Carbon Mitigation Initiative

Third Year Review Report

January 2004
A Letter from the Co-Directors

The ten-year Carbon Mitigation Initiative (CMI) at Princeton University is concluding its third year. Over the first three years we have rooted CMI in four areas of the campus, achieving substantial commitment from faculty, staff, and students. From an initial group of fewer than 20 researchers, CMI has increased its ranks to include 60 investigators. We have built new labs and office space, expanded into new research areas, and developed new relationships with other institutions.

In this, our third annual report, we review our accomplishments, take stock of our program, and spell out our vision for the future. We evaluate how far we’ve come on the path toward finding a climate “solution,” and discuss how we propose to move forward.

We have made considerable progress on our original goals. The Capture Group has evaluated a variety of energy production technologies that could reduce global carbon emissions, and their research is influencing policy in the United States and in China. The Storage Group, having determined that leakage from abandoned wells could impact the effectiveness of CO₂ storage in deep aquifers, is embarking on a new research plan to assess the magnitude of this effect. The Science Group has assessed natural land and ocean sinks as well as strategies for deliberately storing carbon in the natural environment, and new work has identified unforeseen impacts of reforestation and renewable energy production. The Policy Group has modified well-known economic models to incorporate non-linear outcomes identified by climatologists, and has developed a model for emissions trading that may provide a flexible framework for global decreases in greenhouse gas emissions.

In the past year, we have increased our effort to integrate the knowledge possessed by our disparate groups into a coherent picture of what would be required to stabilize atmospheric CO₂ at levels toward the low end of the range usually considered. In the absence of CO₂ controls, emissions of carbon dioxide are commonly projected to double by 2050 due to a global increase in energy demand. Instead, suppose CO₂ emissions were to be no higher in 2050 than today. We are evaluating existing low-carbon technologies that in various combinations could achieve that objective. In the politically charged global discussion of stabilization goals, we are trying to inject a more pragmatic focus on stabilization tools.

In the near future, our major projects will include: engineering studies of the competition among coal, natural gas, and biomass as primary sources for electricity, hydrogen, and synthetic fuels; laboratory studies of changes in cement integrity that will affect CO₂ leakage rates from geological formations; a new software system linking carbon-cycle models with observational data; and studies, using integrated assessment models, of the costs of cutting emissions deeply using a variety of technologies and fiscal incentives. Our integrative activity will sharpen our message that significant carbon management is feasible through the commercialization of existing technologies. And a new outreach effort will allow us to expand our communication with academic and industry colleagues, policymakers, and the general public.

CMI is breaking new ground in the carbon and climate debate by coordinating research in science, technology, and policy to find paths toward a stable climate. We believe we are off to a promising start and look forward to another seven years of progress.

Steve Pacala and Rob Socolow
CMI Co-Directors
CMI: An Overview

If all the world’s coal, oil, gas, and other fossil fuels reserves were burned and the carbon they contain were released to the atmosphere, then atmospheric carbon dioxide (CO₂) levels would reach levels five to ten times higher than today’s. Such high levels of this greenhouse gas would lead to dramatic and damaging climate change. This prospect has prompted many people in the scientific, governmental, corporate, and non-profit communities to call for early action to reduce future CO₂ emissions.

The Carbon Mitigation Initiative is a 10-year, 20 million dollar program jointly funded by BP and Ford that seeks solutions to the CO₂ problem. The goals of this university-industry partnership are to determine

- the size of emissions reductions needed to stabilize atmospheric CO₂ at a safe level
- the feasibility of emission reduction strategies
- the impacts (both positive and negative) of mitigation programs
- the cost of proposed emissions reductions
- the effectiveness of proposed policies for encouraging emissions cuts.

The program officially started in January 2001 and is led by Co-Directors Steve Pacala and Rob Socolow. The CMI is comprised of five teams:

- The Capture Group, led by Bob Williams, focuses on low-emissions options for generating electricity and producing fuels, the logistics of distributing energy to the public, and hydrogen combustion and safety.

- The Storage Group, led by Mike Celia, investigates the short- and long-term fate of CO₂ injected into underground reservoirs using both numerical and experimental methods.

- The Science Group, led by Jorge Sarmiento, concentrates on the global carbon cycle and climate system. The group estimates how the sizes of natural sources and sinks for carbon will change with time.

- The Policy Group, led by David Bradford and Michael Oppenheimer, studies the costs and benefits of carbon mitigation and potential policies for achieving cost-effective mitigation.

- The Integrative Activity, led by Pacala and Socolow, provides coordination, attacks cross-cutting problems, and communicates results to the wider community.

The group has grown to include over 60 university researchers, including 17 faculty members in six departments. The CMI team now also includes 18 professional research and technical staff members, 13 postdocs, and 13 graduate students.

CMI research benefits from interaction with our corporate sponsors, but the research initiatives of the program are investigator-driven.
Research Highlights for 2003

New results are helping to define the size of emissions reductions needed to stabilize atmospheric CO₂, and to assess technologies and fiscal incentives that will lead to a low-carbon economy

Capture – Lowering CO₂ emissions

- New modeling results indicate that facilities coproducing clean carbon-based synfuels, electricity, and hydrogen from coal could offer a bridge to the hydrogen economy while facilitating early carbon capture and storage actions.

- A study of hydrogen infrastructure requirements describes the rate at which central station hydrogen generation could provide the fuel for fuel cell vehicles in urban areas.

- Doping hydrogen fuels with hydrocarbon gases could reduce problems with “knock” in hydrogen-fueled internal combustion engines and decrease the potential for explosion in storage.

Storage – Sequestering CO₂

- Analytical solutions have been developed for determining the characteristics of CO₂ injection plumes, and to estimate leakage rates through abandoned wells, much faster than complex numerical simulators.

- Novel experiments to assess the potential for cement failure in wells and subsequent leakage from storage reservoirs are underway.

- Geochemical experiments have shown that pressure has only minimal effects on mineral dissolution rates in deep aquifers, which will simplify simulation of the fate of CO₂.

Science – Determining Sources & Sinks

- New observational and data-based estimates of terrestrial and ocean carbon sink size and variability confirm previous estimates and are reducing uncertainty in carbon cycle processes.

- New data indicate that polar oceans were stratified during the last glacial period, supporting the hypothesis that decreased evasion of CO₂ from the deep ocean had a cooling influence on climate.

- Data from polar oceans provide the first evidence that natural iron variations produce changes in marine biological productivity, possibly influencing CO₂ uptake.

- A new state-of-the-art climate model has been completed and is running initial simulations.

- Analysis of Wisconsin forests sampled since the 1960’s indicate growth rates have decreased with rising CO₂ levels, undermining the theory that carbon dioxide’s fertilizing effect on land plants will increase CO₂ uptake in the future.

Policy – Economics of Mitigation

- New economic analyses indicate that delaying mitigation of CO₂ emissions by decades could make avoiding specific climate thresholds prohibitively expensive.

- Experiments with a number of integrated assessment models have been initiated to estimate the costs of stabilizing atmospheric CO₂ levels at less than twice the preindustrial level.
### CMI Members 2001-2003 (alphabetical)

<table>
<thead>
<tr>
<th>The Capture Group</th>
<th>The Science Group</th>
<th>The Integration Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leader: Robert Williams</td>
<td>Leader: Jorge Sarmiento</td>
<td>Leaders: Stephen W. Pacala and Robert H. Socolow</td>
</tr>
<tr>
<td>Stefano Consonni</td>
<td>Brian Arbic</td>
<td>Roberta Hotinski</td>
</tr>
<tr>
<td>Luca De Lorenzo</td>
<td>Somnath Baidya Roy</td>
<td>Ranveig Jakobsen</td>
</tr>
<tr>
<td>David Denkenberger</td>
<td>Michael Bender</td>
<td>Elaine Kozinsky</td>
</tr>
<tr>
<td>Yiguang Ju</td>
<td>Curtis Deutch</td>
<td>Stephen W. Pacala</td>
</tr>
<tr>
<td>Thomas Kreutz</td>
<td>Gregory Cane</td>
<td>Robert H. Socolow</td>
</tr>
<tr>
<td>Eric Larson</td>
<td>Saender Clark</td>
<td></td>
</tr>
<tr>
<td>C. K. Law</td>
<td>Sarah Gasda</td>
<td></td>
</tr>
<tr>
<td>Joan Ogden (U.C. Davis)</td>
<td>Jeffery B. Greenblatt</td>
<td></td>
</tr>
<tr>
<td>Robert Socolow</td>
<td>Axel Haenssen</td>
<td></td>
</tr>
<tr>
<td>Samir Succar</td>
<td>Andrew R. Jacobson</td>
<td></td>
</tr>
<tr>
<td>Robert J. Vanderbei</td>
<td>Ants Leetmaa</td>
<td></td>
</tr>
<tr>
<td>Federico Vigano</td>
<td>Sergey Malyshev</td>
<td></td>
</tr>
<tr>
<td>Wei Wang</td>
<td>Irina Marinov</td>
<td></td>
</tr>
<tr>
<td>Robert Williams</td>
<td>Galen McKinley</td>
<td></td>
</tr>
<tr>
<td>Yuan Xue</td>
<td>Bryan Mignone</td>
<td></td>
</tr>
<tr>
<td>Jiao Yuan</td>
<td>Francois Morel</td>
<td></td>
</tr>
<tr>
<td>Delin Zhu</td>
<td>Satish Myneni</td>
<td></td>
</tr>
<tr>
<td>Alumni</td>
<td>Vaishali Naik</td>
<td></td>
</tr>
<tr>
<td>Hande Y. Benson</td>
<td>Stephanie W. Pacala</td>
<td></td>
</tr>
<tr>
<td>Chen Chao</td>
<td>Drew Purves</td>
<td></td>
</tr>
<tr>
<td>Paolo Chiesa</td>
<td>Matthew Reuer</td>
<td></td>
</tr>
<tr>
<td>Oh Chae Kwon</td>
<td>Jorge Sarmiento</td>
<td></td>
</tr>
<tr>
<td>Zheng Li</td>
<td>Patrick Schultz</td>
<td></td>
</tr>
<tr>
<td>Gao Qing (Max) Lu</td>
<td>Linda Seltzer</td>
<td></td>
</tr>
<tr>
<td>Tingjin Ren</td>
<td>Elena Shevliakova</td>
<td></td>
</tr>
<tr>
<td>Christopher Yang</td>
<td>Daniel Sigman</td>
<td></td>
</tr>
<tr>
<td>The Storage Group</td>
<td>Jennifer Simeon</td>
<td></td>
</tr>
<tr>
<td>Leader: Michael Celia</td>
<td>Blake Sturtevant</td>
<td></td>
</tr>
<tr>
<td>Andrew Altevogt</td>
<td>Chris Weaver</td>
<td></td>
</tr>
<tr>
<td>Stefan Bachu</td>
<td>Gustavo Zea</td>
<td></td>
</tr>
<tr>
<td>Robert G. Bruant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Michael Celia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Andrew Duguid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sarah Gasda</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peter R. Jaffé</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li Li</td>
<td></td>
<td></td>
</tr>
<tr>
<td>David Luet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Catherine Peters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jean-Herve Prévost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Michael Puma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mileva Radonjic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>George Scherer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alumni</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daniel Giammar</td>
<td>John Caspersen</td>
<td></td>
</tr>
<tr>
<td>Andrew Guswa</td>
<td>David Ho</td>
<td></td>
</tr>
<tr>
<td>Philippe Pebay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sookyun Wang</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The Policy Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaders: David Bradford &amp; Michael Oppenheimer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>David Bradford</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simon Donner</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Klaus Keller (Penn State)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seung-Rae Kim</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yun Li</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dong-Hal Min (Penn State)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eric Naevdal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Michael Oppenheimer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avneet Singh (Penn State)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Martin Wagner</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The First Three Years
CMI Research Results
2001-2003
The Capture Group

The goal of the capture group, in collaboration with researchers at Tsinghua University (see Box 1) and the Politecnico di Milano (see Box 2), is to assess the feasibility of and potential technology costs for bringing about a low-carbon energy economy.

Production of Hydrogen and Electricity with CO2 Capture

A major focus of the capture group, in collaboration with colleagues at the Politecnico di Milano, has been to examine how fossil fuels - primarily coal and natural gas - can be converted to hydrogen and electricity (both carbon-free energy carriers) with CO2 capture and storage (CCS). This involves chemical conversion of the fuel into a synthesis gas (or “syngas”), followed by a separation process in which CO2 and hydrogen are selectively removed from the syngas. Typically, the remaining components of the syngas are burned in a combined cycle to produce electric power, increasing the overall efficiency of the process.

Tom Kreutz led a series of detailed investigations comparing the thermodynamic and economic performance of various systems that convert fossil fuels into hydrogen and electricity. In one set of studies, coal-to-H2 systems composed of “commercial-ready” components were compared with novel, membrane-based gas separation technologies. The novel plants were found to yield only modest reductions in the cost of hydrogen. In another study, the cost of coal-based hydrogen and electricity production - both with and without CCS - was compared with the cost of production from natural gas as a way of ascertaining which economic conditions (carbon tax and price of natural gas) might lead to large scale capture and storage of CO2. Producing hydrogen from coal was found to offer the lowest cost barriers to large scale CCS, because the incremental CO2 capture costs are quite modest. The CO2 co-product of H2 manufacture from coal is available as a relatively pure stream, so that the capture cost, consisting mainly of CO2 compression costs to make the CO2 disposal-ready, adds only about 10% to the production cost. Co-capture and co-storage of sulfur-bearing species - either H2S or SO2, depending on the system - along with the CO2, has the potential to lower system costs.

H2 and CO2 Infrastructures

Joan Ogden, who recently moved to U.C. Davis, led initiatives to model the logistics of transitioning to a low-carbon economy while with CMI.

Dr. Ogden and colleagues have carried out both generic studies modeling H2 and CO2 pipeline infrastructures and regionally specific studies using GIS data for Ohio.

A major finding of the generic studies is that the cost of CO2 storage in deep aquifers (including the cost of CO2 pipeline transport) is likely to be modest if CO2 transport distances are not too large. For a 100 km transport distance, storage for CO2 from coal adds less than 10% to the cost of H2 with capture. However, this estimate does not include monitoring costs or other post-injection (e.g., remediation) costs.

After analyzing the spatial relationships of population, energy plants, and possible pipeline paths in Ohio, the researchers determined that delivery of hydrogen will likely be economical for urban centers, where the majority of the population lives.

In contrast, distributing hydrogen to rural areas with low population densities is unlikely to be cost-effective. The high costs of transporting hydrogen gas through pipelines or liquid hydrogen by truck, coupled with low demand, will likely hinder market penetration into rural areas and present significant obstacles to making hydrogen fuels as convenient as gasoline without breakthroughs in hydrogen storage technology.
Liquid Fuel, Electricity and H₂ from Coal with Low System-Wide Emissions. In this system the H₂ and electricity coproducts of liquid fuel manufacture are produced with near-zero CO₂ emissions.

**CO₂ Capture and Storage in Manufacturing Synthetic Liquid Fuels**

There are likely to be some fuels markets even in the long term that cannot easily be served by either H₂ [e.g., in low energy use density (rural) regions] or electricity. Some mix of biofuels, liquid fuels derived from natural gas, and liquid fuels derived from synthesis gas via gasification of carbon-rich fossil fuel feedstocks would be needed. In a climate-constrained world carbon-neutral biofuels would be the most desirable, but the extent to which they can meet this need is uncertain because of land-use constraints. Fossil fuel-based liquid fuels might also thus be needed.

As part of the CMI collaboration with Tsinghua University (see Box 1), Bob Williams is leading a research effort that is exploring the production of liquid fuels from gasification-derived synthesis gas under a climate constraint. Because coal is the main fossil fuel resource in China, this effort is focusing initially on coal as the gasification feedstock, but the findings for coal are broadly applicable to other carbon-rich feedstocks (tar sands, petroleum residuals, heavy oils) as well.

The basis approach involves making high H/C liquid fuels (H/C ~ 2-4) from coal, for which H/C ~ 0.8. As in the case of making H₂ from coal, the CO₂ coproduct of liquid fuel manufacture is typically available as a relatively pure stream, so that CO₂ capture costs are modest. Under a climate constraint, nearly all of the carbon originally in the coal feedstock that is not contained in the liquid fuel itself can be recovered and disposed of underground as CO₂. With full CCS, there are still CO₂ emissions associated with the combustion of these liquid fuels, but on a fuel cycle-wide basis, greenhouse-gas (GHG) emissions per unit of synthetic fuel energy might typically be ~ 0.8 times the GHG emissions liquid fuels derived from natural gas or crude oil.

The research is showing that the most cost effective configurations often involve “once-through” synthesis, which obviates the need for costly synthesis gas recycle equipment. In these systems the synthesis gas passes only once through the synthesis
reactor (in which the synthetic fuel is made) and the
gas not converted in a single pass is used either to
make co-product electricity in a combined cycle
power plant or to make a mix of H₂ and electricity
(see figure above). The latter option is an especially
promising way to introduce H₂, because the
CMI/Milan collaborative research shows that there is
no “preferred” H₂/electricity output ratio from
production cost and thermodynamic perspectives, so
the ratio of H₂ to electricity output can be adjusted to
match demand.

Such “polygeneration” systems are already
established in many countries at refineries and
chemical process plants that coproduce electricity and
chemicals—mainly via gasification of petroleum
residuals. It is straightforward to extend the
technology to co-production of liquid fuels and to
coal as a feedstock. The extension is probably easier
in China than in most other regions because China’s
chemical process industry is to a considerable extent
already based on use of modern coal gasification
technology.

An important finding is the possibility of gaining
experience with CCS in polygeneration systems even
before a market value is put on CO₂ emissions—in
conjunction with an innovative approach to “acid gas
management” for such systems. The possibility arises
because maximizing synthesis gas conversion to
liquid fuel in a single pass through the synthesis
reactor requires partial shifting of the synthesis gas
upstream of the synthesis reactor and removal of the
CO₂ produced as a relatively pure stream. H₂S must
also be removed from the synthesis gas ahead of the
synthesis reactor to protect synthesis catalysts. There
are two alternative possibilities for managing these
acid gases. They might be removed separately, with
H₂S reduced to elemental sulfur and CO₂ vented, or
they might be removed together and stored
underground. The CMI/Tsinghua analyses suggest
that in some instances the latter would be the less
costly option. The amounts of CO₂ involved depend
on the synthetic fuel produced but can be
significant—typically involving CO₂ quantities
equivalent to 30% or more of the carbon in the coal,
Disposal rates at a typical facility would be 1-2
million tonnes of CO₂ per year. However, it is
uncertain whether underground CO₂/H₂S co-storage is
a viable option at such large scales in widespread
applications. Successful experience with 39 small
acid gas disposal projects in Western Canada in
conjunction with the production of sour natural gas
resources is promising. More research and
“megascale” demonstration projects are needed to
ascertain the viability of this option.

### Costs of Fuel Cell Vehicles

Analysis by Dr.’s Ogden, Williams, and Larson
shows that future hydrogen fuel cell cars would not be
competitive if taxes on conventional fuels account
only for their contribution to climate damages, even
under relatively optimistic assumptions about future
costs for fuel cell cars. However, when air pollution
and energy security externalities are also included in
the lifetime-cost calculations, it appears that
hydrogen fuel-cell cars might be competitive. The
researchers observe that there are large uncertainties
in the valuation of these externalities, and that it not
yet known how to bring fuel cell car costs down to the
levels assumed in their analysis.

### Biomass

Eric Larson leads an effort to assess
advanced technologies for using biomass
for energy—exploring prospective
performance, costs, GHG and air
pollutant emissions, and other impacts.

#### Black Liquor Gasification

One research area has been gasification of “black
liquor.” Currently, black liquor, the lignin-rich
byproduct of kraft pulp making, is burned in boilers
to provide steam and power for the pulp mill.
Gasification technologies are being developed that
could be used to provide electricity and heat for a mill
much more efficiently and cleanly than today’s
technologies, enabling substantial electricity exports
to the grid where they could displace fossil fuel
electricity. Analysis by Larson and colleagues
indicates that black liquor gasification would be cost
competitive with conventional technology if scaled-
up for commercial use, even in the absence of
financial incentives for low-emissions technologies.
Box 1: CMI/Tsinghua Collaboration

The group’s collaboration with the BP-sponsored “Clean Energy Facing the Future” program at Tsinghua University, begun in 2001, has expanded its capacity to model clean and climate-friendly energy systems. The collaboration has focused on study of polygeneration systems for making electricity, chemicals, fuels, and heat from fossil fuels.

Prof. Ren Tingjin from Tsinghua visited Princeton for a one-year period during 2002-2003 to collaborate on modeling production of liquid fuels (dimethyl ether and methanol) via coal gasification.

CMI and Tsinghua researchers were major participants in an August 2003 workshop in Beijing organized by the Task Force on Energy Strategies and Technologies (TFEST) of the China Council for International Cooperation on Environment and Development (CCICED) to review coal gasification-based energy strategies for China that are being developed in the CMI/Tsinghua collaboration. CMI/Tsinghua research provided the key technical analysis supporting the broad findings and recommendations of the TFEST report to the CCICED. This TFEST report has recently been presented to the highest levels of the Chinese government. A special issue of the journal, *Energy for Sustainable Development*, guest-edited by Eric Larson and Li Zheng (Tsinghua) and published in December 2003, is an edited and peer-reviewed collection of dedicated to papers from the TFEST workshop.

If gasification-based energy strategies are adopted in China, it will be possible to reduce air pollution from coal use and decrease dependence on imported oil, while putting in place a key enabling technology (gasification) for carbon capture and storage.

Box 2: CMI/Politecnico di Milano Collaboration

The CMI Capture group began a formal research collaboration with the Energy Department at Politecnico di Milano in the fall of 2001, tapping into their expertise in designing and modeling innovative power cycles. The group, headed by Ennio Macchi and including Giovanni Lozza, Stefano Consonni, and Paolo Chiesa, is known worldwide for its research in advanced energy systems. The CMI collaboration strengthened a longstanding, less formal partnership between the two groups which has been active since Stefano Consonni received his Ph.D. (modeling advanced gas and steam turbine cycles) at Princeton in 1992.

Prof. Chiesa spent six months visiting Princeton in 2001, collaborating on zero CO₂ emission coal-to-H₂ systems that employ hydrogen separation membrane reactors. More recently, Prof. Consonni and a graduate student, Federico Vigano, spent the 2002-2003 academic year at Princeton, collaborating on a number of studies examining the production of H₂ and electricity from both coal and natural gas using “commercially ready” technologies.

The collaboration has led to a number of joint papers and on-going projects.
Economics of Biomass Refineries

Dr. Larson is playing a leading role in a new 2-year, multi-institution project assessing possible future roles for biomass in the US energy economy. His team is analyzing alternative thermochemical (gasification-based) conversion technologies and costs for large-scale electricity and transportation fuels production from plantation-grown biomass (switchgrass). A goal is to find paths to large-scale biomass energy production that ultimately will be sustainable without government subsidies. This study will help provide a better understanding of the competition between liquid biofuels and H₂ in transportation, as well as the competition between liquid biofuels and fossil fuels used directly in markets not easily served by H₂ and electricity.

Combustion of Alternative Fuels

Proponents of a hydrogen economy envision that cars and trucks would be ultimately be powered by fuel cells that use hydrogen as an energy source and produce only water vapor as exhaust. Before this advanced technology becomes available, substantial emissions reductions could be achieved by adapting conventional internal combustion engines (ICE’s) to burn hydrogen fuel.

Because hydrogen gas has a low power density, hydrogen ICE’s are supercharged to boost performance. Supercharging, however, promotes other combustion problems, especially the propensity for pre-ignition and engine knock which limit fuel efficiency. Adoption of hydrogen as a fuel is also hampered by the potential for explosion from slow-leaking or punctured hydrogen tanks.

Chung K. Law and colleagues are carrying out simulations and experiments to find solutions for hydrogen combustion and safety problems. The team has determined the conditions for hydrogen ignition, and shown that mixing propane with hydrogen moderates the burning intensity of hydrogen flames such that the tendency to knock could be correspondingly reduced. In addition, combining propane with hydrogen lowers the potential for explosion in storage.

In a related project, Yiguang Ju is leading an effort to study the combustion of dimethyl ether (DME), a synthetic liquid fuel. This research has demonstrated that DME combustion is very unstable under high pressure, and that flame speeds are inconsistent with current kinetic models. The group therefore intends to compile measurements of chemical kinetics for DME-air combustion to improve the accuracy of numerical modeling for industrial application. The group’s numerical simulations also demonstrate that a lean DME-air mixture behaves much differently than mixtures of other large hydrocarbon fuels. Dilution of the DME fuel mixture with CO₂ in air will lift the DME-air flame and significantly reduce the soot emission. This result is contrary to current theory, and provides important fundamental data and information for DME combustor design.
The Storage Group

The storage group has been studying the complications involved in geological sequestration of carbon dioxide, including the potential for leakage and assessment of environmental consequences. Their work has led to group members’ participation in IPCC reports on impacts on sequestration from man-made features, including abandoned wells.

Aquifer Simulation

Work on predicting the fate of injected CO₂ is being pursued on a variety of fronts. While work continues on the in-house code Dynaflow, the team has also moved into working with analytical models that are considerably faster than complex simulators.

Simulator Development

Since the beginning of the CMI grant, Jean-Hérve Prévost and colleagues have expanded the capabilities of Dynaflow to include multiphase, multicomponent flow. The model is now capable of simulating the behavior of CO₂ and other components in brine systems, and initial simulations show significant improvement over previous models with less sophisticated treatment of chemistry and geomechanics. The team is currently adding calculation of pH to the model’s capabilities, which, along with subsequent geochemical routines, will allow study of the long-term fate of CO₂.

Analytical models

On timescales of a few hundred years, most of the CO₂ injected into a saline aquifer will not dissolve into the surrounding brine but instead remain as a separate, buoyant fluid. These early times are thus the critical period for potential leakage out of the injection reservoir. By focusing on single- and two-fluid flow dynamics, Mike Celia’s group has developed new analytical models for CO₂ plume evolution, including possible leakage through abandoned wells. These analytical solutions are much faster than full numerical simulators for estimating short-term reservoir leakage.

A study of the Alberta Basin indicates that this speed advantage will be important. Spatial analysis of existing wells in the basin indicates that they are the most significant potential leakage pathways for CO₂. Because of the wells’ clustered distribution, the CO₂ plume from a typical injection well could impinge upon hundreds of other wells. Estimating total reservoir leakage therefore requires modeling large numbers of wells simultaneously, which would be very time-consuming with more complex numerical models.

The group is currently working to expand the capabilities of the analytical model to include an arbitrary number of potentially leaky wells and multiple aquifers within the domain. These analytical solutions will then be combined with spatial analysis of well locations and cement degradation data (see below) to provide field-scale leakage estimates.
Deterioration of Cements

George Scherer’s group is studying degradation of well cements, which has the potential to increase reservoir CO₂ leakage rates. Interaction with low pH groundwater could lead to rapid dissolution of 20% of the material in cements followed by structural collapse, but their behavior under sequestration conditions is not well known. After setting up a laboratory and making initial analyses to characterize sample cements, the group currently has experiments underway.

The experiments will focus on the physical and chemical changes that take place at the wall of a well where cement and rock meet. Tubular samples of a representative sandstone and limestone have been filled with relatively impermeable cement and will be exposed to brine solutions with varying temperatures and pH values for a year. At frequent intervals during the experiment, the group will examine the rock-cement interface for physical and chemical changes that would affect cement permeability.

As cement permeabilities are very low in relation to formation stones, changes in well cements are unlikely to result in large changes in CO₂ transport through an aquifer. Compared to cap rocks with very low permeability, however, degradation of cement could make a well a more significant conduit of CO₂. Future plans are to carry out similar experiments with cap rock samples supplied by BP.

Results of the corrosion experiments will provide input for the modeling studies by Prévost, including rates of dissolution of cement by flowing brine and cracking at the cement/formation interface from rising injection pressure.

Deep Aquifer Geochemistry

Catherine Peters and colleagues have been carrying out geochemical experiments to mimic the effects of CO₂ injection under the temperature and pressure conditions found in deep aquifers.

Prior theoretical work had predicted that when CO₂ is injected into a reservoir, metals released from silicate minerals could react with carbon in the aquifer to form new carbonate minerals that could sequester CO₂. Calculations indicated that these reactions could take up 10-20% of the carbon injected into aquifers, but the speed of the reaction in a deep aquifer under high pressure was previously unknown.

A surprising result of the group’s experiments has been that although dissolution of precursor silicate minerals was relatively quick, solutions had to be highly supersaturated before new carbonate minerals would form. This indicates that sequestration via carbonate mineral formation may be difficult to achieve in real aquifers.

The group’s findings also indicate that, although temperature and pH have strong influences on dissolution rates, pressure has only a minor effect. Models can thus scale up existing rate laws for lower pressure conditions, making simulation of aquifers less complicated.

Finally, the group is using a computational approach to translate small-scale findings to the rock scale. For the first time, the group has used pore scale network models to simulate the effects of surface area, connectivity, and mineral heterogeneity on geochemical reaction rates.

Environmental Risks

Peter Jaffé and colleagues have been working on the impacts of leaks of CO₂ from deep aquifers and their possible environmental risks.

Impacts of CO₂ Leakage on Drinking Water

The team’s early work involved identifying contaminants that might be released if minerals in shallow aquifers were dissolved by CO₂-rich fluids. Initial analysis of a USGS dataset indicated that
arsenic was the only common element likely to exceed recommended maximum concentrations. However, as arsenic also becomes less mobile with increasing acidity, the group found that leakage of CO$_2$ into shallow aquifers is not likely to impact water quality adversely.

Iron as a CO$_2$ “Alarm”

Large CO$_2$ fluxes into shallow soils would make soils anoxic and could result in high iron levels in groundwater. The appearance of this iron in local streams could thus serve as sort of CO$_2$ “alarm.” To test the viability of this indicator, the group is performing soil column experiments to quantify the amount of iron that might be released from anoxic soils. This work also has implications for the sequestration of CO$_2$ in soils as iron carbonate.

Risks from large point sources of CO$_2$

In another program, field observations, combined with modeling of CO$_2$ transport in soils, are helping to quantify risks from large underground point sources of carbon dioxide.

Myneni’s team investigated the soil chemistry in regions with high CO$_2$ fluxes. They found that minerals are more intensely weathered in these areas and that the nutrients released from this weathering were washed away rather than retained in soils. In addition, root systems of certain trees were altered by high CO$_2$ concentrations in soils, spreading out at shallow depths rather than growing down into deep layers as they normally would.

To gain more insight into the impacts of high CO$_2$, the group is examining the feasibility of installing instrumentation at Mammoth Mountain to continuously record CO$_2$ concentrations throughout a soil profile. Current measurements are made only at the ground surface and provide no information about CO$_2$ levels deeper within soils where impacts are observed.

Although Mammoth Mountain provides an excellent natural laboratory for studying a large CO$_2$ point source, the young, ash-based soils around the resort are not a good analogue for average soils. Myneni and colleagues are thus carrying out complementary work on soils influenced by another kind of CO$_2$ point source - underground coal fires. Coal fires in Pennsylvania cause large fluxes of carbon dioxide into overlying soils that are more typical in their makeup than those at Mammoth Mountain. Comparing the impact of high CO$_2$ in the two soil types will therefore allow the researchers to predict whether impacts seen at Mammoth Mountain can be extrapolated to other areas that experience high CO$_2$ fluxes.
The Science Group

The Carbon Science group works to explain historical changes in atmospheric carbon dioxide levels, the nature and variability of carbon sources and sinks, and the feasibility and impacts of large-scale carbon mitigation. During the past 3 years, advances have been made on all fronts.

Interannual Variability of CO₂

Michael Bender’s group has been making observations of atmospheric composition to constrain the magnitude of carbon sinks and their interannual variability.

Sampler Deployment

Since the inception of the grant, the group has built seven automated sampling devices that are significantly increasing the accuracy of atmospheric argon and oxygen records. Two of the samplers have already been deployed in the Equatorial Pacific and Tasmania, and the remaining five will be deployed around the world in the coming year.

Carbon Sink Estimates

Better measurements allow the group to make increasingly reliable estimates of the size and variability of carbon sinks. The latest estimates for the annual carbon sinks are 1.1 ± 0.7 billion tons on land versus 1.8 ± 0.5 billion tons in the ocean. These refined estimates are slightly lower than, but in rough agreement with, previous calculations. Measurements also indicate that, from 1996 to 2001, almost all interannual variability in CO₂ was due to the land sink, and that the land biosphere is a large source of CO₂ during El Niño events.

Model-Data Comparison

The new measurements are also allowing the group to test ocean model predictions. Their work has revealed a substantial difference in timing of seasonal ocean gas fluxes between models and observations. This discrepancy in upper ocean dynamics could impact the models’ ability to predict biological productivity and carbon fluxes, so the observations are driving a simultaneous effort to improve simulation of mixed layer physics.

In a second case, new measurements lend some support to a model prediction. Computer simulations have long indicated that the equatorial Pacific ocean should be a net source of oxygen to the atmosphere, emitting more than it absorbs. The group’s preliminary measurements show a peak in atmospheric oxygen concentrations in the region, but its amplitude is much smaller than models predict. A more comprehensive study is currently underway.

Biological productivity estimates

Bender’s group is also currently working on a new technique to take the pulse of micro-organisms at the ocean surface. By measuring biological oxygen fluxes in surface waters and combining that information with oxygen isotope data, the group is currently measuring the variability of marine biological activity in space and time in two oceanographically interesting regions, the equatorial Pacific and the Southern Ocean.

CO₂ and glacial cycles

Daniel Sigman and colleagues are working to explain the long-term changes in atmospheric CO₂ content between ice ages and interglacial periods. The group has proposed that parts of the ocean were more stratified during glacial times, which prevented CO₂-rich deep waters from mixing upward and expelling their CO₂ into the atmosphere.

Because upwelling of such deep waters also impacts surface nutrient concentrations, the team is analyzing evidence of ancient nitrogen levels in
surface waters to test their theory. Since the inception of the CMI grant, they've developed a new method for analyzing minute quantities of organic nitrogen from the skeletons of microscopic organisms preserved in deep-sea sediments. The new data indicate that upwelling rates in two critical polar regions, the Antarctic and the Subarctic North Pacific, were indeed lower during the last ice age.

In addition to supporting the hypothesis of polar stratification during ice ages, the new data suggest that natural changes in iron input have had a significant impact on biological productivity in polar ocean waters. This result, which represents geologic validation of the “iron hypothesis,” was completely unexpected on the basis of previous studies of bulk sediments.

Since most short-term computer simulations predict greater stratification with climatic warming, increased stratification in a cold climate runs counter to expectations. The Sigman group is now working to place these short-term model experiments into a broader framework of how climate and ocean circulation interact.

**The Future of the Ocean Sink**

**Jorge Sarmiento and colleagues** are working on a variety of projects that investigate the ocean’s ability to act as a sink for carbon.

**Deep-Sea Injection**

One project completed during the first three years is a study of the potential of deep-sea injection as a sink for CO₂. Results from a suite of general circulation model simulations indicate that at least 70% and up to 93% of the carbon injected below 3000 meters water depth remains in the oceans after 500 years. These results indicate that deep-sea injection would be effective in storing CO₂, but possible environmental impacts raised by other researchers need to be addressed before deep-sea injection could be implemented.

**Ocean Fertilization**

Another early study investigated the possibility of fertilizing the ocean to enhance phytoplankton uptake of CO₂ and the delivery of this carbon to the deep ocean via an increased flux of organic matter. The group’s model simulations suggest that only 2-10% of additional carbon flux to the deep ocean would come from the atmosphere, and that fertilization might eventually decrease biological production and impact fisheries. It thus seems that ocean fertilization would be less effective than originally envisioned and could ultimately backfire by decreasing ocean biological productivity in the future.

**Climate Change Impacts on Ocean Chemistry & Biology**

A longer timescale study on ocean chemistry suggests that the ocean sink of carbon dioxide will shrink in the future, and that this decline should be considered in specifying leakage limits for underground CO₂ storage. The group’s ocean model simulations indicate that the carbonate buffer that now allows the ocean to absorb large quantities of atmospheric carbon will become saturated in a few centuries.
A study carried out this year provides new estimates of recent ocean uptake of carbon dioxide. The team analyzed a suite of global ocean models and selected only those that correctly predicted distributions of CFC’s and radiocarbon derived from the atmosphere. Using these models, the team calculated the size the ocean carbon dioxide sink in the 80’s and 90’s. Their estimates confirm previous observational work and narrow the uncertainty in ocean CO₂ uptake.

Also in this year, the group has linked chlorophyll and primary production models to a 3-D ocean model to estimate changes in biological productivity with climatic warming. Their results indicate that the total warming of the climate between the beginning of the Industrial Revolution to 2050 could be accompanied by a 0.7 to 8 % increase in primary productivity. Even in the most extreme case considered, this change would have only a modest effect on export production and atmospheric CO₂ levels.

The Future of the Terrestrial Sink

Steve Pacala’s group has been investigating the human influence on land-based carbon sinks and the impacts of renewable energy production on the environment.

Land Use vs. Fertilization

Since the inception of the grant, the group has been investigating the source of the large land-based carbon sink in the coterminous United States in the 20th century. There are two competing theories for the origin of the large sink. One proposes that increasing levels CO₂ had a fertilizing effect on land plants, increasing growth rates and causing heightened carbon uptake. The second suggests that land-use changes encouraged regrowth of forests that stored large amounts of CO₂. The group’s most recent data show that forest growth rates in Wisconsin have actually decreased with rising carbon dioxide concentrations since the 1960’s, suggesting that the big U.S. carbon sink is more likely due to land use changes than fertilization.

Because the terrestrial biosphere is largely recovered from past land use, this finding indicates that the terrestrial carbon sink is likely to shrink in the future. Such a decrease would require steeper cuts in emissions than currently anticipated to stabilize atmospheric carbon dioxide levels.

Impacts of Renewable Energy

Pacala’s group has also been studying potential impacts of large-scale renewable energy production on the environment.

Impacts of Wind Turbines

A preliminary study incorporating the effects of wind turbines on climate suggests that wind energy production would have minimal impact on global average surface temperature, even if wind power was scaled up to produce 20 trillion watts of electric power. On regional scales, however, simulations indicate that temperature changes of up to half a degree Celsius and small but significant changes in precipitation might occur.

Ozone precursors

Another project on renewables analyzed the impacts of forest plantations on air quality. Previous work had indicated that certain trees are a significant source of volatile organic carbon species (VOC’s) that contribute to tropospheric ozone formation and smog. The new work reveals that while reforestation by natural succession tends to decrease forest VOC emission, “managed” reforestation increases the level of VOC’s released to the atmosphere and has a negative impact on air quality. The group’s study suggests that changes in current forest management practices to allow more natural succession could bring significant benefits for air quality and human health.
Earth System Model

In the first three years of the grant, CMI researchers partnered with the Geophysical Dynamics Laboratory in developing a state-of-the-art climate model. This year, the team succeeded in linking completely new components for the atmosphere, ocean, sea ice, land, terrestrial biosphere and ocean biosphere. CMI researchers led development of the terrestrial and ocean ecosystem components of the ESM, which are at the leading edge of those available in coupled climate models. Simulations incorporating these modules will be carried out in Year 4.

The new model has a climate comparable to those of the best coupled models previously available, and it is the first coupled model of its type to produce a realistic El Niño event in a long model run. This new tool should increase confidence in future climate predictions, and substantially increase our insight into carbon cycle processes.
The Policy Group

CMI’s policy group is the only group whose mission was not outlined in the original CMI proposal. The group’s goals are to search for viable paths to a low-carbon economy and to analyze policies that will promote traveling those paths.

Economic Modeling

Previous benefit-cost studies have generally concluded that delaying action to reduce carbon emissions may be a sound policy, as it would carry only small costs and because, over time, key uncertainties may be reduced. In contrast, research led by Klaus Keller, now at Penn State University, suggests that early action may have substantial economic benefits, once realistic climate thresholds are considered.

Carbon Sequestration

In the area of carbon sequestration, the group’s work has shown that investing early in CO$_2$ sequestration can be more cost-effective than previous models suggested, due to cost savings that accrue as society learns over time to mitigate emissions more efficiently. These savings lower the tax required to make sequestration economical, improving the outlook for lowering emissions.

Dangerous Human Interference

Work on introducing uncertain climate thresholds into models contradicts a common assumption that waiting to learn more about the climate system before taking action will lead to more cost-effective mitigation strategies. Simulations with an optimal growth model indicate that uncertainty in climate sensitivity and economic damages does reduce the size of optimal near-term abatement efforts, but that even small future damages would justify considerable near-term investments.

Potential Regrets

New work this year has focused on a study of the regrets society will face if carbon mitigation is postponed but abatement is pursued later to avoid crossing “climate thresholds.” Because avoiding climate thresholds becomes more difficult as policies are delayed, decades of delay would carry economic costs of trillions of dollars (see figure).

Purchase of a Public Good

David Bradford is leading a study on an alternative to traditional “cap and trade” programs for reducing carbon emissions. Rather than establish emission caps for individual countries, this program would determine desired reductions of emissions for the globe and allow market forces to determine the distribution of reductions.
Under the plan, which would focus initially on “upstream” sources of fossil fuel, the world’s countries would participate in an international institution that would determine the size of fossil fuel use cuts necessary for the global good, then jointly fund the purchase of the reductions. The novel element is the granting to each country a baseline level of fossil fuel use that exceeds the business-as-usual level. Countries would profit from sale of abatement from the baseline; the financial burden would be shared on the basis of conventional criteria, such as a country’s relative wealth or its benefit from climate control. An important objective is to obtain the advantages of a cap and trade system, including allowing market forces to determine where and how emissions would be reduced and to spur innovation, with fewer problems of enforcing limits.

This system has distinct advantages over traditional emission cap schemes. For one, an “invisible hand,” rather than government negotiators, determines the distribution of emissions cuts among countries. In addition, unlimited trading should lower the costs of emissions reductions made. At this stage the group is working on both refinements of the conceptual model and simulations of its implementation, using a suite of economic models to quantify the costs and benefits of this alternative trading system.

Other current modeling work includes:
- improving the carbon cycle models in integrated assessment models
- quantifying the tradeoffs between decreased pollution and increased warming in optimization studies with aerosols
- optimizing models with learning and thresholds
- identifying policies that allow for large uncertainties associated with climate change.

**Policy Analysis**

Impacts of Emissions Scenarios

Michael Oppenheimer’s work has centered on analyzing the impacts of various CO₂ emissions trajectories. By estimating the atmospheric CO₂ concentrations likely to cause particular climate impacts, a study published last year allows climate-related damages to be linked to particular emissions scenarios. These ties sharpen the carbon-climate debate by illustrating the connection between energy policies and their environmental consequences.

Dr. Oppenheimer and colleagues are presently analyzing the environmental and social consequences of overshooting concentration targets, then lowering emissions to meet these targets at a later date. Their preliminary work indicates that interim warming during the overshoot period will be faster and larger than that experienced if a linear path to a stabilization target were pursued. This work suggests that delaying emissions reductions may have unexpected consequences not predicted in traditional simulations.

Additional work currently being carried out by Oppenheimer and colleagues includes investigating the effect of future climate on nitrogen cycling and developing a credible system of monitoring and accounting for carbon sequestration through agriculture.

**Impacts of Decreasing Population**

The United Nations Population Division suggests that world population growth may become negative after 2050. Jeffery Greenblatt leads a new investigation of the effect of a decreasing population on carbon emissions under an atmospheric stabilization policy framework. Downward revision of population estimates may increase public support for investment in mitigation strategies, since the size of the total effort needed to stabilize CO₂ would be reduced and decline with time.
Early on in the project, we committed to a third-year goal of producing a comprehensive assessment of proposed solutions to the carbon and climate problem, as well as our own recommendations. Toward this end we are now writing a document that addresses the feasibility of different strategies in cutting emissions through 2050, using the concept of a “stabilization wedge.”

The Stabilization Wedge

Our document is a response to an argument in the scientific and popular press over whether currently known low-emissions technologies could displace enough CO₂ emissions from the global energy system to mitigate future climate change. On one side are scientists who look far into the future and call for investing in research and development for “magic bullet” technologies that would solve the problem in one fell swoop. On the other side are scientists who maintain that existing technologies can be scaled up to tackle the problem gradually if action is started now.

Our approach focuses on the carbon emissions problem from now through 2050. Between now and that time, global emissions are typically projected to double from 7 to around 14 billion tons of carbon per year. An alternative path would keep emissions at current levels, cutting out a “Stabilization Wedge” of emissions equal to 175 billion tons of carbon over 50 years. This wedge is represented by the central pink triangle in the diagram above, and grows from zero today to replacing 7 billion tons of carbon per year in 2050. The alternative path is consistent with some of
the lower stabilization targets under discussion today; it most resembles stabilization at 500 ppm.

We divide this wedge up into seven “slices,” which represent activities that grow from nothing now to preventing 1 billion tons of carbon from entering the atmosphere per year in 2050. We ask: Can existing technologies provide the slices to build this wedge? Our estimates indicate that scaling-up technologies and programs that exist today could provide more than enough slices to replace this wedge of emissions, while at the same time keeping pace with the world’s energy needs. The strategies we believe could provide one or more slices include:

1. Energy efficient technologies
2. Replacing coal use with natural gas
3. Zero-carbon electricity from solar cells, wind turbines, and nuclear plants
4. Zero-carbon fuels from biomass
5. Carbon capture and underground storage
6. Biological storage

This simple wedge model is proving to be a useful focal point for our internal objective of an integrated research plan.
The Next Three Years
Future Work

Research over the first three years of the grant has resulted in the expansion of some new research programs and the contraction of others. In the next three years, our groups will contribute to our “stabilization wedge” assessment, while continuing to conduct investigator-driven research in their various fields.

Integration

Work on the Stabilization Wedge will continue. Results developed by the capture, storage, and policy groups will be turned into cost estimates for packages of slices. The initial focus exclusively on what could be in place in 2050 will be augmented by descriptions of 2025.

We will continue to steer a fraction of the research initiatives in each group toward areas that will refine our understanding of aspects of the Stabilization Wedge. As mentioned earlier, the strategies we are assessing include:

1. Energy efficient technologies
2. Replacing coal use with natural gas
3. Zero-carbon electricity from solar cells, wind turbines, and nuclear plants
4. Zero-carbon fuels from biomass
5. Carbon capture and underground storage
6. Biological storage

In the capture group, work on the effect of a CO₂ capture requirement on the coal vs. natural gas vs. biomass competition will clarify details of Strategies #2 and #5. Work on hydrogen couples to Strategy #1,

In the storage group, work on leakage through abandoned wells will inform discussions of geological CO₂ sequestration and thus illuminate Strategy #5.

In the science group, work on climate change impacts of various CO₂ emission trajectories will support work on the required size of the wedge as a whole, and work on the environmental consequences of large-scale renewable energy will address upper limits to the number of slices from strategies #3, #4, and #6.

In the policy group, integrated assessment modeling will provide trajectories of imputed costs of carbon emissions; these costs will permit quantitative assessments of the future competitiveness of all six strategies.

The Capture Group

The group is extending its work to clarify the competition between coal and natural gas for both electricity and synthetic fuels markets. Modelling will be expanded to investigate the polygeneration of chemical fuels, hydrogen, and electricity, and gasification analyses will incorporate low quality fossil fuel feedstocks other than coal.

The polygeneration/carbon-capture strategy is expected to remain the largest component of the capture program over the next three years. Collaboration will continue with the Politecnico di Milano and with Tsinghua University in a more integrated, three-way collaboration. At least one new collaboration, preferably in the developing world, will be sought.

Among specific topics under consideration are: scale dependence and “multiple training” of gasifiers, reactors, etc., to understand better reliability/capital cost tradeoffs; the role of economic dispatch in determining capacity factors and thereby shaping the economic competition between natural gas and low-quality primary energy sources; the potential for cost reduction for energy systems via advanced oxygen
production technologies and how this might impact the competition between coal and natural gas-based energy systems; co-polygeneration systems using fossil and biomass feedstocks as co-inputs; firing of fossil fuels with biomass fuels, polygeneration systems with the flexibility to produce variable ratios of products; and evolutionary strategies for national systems, including systems that involve co-capture with CO$_2$ of pollutants like sulfur.

Work on hydrogen fuel issues will continue as the second thread of the Capture Group. On the production side, they will complete an economic analysis for systems co-producing hydrogen and electricity from natural gas and make a side-by-side comparison of systems for making hydrogen from coal and natural gas. More attention will also be given to examining hydrogen as an evolutionary element in a polygeneration system and understanding the prospects for hydrogen in markets other than transportation.

It is hoped that the work on Hydrogen Combustion can become more of a collaboration with Ford. Work on hydrogen/CO$_2$ infrastructures will be continued and extended to include polygeneration systems, as a collaboration with the University of California at Davis, where Prof. Joan Ogden is now building a research group.

Work with outside partners will continue exploring long-term prospects for large-scale conversion of biomass energy crops to fuels with and without electricity co-product. This research will enable CMI researchers to compare relative prospects for fuels from coal and other low-quality fossil fuel feedstocks with carbon capture and storage, fuels from natural gas, and fuels from biomass.

The Storage Group

After analyzing a potential test basin (the Alberta Basin), the group has concluded that leaky abandoned wells could be the most important factor determining CO$_2$ leakage rates from deep saline aquifers. This discovery has prompted the addition of two new activities. First, George Scherer has begun experiments on cement deterioration to assess potential impacts on CO$_2$ leakage. Second, Mike Celia, confronting the need to simulate the impacts of hundreds of existing wells, has begun to develop fast analytical models to predict short-term leakage.

The group’s current plan for the next three years emphasizes the empirical research on physical and structural changes that occur in well cements under high CO$_2$ conditions. In support of this work, the researchers will improve on software now available to simulate the region where well meets reservoir in a CO$_2$-rich setting. In parallel, they will continue to develop powerful analytical solutions for the near-term consequences of CO$_2$ injection into reservoirs.

The Science Group

The science group has been organized around three problems: the glacial/interglacial cycle, natural sources and sinks for atmospheric carbon, and frontier mitigation technologies. These foci will be retained, but with sharper emphasis on the critical questions unearthed during the past three years and with greatly added power provided by the new Earth System Model (ESM). The group will continue to leverage the much larger level of funding provided by other sponsors. This base has been expanded recently by the naming of a NOAA Joint Institute at Princeton on the carbon and climate problem (funded this year at 3.5 million dollars).

Beginning this year, CMI researchers will take part in a GFDL project using the new ESM to make climate change predictions under a series of emissions and stabilization scenarios for the next IPCC Assessment. At the same time, D. Sigman and his group will continue to work on solving the paleoclimate problem of glacial/interglacial cycles.

In partnership with GFDL/NOAA, CMI researchers will lead the development of a new software system to link carbon cycle models to observational data from a wide variety of existing sources (images of the biosphere, meteorological data, atmospheric data from the global sampling network, eddy flux measurements, forest inventory data, etc.). The
system will generate real-time maps of the sources and sinks for atmospheric carbon around the planet.

The group will continue to provide frontier scouting of the feasibility and environmental impact of mitigation technologies, following up in two specific areas. First, with GFDL and Ford researchers they will study the interaction of the carbon and air quality problems. Second, they will build on intriguing early results on climate change and wind power, with an emphasis on turbine and wind farm designs that minimize impacts.

The Policy Group

The policy group will further build up its in-house integrated assessment capability and its working relationships with those who manage integrated assessment models elsewhere. Two relationships currently under development are with the International Institute for Applied Systems Analysis (IIASA) in Vienna and with the Pacific Northwest National Laboratory at the University of Maryland.

The group will build the work of the other three groups into such models to develop its own estimates of the costs of stabilization, and of our “Stabilization Wedge” in particular. The group will also continue development of models of market-driven international mechanisms for cutting global CO₂ emissions.

In addition, the group will continue research in three related areas:

1. The team will use existing economic models and develop more advanced ones to address the issue of how to make decisions in the face of both parameter and model uncertainty. They will build on current work to elucidate the relative roles of emissions mitigations, sequestration, and adaptation in future economic scenarios. They will also focus on building more accurate representations of climate thresholds and economic systems into their models.

2. Exploring institutional issues related to long-term stabilization targets is another of the group’s objectives. Specifically, they will analyze whether present agreements provide an adequate framework for implementing climate goals, what further scientific research is needed to develop such goals, what institutions should coordinate discussions, and how private efforts can be transformed into public initiatives.

3. The group will also explore specific mechanisms, e.g., trading schemes, that could be used to implement a long term target. Its goal is to build a conceptual map of policy options that foster early action.

Outreach

Over the next three years CMI plans to expand its communications with industry, academic colleagues, the media, policymakers, and the general public. To further this effort, we have hired a new information officer and corporate liaison, Dr. Roberta Hotinski.

Dr. Hotinski will work full-time on communicating our work to both our corporate sponsors and the broader community. Her role will be to identify target audiences and deliver products to them via personal communication, our website, media releases, workshops, and other venues. We remain committed to generating a series of papers to serve as a primer on the issue of stabilization at the level of an undergraduate text. Along the way, we will also distill its work into a variety of shorter documents for audiences with broad range of expertise and interest in the climate problem.

The Capture Group


Ming, Y., “Influence of health-based policy on climate”, part of Ph.D. thesis for Civil and Environmental Engineering, Princeton University


The Storage Group


Ciardullo, J.P., D.J. Sweeney, and G.W. Scherer, Thermal expansion kinetics: Method to measure permeability of cementitious materials, IV. Effect of thermal gradients. To be submitted to the Journal of the American Ceramic Society


Dahle, H.K., M.A. Celia, S.M. Hassanizadeh, and
The Science Group


Can Windfarms Generate Their Own Weather? (Submitted to Journal of Geophysical Research)


Blunier, T., B. Barnet, M. L. Bender and M. B. Hendricks (2002) Biological oxygen productivity...
during the last 60,000 years from triple oxygen isotope measurements, Global Biogeochemical Cycles, 16 (3), art. No. 1029, July-August.


B. K. Mignone, J. L. Sarmiento, R. D. Slater, A. Gnanadesikan, Sensitivity of Sequestration Efficiency to Mixing Processes in the Global Ocean Accepted for publication in Energy


Pacala, S.W., J. P. Caspersen and M. Hansen. 2004. Forest Inventory Data Falsify Ecosystem Models of CO2 Fertilization. (Manuscript.)


Sarmiento, J. L., N. Gruber, M.A. Brzezinski, and J. P. Dunne, in press. High latitude controls of the global nutriline and low latitude biological productivity. (Nature.)

The Policy Group


Eric, Nævdal, Dynamic Optimisation in the Presence of Threshold Effects when the Location of the Threshold is Uncertain - With an Application to a Possible Disintegration of the Western Antarctic Ice Sheet. Submitted to *Journal of Economic Dynamics and Control*.


The Integrative Activity


