Introduction to CMI-16:
The sixteenth annual meeting of the Carbon Mitigation Initiative

Steve Pacala and Robert Socolow
Carbon Mitigation Initiative (CMI)
Princeton University

April 4, 2017
Co-Directors:
S. Pacala
R. Socolow

BP:
C. Feilding
G. Hill

Advisory Council:
S. Benson, Stanford
D. Burtraw, Resources for the Future
D. Hawkins, Natural Resources Defense Council
M. Levi, Council on Foreign Relations
D. Schrag, Harvard

Research Groups:
Science
Technology
Integration

Collaborators (partial list):
GFDL, Princeton NJ
Tsinghua University
Politecnico di Milano
University of Bergen
Climate Central, Princeton NJ

Alternate meetings in London and Princeton
Laboratory Safety

BP monitors laboratory safety annually, either visiting individual labs or learning about new developments at the University level.

**Princeton lab safety reports are sent to Gardiner each year.**

CMI’s Current Labs:

Science labs: Bender (gasses in ice) and Morel (ocean geochemistry)

Engineering labs: Bourg (geological engineering), Steingart (batteries), and Stone (fluids)

**Feb 14, 2017:** Presentation to Cindy and Gardiner from Princeton Environmental Health and Safety (EHS, [http://ehs.princeton.edu/](http://ehs.princeton.edu/)) about SHIELD (Safety, Health, Inspection and Equipment Logistics Database). SHIELD is new campus-wide health/safety software that is “revolutionizing” information management.
CMI began in 2000, at a time when John Browne sensed that the world might pass through a discontinuity and begin to take climate change seriously.

Browne wanted BP to develop a comfortable relationship with a research center that would advance climate science and analyze low-carbon technology.

This remains our joint objective.
Timeline (last two years)

2016
- Jan. Cindy Yeilding replaces Felipe Bayon as Executive Sponsor for Princeton
- Feb. Gardiner Hill visits Princeton. Announcement of Best Paper Award to Caroline Farrior
- Apr. CMI 15th Annual meeting at BP headquarters (first-ever) in London with additional side meetings
- Apr. John Mingé and Cindy Yeilding visit Princeton
- May Socolow and Pacala conduct townhall meeting during 3-day visit to Naperville
- Dec. Socolow and Pacala meet with senior BP officials over 3-days at Westlake Campus, Houston
- Dec. Secretary of Energy Advisory Board Task Force report on carbon management (Socolow, member)

2017
- Feb. Cindy Yeilding and Gardiner Hill visit Princeton
- Mar. National Academies study of carbon dioxide removal announced (Pacala, chair)
- Apr. CMI 16th Annual Meeting, Announcement of the Best Paper Award went to Bhargav Rallabandi
- Apr. Retirement event for Bob Williams, founding member of CMI and Head of Energy Systems Analysis Group
“A dangerous moment for climate change and for science”

“The scrimmage line for climate change has moved dramatically, and the game has become more dangerous...Scientists must find innovative ways to address the dissident views of climate change science that have had such a strong influence on the Republican Party.”

“The public policy problem of climate change is, at its core, a problem of risk management in the face of imperfectly understood risks. Business and military leaders are natural partners, because they understand risk management.”
Risks of climate change for BP

The climate problem has the potential to disrupt BP’s core business in at least three ways:

1. Effective climate policies can emerge that discourage fossil fuel consumption, that impose environmental performance standards on production processes, and that subsidize or otherwise promote efficiency and low carbon energy.

2. Climate-motivated research can create disruptive new energy technology.

3. The consequences of climate change can directly disrupt BP’s investments in energy production infrastructure and supply chains.
BP supports CMI to help manage risks

1. CMI sharpens BP’s corporate perspective on climate change. It provides BP with strategic understanding of the potential physical, biological and human systems impacts.

2. BP benefits when CMI disseminates sound information that supports effective public policy discussions.

3. BP leverages the much larger research programs of the CMI investigators.
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Princeton Environmental Institute
A Center of Excellence for Environmental Research and Teaching
Every year CMI awards a prize to a post-doctoral fellow who has made a strong contribution to a strong paper. This year’s winner is Bhargav Rallabandi. The paper is:


Ice bridges form only beyond a critical thickness of the sea ice, related to wind stresses and the width of the strait. Ice bridges “clog” a strait, inhibiting the export of Arctic sea ice into the warmer Atlantic Ocean. In a warming climate, stable ice bridges may not form, accelerating the loss of Arctic sea ice.

This is a bridge paper in a second sense: a new GFDL-campus collaboration.
Posters

Science Group:
Kieran Bhatia: "The influence of climate change on tropical cyclones in the HiFLOR model"
Stuart Evans: "Influence of land surface processes on seasonal and interannual variability of Australian dust and climate in the NOAA/GFDL CM3 model"
Brandon Reichl: "Ocean surface waves in coupled climate modeling"
Bhargav Rallabandi: “Sea ice dynamics and bridge formation in Arctic straits”
Marjolein van Huijgevoort: “Implementation of water management practices in a global scale land model” (presented by Chris Milly)

Technology Group:
Ian Bourg: “Hydrophobic adsorption at clay-water interfaces”
Greg Davies: "Battery state of health estimation via machine learning and ultrasonics”
Kevin Knehr: “Bromine capture in minimal architecture zinc-bromine batteries”
Ching-Yao Lai: “Fluid-driven fracture: scaling, flowback and foams”
Yiheng Tao: "Vertically-integrated dual-permeability model for CO₂ injection in fractured reservoirs“

Integration Group:
Hans Meerman: “‘Drop-in’ transport fuels via hydropyrolysis of biomass: an economic option for negative emissions?”
Lei Zhao: “Interactions between urban heat island and heatwave events”
(presented by Jane Baldwin)
Advisory Committee (see facebook)

Sally Benson
Stanford University
Professor of Energy Resources Engineering
(unable to attend)

Frans Berkhout
King’s College London
Executive Dean of the Faculty of Social Science and Public Policy; Professor of Environment, Society and Climate

Ottmar Edenhofer
Potsdam Institute for Climate Impact Research
Deputy Director and Chief Economist
(unable to attend)

David Hawkins
Natural Resources Defense Council
Director of Climate Programs

Daniel Schrag
Harvard University
Professor of Geology; Professor of Environmental Science and Engineering; Director of the Center for the Environment; Director of the Science, Technology and Public Policy Program at the Kennedy School
Agenda: This morning

Day One: Tuesday, April 4, 2017

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<td>8:00-8:30 a.m.</td>
<td>Breakfast available</td>
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<td>8:30-8:45 a.m.</td>
<td><strong>Welcome and Safety Moment</strong></td>
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<td>Lynn Loo, Director, Andlinger Center for Energy and the Environment; Theodora D. '78 and William H. Walton III '74 Professor in Engineering; Professor of Chemical and Biological Engineering</td>
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<td>8:45-9:45 a.m.</td>
<td><strong>Overview of CMI</strong></td>
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<td>Stephen Pacala &amp; Robert Socolow</td>
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<td>9:45-12:45 p.m.</td>
<td><strong>Research Review</strong></td>
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<td>Jorge Sarmiento (30 minutes)</td>
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<td>François Morel (30 minutes)</td>
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<td><strong>DISCUSSION (15 minutes)</strong></td>
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<td><strong>BREAK (30 minutes)</strong></td>
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<td>Stephen Pacala (30 minutes)</td>
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<td>Gabriel Vecchi (30 minutes)</td>
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<td><strong>DISCUSSION (15 minutes)</strong></td>
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<td>12:45-1:00 p.m.</td>
<td>Group photo (in front of Computer Science Building by Shapiro Walk)</td>
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<td>Time</td>
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<td>1:00-2:20 p.m.</td>
<td>Lunch and review of posters</td>
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<td>2:20-5:00 p.m.</td>
<td><strong>Deep Dive (Disruptive Technologies: What’s Next?)</strong></td>
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<td>Ellen Williams, University of Maryland, and former director, ARPA-E (40 minutes)</td>
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<td>Daniel Steingart (20 minutes)</td>
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<td>Robert Williams (20 minutes)</td>
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<td><strong>Break (20 minutes)</strong></td>
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<td>Daniel Schrag, Harvard University (20 minutes)</td>
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<td>Christopher Greig, University of Queensland (20 minutes)</td>
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<td><strong>Discussion (20 minutes)</strong></td>
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<td>5:30-6:30 p.m.</td>
<td><strong>Reception and Announcement of CMI 2016 Best Paper Award at Prospect House</strong></td>
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<td>Awarded to Bhargav Rallabandi, presented by Angela Strank, Chief Scientist, BP</td>
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<td>6:30-9:30 p.m.</td>
<td><strong>Dinner at Prospect House</strong></td>
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<td><em>Speaker:</em> John Holdren, Harvard University, senior advisor to President Obama on science and technology (2009-2017)</td>
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<tr>
<td>Time</td>
<td>Session</td>
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<tr>
<td>8:00-8:30 a.m.</td>
<td>Breakfast available</td>
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<tr>
<td>8:30-9:15 a.m.</td>
<td><strong>BP Context</strong>&lt;br&gt;    Cindy Yeilding, Senior Vice President, BP America</td>
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<td>9:15-9:45 a.m.</td>
<td><strong>Advisory Council Reflections</strong></td>
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<td>9:45-12:45 p.m.</td>
<td><strong>Deep Dive (Climate Change in the Era of Trump)</strong></td>
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<td><em>Co-Chairs: Henry Lee, Harvard University, and Kelly Sims Gallagher, Tufts University</em>&lt;br&gt;  <em>Session 1: The D.C. Perspective</em>&lt;br&gt;    Joseph Aldy, Harvard University (15 minutes)&lt;br&gt;    Kevin Knobloch, Tufts University (15 minutes)&lt;br&gt;    David Hawkins, Natural Resources Defense Council (15 minutes)&lt;br&gt;  <em>DISCUSSION (30 minutes)</em>&lt;br&gt;  <strong>BREAK (30 minutes)</strong>&lt;br&gt;  <em>Session 2: The Global Perspective</em>&lt;br&gt;    Frans Berkhout, King’s College London (15 minutes)&lt;br&gt;    Kelly Sims Gallagher, Tufts University (15 minutes)&lt;br&gt;    Michael Oppenheimer (15 minutes)&lt;br&gt;  <em>DISCUSSION (30 minutes)</em></td>
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<tr>
<td>12:45-1:00 p.m.</td>
<td><strong>CMI Annual Meeting Close: Discussion / Reflection / Wrap-up</strong></td>
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<td>1:00 p.m.</td>
<td>Meeting adjourns</td>
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<tr>
<td>1:00-2:00 p.m.</td>
<td>Lunch and review of posters</td>
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CMI Principal Investigators

- PACALA
- SARMIENTO
- MOREL
- BENDER
- VECCHI
- SOCOLOW
- WILLIAMS
- OPPENHIMER
- PACALA
- CELIA
- STEINGART
- STONE
- BOURG
- TECHNOLOGY
- INTEGRATION
Over to Steve
Predicting Carbon Sinks

Pacala, Sarmiento, Shevliakova

Net zero and negative emissions

Pacala, Shevliakova

Extreme weather under climate change

Vecchi, GFDL

Global methane cycle

Zhang, Horowitz, Poulot, Morel, Shevliakova
Fate of anthropogenic CO₂ emissions (2006-2015)

Sources = Sinks

34.1 GtCO₂/yr
91%

16.4 GtCO₂/yr
44%

9% 3.5 GtCO₂/yr

31% 11.6 GtCO₂/yr

26% 9.7 GtCO₂/yr

Changes in the budget over time

Sinks have been increasing for more than 50 years.

CMI Science 2017

Predicting Carbon Sinks  
Pacala, Sarmiento, Shevliakova

Net zero and negative emissions  
Pacala, Shevliakova

Extreme weather under climate change  
Vecchi, GFDL

Global methane cycle  
Zhang, Horowitz, Poulot, Morel, Shevliakova
Paris Scenario Fossil Emissions - CO$_2$ stabilizes at 442 ppm in 2050 and reaches 1.75 °C in 2100

This would be zero without the oceanic and terrestrial sinks.

Predictions of the NOAA GFDL Earth System Model
Paris negative-carbon wedges
Chair, Stephen Pacala (NAS), Princeton University
Mahdi Al-Kaisi, Iowa State University
Mark A. Barteau (NAE), University of Michigan
Erica Belmont, University of Wyoming
Sally M. Benson, Stanford University
Richard Birdsey, Woods Hole Research Center
Dane Boysen, Cyclotron Road/Lawrence Berkeley National Laboratory
Riley Duren, Jet Propulsion Laboratory
Charles Hopkinson, University of Georgia
Christopher Jones, Georgia Institute of Technology
Peter Kelemen (NAS), Columbia University
Annie Levasseur, École Polytechnique de Montréal
Keith Paustian, Colorado State University
Jianwu (Jim) Tang, Marine Biological Laboratory
Tiffany Troxler, Florida International University
Michael Wara, Stanford University
Jennifer Wilcox, Colorado School of Mines
Predicting Carbon Sinks  Pacala, Sarmiento, Shevliakova
Net zero and negative emissions  Pacala, Sheviliakova
Extreme weather under climate change  Vecchi, GFDL
Global methane cycle  Zhang, Horowitz, Poulot, Morel, Shevliakova
Most impactful hurricanes tend to be strongest. Need prediction models that can capture them. New prototype model ("GFDL-HiFLOR", first run May 2014) able to simulate Cat. 4-5s

(25km FV3 atmosphere coupled to 1° MOM5)

Murakami et al. (2015, J. Clim)
CMI Science 2017

Predicting Carbon Sinks
Pacala, Sarmiento, Shevliakova

Net zero and negative emissions
Pacala, Shevliakova

Extreme weather under climate change
Vecchi, GFDL

Global methane cycle
Zhang, Horowitz, Poulot, Morel, Shevliakova
Unlike CO₂, methane is relatively short-lived in the atmosphere, but 120 times more potent per unit mass as a greenhouse gas.

Humanity must limit emissions of both methane and CO₂ to achieve the Paris targets.

Anthropogenic Methane Sources (2000s)

- Fossil fuels: 85-105 Tg/yr
- Waste decomposition: 65-90 Tg/yr
- Rice cultivation: 30-40 Tg/yr
- Domestic ruminants: 85-95 Tg/yr
- Biomass burning & biofuels: 30-40 Tg/yr

Global Carbon Project 2013; Figure based on Kirschke et al. 2013
New Supplementary Award From BP to Study Global Methane: 2017-2020

Quantifying the contribution of individual sources and sinks to atmospheric methane variability at global scales.

Discovering controls on microbial methane metabolism and its isotopic signatures.
CMI Science 2017

Other Studies Described in Posters and in the CMI Annual Report:

Francois Morel: Ocean acidification and the availability of trace metals.
Michael Bender: > million year old ice supports current understanding of the link between CO2 and climate.
Howard Stone: Ice dynamics on land and sea.

Kieran Bhatia: "The influence of climate change on tropical cyclones in the HiFLOR model"
Stuart Evans: "Influence of land surface processes on seasonal and interannual variability of Australian dust and climate in the NOAA/GFDL CM3 model"
Brandon Reichl: "Ocean surface waves in coupled climate modeling"
Bhargav Rallabandi: “Sea ice dynamics and bridge formation in Arctic straits”
Marjolein van Huijgevoort: “Implementation of water management practices in a global scale land model” (presented by Chris Milly)
The weak case for CCU-fuels

In the second half of 2016 I served on a task force that wrote a report for the U.S. Department of Energy. Entitled “Task Force Report on CO₂ Utilization and Negative Emissions Technologies,” it was submitted to Secretary of Energy, Ernest J. Moniz, on December 13, 2016. It is online at https://energy.gov/seab/downloads/final-report-task-force-co2-utilization, where the task force participants and a DOE “Assessment” of the report are also found.

Here I explore an issue that our report left unresolved. It goes beyond my Highlight in the 2016 Annual Report.

Acknowledgements: Nate Lewis, Arun Majumdar, Sally Benson, Emily Carter, Mike Ramage, Eric Toone; Julio Friedmann, Jonathan Forsyth, Ian Luciani, Robert Williams.
Today’s anthropogenic carbon flows are dominated by extraction of fossil fuel and CO₂ emission to the atmosphere.

An economy responsive to climate change modifies these flows. Our committee excluded consideration of the non-carbon economy (all renewables and nuclear). We looked only at modifications that retain a flow of carbon. These can be reduced to combinations of three building blocks.
Two net-zero building blocks

Current Economy

Atmosphere

Subsurface

Economy

Prevent CO$_2$ emission

Atmosphere

Economy

Gas+CCS

Electric vehicles

Subsurface

Use carbon only from air

Atmosphere

Economy

Biopower, wind+batteries;

biofuel, air-CO$_2$ synfuel

Convert CO$_2$ to a hydrocarbon
In combination: Negative Carbon

- Atmosphere
- Economy
- Subsurface

Biopower with CCS (BECCS) + electric vehicles; solar hydrogen and hydrogen vehicles.
Augmented sinks: a third building block

In this idealization, the flows of carbon through the economy are unchanged.
What about the half building block: CO$_2$ capture and use (CCU) for fuel?

Motivation for CCU-fuel: Surely there is something better to do with CO$_2$ than stick it underground!

But, when does CCU-fuel make sense?

Other names for CCU: “Carbon recycle,” “Using carbon twice.”
The CCU-fuel story line

**Storyline:** A carbon-based transport fuel with no CO₂ emissions is desired. Carbon from CO₂ that otherwise would have been emitted at a fossil fuel power plant meets this criterion.

What needs to be true?

A. Electric vehicles, H₂ vehicles, and biofuel are unattractive
B. High carbon price, but fossil fuel power still abundant
C. CO₂ capture and reduction achievable at modest cost
D. CO₂ storage unavailable
The enabling energy (green arrow) must be low-carbon, and in quantity it must exceed the energy released when the vehicle fuel is burned.

It is natural to ask: Are there better systems, where the enabling energy is used differently?
Use the enabling energy for vehicles?

CCU-fuel wins this competition only if (as we have agreed to assume) electric vehicles, H₂ vehicles, and biofuels are not available.
Use the enabling energy to displace fossil power?

CCU-fuel loses this competition even at a high oil price, because then synfuels can be produced from whatever would have been the CCU feedstock (coal, nat. gas, biomass). In contrast to CCU, the synfuels plant is integrated, and C does not go all the way to $\text{CO}_2$ before reduction; the C goes only to $\text{CO}$.
Other variants: Special initial conditions

Three variants where CO₂ is already there, for some reason:

CCS thrives but then is thwarted (a leak). CCU-fuel os chosen instead of discarding the CC unit.

On a grid, both solar power and natural gas with CCS are abundant. CCU is an alternative to “curtailment.” At noon, CCS becomes CCU (low capacity factor for the CCU unit). CCU fuel competes with load-shifting, storage.

CO₂ for CCU comes from the air, not from a power plant.
Two further observations:

1. The SEAB Committee charge was to look only at >1GtCO₂/yr markets, which means synfuel for all sectors and maybe plastics. We ignored high-value niche markets, e.g., pharmaceuticals, membranes.

2. CCU is not a storage strategy. Only the likes of a plastic bench will keep CO₂ out of the atmosphere for a century or more. The “delay time,” (time from first to second hydrocarbon oxidation) is typically only months.
Distinguish CCU-EOR and CCU-fuel

Distinguish CO₂ use after conversion to a hydrocarbon vs. use as CO₂.

Use of CO₂ for modified enhanced oil recovery (EOR) may become an important carbon management strategy.

Current EOR has roughly a 1:1 carbon-flow ratio (one external C is stored in the reservoir for each C produced).

Modified EOR may feature a much larger ratio; say, 3:1. This would involve entirely different reservoir management.

Modified EOR may be the only credible realization of CCU.