




Global Climate & Energy Project

STANFORD UNIVERSITY

Global Climate & Energy





*"In 1904, Jane Stanford defined the
challenge for this young university:
'Let us not be afraid to outgrow old thoughts and ways,
and dare to think on new lines.'
The Global Climate and Energy Project takes up
Jane Stanford's challenge to posterity, embracing the
innovative spirit and pioneering tradition for which
Stanford University is known."*

John Hennessy

President
Stanford University

Contents

3 | Directors' Message

5 | The Project

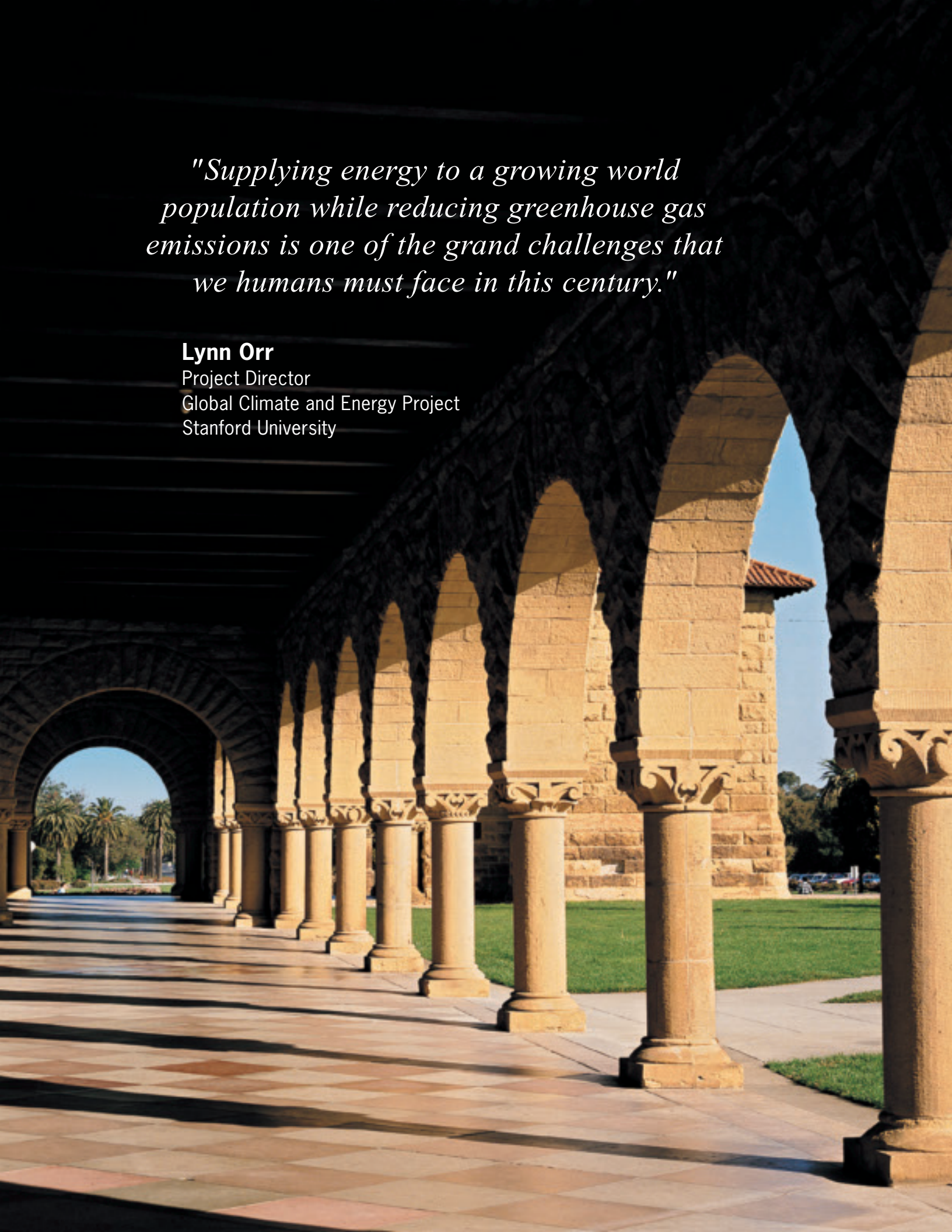
Objectives.....	6
Strategies.....	7
Outreach.....	7

9 | GCEP Activities

Analysis	10
Technology Assessment.....	11
Systems Analysis.....	11
Research	12
Renewable Energy.....	14
Solar.....	14
Biomass.....	16
Hydrogen Production, Storage, and Use..	18
Advanced Combustion Science and Engineering.....	20
CO ₂ Capture and Separation.....	22
CO ₂ Storage	24
Advanced Materials and Catalysts.....	26
Integrated Assessment.....	27

29 | Looking Ahead

31 | GCEP Participants



"Supplying energy to a growing world population while reducing greenhouse gas emissions is one of the grand challenges that we humans must face in this century."

Lynn Orr

Project Director

Global Climate and Energy Project

Stanford University

Directors' Message

We are pleased to present the Global Climate and Energy Project (GCEP), a long-term collaborative effort of the scientific and engineering community in universities, research institutions, and private industry. Our purpose is to conduct fundamental, pre-commercial research to foster the development of global energy technologies with significantly reduced greenhouse gas emissions.

It is apparent that humans are interacting with the planet on a global scale. The concentration of carbon dioxide (CO₂) in the atmosphere has increased by a third from its pre-industrial levels, and the pH of the upper ocean has also declined as the CO₂ from the atmosphere dissolves. With a growing population and energy demand in the world, there is a pressing need for research to create energy options with much lower emissions of greenhouse gases. GCEP helps to fulfill that need.

We are now considering the underlying science and engineering of technology options that would have much lower emissions of greenhouse materials such as carbon dioxide, methane, and black soot. GCEP works toward these goals with the support of a group of global corporations made up of ExxonMobil, General Electric, Schlumberger, and Toyota. A multi-year project with funding of \$225 million, GCEP is tapping the creativity of faculty and students at Stanford and at other universities and research institutions worldwide. We continue to seek out participation throughout the world as we work together to create an energy future that is both feasible and sustainable.

We are building a diversified portfolio of research projects: finding ways to use our existing energy resources more effectively, capturing the CO₂ to prevent it from entering the atmosphere, examining new types of energy transformations, storage, and supply, and assessing their potential impact on global emissions. In addition, our analysis group is tying together these research projects, estimating their relative feasibility for application, and suggesting appropriate next steps. As we work to make a difference in the world's future, we look forward to your interest and support.



A handwritten signature in dark ink, appearing to read "Lynn Orr".

Franklin "Lynn" M. Orr, Jr.
Project Director



A handwritten signature in dark ink, appearing to read "C. Edwards".

Christopher Edwards
Deputy Director



A handwritten signature in dark ink, appearing to read "Richard Sassoon".

Richard Sassoon
Managing Director



*Imagine a global energy system
where greenhouse gas emissions to the
atmosphere are a small fraction of
what they are today*

Graduate-student researcher Venkatesh Vasudevan uses a ring dye laser in the Mechanical Engineering Department at Stanford University to develop smart sensors for advanced combustion systems.

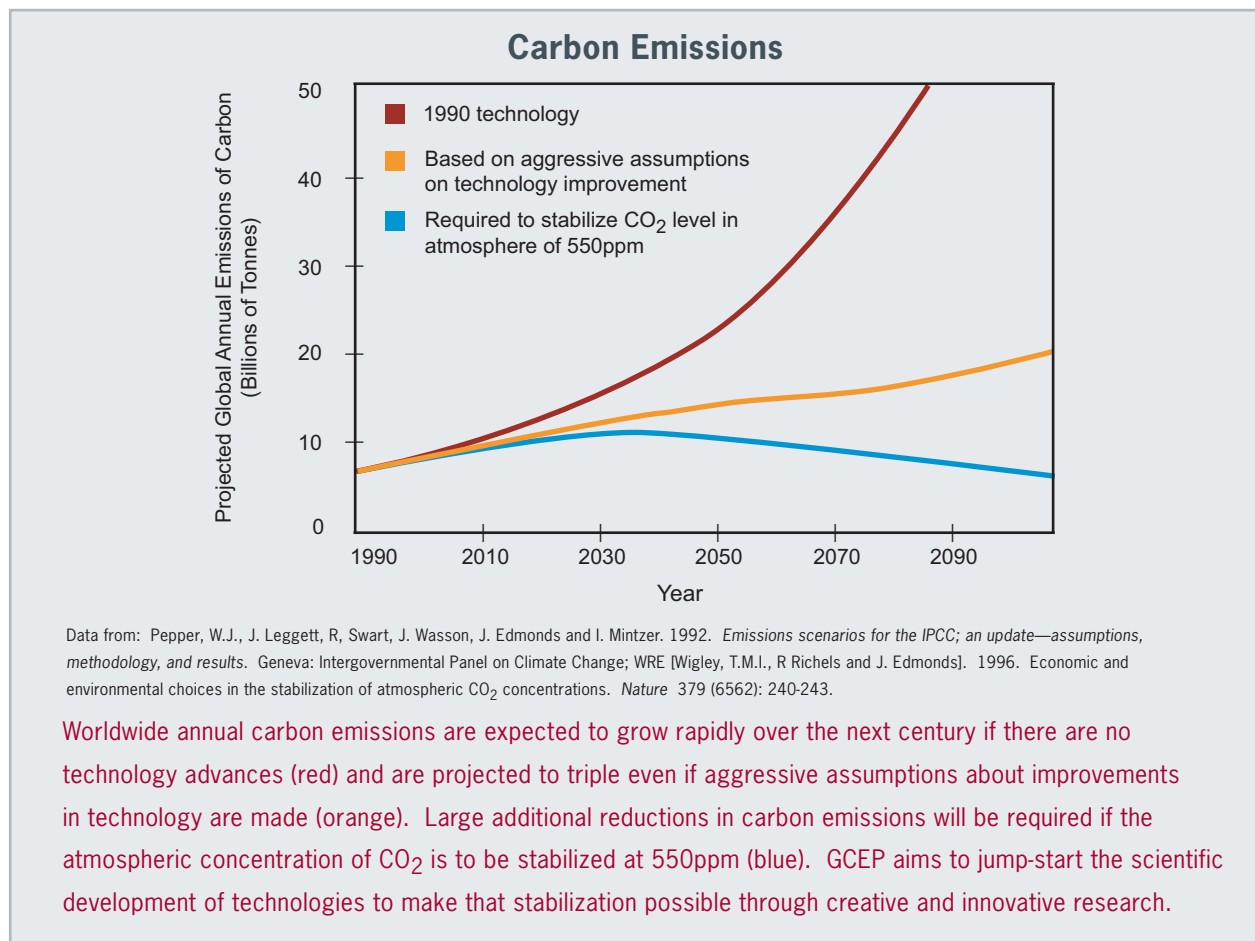
The Project

The Global Climate and Energy Project at Stanford University seeks new solutions to one of the grand challenges of this century: supplying energy to meet the changing needs of a growing world population in a way that protects the environment.

Our mission is to conduct fundamental research on technologies that will permit the development of global energy systems with significantly lower greenhouse gas emissions.

With the support and participation of four international companies—ExxonMobil, General Electric, Schlumberger, and Toyota—GCEP is a unique collaboration of the world's energy experts from research institutions and private industry. The Project's sponsors will invest a total of \$225 million over a decade or more as GCEP explores energy technologies that are efficient, environmentally benign, and cost-effective when deployed on a large scale.

Launched in December 2002, GCEP is well on its way to developing and managing a portfolio of innovative energy research programs. We currently have a number of exciting research projects taking place across disciplines throughout the Stanford campus and at other leading institutions worldwide.

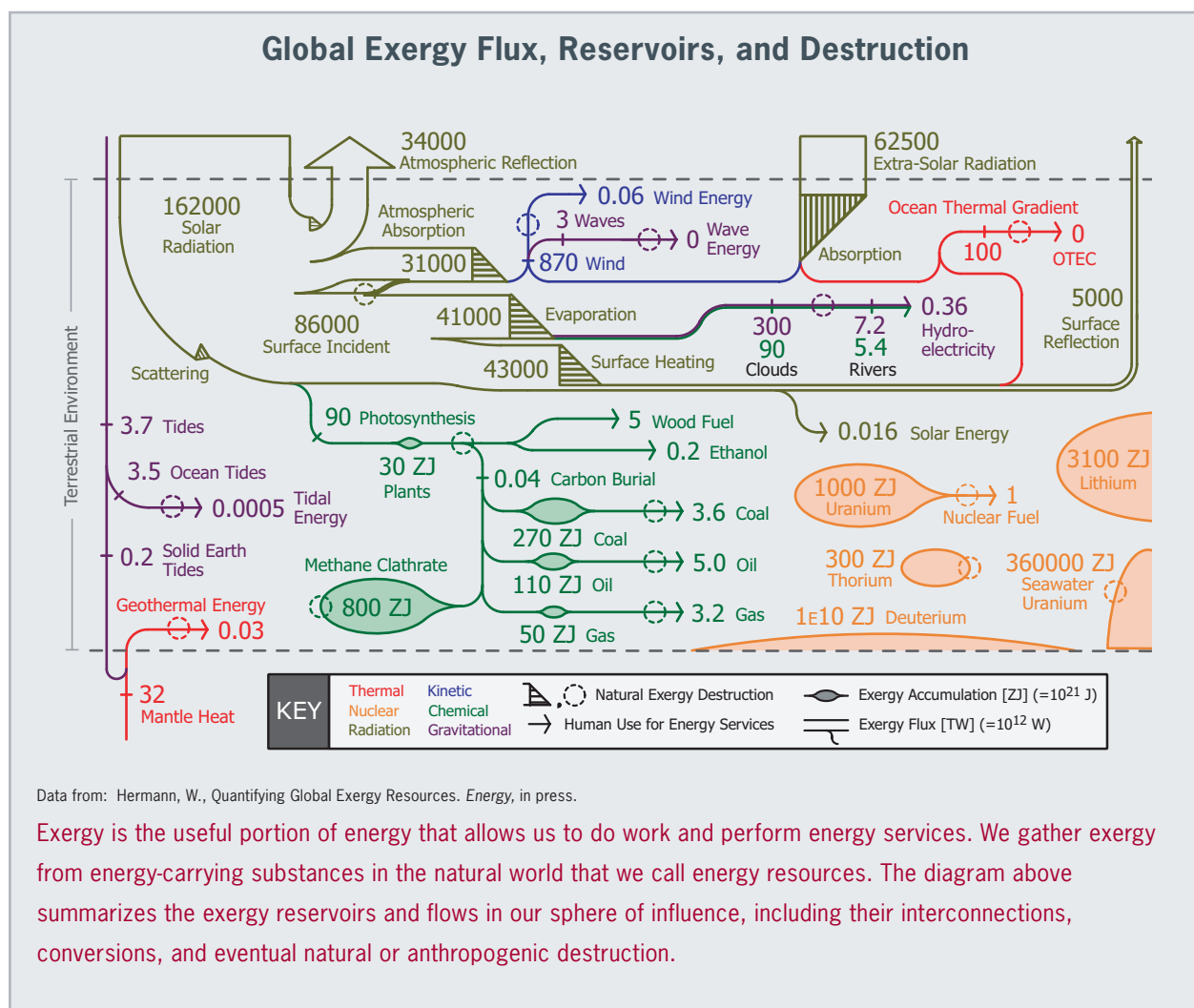


Objectives

We believe that no single technology is likely to meet the energy challenges of the future on its own. It is essential that GCEP explore a range of fundamental research that could lead to a spectrum of globally significant energy resources and uses. As a result, our primary objective is to build a diverse portfolio of research on energy conversion options that will reduce greenhouse gas emissions, if successful in the marketplace.

Among GCEP's specific goals:

1. Identify promising research opportunities for low-emissions, high-efficiency energy technologies.
2. Identify barriers to the large-scale application of these new technologies.
3. Conduct fundamental research into technologies that will help to overcome these barriers and provide the basis for large-scale applications.
4. Share research results with a wide audience, including the science and engineering community, media, business, governments, and potential end-users.



Strategies

To achieve our goals, GCEP focuses on research that could lead to “game-changing” technologies. We encourage innovative research that combines high risk with the potential for high reward and understand that, while some research efforts may fail, others may succeed in a way that could greatly improve our energy future. This kind of risk-taking, we believe, is the key to creating dramatic change.


GCEP continues to seek and work with the best research talent at Stanford and other leading institutions around the world to help build and shape its portfolio. We also plan to collaborate with institutions in developing countries with fast-growing economies that are likely to produce significant emissions of greenhouse gases in the future. This collaboration will be critical because the demand for energy will increase most rapidly in these nations. With their involvement, we hope to develop and encourage the use of new, cleaner technologies from the start.

Outreach

An important part of our efforts is for GCEP to communicate our project activities and research results to a wide audience. Through our website, reports, publications, and events, GCEP is providing a vehicle for an international dialogue about future energy systems with low greenhouse gas emissions. To share our research results with the public, we hold annual energy symposia, such as the June 2005 event “Meeting the Challenge of Reducing Global GHG Emissions Through Energy Research” held at Stanford. Each year, we also host and sponsor a number of technical area workshops. Since 2003, we have held workshops on Hydrogen, Wind Power, Carbon Capture and Separation, Biomass, Solar Energy, Advanced Coal, Advanced Transportation, Breakthrough Research, and an Advanced Coal Conversion/CO₂ Capture and Storage workshop in Beijing, China.



Geophysics Professor Mark Zoback and graduate-student researchers Lourdes Colmenares (left) and Amie Lucier (middle) discuss their work in CO₂ sequestration.

A photograph of two men, Professor Anders Nilsson and graduate-student researcher Anton Nikitin, working in a laboratory. They are both wearing blue shirts and glasses. Professor Nilsson is on the right, leaning over a complex piece of scientific equipment, which appears to be a synchrotron radiation setup. Anton Nikitin is on the left, looking intently at the equipment. The background is a warm, reddish-brown color, possibly a wall or a large piece of machinery. The lighting is focused on the men and the equipment, creating a professional and scientific atmosphere.

*Creating a path toward an
energy future with
significantly reduced greenhouse
gas emissions*

Professor Anders Nilsson (right) and graduate-student researcher Anton Nikitin work on characterizing nanomaterials in the Stanford Synchrotron Radiation Laboratory.

GCEP Activities

GCEP's activities fall into two complementary categories: Analysis and Research. In the Analysis area, we assess the potential of processes and technologies to deliver useful energy and reduce greenhouse gas emissions. In our Research area, we develop the science and technology that will help us reach this goal.



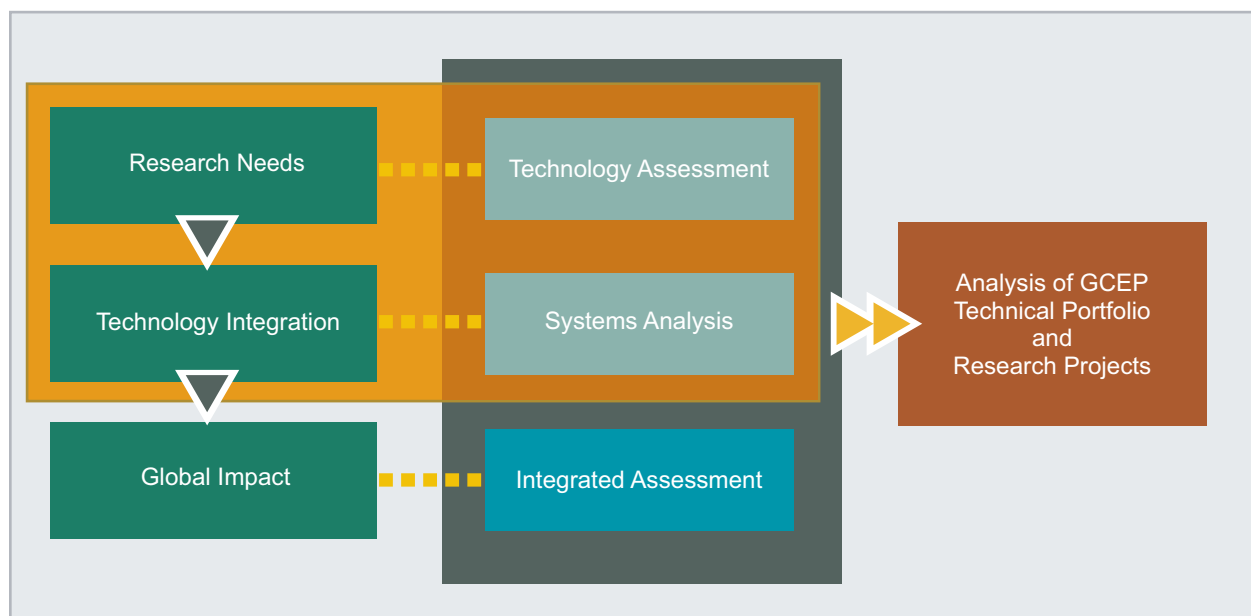
Professor Jonathan Stebbins and post-doctoral researcher Namjun Kim use a nuclear magnetic resonance (NMR) spectrometer to study the structure and dynamics of ceramics for applications in fuel cells.

"Energy is a central issue at the intersection of environment and development. If we can get energy right, we can solve many of our other environmental problems. GCEP's research activities will accelerate the development of breakthrough technologies that will help provide clean energy sources for our future."

Pamela Matson

Dean, School of Earth Sciences
Stanford University

Analysis



GCEP conducts both Technology Assessment and Systems Analysis. In collaboration with our Integrated Assessment project, these analyses can explore whether a research concept might be feasible, as well as to what degree the concept may lead to an improvement of our environment.

Delivering and using energy efficiently while reducing greenhouse gas emissions requires many good ideas, creative proposals, and innovative research projects. Finding the most promising of these projects—and determining whether the technologies developed can be successfully integrated together—is vital to our mission.



The GCEP analysts assess the potential of research concepts to contribute to efficient energy systems with reduced greenhouse gas emissions. (From left: Paolo Bosshard, A.J. Simon, Rebecca Hunt, Emilie Hung, Wes Hermann.)

Technology Assessment

GCEP analysts perform technology area assessments on the current state of the art to identify basic research opportunities that may enable dramatically lower greenhouse-gas-emitting energy technologies. The assessments consider the technical barriers to the establishment or adoption of promising technologies, and identify opportunities for science and engineering research to overcome them. The analysts produce these reports as a guide for the Project and as a service to the greater energy community. The technical areas we are currently assessing, as well as those we plan to consider in the future, are shown below.

Current:	Future:
<ul style="list-style-type: none">▪ Hydrogen Production, Storage, and Use▪ CO₂ Capture▪ Wind Energy▪ Biomass Energy▪ Solar Energy▪ Advanced Transportation▪ Advanced Coal Technologies▪ Other Renewables	<ul style="list-style-type: none">▪ Advanced Nuclear Energy▪ Energy Distribution, Storage, and Infrastructure▪ Geoengineering

Systems Analysis

Systems analysis provides data on how energetically viable a technology may be. GCEP's goal is to assess the potential of technologies to transform energy and matter into forms we can use. We do this by developing computational models that provide us with detailed information on technologies, both existing and proposed, whether they are operated individually or as part of a complete energy system. In developing our models, we are building new analysis tools that could assist in technology innovation as well as energy integration.

Our models provide information crucial to discovering which technologies may be most promising and how we might improve technologies already in use. Just as important, they give us the means to compare the performance of technologies against thermodynamic limits. Using this information, we are able to compare potential technologies to one another and to focus on those that prove most promising.

Graduate students and staff from the GCEP Systems Analysis Group discuss energy systems modeling in the control room of the Advanced Energy Systems Lab.



Research

GCEP is organized around a variety of research areas it is considering over the course of the Project. We are working to build a diverse portfolio of innovative technologies to reduce greenhouse gas emissions. Currently, we have 28 research efforts underway at Stanford and at leading research institutions in the United States and worldwide in the following areas:

- Solar Energy
- Biomass Energy
- Hydrogen
- Advanced Combustion
- CO₂ Capture and Separation
- CO₂ Storage
- Advanced Materials and Catalysts
- Integrated Assessment

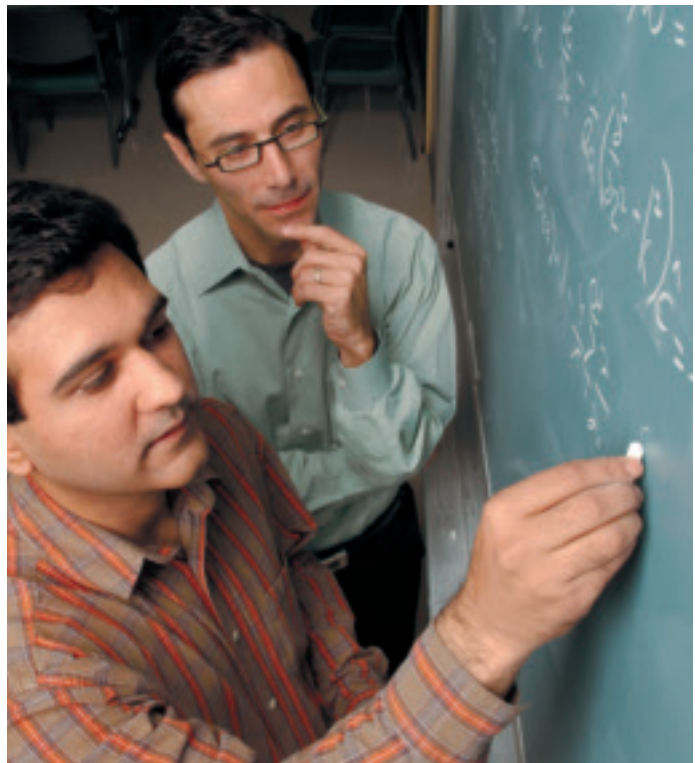
GCEP will continue to request, review, and award projects in these and other research areas.

"The cutting-edge research that GCEP is conducting today could have a profound effect on our future.

The technologies developed under this program could shape the way we use energy in the next 10 to 50 years."

Arthur Bienenstock

Vice Provost and Dean
Research and Graduate Policy
Stanford University



Petroleum Engineering Professor Hamdi Tchelepi (right) and post-doctoral researcher Amir Riaz formulate equations for a numerical simulation framework for the sequestration of CO₂.

GCEP Ongoing Research Efforts

Solar Energy

- > Ordered Bulk Heterojunction Photovoltaic Cells
- > Inorganic Nanocomposite Solar Cells by Atomic Layer Deposition
- > Nanostructured Metal-Organic Composite Solar Cells
- > Nanostructured Silicon-Based Tandem Solar Cells
- > Photosynthetic Bioelectricity

Biomass Energy

- > Genetic Engineering of Cellulose Accumulation
- > Directed Evolution of Novel Yeast Species

Hydrogen

- > Biohydrogen Generation
- > Monitoring Bioconversion Processes
- > Micro and Nano Scale Electrochemistry Applied to Fuel Cells
- > Nanomaterials Engineering for Hydrogen Storage
- > Hydrogen Effects on Climate, Stratospheric Ozone, and Air Pollution
- > Nuclear Magnetic Resonance Studies of Ceramic Materials for Fuel Cells
- > Atomic Force Microscopy Measurements of PEM Fuel Cell Processes

Advanced Combustion

- > Controlled Combustion
- > Development of Low-Irreversibility Engines
- > Sensors for Advanced Combustion Systems
- > Coal and Biomass Char Reactivity
- > Process Informatics
- > Optimization of Synthetic Oxygenated Fuels

CO₂ Capture and Separation

- > Advanced Membrane Reactors for Carbon-Free Fossil Fuel Conversion
- > Development of Innovative Gas Separation Membranes

CO₂ Storage

- > Rapid Prediction of Subsurface CO₂ Movement
- > Seal Capacity of Potential CO₂ Sequestration Sites
- > Geophysical Monitoring of Geologic Sequestration
- > A Numerical Simulation Framework for CO₂ Sequestration

Advanced Materials and Catalysts

- > Electrocatalysis with Discrete Transition Metal Complexes

Integrated Assessment

- > Integrated Assessment of Technology Options

"The challenge of developing solutions to the global energy problem requires the combination of many disciplines through the natural sciences, engineering, and social sciences. Stanford provides a unique venue where basic and applied work in each of these areas can come together. The problem of providing energy in a time of limited fossil fuels is critically important for the economy, for our free society, and for the national and global environments."

Sharon Long

Dean, School of Humanities and
Sciences
Stanford University

Renewable Energy

Renewable energy resources are a growing part of our energy mix. As technology progresses, wind, solar, geothermal, biomass, and ocean-based power will become more viable. But to become fully competitive with other energy resources, we must improve the power density, efficiency, and cost of renewable energy devices.

Solar

Direct solar-electricity energy conversion generally requires the fewest transformations from the primary resource to create electricity and emits no greenhouse gases. The best solar cells now available commercially cost about \$3 per watt of power, but to be competitive, the cost must drop to around \$0.30 per watt. GCEP is sponsoring five projects in this area, of which four focus on solar cells at the nano scale. Each is taking a different approach to addressing the need to increase efficiency of these cells and reduce the costs of energy conversion.

Professors Stacey Bent, James Harris, and Michael McGehee, of the departments of Chemical Engineering, Electrical Engineering, and Materials Science and Engineering, respectively, are attempting to fabricate **inorganic nanocomposite solar cells by atomic layer deposition (ALD)**. They are applying this technique to manufacture solar cells by depositing multiple layers of material that are just several atoms thick on rough surfaces. If successful, this activity could lead to ways to quickly and cheaply produce improved inorganic solar cells.

Professor Martin Green and Dr. Gavin Conibeer of the University of New South Wales (UNSW) in Sydney, Australia, are developing **nanostructured silicon-based tandem solar cells**. By creating a lattice of quantum dots made from silicon or similar materials within a set of silicon-based thin films, this project offers the potential for developing highly efficient solar cells with materials that are inexpensive, abundant, stable, non-toxic, and durable.

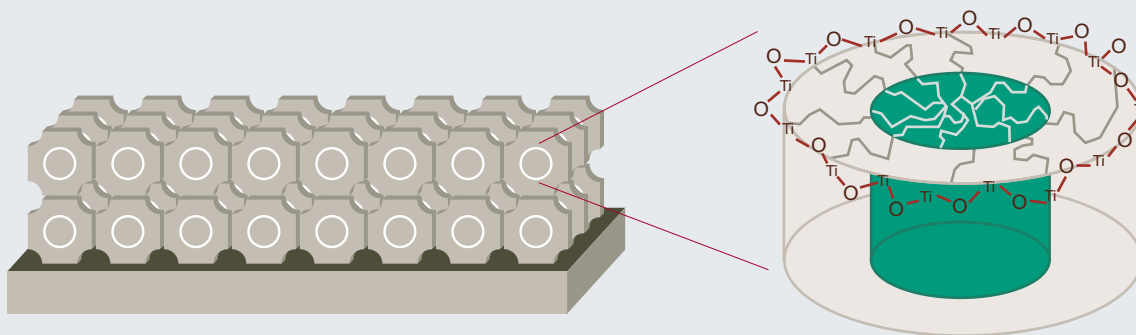
In another project, Professor McGehee and his research team hope to achieve a breakthrough by producing **ordered bulk heterojunction photovoltaic cells** on flexible sheets that could be produced using reel-to-reel coating machines similar to those that make food packaging (see box on next page).



Professor Martin Green (right), Dr. Gavin Conibeer (left), and graduate-student researcher Giuseppe Scardera (middle) of UNSW operate a Plasma-Enhanced Chemical Vapor Deposition Machine to create low-cost, efficient, and long-lasting solar cells.

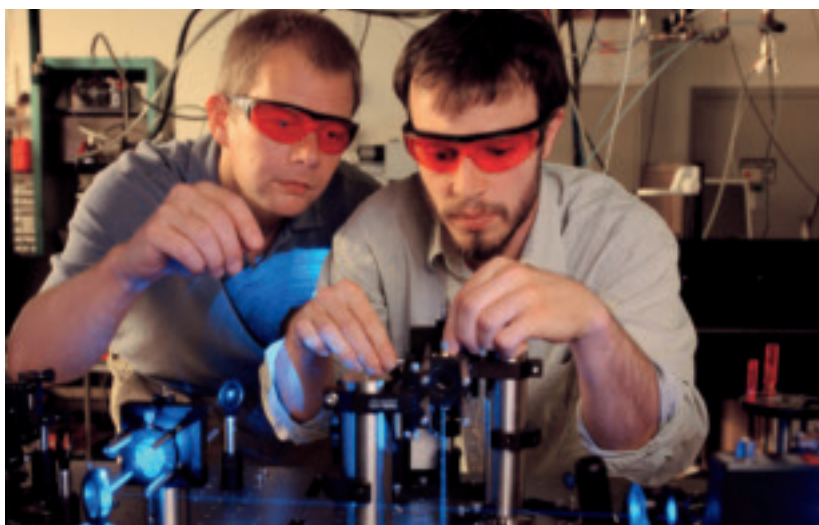
A New Solar-Cell Design

Designing high-efficiency bulk heterojunction solar cells is a major challenge requiring specialized forms and configurations of materials. For example, cell materials must be thick enough to absorb light effectively, but thin enough such that the electrons and holes (the energy carriers created by sunlight in these materials) do not have a chance to re-combine before they can be harvested for electricity production. Professor Michael McGehee of the Materials Science and Engineering Department at Stanford and his research team are meeting this challenge by developing well-ordered interpenetrating networks of organic and inorganic semiconductors to create nanostructured photovoltaic cells. In these structures, electrons and holes have direct pathways to electrodes, ensuring that they travel the shortest possible distance and are not trapped at dead ends. To make the interpenetrating nanostructures that are needed, the researchers are fabricating nanoporous films or nanowire brushes using an inorganic semiconductor and filling the pores with a semiconducting polymer. One example of such a strategy is shown here in which a hydrophobic polymer (green) is burned out, leaving a nanoporous structure (grey) more than 100 layers tall (two layers are shown below). This structure is thick enough to absorb light, yet has a length between pores short enough to minimize recombination of electrons and holes.

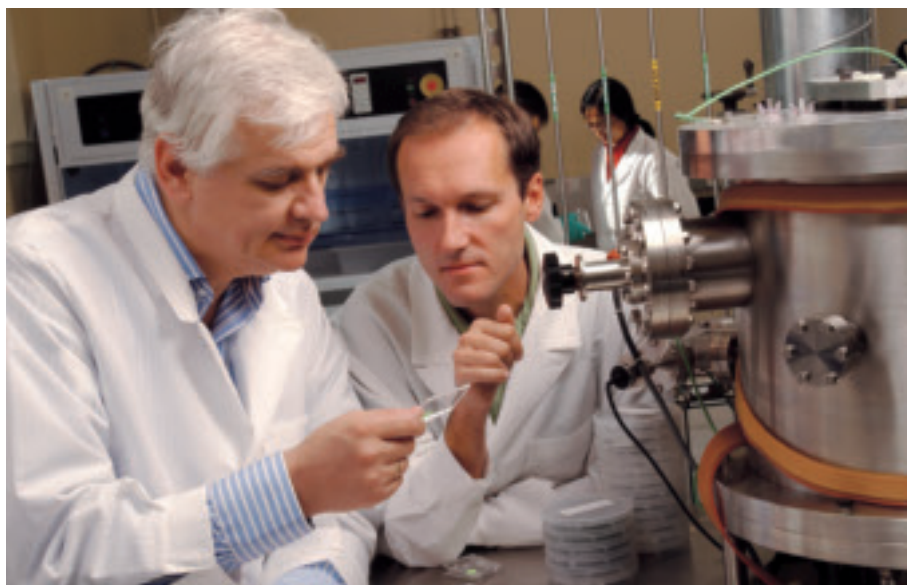


A project using **nanostructured metal-organic composite solar cells** aims to reduce the cost of photovoltaics by creating a hybrid cell design that pairs organic photovoltaics with metal nanoscale features. Because organic-based solar cells should be less expensive but are typically less efficient than inorganic solar cells, Professors Mark Brongersma of Materials Science and Engineering and Peter Peumans and Shanhui Fan of Electrical Engineering are working with their teams to integrate nanopatterned metal films and embedded metal nanostructures into organic cells. The metal particles will be used to focus light at the junctions where the electric charge is separated, thereby increasing the efficiency of these organic photovoltaics.

Materials Science and Engineering
Professor Mark Brongersma and
graduate-student researcher
Alex Guichard use an Argon ion laser
to perform optical experiments on
organic materials for use in highly
efficient photovoltaic cells.



Professors Fritz Prinz of Mechanical Engineering and Materials Science and Engineering and Arthur Grossman from the Department of Plant Biology at the Carnegie Institution of Washington are **monitoring and assessing cellular photosynthesis electrical energy as a potential source of bioelectricity**. They are exploring the possibility of capturing electricity directly from living biological cells by inserting nanoscale electrodes into their chloroplasts.



Mechanical Engineering Professor Fritz Prinz and research colleague Rainer Fasching in the Rapid Prototyping Laboratory at Stanford University examine materials for nanoprobe that could be used in the generation of bioelectricity.

Biomass

Net reductions in CO₂ emissions can be achieved by replacing some of our geologically-derived energy with biologically-derived energy. To accomplish this, we would need to enhance the efficiency and flexibility of biomass production and conversion through improvements in both thermochemical and biochemical processes.

Professor Christopher Somerville of the Department of Biological Sciences is working with his team on **genetic engineering of cellulose accumulation**. Their plan is to modify the cells of *Arabidopsis thaliana* to generate an artificial secondary cell wall containing cellulose, thereby increasing the yield of biomass material without using additional resources.

Biological Sciences Professor Christopher Somerville (right) and Lab Technician Natalia Khitrov collect samples for their research in genetic engineering of cellulose accumulation.



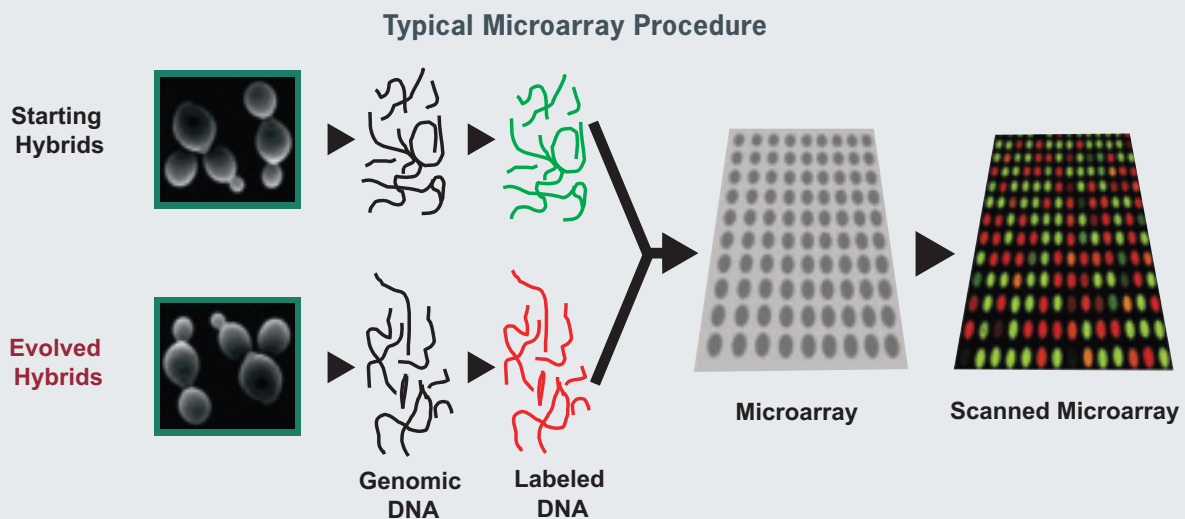
In a project that explores **directed evolution of novel yeast species**, Professor Gavin Sherlock of the Department of Genetics at the Stanford University School of Medicine and Professor Frank Rosenzweig of the Division of Biological Sciences at the University of Montana are using directed natural selection to generate new yeast species that convert xylose from plant biomass to ethanol at higher efficiencies (see below).

A Novel Yeast Species for More Efficient Biomass Conversion

In order to reduce the costs of bioethanol production and make large-scale use feasible, we must be able to ferment a wider range of biomass feedstocks. While typically only simple sugars and starches are utilized for ethanol production, cellulose and lignin make up the majority of the material in plants. Significant cost reductions may result from using a larger portion of a given plant for ethanol production. In order to ferment lignocellulosic material, we need a microbial system capable of breaking down these molecules and fermenting the resulting hexose and pentose sugars.

Biochemical processes to convert biomass will benefit greatly from hybrid yeast strains that can aggressively ferment sugars from pretreated forest and agricultural residuals. Professor Gavin Sherlock and his team from the Stanford University School of Medicine are partnering with Professor Frank Rosenzweig and his team from the University of Montana to evolve adaptively a hybrid yeast strain that would double the production of ethanol from biomass.

The researchers have chosen to work with an organism called *Saccharomyces cerevisiae*. While it is able to ferment the hexose sugars in cellulose to ethanol, this organism normally lacks the ability to produce ethanol by the fermentation of pentose sugars. The teams will attempt to evolve a hybrid variety of yeast that can accomplish both by using a microarray procedure as shown below. They will create libraries of hybrid yeast strains and apply evolutionary pressures to the hybrid yeasts that exhibit phenotypes useful for producing ethanol from plant biomass.



Hydrogen Production, Storage, and Use

Hydrogen can be a carbon-free energy carrier. GCEP is sponsoring seven diverse projects to help overcome the technical barriers to producing, storing, and using hydrogen in an environmentally compatible way.

Through **biohydrogen generation**, Professors James Swartz of Chemical Engineering and Alfred Spormann of Civil and Environmental Engineering and their research teams are working toward converting solar energy into molecular hydrogen. In this project, they are attempting to develop a conversion system using genetically engineered organisms that can directly use sunlight to generate hydrogen.

In an effort to understand fuel cell behavior at the fundamental level, Mechanical Engineering Professor Fritz Prinz and his research group are **applying micro- and nano-scale electrochemistry to fuel cells**. This kind of scientific understanding of minute processes within fuel cells is crucial to lowering operating temperatures, reducing costs, and making further progress in hydrogen power.

In their **nuclear magnetic resonance (NMR) studies** project, Professor Jonathan Stebbins of Geological and Environmental Sciences, Professor Prinz, and their research teams aim to provide a better basis for predicting and optimizing the properties of ceramic materials for use in fuel cells. Their goal is to improve the performance of ceramic materials in fuel-cell-based hydrogen power systems.

One key challenge of hydrogen-based power is producing hydrogen without producing carbon dioxide as a by-product. Through research in **micro-scale electrochemical probes for monitoring bioconversion processes**, Professor Prinz and his graduate-student researchers are developing measurement techniques and tiny sensors for tracking the direct production of hydrogen in engineered biological systems.

Wing-On (Jacky) Ng, a post-doctoral researcher in Civil and Environmental Engineering, examines cyanobacterial cultures that will be used in a biohydrogen experiment.



Solid polymer fuel cells could be an efficient and clean power source, but a better understanding of ion diffusion is needed. Professors Peter Pinsky of Mechanical Engineering and David Barnett of Materials Science and Engineering and their group are examining the properties of polymer electrolyte membranes through **modeling, simulation, and characterization of ionic transport and impedance in proton exchange membrane fuel cells**. This knowledge could enable creation of new classes of solid polymer fuel cell membranes with improved performance.

Due to their large surface areas and relatively small mass, single-wall carbon nanotubes have long been thought to have potential for high-capacity storage of hydrogen. But variability in early experimental results cooled many scientists' enthusiasm. In our **nanomaterials engineering for hydrogen storage** project, an interdisciplinary research team is systematically studying high-capacity carbon nanotube materials that store hydrogen (see below).

Finally, we are examining **hydrogen's effects on climate, stratospheric ozone, and air pollution**. Using a numerical model that represents the replacement of current and future fossil fuels emissions with hydrogen-related emissions, Professors Mark Z. Jacobson of Civil and Environmental Engineering and David Golden of Mechanical Engineering, and their research group are creating a comprehensive assessment of the potential effects on the atmosphere of converting vehicle and electric power sources worldwide to hydrogen.

Designing Carbon Nanotubes for Storing Hydrogen

Carbon nanotubes have the potential to store H_2 at a high specific energy density. However, not all carbon nanotubes act in the same way, and this has led to inconsistent results in previous research. GCEP has assembled an interdisciplinary team of scientists and engineers with a mission to design high-hydrogen-capacity carbon nanotubes and provide a definitive answer to the question of hydrogen storage in these materials. This team is systematically investigating the capacity of carbon nanotubes for hydrogen storage and is developing nanotubes that will allow easy capture and release of hydrogen. The process being followed is shown in the chart below.

Professor KJ Cho of the Mechanical Engineering Department is using Intelligent Computer Aided Materials Design to determine material requirements at the quantum level. Professor Hongjie Dai of the Chemistry Department is investigating the chemical reactivity of the material, which depends on both the nanotube size and the composition of the embedded catalyst particles. Professor Bruce Clemens of the Materials Science and Engineering Department is using a variety of techniques to build the nanotubes in a reliable and repeatable fashion. Finally, Professor Anders Nilsson of the Stanford Synchrotron Radiation Laboratory is employing X-Ray Spectroscopy and Temperature Desorption Spectroscopy to characterize the nanotubes and ensure uniformity of manufacturing and storage capacity.



Advanced Combustion Science and Engineering

Combustion science has increased our understanding of the chemical processes that transform fuel and oxygen to energy we can use. GCEP is sponsoring six research projects in combustion science in the Mechanical Engineering Department at Stanford. Each looks at this topic from a different vantage point, and each strives to advance knowledge that will make our use of fuels more efficient and less polluting.

Chemistry is the essence of combustion systems, from internal combustion engines to gas turbines. Understanding combustion processes is at the heart of designing new devices that will increase efficiency and limit pollution.

Professor David Golden leads the **process informatics** group, which is working to develop standardized computational models of chemical reactions that will be accepted worldwide, leading to faster design of new, more efficient combustion devices.

In a conventional engine, combustion occurs very rapidly in an uncontrolled process that cannot be reversed once it has begun. Through GCEP, teams of researchers are working toward taming the combustion process so that it delivers more work, more efficiently. Professor Craig T. Bowman and his team, for example, are looking into the fundamental processes of **controlled combustion**, work that must be completed before engineers can design more efficient high-pressure combustion systems such as gas turbines and diesel engines.

The work of the controlled combustion team will complement the research of another GCEP group—led by Professor Christopher Edwards—studying the **development of low-irreversibility engines**. These engines of the future hold the promise of significantly improving efficiency by capturing and putting to work chemical energy that is released—and currently unused—during the combustion process.

High-efficiency diesel engines can contribute significantly to reducing greenhouse gas emissions from transportation. Synthetic oxygenated fuels would allow these engines to operate with extremely low soot emissions. Professors Bowman, David Golden, Ronald Hanson, and Heinz Pitsch of the Department of Mechanical Engineering, in collaboration with Dr. Ripudaman Malhotra from SRI International, are studying the **optimization of synthetic oxygenated fuels**. Their research aims to develop new oxygenated fuels and establish the chemical kinetic models required to design next-generation combustion engines that could run on those fuels.



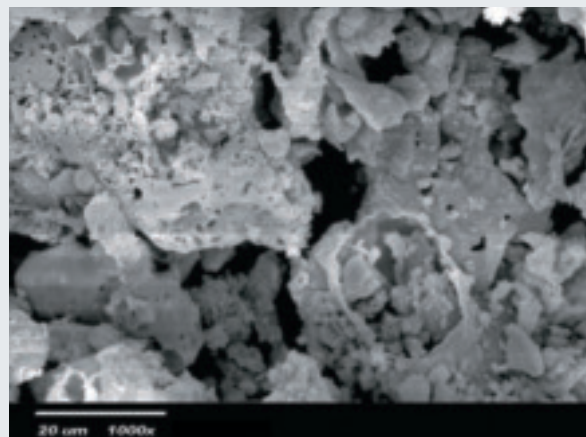
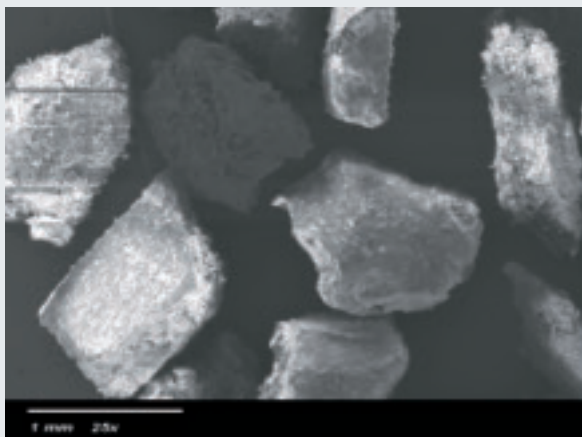
Mechanical Engineering graduate-student researcher Adela Bardos works on a high-pressure flow reactor to investigate combustion of synthetic oxygenated fuels.

In another project, Professor Hanson and his research team are seeking to develop **sensors for advanced combustion systems** that will help engineers design the fuel-efficient, clean-burning combustion engines of the future. These sensors may one day be used to detect instabilities in the combustion process as soon as they begin. With sensors in place, engine designers will have more control over the combustion process, which we hope will lead to improvements in fuel efficiency and air quality.

By increasing the percentage of our national energy supply that comes from renewable sources, we hope to lessen the impact of fossil fuels on our environment. In an effort to combine renewable energy and energy from fossil fuels, Mechanical Engineering Professor Reginald Mitchell and his research group are studying **coal and biomass char reactivity**. Ultimately, this work will help engineers design processes to efficiently convert coal and wastes from plants and animals to energy, and to determine the best conditions for doing so (see below).

Characterizing Coal and Biomass Char

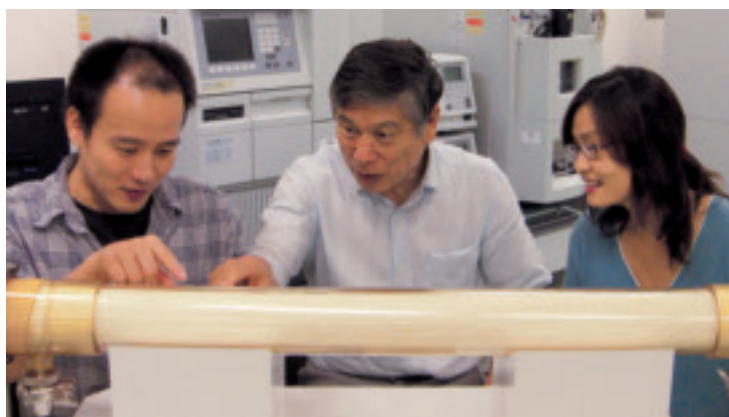
Replacing coal with biomass in power plants offers a potentially attractive option to achieving a net low-CO₂-emitting energy system. However, the combustion characteristics of various forms of biomass are sufficiently different from each other (and from coal) that combustor designs must be significantly changed. The temperature, pressure, and residence time in the combustor all influence the efficiency of energy conversion and nature of the combustion products. Some biofuels have high gas yields upon heating, rendering them suitable for gasification and reburn applications, while others have high char yields, and are better-suited for co-firing in direct combustion configurations. Professor Reginald Mitchell of the Mechanical Engineering Department and his team are conducting experiments on biomass char reactivity to provide a detailed knowledge of the combustion process for various fuels. For example, the figure below shows a Scanning Electron Micrograph of unburned (left) and partially burned (right) almond shell particles. By taking a "snapshot" of the fuel particles during the combustion process, they can collect the data to optimize the conversion efficiency of this renewable resource.



CO₂ Capture and Separation

It is possible for greenhouse emissions to be reduced by capturing and storing CO₂, but to do so, the CO₂ must first be separated from other gases. One method of CO₂ separation utilizes membranes that are capable of allowing some gases to pass through while others remain trapped. Membranes may be organically based, made up of plastic-like materials with chemical binders on them, or they may be inorganic with pores that are selective for CO₂ or other desired products. GCEP is funding two projects examining membranes in different ways.

Drs. Koichi Yamada, Shingo Kazama, and Katsunori Yogo at the Research Institute for Innovative Technology for the Earth (RITE) in Japan are developing **innovative gas separation membranes through sub-nanoscale materials control**. RITE has found a way to control pore geometry to a few tenths of a nanometer to better select for CO₂ from H₂ or N₂ and to allow for more efficient separation.



RITE investigator Koichi Yamada (middle) examines a CO₂ separation membrane module with researchers Satoshi Kodama (left) and Masayo Okuda (right).

Organic materials tend to melt at high temperatures, so a collaborative effort between the Energy Research Centre of the Netherlands (ECN) and the Delft University of Technology (TU Delft) is investigating the use of inorganic membrane materials for H₂ and CO₂ separation. Use of these materials that have the ability to withstand higher temperatures could allow membranes to be used during combustion rather than in a separate process, thereby greatly increasing the efficiency of the process. This project addressing **carbon-free conversion of fossil fuels using advanced membrane reactors in energy systems** is being led by investigators Daniel Jansen, Wim Haije, Jan Wilco Dijkstra, and Ruud van den Brink of ECN and Professors Cor Peters and Joop Schoonman of TU Delft (see box on next page).



ECN investigator Wim Haije and graduate-student researcher Virginie Feuillade use a test rig to screen catalysts for advanced membrane reactors.

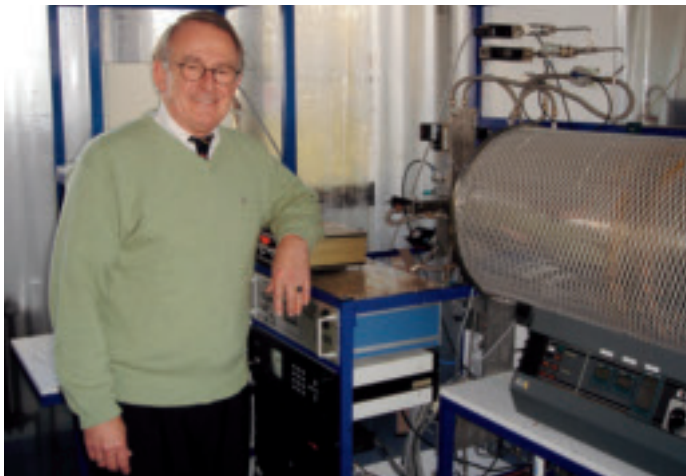
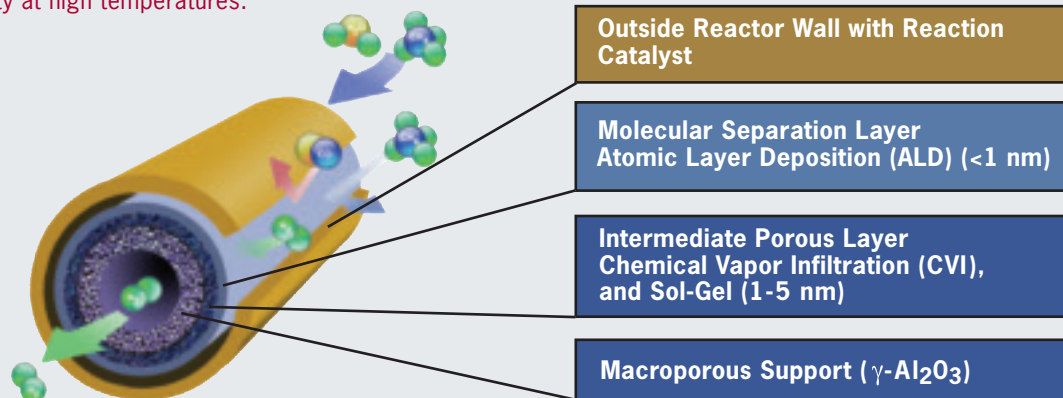
A One-Step Process for Separating CO₂ in Reforming Reactors

Since many CO₂ separation processes involve organic membranes, which have a relatively low melting point, they cannot be used during combustion activities. Therefore, natural gas reforming for carbon-free hydrogen production or electricity generation currently requires an additional step to separate CO₂, adding time and cost to the process.

Investigators Daniel Jansen, Wim Haije, Jan Wilco Dijkstra, and Ruud van den Brink of the Energy Research Centre of the Netherlands (ECN), and Professors Cor Peters and Joop Schoonman of the Delft University of Technology (TU Delft) are collaborating to develop new membranes that will operate at temperatures over 400°C for compatibility with natural gas reforming. They are focusing on three membrane materials for CO₂ separation: functionally-graded H₂ membranes, hydrotalcite membranes, and ionic liquid membranes.

The team is building tubular nano-porous ceramic structures to separate hydrogen. Chemical Vapor Infiltration and Atomic Layer Deposition techniques are being used to tune the pore size at the nano scale to allow selective diffusion of hydrogen. Hydrotalcite and ionic liquid membranes separate CO₂ by adsorbing it from the gas mixture present in the reformer and subsequently releasing it in a separate volume.

All these membranes are being engineered to achieve not only optimal stability but also high selectivity and permeability at high temperatures.



TU Delft Professor Joop Schoonman uses the Atomic Layer Deposition technique to control the pore sizes of new membrane materials.

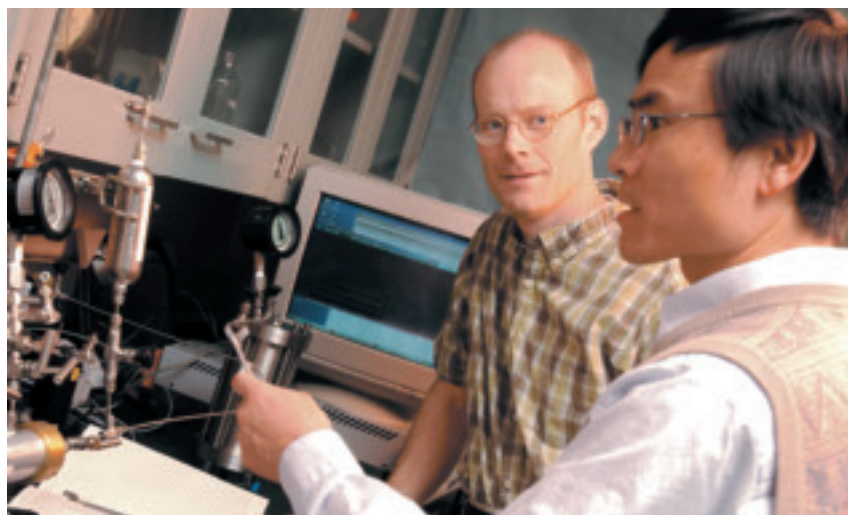
CO₂ Storage

Whatever transitions in energy systems take place over the coming decades, the storage of carbon dioxide in geologic structures is needed as one way to reduce the level of emissions from the use of fossil fuels. To that end, GCEP is currently sponsoring a number of research projects in CO₂ storage.

The Earth's crust offers three major classes of geologic formations that may be suitable for long-term storage of carbon dioxide: deep formations containing salt water (aquifers), coal beds that cannot be mined, and oil and gas reservoirs. But before we inject carbon dioxide into geologic formations on a large scale, we must be able to predict the movement of the gas and the potential for long-term storage. Petroleum Engineering Professor Anthony Kavscek and his research team are studying the **rapid prediction of CO₂ movement** and developing numerical methods to predict flow that are accurate, high in resolution, and low in computational costs. Their goal is to help determine the best places to inject carbon dioxide for high storage over the long term.

Professors Hamdi Tchelepi, Louis Durlofsky, and Khalid Aziz from the Department of Petroleum Engineering, in collaboration with Dr. Patrick Jenny from the Swiss Federal Institute of Technology Zürich, are working on a **numerical simulation framework for CO₂ sequestration in subsurface formations**. They plan to identify the physical mechanisms associated with CO₂ injection and storage in subsurface formations and develop mathematical models of this complex scenario. These models will span multiple time scales, from the CO₂ injection period all the way out to the thousands of years required to assess long-term containment.

Another GCEP team of researchers, led by Geophysics Professor Mark Zoback, is investigating **geologic integrity of oil and gas reservoirs, aquifers, and coal beds for potential use in CO₂ sequestration**. Because carbon dioxide is more buoyant than the water or oil originally found in storage reservoirs, pressure can build at the top or deep within the holding area. The pressure could fracture the cap of the reservoir causing a leak from the top, or it may activate faults inside the reservoir causing a leak of gas from within. GCEP scientists have traveled to sites in West Virginia, Saskatchewan, the San Juan Basin of New Mexico, and the Powder River Basin of Wyoming to investigate the seal capacity of reservoirs and to determine their potential use for CO₂ storage.



Professor Anthony Kavscek and Research Associate Tom Tang discuss their experiment examining the movement of CO₂ through coal. They are working to predict accurately the behavior of CO₂ injected in various geologic formations.

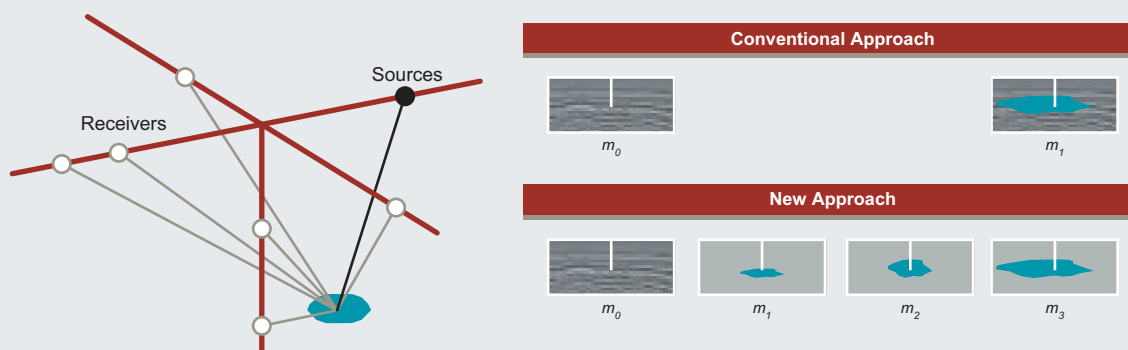
GCEP research in **geophysical monitoring of geologic sequestration** allows us to keep track of carbon dioxide below the surface of the Earth. This monitoring project has two purposes: to determine the effectiveness of a CO₂ injection and to verify that the gas is contained safely. Geophysics Professor Jerry M. Harris and his research group are studying several methods of monitoring oil and gas reservoirs and saline aquifers during CO₂ injection. In addition to verifying the safe containment of carbon dioxide, they hope to propose new, low-cost methods and strategies for monitoring systems.



Professor Jerry M. Harris (left) and graduate-student researchers Chuntang Xu (middle) and Martins Akintunde (right) discuss subsurface monitoring of geologic sequestration.

Monitoring the Performance of Carbon Dioxide Storage Projects

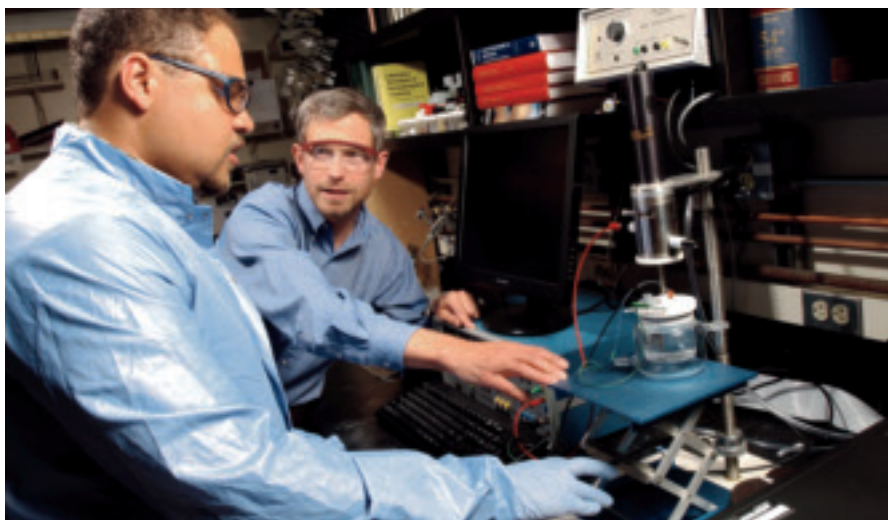
Critical to underground CO₂ storage becoming an acceptable greenhouse gas mitigation technique is the ability to detect, at a reasonable cost, the movement of the injected gas to determine if there is a possibility that it might reach the surface. This need to monitor the health of the reservoir over time cannot be met using current seismic measurement techniques, which tend to be costly and slow. Professor Jerry M. Harris of the Geophysics Department has proposed a solution to both the cost and speed issues. His team asserts that one can conduct monthly, if not weekly, reservoir monitoring at a fraction of the cost of traditional measurements from a single high-resolution picture of the reservoir. The Stanford Cross Linear Array (below, left) is the key to this technique, where sources and detectors are distributed along three linear arrays, two along the surface and one along the injection borehole. The 3-axis array provides reduced 3-D resolution but at greatly reduced acquisition and processing costs relative to the usual 2-D surface array. Both the sources and the receivers are permanently embedded to maximize survey repeatability and reduce deployment costs. The results are shown in the figure (below, right). The top sequence of images is obtained using a traditional technique, in which acquisition times may be too long to take action to prevent a leak. The bottom sequence combines the initial survey data with frequent, low-resolution, low-cost updates to ensure that the direction of CO₂ movement is known at all times.



Advanced Materials and Catalysts

The performance of systems that extract, distribute, store, and use energy is dependent on the properties of the materials from which those systems are built. If we apply optimized materials to standard and new energy conversion processes, we can expect to see improvements in system performance and reductions in CO₂ emissions. Although initially material development may be targeted towards a specific application, the discovery of improved materials is often capable of affecting a wide array of energy technologies.

Chemistry Professor Christopher Chidsey (right) and graduate-student researcher Charles McCrory measure the electrochemical response of a catalyst designed to improve oxygen reduction in fuel cells.



GCEP has several projects whose main focus is material development; however, most of these are listed under their application area. In the specific area of Advanced Materials and Catalysts, Professors Christopher Chidsey, Daniel Stack, and Robert Waymouth from the Department of Chemistry are working with their teams of researchers on **electrocatalysis with discrete transition metal complexes** to develop efficient catalysts for direct-hydrocarbon fuel cells. The objective is to allow the development of fuel cells that create electricity directly from fossil fuels rather than from hydrogen. These fuel cells might be able to operate in two directions through the use of novel catalysts, either generating electricity from hydrocarbons or hydrocarbons from electricity.

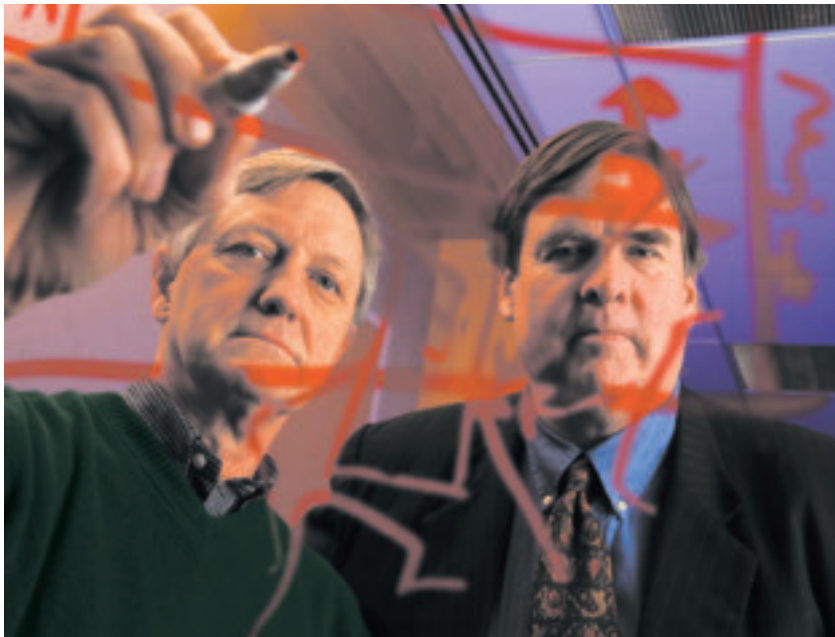
Post-doctoral researcher Xavier Ottenwaelde, seeking to understand how oxygen can be most effectively activated in fuel cells, prepares a frozen solution of a copper compound for spectroscopic study.




Integrated Assessment

Extensive research in innovative technologies, materials, and processes may have an enormous impact on the world's future energy consumption and environment. In order to optimize their research portfolios, organizations such as GCEP require tools to quantify the impact of proposed solutions. Technology research presents a particular challenge because the performance and cost of any given technology is not usually known. In order to estimate the relative success of various research efforts, a systematic integrated assessment can help predict impacts under a range of cost and performance scenarios. This assessment evaluates the significance of GCEP research and how it would impact greenhouse gas emissions.

The **integrated assessment of technology options** seeks to develop a comprehensive analysis system that will serve as a foundation for evaluating the potential of technological options for energy systems with low greenhouse gas emissions. Once in place, the system will give us a way to forecast how quickly innovative technologies might be adopted around the globe. This analysis of technologies—led by Professors James Sweeney and John Weyant of Management Science and Engineering—includes estimates of greenhouse gas emissions and their expected changes over time, individual technology costs and impacts, and the potential for the evolution of the entire energy system at a global scale.



Management Science and Engineering Professors James Sweeney and John Weyant develop programs for assessing technology options for GCEP.

A close-up photograph of a woman with dark hair and a focused expression, looking upwards at a Petri dish she is holding in her right hand. The Petri dish contains a clear agar medium with several dark, streaked bacterial colonies. The background is a blurred laboratory setting with blue and purple lighting. The text is overlaid in the upper right corner.

*Sharing knowledge to address
one of the world's most
challenging energy
and environmental issues*

Research Assistant Soni Shukla checks bacterial growth
in a Petri dish for a biohydrogen generation project.

Looking Ahead

GCEP's goals are admittedly ambitious. It will take the best minds working at the top of their capabilities to meet the challenge of providing more energy while using it more efficiently with less impact on the environment. We work toward meeting our objectives by:

- Expanding our areas of primary research
- Assessing the feasibility of technologies
- Adding more research projects to our portfolio
- Working with and reaching out to institutions around the world
- Communicating our project activities and research results to a growing global audience

GCEP encourages mutually beneficial relationships between our research teams and those at other institutions in both developed and developing countries. We will continue to bring together representatives from academia, industry, and government to create a new path towards an energy future with significantly reduced greenhouse gas emissions.



Graduate-student researchers Steve Compton and Shannon Miller investigate more efficient combustion engines in the Advanced Energy Systems Lab.

"The only way to solve the global energy problem and its related environmental issues is to create technical options for the future—new, clean, renewable energy sources that are economic on a global scale. It is unlikely that a single 'silver bullet' will be found. Multiple technologies, working together in an integrated worldwide fashion, represent the likely future scenario. GCEP is a major initiative, and an exciting new program aimed at discovering some of those options."

James Plummer

Dean, School of Engineering
Stanford University



*Tapping the creativity of
Stanford faculty and students and
talented researchers worldwide
to work on one of the grand challenges
of this century*

Graduate-student researcher Jeong-Hee Ha takes a closer look at thin film materials for an atomic structure study using X-ray diffraction.

GCEP Participants

Stanford Investigators and their Primary Affiliations

Khalid Aziz: *Petroleum Engineering*

David Barnett: *Materials Science and Engineering*

Stacey Bent: *Chemical Engineering*

Craig T. Bowman: *Mechanical Engineering*

Mark Brongersma: *Materials Science and Engineering*

Christopher Chidsey: *Chemistry*

Kyeongjae (KJ) Cho: *Mechanical Engineering*

Bruce Clemens: *Materials Science and Engineering*

Hongjie Dai: *Chemistry*

Louis Durlofsky: *Petroleum Engineering*

Christopher Edwards: *Mechanical Engineering*

Shanhui Fan: *Electrical Engineering*

David Golden: *Mechanical Engineering*

Ronald Hanson: *Mechanical Engineering*

James Harris: *Electrical Engineering*

Jerry M. Harris: *Geophysics*

Mark Z. Jacobson: *Civil and Environmental Engineering*

Anthony R. Kovscek: *Petroleum Engineering*

Michael McGehee: *Materials Science and Engineering*

Reginald Mitchell: *Mechanical Engineering*

Anders Nilsson: *Stanford Synchrotron Radiation Laboratory*

Franklin M. Orr, Jr.: *Petroleum Engineering*

Peter Peumans: *Electrical Engineering*

Peter Pinsky: *Mechanical Engineering*

Heinz Pitsch: *Mechanical Engineering*

Fritz Prinz: *Mechanical Engineering*

Gavin Sherlock: *Genetics*

Christopher Somerville: *Biological Sciences*

Alfred Spormann: *Civil and Environmental Engineering*

Daniel Stack: *Chemistry*

Jonathan Stebbins: *Geological and Environmental Sciences*

James Swartz: *Chemical Engineering*

James Sweeney: *Management Science and Engineering*

Hamdi Tchelepi: *Petroleum Engineering*

Robert Waymouth: *Chemistry*

John Weyant: *Management Science and Engineering*

Mark Zoback: *Geophysics*

External Investigators

Gavin Conibeer: *University of New South Wales*

Jan Wilco Dijkstra: *Energy Research Centre of the Netherlands*

Martin Green: *University of New South Wales*

Arthur Grossman: *Carnegie Institution of Washington*

Wim Haije: *Energy Research Centre of the Netherlands*

Daniel Jansen: *Energy Research Centre of the Netherlands*

Patrick Jenny: *Swiss Federal Institute of Technology Zürich*

Shingo Kazama: *Research Institute of Innovative Technology for the Earth*

Ripudaman Malhotra: *SRI International*

Cor Peters: *Delft University of Technology*

Frank Rosenzweig: *University of Montana*

Joop Schoonman: *Delft University of Technology*

Ruud van den Brink: *Energy Research Centre of the Netherlands*

Koichi Yamada: *Research Institute of Innovative Technology for the Earth*

Katsunori Yogo: *Research Institute of Innovative Technology for the Earth*

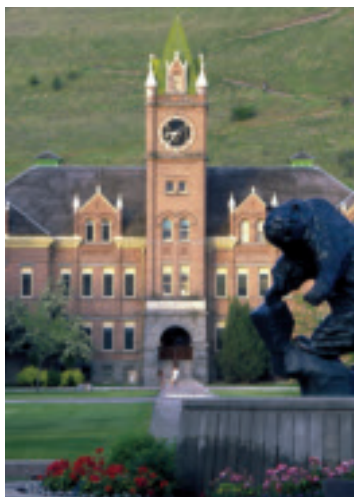
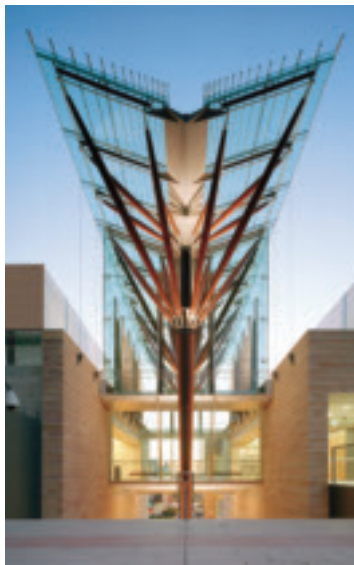


University of Montana Professor Frank Rosenzweig and post-doctoral researcher Heidi Kuehne select for traits in hybrid yeast that could increase ethanol production from biomass.

External Institutions

GCEP works with other leading institutions around the world to help complete its research portfolio. These external institutions have specific expertise that complements our research strengths at Stanford, and include:

- Carnegie Institution of Washington
- Delft University of Technology, Netherlands
- Energy Research Centre of the Netherlands
- Research Institute of Innovative Technology for the Earth, Japan
- SRI International
- Swiss Federal Institute of Technology Zürich, Switzerland
- University of Montana
- University of New South Wales, Australia



Clockwise from upper left: Delft University of Technology, University of New South Wales, Energy Research Centre of the Netherlands, Swiss Federal Institute of Technology Zürich, University of Montana, Research Institute of Innovative Technology for the Earth

Graduate, Post-Doctoral, and Other Researchers 2002–2005

Uraib Aboudi	Jeffrey Gable	Yong-Won Lee	Rick Reijers
Martins Akintunde	Kenneth Gillingham	Jose-Manuel Leon	Benjamin Reineman
Cristina Archer	Sandeep Giri	Paul Levine	Amir Riaz
Neelabh Arora	Keith Gneshin	Hejie Li	Gregory Rieker
Natsumi Baba	Vignesh Gowrishankar	Wen Juan Lin	Jolene Robin-McCaskill
Seoung-Jai Bai	Hervé Gross	Henry Liu	Hannah Ross
Adela Bardos	Alex Guichard	Jonathan Liu	Michael Rowell
Rob Bardos	Amy Guy	Michael Liu	Giuseppe Scardera
Sebastian Behrens	Paul Hagin	Xiang Liu	Astrid Schilderman
Robin Bell	Shravan Hanasoge	Yu-Xiang Liu	Katja Schwartz
Debarun Bhattacharjya	Erin Hazel	Amie Lucier	Shawn Scully
Geoffrey Blanford	John Heberle	Kent Lyle	Jason Sese
Marcus Boyer	Wes Hermann	Kelsey Lynn	Carolyn Jennifer Seto
Daniel Braithwaite	Marc Hesse	Lin Ma	Dhruv Sharma
Jennifer Brantley	Katherine Hoffmann	Liqiang Ma	Shashank
Mahmut Deniz Cakici	Tim Hong	David Mann	Yongxing Shen
Katherine Calvin	Zekai Hong	Oscar Mascarenhas	Adam Simpson
Paul Campbell	Cheng-Han Hsieh	Daniel Mattison	Bhavani Shankar Srinivasan
Michiel Carbo	Hong Huang	Charles McCrory	Magdalena V. Sta. Maria
Patrick Caton	Yidan Huang	Galit Meshulam-Simon	James Stapleton
Peter Catrysse	Zubin Huang	G. Michalopoulos	Matthew Svrcek
Marwan Chaar	Taku Ide	Shannon Miller	Tom Tang
Albert Chan	Prahallad L. Iyengar	Jennifer Milne	Eric Tao
Anu Chandran	Jay Jeffries	Jeffrey Moseley	Kwee-Yan Teh
Tanmay Chaturvedi	Kristian Jessen	Brooks Moses	Thorsten Trupke
Jeremy Cheng	Chu-Wei Jiang	Tapan Murkeji	Manav Tyagi
Laura Chiaramonte	Rishabh Kasliwal	Wing-On Ng	Jaime Urban
Alex Choo	Gerard Ketefian	Anton Nikitin	Paul van Beurden
Firoz Alam Chowdhury	Natalia Khitrov	Jonas Olov Nilsson	Subith Sumathi Vasu
Kevin Coakley	Bum Jick Kim	Matthew Oehlschlaeger	Venkatesh Vasudevan
Ian Coe	Namjun Kim	Hirohito Ogasawara	Robin Walsh
Whitney Colella	Sang-Min Kim	Ryan O'Hayre	Kevin Walters
Lourdes Colmenares	Regis Kline	Xavier Ottenwaelde	Chia-wei Wang
Nick Conley	Adam Klingbeil	Zachary Owens	John Weir
David Davidson	Steven Kluiters	Archan Padmanabhan	Kim Woodrow
Anando Devadoss	Satoshi Kodama	Ron Painter	Cindy Wu
Rostam Dinyari	Dirk Koenig	Seongjun Park	David Wynn
Jarrett Dumond	Jason Komadina	Terry Paulish	Wei Xiao
Barbara Dunn	Arthur Kruckeberg	Jean Pierre Pieterse	Chungtang Xu
Zachary Dunn	Jon M. Kuchenreuther	Katie Plzak	Sayaka Yamamoto
Tibor Fabian	Heidi Kuehne	Rojana Pornprasertsuk	Junhao Yang
Kai Fan	Karen H. Law	Jodie Prud'homme	Jacob Zahn
Yaqing Fan	Andrew Lee	Tom Puzzer	Guangyu Zhang
Mathew Farrell	Byeongchan Lee	Pengfei Qi	Zhiyong Zhang
Rainer Fasching	Jung-Yong Lee	Youli Quan	Hui Zhou
Virginie Feuillade	Minhwan Lee	Sona Raeissi	

"Industry perspectives can illuminate the university research process in very important ways: posing questions, challenging researchers, and helping the research groups understand current barriers to technology implementation. GCEP creates a sustained university/industry collaboration on the technical issues of energy use with low greenhouse gas emissions."

Lynn Orr

Project Director

Global Climate and Energy Project
Stanford University

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Maxine Lym, Communications Manager

Kersti Miller, Administrative Associate

Nancy Sandoval, Administrative Associate

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Lee Wood, Administrative Manager

GCEP Sponsors

GCEP sponsors include private companies with experience and expertise in key energy sectors. The sponsoring companies contribute significant financial resources (anticipated up to \$225 million over a decade or more), technical expertise, and insights concerning eventual deployment of energy technologies.

The Project has four sponsors:

ExxonMobil

The world's leading publicly traded petroleum and petrochemical company, plans to invest up to \$100 million.

General Electric

The world leader in power-generation technology and services, plans to invest up to \$50 million.

Schlumberger

The world's leading oilfield services technology company, plans to invest up to \$25 million.

Toyota

The world's second-largest automobile manufacturer, plans to invest up to \$50 million.



Chemical Engineering
Professor Stacey Bent and
graduate-student researcher
Sandeep Giri are developing
an atomic layer deposition
process for making
nanostructured solar cells.

Advisory Board

GCEP has established an external advisory board to provide broad-based advice on the content, direction, quality, and progress of the Project.

Its members are:

Freeman Dyson, *Professor Emeritus, Princeton University*

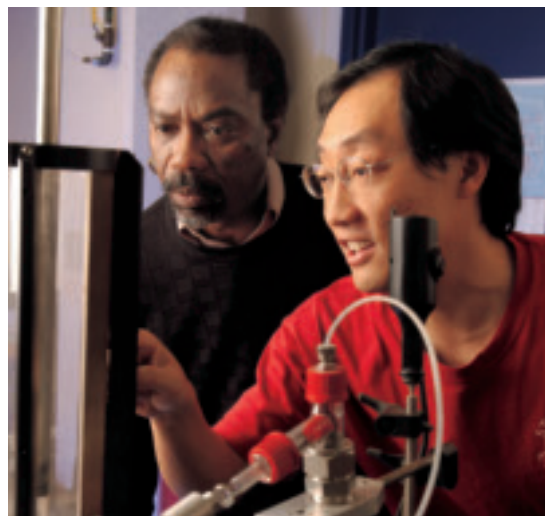
Takao Kashiwagi, *Professor at Tokyo University of Agriculture and Technology, Kyushu University, and Nagoya University*

Martha Krebs, *Former Director of the Office of Science, U.S. Department of Energy*

Frank Press, *Former President of the U.S. National Academy of Sciences, former Science Advisor to the President of the U.S.*

William Reilly, *Former Administrator of the U.S. EPA, President and CEO of Aqua International*

Mark Wrighton, *Chancellor and Professor of Chemistry at Washington University in St. Louis, former Provost at MIT*



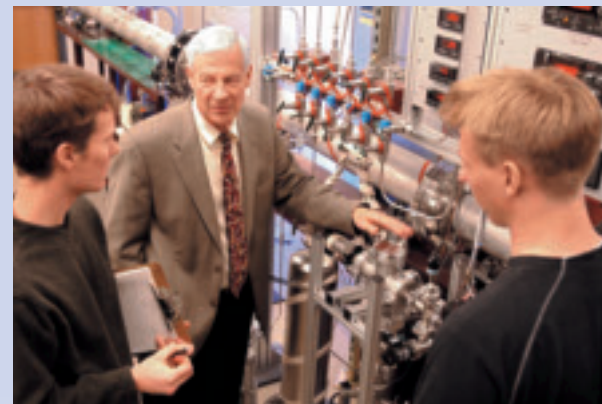
Professor Reginald Mitchell and graduate-student researcher Liqiang Ma investigate the process of converting biomass char to a gaseous species.



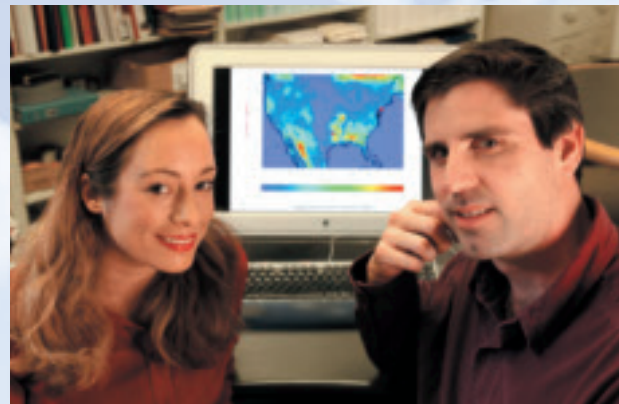
Professors David Barnett (left) and Peter Pinsky (middle) and graduate-student researcher Yongxing Shen (right) discuss their finite element modeling aimed at improving the performance of solid polymer fuel cells.

Professor Gavin Sherlock (right) and senior researcher Barbara Dunn of the Department of Genetics examine a continuous culture system for evolving novel yeast strains that could lead to more efficient conversion of biomass into ethanol.

Chemical Engineering Professor James Swartz (right) and graduate-student researcher Marcus Boyer discuss the production of hydrogenase, an enzyme catalyst for biological hydrogen production.




Mechanical Engineering Professor Ronald Hanson (middle) and graduate-student researchers Matthew Oehlschlaeger (left) and Zachary Owens (right) review the results of their combustion tests in the Shock Tube Laboratory.



Civil and Environmental Engineering Professor Mark Z. Jacobson (right) and post-doctoral researcher Whitney Colella are investigating how the use of hydrogen could impact the atmosphere.



Professor Arthur Grossman (right) and post-doctoral researcher Jeffrey Moseley of the Carnegie Institution of Washington study how different strains of green algae may allow for generation of bioelectricity from light energy.



"The GCEP initiative is grounded in the traditions of the great research universities, bringing a wide range of the basic and applied sciences together in the search for new knowledge. And in so doing, GCEP is building a scientific foundation for creative solutions to bear on some of the Earth's most daunting challenges."

John Hennessy

President
Stanford University

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