate nucleation using bulk and interfacial molecular dynamics simulations, as detailed in Prof. Debenedetti's section on "Molecular simulation of hydrate melting and formation."

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Policy & Integration Group

The objective of the Policy & Integration Program is to bring new thinking into policy formulation and to communicate the policy relevance of CMI research. The faculty members involved are Co-Directors **Steve Pacala** & **Rob Socolow**, **Alex Glaser, Michael Oppenheimer**, and **M.V. Ramana**.

This year the group has continued its efforts to assess the potential of mitigation strategies and educate policy-makers and the public, while seeking to "restart" the discussion on carbon mitigation strategies.

Highlights

Assessing mitigation options

- Continued efforts were made to engage various stakeholders (via meetings, presentations, and publications) in the debate over carbon dioxide removal from the atmosphere and to educate the public about such negative emissions strategies.
- Findings from a project on small modular nuclear reactors indicates that the reactors would require enhanced safeguards and novel fuel-cycle architectures to avoid a higher proliferation risk than current gigawatt-scale reactors.

Communicating climate change risks

- An article in the *Vanderbilt Law Review* urges the environmental community to "restart" the carbon and climate debate by communicating hard truths to the public and framing mitigation as a risk management issue.
- Several CMI members have authored an open letter to President Obama urging quick action on climate change to move back the hands of the "Doomsday Clock."
- A new framework being is being developed to provide a global map of the local probability distribution of ice-sheet driven sea level rise.

Outreach

- The stabilization wedges concept continues to be widely used in courses and textbooks, and a new LEGO model is being developed as an educational tool for schoolchildren in the Midwest.
- Work continues on enabling the development of open-source energy models, with a particular focus on a low-carbon growth strategy for India.
- CMI has continued its close relationship with Climate Central, which may be strengthened by the group's partnership in a proposed NSF Science & Technology Center to be led by Jorge Sarmiento of the Science Group.

Assessing Mitigation Options

Robert Socolow, Alexander Glaser, and **M.V. Ramana** have led efforts to assess the challenges and benefits of negative emissions strategies and new nuclear technologies.

Prospects for direct air capture of CO_2

A major focus of Robert Socolow and colleagues in 2012 was bridging the gaps between various stakeholders in the debate over the mitigation potential of carbon dioxide removal (CDR) from the atmosphere. The previous year's publication of an American Physical Society Report co-chaired by Socolow and BP's Michael Desmond suggested that air capture costs would be ~\$600/ton CO_2, much higher than previously suggested by CDR proponents. In a paper written with report co-authors Marco Mazzotti and Renato Baciocchi, Socolow and Desmond this year updated the cost estimate using an optimized design, but costs were reduced by only 7%. In light of these findings, Socolow attended a meeting of major players in the field of air capture in March and emphasized that CDR will only make sense after the majority of large-scale CO_2 sources have been decarbonized, and encouraged participants not to allow audiences to infer that humanity can "solve" climate change while being relaxed about fossil fuels

Socolow and Massimo Tavoni were also instrumental in assembling a compendium of papers on CDR strategies that will be published as a special issue of Climatic Change edited by Michael Oppenheimer. The issue provides an original and self-contained assessment of the role of negative emissions by bringing together leaders of the integrated assessment community with experts on technology, natural science, and political science. Socolow and Tavoni wrote the introductory article for the issue, and worked with the journal to make it available to the public free of charge.

Re-engineering the nuclear future

Two years after the Fukushima accident, many countries around the world continue to consider an increasing role for nuclear power. An important component in future nuclear installations will likely be a new generation of small modular reactors (SMRs), with power outputs of 100 to 300 MW_e, being developed in several countries. These reactors are expected to cost significantly less than current gigawatt-scale reactors and thereby address some of the economic challenges faced by utilities interested in constructing nuclear power plants.

The main focus during the past year of the *Re-engineering the Nuclear Future* project led by Alexander Glaser and M. V. Ramana has been to estimate resource requirements, waste generation, and proliferation risks associated with SMRs of different kinds relative to current light-water reactors. Their computer simulations show that SMRs based on light-water reactor technologies have a significantly higher uranium and enrichment demand, which could affect fuel-cycle choices in some countries. In contrast, SMRs with long-lived cores based on fast neutrons have substantially lower uranium and enrichment demand, and produce a smaller volume of waste relative to both conventional and small light water reactors. However, all SMRs examined so far produce substantially greater amounts of plutonium per MWh of electrical energy generated than conventional reactors.

Due to the larger amounts of plutonium generated, the results of a probabilistic model of proliferation applied to SMRs suggest that if a fleet of SMRs is deployed with the same efficiency of safeguards, it

would have a somewhat increased proliferation risk compared to a fleet of gigawatt-scale reactors generating the same electric power. This finding highlights the importance of "safeguards-friendly" design choices for SMRs and, ideally, new fuel-cycle architectures to reduce these risks.

	Standard LWR (50 MWd/kg)	iPWR (30 MWd/kg)	LLC SMR (fast spectrum, once-through)
Uranium requirements (to make fuel)	6200 tons (reference)	10320 tons (67% increase)	2910 tons (53% reduction)
Fuel demand	540 tons (5%-enriched fuel)	900 tons (5%-enriched fuel)	102 tons (12%-enriched starter fuel)
Enrichment	3.90 million SWU (reference)	6.48 million SWU (67% increase)	2.19 million SWU (44% reduction)
Plutonium inventory in spent fuel	6.5 tons (12 kg per ton of fuel)	9.0 tons (10 kg per ton of fuel)	14.0 tons (69 kg per ton of fuel)
Waste volume	540 tons (reference)	900 tons (67% increase)	204 tons (38% reduction)

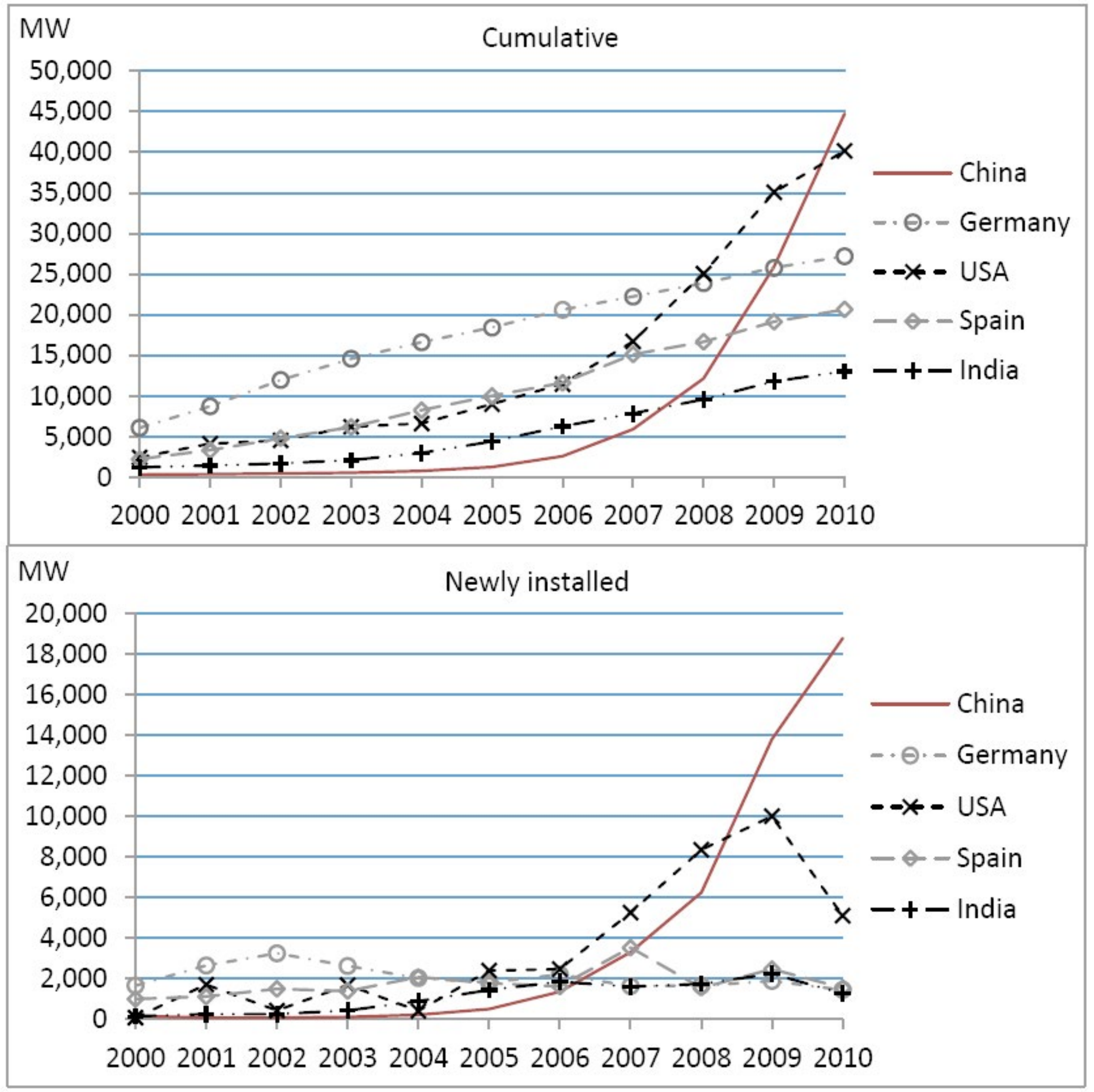
Figure 22. Basic resource and fuel requirements for a currently standard light-water reactor (1000 MW(e)), five small modular LWRs (iPWRs, 200 MW(e) each), and five notional SMRs (200 MW(e) each) with long-lived cores. Significant differences to the reference case are highlighted (increases in red, reductions in green). All numbers are scaled to a power generation of 1000 MW(e) for 9000 effective full-power days (e.g. 30 years, 300 days per year).

Glaser and Ramana have been involved in analyzing several policy issues for SMR licensing critical to determining the economic viability of these reactors, including security requirements, insurance and liability arrangements, and the size of the emergency planning zone. In future work, they will be analyzing the concern that the promised safety enhancements in SMR designs could be "offset" by a simultaneous relaxation of licensing requirements, e.g., by siting SMRs closer to urban areas.

As part of the *Re-engineering the Nuclear Future* project, the researchers are also engaging students on research related to the project. Edward McClamrock (MAE, Class of 2013) is writing his Senior Thesis on Molten Salt Reactors and the potential of thorium fuel, which has been considered as an alternative to uranium because it is much more abundant. Similarly, as a recipient of a PEI/STEP fellowship, David Turnbull (PhD candidate, MAE) examined the "option value" of fusion energy for low-carbon energy scenarios. We are collecting these results to make them available to a broader audience on our website dedicated to the *Re-engineering the Nuclear Future* project (http://nuclearfutures.princeton.edu/).

Wind catch-up in China

Working with Robert Socolow, Nicolas Lefevre has completed a Ph.D. thesis on technological "catch up" as illustrated by the rise of the Chinese wind turbine industry. Lefevre's hypothesis is that firms in a developing country can develop the capability to compete at a global technological frontier previously dominated by industrialized country firms, provided the developing country enables its domestic firms to pursue coherent and long-term strategies and provided the frontier is not evolving especially rapidly. The thesis zeroes in on the windpower industry in China, where the catch-up process is nearly complete (Figure 23). Firm-level analysis for Chinese windpower developers reveals rapid passage from an initial period of learning from western firms to a period of strong government support for dramatic expansion into large domestic markets. At the same time, the wind power frontier was evolving relatively slowly due to limited early support from the governments of industrialized countries, which facilitated the process of technological catch-up by Chinese firms.



Note: Data from Alternative Energy e-Track[43]

Figure 23. Cumulative and incremental installed wind power capacity by country from Lefevre (2013).

Communicating Climate Risks

The **Socolow** and **Oppenheimer** groups are working to re-energize climate discussions by suggesting new strategies for climate communication and providing descriptions of climate risks relevant to policymakers.

Hard truths of managing climate change

In 2011, Robert Socolow authored an article entitled "Wedges Reaffirmed" that called for a shift in communication strategy by the environmental community to motivate action on carbon mitigation. This year, Socolow continued that theme in an article in the *Vanderbilt Law Review* entitled "Truths We Must Tell Ourselves to Manage Climate Change," which encouraged environmentalists to find "restart buttons" for the climate dialogue by changing the conversation. Socolow advocates for communicating some hard truths to the public about carbon and climate by acknowledging that:

- climate change is "unwelcome news" and that tackling the problem will require a huge effort by the planet's citizens;
- there is still considerable uncertainty in climate projections;
- the risk of climate change must be balanced with the risk of disruption from mitigation; and
- a 2°C target may not be attainable.

Socolow argues that the public is sophisticated enough to understand climate change problem as a risk management problem, and that is up to the environmental community to convey the magnitude of potential climate risks and make the case for global participation in the solution.

Bulletin letter to President Obama

CMI-associated faculty members Alexander Glaser, M.V. Ramana, and Robert Socolow serve on the Science and Security Board of the Bulletin of the Atomic Scientists. In January 2013, the Board authored an open letter to President Barack Obama regarding this year's setting of the Bulletin's "Doomsday Clock." Originally conceived to highlight the dangers of nuclear weapons, the assessment now also encompasses "climate-changing technologies and new developments in the life sciences that could inflict irrevocable harm."

After moving the hands of the clock back one minute following the first year of President Barack Obama's presidency (to six minutes before midnight), the Society has since moved the hands forward one minute and this year they remain in that position. In addition to urging the President to mitigate nuclear risks, the authors urged President Obama to make climate change a high priority; specifically, to work to forge an international response to climate change, ensure natural gas is exploited in an environmentally safe manner, promote carbon capture and storage, and clear barriers to renewables expansion.

Socolow, Chair of the Science and Security Board, noted, "We have as much hope for Obama's second term in office as we did in 2010, when we moved back the hand of the Clock after his first year in office. This is the year for U.S. leadership in slowing climate change and setting a path toward a world without nuclear weapons."

Assessing risk from sea level rise

Current continental-scale models of the Greenland and Antarctic ice sheets do not adequately represent the physical processes underlying rapid, climate-driven dynamic ice loss, and are thus insufficient to project the ice sheet contribution to sea level rise. To improve predictions of future sea-level change, Chris Little and Michael Oppenheimer have focused on improving ice sheet models and developing sea level projections that are more conducive to a risk management approach.

To this end, the researchers have developed a "bottom-up" approach to projecting sea level change. Applying a Bayesian probabilistic framework to the Antarctic ice sheet (Figure 24), they have transformed disparate sources of information constraining future ice sheet behavior into probability distributions. This novel methodology allows a consistent comparison with other projection techniques and also resolves the quantitative impact of key physical uncertainties, clarifying observational and numerical modeling research priorities.

This year, the group will extend this framework to include: 1) changes in the Greenland ice sheet mass balance; 2) the solid earth and gravitational response that modulate sea level changes at the local level; and 3) new constraints from process-based ice sheet models, smaller-scale observations of ice loss, paleo-sea-level observations, and expert judgment. These extensions will allow the development of a global map of the local probability distribution of ice-sheet driven sea level rise, facilitating the assessment of sea-level rise alongside other climate-related risks.

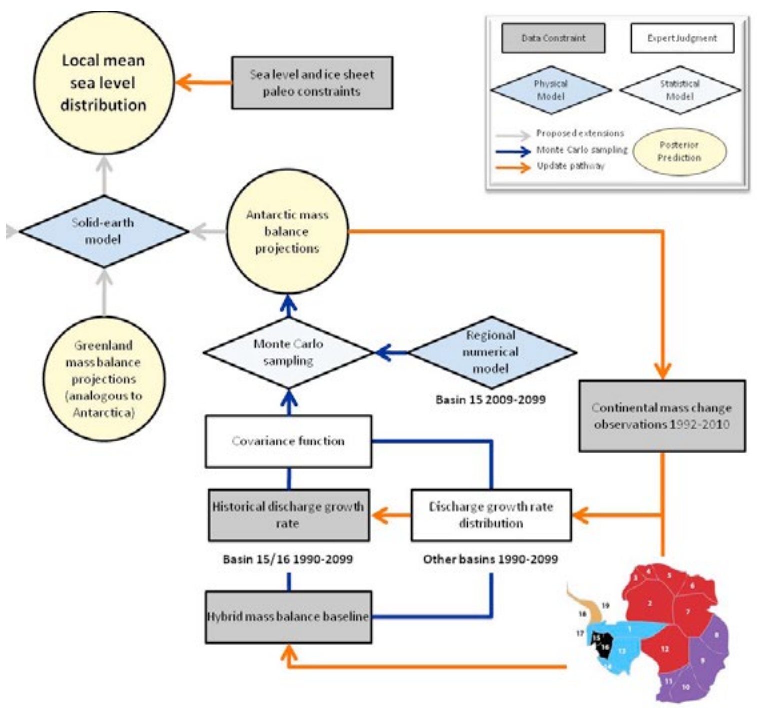


Figure 24: A schematic illustration of the methodology used to generate mass balance projections for Antarctica in Little et al 2013b, and extensions as proposed here (grey arrows). Boxes indicate prior assumptions, diamonds indicate physical or statistical models used to convert prior assumptions into posterior SLR projections, and ovals indicate projections of sea level components. Orange arrows indicate data sources available to update projections; other sources of information may also be integrated. The inset map of Antarctica shows the 18 drainage basins for which mass balance projections are calculated in Little et al 2013b. Basins with a common color experience correlated mass balance trends.

Policy-Relevant Tools for Education and Research

In 2012 CMI continued its commitment to providing the public with tools for understanding climate change and options for reduction of carbon emissions.

Stabilization Wedges

The stabilization wedges concept for cutting carbon emissions remains a popular tool in the environmental and education communities. Roberta Hotinski continues to field dozens of questions from educators at all levels interested in using the wedges game in their courses, and wedges graphics appeared in 7 textbooks in 2012, as well as in Sierra Magazine and the Orange County Register.

In one of the most innovative applications of the wedges we've heard of, Brian Alano, an engineer and member of the Indiana group Greenfield LEGO User Education, is constructing a time-dynamic interactive simulation of the wedges concept out of LEGO elements. The goal is to simulate emissions as a flow rate of LEGO soccer balls, and to allow participants to select mitigation policies each year which reduce or direct emissions away from the atmosphere. With feedback from Hotinski, Alano has created an Excel model of carbon flows for the simulation and constructed modules for a coal power plant, a cloud (representing atmospheric CO_2), and land and ocean carbon sinks that were displayed at Brickworld 2013 in Chicago.

Alano plans to finish the prototype by June this year, play-test it throughout the summer, and have a full-scale model complete by the end of the calendar year. In addition to showing the model as an interactive display at LEGO exhibitions, he plans to take the wedges simulation into schools to empower kids to act against rapid climate change and to encourage them to be engineers--a profession whose skills are vital to mitigating climate change and its effects.

Open-source energy-economics models

Another focus of the Policy & Integration Group has been the development of energy-economics models for use by the wider community. Shoibal Chakravarty has combined a number of various open source software tools to create a platform for fast and collaborative development of energy-economics models. The model is written in the open-source and popular programming language Python, using mathematical modeling software from the COOPR project (https://software.sandia.gov/trac/coopr). The models can be solved using solvers from COIN-OR (http://www.coin-or.org/) project of the Operations Research community. Chakravarty and colleagues are developing a web-based user interface for interactive data input and graphical data output from the model runs. The goal is to make it easy to rapidly prototype, develop and collaborate on such topics across various computing platforms. A web based interface can be used on all computers - Windows, Linux or Mac. Publishing model runs and results on the web can also become automatic.

One short term goal of the project is to collaboratively develop an energy-economics model for a low carbon growth strategy for India. This will be developed in an open online collaboration with energy experts in India.

Policy & Integration

Climate Central

CMI continues to have close ties with Climate Central, a non-profit organization in Princeton dedicated to providing the public and policy-makers with clear and objective information on climate change trends and impacts. Steve Pacala and Michael Oppenheimer serve on the board of Climate Central (CC), Eric Larson of the Low-Carbon Energy group works at CC part-time, and CMI researchers have both advised the group and served as topics of the organization's stories. A new tie has also been forged between Princeton and CC over the last year as Heidi Cullen, CC's Chief Climatologist, has worked with the CMI Science Group's Jorge Sarmiento on the education and outreach component of a proposal for a Center for Southern Ocean Biogeochemical Observations and Modeling (see summary in the Carbon Science Group section, p. 14). A video produced for the proposal site visit is already gaining attention, raising the profile of the Southern Ocean's role in climate and the carbon cycle and generating excitement over the robotic observing system proposed.

Figure 25: Brian Alano with his preliminary model at the Greenfield Brick Expo in January, 2013. Credit: Bruce Nelson.

Policy & Integration Publications

Glaser, A., L. B. Hopkins and M. V. Ramana. "Resource Requirements and Proliferation Risks Associated with Small Modular Reactors." *Nuclear Technology.* Forthcoming, 2013.

Little, C., M. Oppenheimer, N.M. Urban. "Upper bounds on 21st century Antarctic ice loss assessed using a probabilistic framework." *Nature Climate Change.* In press. 2013.

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