S. HRG. 110–380

AMERICA'S ENERGY FUTURE: BOLD IDEAS, PRACTICAL SOLUTIONS

HEARING

BEFORE THE

COMMITTEE ON FINANCE
UNITED STATES SENATE

ONE HUNDRED TENTH CONGRESS

FIRST SESSION

FEBRUARY 27, 2007

Printed for the use of the Committee on Finance

U.S. GOVERNMENT PRINTING OFFICE

41–802—PDF WASHINGTON : 2007

For sale by the Superintendent of Documents, U.S. Government Printing Office
Internet: bookstore.gpo.gov Phone: toll free (866) 512–1800; DC area (202) 512–1800
Fax: (202) 512–2104 Mail: Stop IDCC, Washington, DC 20402–0001

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C O N T E N T S

OPENING STATEMENTS

WITNESSES

ALPHABETICAL LISTING AND APPENDIX MATERIAL

Page

COMMUNICATIONS

AMERICA'S ENERGY FUTURE: BOLD IDEAS, PRACTICAL SOLUTIONS

TUESDAY, FEBRUARY 27, 2007

U.S. SENATE,
COMMITTEE ON FINANCE,
Washington, DC.

The hearing was convened, pursuant to notice, at 10:05 a.m., in room SD–215, Dirksen Senate Office Building, Hon. Max Baucus (chairman of the committee) presiding.

Present: Senators Rockefeller, Bingaman, Stabenow, Salazar, Grassley, Snowe, Thomas, and Bunning.

OPENING STATEMENT OF HON. MAX BAUCUS, A U.S. SENATOR FROM MONTANA, CHAIRMAN, COMMITTEE ON FINANCE

The CHAIRMAN. The hearing will come to order.

In the beginning, God began with energy. God said, "Let there be light," and there was light. We need to begin to think much more about energy because, when we flip on the switch, we still want the sentence to end "and there was light."

America is too dependent on unstable foreign energy sources. Our energy needs are as ubiquitous as the light of day, so disruption of our energy sources could have devastating effects on our economy. Energy security, thus, affects our National security.

So America has a big energy problem, but America finds solutions to big problems. Led by FDR in the 1930s and 1940s, we beat Hitler to the first nuclear bomb by instituting the Manhattan Project. A decade later, an American found the cure for the disease that disabled FDR.

A decade after that, we rose to the challenge of Sputnik and put a man on the moon. Two decades after that, thanks to a good, hard American shove, we saw the empire that created Sputnik fall. I see no reason why we cannot rise to the occasion on energy as well.

Over the next weeks and months, I plan to hold more hearings on energy competitiveness, on energy conservation, and on oil, gas, coal, and alternative fuels.

Other committees are working on this as well, and I want to acknowledge Senator Bingaman's leadership on the Energy Committee. He is doing an excellent job, and I appreciate all the work. I know I speak for everyone in the Senate in thanking him for all he is doing, and we look forward to working with that committee as well.

We need to solve this problem, and we haven't a moment to waste. Today we will get a feel for the energy landscape from four key perspectives: from the States; from science; from the street—that is, Wall Street—the investment community; and security.

What is the answer to the energy problem? I believe there are many. I believe that we should start with another Manhattan Project for energy, and today I am introducing legislation to create an ARPAE.

That is not my original idea, many have come up with it before, but I think it makes sense: Advanced Research Projects Agency for Energy. ARPAE would be a new research agency to help our Nation solve the energy problem that we face.

The new agency would be modeled on DARPA, the Defense Advanced Research Projects Agency, in the Department of Defense. Among the revolutionary technologies that DARPA produced are the Internet and stealth technology for aircraft.

DARPA has been a tremendous success, and I think we can do the same with an ARPAE. ARPAE and other energy efforts will help develop new energy technologies, and these will lead to new products that Americans can sell, both here in the U.S. and overseas.

I believe that other answers to the energy problem lie in alternative energy, in renewable energy, in conservation, and in more efficient uses of conventional sources, with strong consideration for climate change. We have a responsibility to address climate change.

On alternative energy, I believe that we should keep moving on biofuels such as, say, cellulosic ethanol, as well as corn-based. My good friend from Iowa here will certainly appreciate that.

I was pleased to see a cellulosic ethanol plant break ground in Louisiana just a couple of weeks ago, and even more pleased to see one break ground in my home State of Montana, which has abundant biomass for cellulosic ethanol production.

I look forward to hearing what Dr. Arvizu has to say about the widespread production and use of cellulosic ethanol. I am also looking forward to hearing the testimony of Mr. Aimone and his perspective on alternative fuel, especially its use in the Air Force, and the DoD, generally.

Dr. Arvizu is Director of the National Renewable Energy Laboratory, a Federal laboratory that brings science from the research laboratory to the market and consumer use, primarily in the areas of renewable electricity and fuels.

And they say that Mr. Aimone knows more about the Air Force's efforts on alternative fuels than anyone else in the Pentagon. He also happens to have spent a good many years in Montana at Nellis Air Force Base.

On conservation, I believe that we should improve our energy efficiency. As Dr. Dan Reicher will explain—and he is efficiently trying to get from the airport to here right now—there are tremendous gains to be made simply by making good use of the energy that we have.

We can build smarter buildings. We can turn on more efficient light bulbs. We can produce and use electricity more efficiently. We can even do things as simple as turning off our computers at night. Turning off American computer monitors alone could save more than $1 billion a year and millions of tons of greenhouses gases.

Dan heads Google's new Energy and Climate Initiatives, and he will give us an overview of how the investment community can help America make gains in energy efficiency.

And on a more efficient use of conventional sources, we should keep working on ways to burn coal more cleanly. Montana and many other States have a great deal of coal. Montana has about 8 percent of the world's coal reserves. We should make use of this abundant resource, and we should do it responsibly.

Sequestering the carbon emitted from coal-fired plants is the right thing to do, and I am looking forward to hearing Dr. Robert Socolow's testimony on how we can do that.

As Governor Brian Schweitzer knows, we in Montana have more than a passing interest, and we think we have some good ideas on how to accomplish this.

I am very pleased to have with us today my good friend, the Governor from Montana, Brian Schweitzer. As Governor since 2005, Governor Schweitzer has made energy policy the cornerstone of his administration. He has worked hard on renewable sources, on ethanol, biodiesel, and clean use of Montana's vast coal reserves. Brian, thank you so much for taking the time to be with us today.

Dr. Socolow is professor of physics at Princeton and co-director of the Carbon Mitigation Initiative. He will explain, when it comes to energy, there is no silver bullet. There are many things that we can do, and should do, on energy policy and climate change.

Back in the beginning, "God saw that the light was good." We have found it pretty good as well. So let us begin to think and talk more about solving energy problems so that we can continue to let there be light as far as the eye can see.

I would like to turn to my good friend, Senator Grassley.

OPENING STATEMENT OF HON. CHUCK GRASSLEY, A U.S. SENATOR FROM IOWA

Senator GRASSLEY. Yes. Mr. Chairman, you just said something about turning off computers. That reminds me. I want to issue an edict that the Grassley staff turn off their computers, because every morning I come in, half the computers are on, and even some televisions are on and there is nobody working at that hour. So, you are right, we can set an example.

The CHAIRMAN. I thought you worked at that hour.

Senator GRASSLEY. And also, Mr. Chairman, I thank you very much for holding this hearing. There are a lot of things that the Chairman and I have to work on that are not fun and are very difficult to solve. This is one of those that is very fun to work on. It is not necessarily easy to solve, but one that really is an enjoyable issue to have before us.

Over the last 6 years, the Chairman and I have been very successful in identifying energy tax issues that are not only good for the States' economies, our country's economy, but also created domestic energy options for the Nation.

Everyone wants to talk about shaking our growing dependence on foreign fossil fuels, but we will never have that opportunity in our lifetimes, and maybe not in our children's lifetimes, if we do not aggressively identify domestic energy options.

The Finance Committee, of course, has jurisdiction over these things that, through taxes or trade provisions, help create a consistent, sustainable energy policy for this Nation.

As a long-term member of this committee, and just recently chairman, I have aggressively proposed utilizing the tax code to help level the playing field between traditional fossil fuel-powered electricity and petroleum-based fuel refineries.

That has always been done in a bipartisan way, and it has always been done in conjunction with the Senator from Montana, and everybody else on this committee working together.

In fact, for years I have worked to decrease our reliance upon foreign sources of energy and accelerate diversified domestic energy production. I believe public policy ought to promote renewable domestic production that uses renewable energy, and at the same time it will help foster economic development.

Specifically, the development of alternative energy sources should alleviate domestic energy shortages and insulate the U.S. Government from hostile governments that are in the process of supplying a great deal of our oil right now. In addition, the development of renewable energy resources conserves existing natural resources and protects the environment.

Finally, alternative energy development provides economic benefits to farmers, ranchers, and forest land owners such as those in my State of Iowa, who have launched efforts to diversify the State's economy and to find creative ways to extract a greater return from abundant natural resources.

I have been a constant advocate of alternative energy sources. I proposed, and got passed, the first original wind energy credit, and from its inception 14 years ago since we passed it, wind energy production has grown from being almost non-existent to a success story today.

In addition, wind represents an affordable and inexhaustible source of domestically produced energy. It is my hope that the Senate will continue to support this maturing green energy source that has environmental benefits.

Every 10,000 megawatts of wind energy produced in the United States can reduce carbon monoxide emissions by 33 million metric tons by replacing the combustion of fossil fuels. These are important issues as we consider this option today and into the future.

Today I expect to hear many bold ideas on energy policy, but I will be most interested in those ideas that help to empower our rural communities to reap continued economic benefits and the diversifying of our dependence upon foreign oil.

Also important to our future, energy policy studies show that biomass crops could produce between $2 billion and $5 billion in extra farm income for American farmers. If you consider the recent success of ethanol since the Energy Policy Act of 2005, this number may be low. As another example, over 450 tons of turkey and chicken litter are under contract to be sold to a power and electricity plant using only poultry litter.

The plant was built in Minnesota and scheduled to open next month. Coincidentally, that plant is placed right next door to a successful ethanol plant that can now purchase green power.

This is a win-win, not only for the farmer not having to pay to dispose of the litter, but they also get paid to sell it, and the Nation gets 55 megawatts of electricity generated from renewable biomass, not from a fossil fuel.

Luckily, you can find similar examples throughout the Midwest and farm regions across America. In addition, marginal farm lands incapable of sustaining traditional yearly production are often capable of generating native grasses and organic materials that are ideal for biomass energy production.

Turning tree trimmings and native grasses into energy provides an economic gain and serves an important public interest. I hope our continued review of energy policy will promote our research and success in utilizing biomass not only for electricity production, but for alternative fuel markets.

Now to the issue of trade for this committee. I have a growing concern—we all have a growing concern, for that matter—about the U.S. trade deficit. It has been substantially impacted by our continued reliance upon foreign fossil fuels and U.S. reliance upon foreign technology and imported equipment needed to fully utilize capturing and converting wind, solar, and biomass energy options.

Now, according to data published by the Department of Commerce, as a result of the overall rise in the value of energy-related imports in 2006, such imports now account for about one-third of the total value of the U.S. trade deficit.

In 2 years, that has grown very much. It seems, with that sort of a statistic, with such a reliance upon foreign sources of energy, that we need to move in the direction that this committee is headed, as evidenced by this committee and this Chairman's leadership.

The CHAIRMAN. Thank you very much, Senator Grassley.

Now I will begin with witnesses. I urge you to speak in 5, 6, 7, 8 minutes. Your printed testimony will be in the record. But here is your chance to say what you think.

I will begin with you, Governor. Thank you very much, Brian Schweitzer, for coming here.

STATEMENT OF HON. BRIAN SCHWEITZER, GOVERNOR, STATE OF MONTANA, HELENA, MT

Governor SCHWEITZER. Well, thank you very much, Chairman Baucus. I practiced that a lot, because some of you call him Chairman, some of you call him Senator. In Montana, we just call him "Max." So, Chairman Baucus—I have that out right now—thank you for inviting me in.

And Republican Ranking Member Grassley, co-chair, I do not know how you guys run this thing, but I have to tell you, you have been an inspiration, the two of you, for myself when I picked a Republican to be my running mate so that, in Montana, we have a Democrat and a Republican working together in the executive branch. It was the model that the two of you have put together here in Washington, DC that was our inspiration.

Senator Grassley, we were talking about wind, the rural electrification program that brought electricity to your farm. Senator Salazar, has electricity made it to the Salazar ranch yet?

Senator SALAZAR. It just got there.

Governor SCHWEITZER. All right. In farm country, old-timers, and even young-timers, still talk about when we got hooked up.

A few months ago, I was visiting with my 87-year-old father and I said, "Dad, what was the biggest change in your life when electricity made it to the farm?" He considered that for a moment and then he said, "We could weld at a hotter temperature."

You see, they had been generating electricity on their farm for 25 years. They had batteries in their basement. The whole Great Plains had distributed energy, green energy, and they were energy independent 75 years ago.

About 30 years ago, there were Senators sitting in these same chairs and we were discussing the same things in 1978. We were bemoaning that we are importing a large percentage of our oil, and we are importing it from people who are not friendly to our way of life. We had ideas about wind energy and solar energy. Then we lost our resolve.

So I think this time around it is a question of resolve. We do have the technology and we have technologists who are sitting at this table. It is a question of resolve.

In 1980, in response to the last oil shock, American farmers were saying "All right" to the Arabs, the King of Saudi Arabia, "a bushel of wheat for a barrel of oil." Do you remember those days?

While I was a young agronomist, I went to Saudi Arabia. I developed irrigation for 6 years in Saudi Arabia and, in a 7-year period, they went from a position of importing nearly 100 percent of their food to being food exporters because they had a resolve. They said, our way of life is dependent on us being food-independent.

We have an opportunity. We consume 6.5 billion barrels of oil in this country. We produce about 2.5 billion barrels. I think, with new techniques, we can continue to produce that 2.5 billion barrels. Our problem is the 4 billion barrels that we import.

Conservation is the most important thing that we can do today, and it is the only thing that we can do as we speak today: computers, cars, the way we live, the way we travel. The administration has said, is it "Save 20 percent by 2010?" Is it 20 by 10? Is it 10 by 20?

Whatever it is, the administration says we should decrease our consumption by 20 percent. We can do that. I know we can do it, because we did it in that period from 1975 to 1983. We decreased our consumption by 17 percent.

The administration said that we can produce nearly a billion barrels using biofuels. I think we can do that, but do we have the resolve? Because, you see, in order to achieve that goal, nearly every acre of wheat, corn, and soybeans that we currently export needs to be converted to production of fuels.

During the course of the last year, the price of corn has increased by 25 percent, and we are only using a small percentage of those crops to produce fuels. Do we have the resolve to convert those acres to biofuels, with the consequences that food will increase in price? It is a question of resolve.

So now we have decreased consumption by a billion barrels, we have produced a billion barrels of biofuels, and we are still two billion barrels short. I submit to you that some of these solutions will be our neighbors to the north in Alberta.

They have a great quantity of oil that is captured in those sands. It used to be called "tar sands" and then the price of oil went to 50 bucks and they are now called "oil sands." They have enough to replace all of the oil that we are bringing from the Middle East today.

Then another solution is going to be coal gasification. As I look around the room: Kentucky, Wyoming, Montana, West Virginia, New Mexico, Colorado, all coal States. But I submit to you, unless we develop carbon sequestration, unless we are able to store that carbon beneath the surface, coal will not be part of the future portfolio.

So I ask you here today, will you lead? Will you have the resolve? Will you create not only the tax incentives, but the loan guarantees to develop carbon sequestration so that coal can be part of the future portfolio?

We have 400 billion tons. If we converted that at a rate of two barrels per ton, that is 800 billion barrels of oil equivalent. That is a 400-year replacement of that imported oil. I think the time to move is now.

I am just going to give you some suggestions. I have to tell you, thanks for inviting me in today because we have the National Governors here in town. I rented the suit for the entire week, so I was able to get two or three events out of the same suit. Thank you. [Laughter.]

Put a base price of $40, a base price on fuels, domestically produced, technology-neutral, whether you are drilling oil and gas or producing biofuels, or whether you are producing fuels with coal, coal to liquids.

Develop a cap-and-trade system. We have States that are going it alone: Washington, Oregon, Arizona, New Mexico and California announced yesterday. There will be other coalitions. We cannot have a cap-and-trade system that is regional, we need a cap-and-trade system for carbon dioxide that is national.

We have to develop the liability system. Who is responsible for the carbon dioxide that is pumped under my ranch? Who owns the mineral rights under my ranch? I understand that. I do not actually understand who has the rights to put carbon dioxide under my ranch. That has to be developed in the West.

We mentioned it one time before: we need a production tax credit extended for 10 years for these alternatives. We have some great companies around the world that produce wind energy machines, and the waiting period is almost 3 years now because they are not exactly sure whether you are going to act to extend the Production Tax Credit. Please do that for both solar and wind.

I think we need $10 billion for research and development of carbon sequestration. Again, coal will not be the fuel of the future unless we get carbon sequestration correct. We need those loan guarantees to develop these coal gasification plants.

I just would conclude by saying, do we have the resolve to do it in this generation, or will there be another Governor sitting in this chair talking to another group of Senators 30 years from now with the same words and the same language that we used in 1978?

Thank you very much for the opportunity.

The CHAIRMAN. Thank you, Governor, very, very much.

[The prepared statement of Governor Schweitzer appears in the appendix.]

The CHAIRMAN. Now I would like to hear from Mr. Aimone.

STATEMENT OF MICHAEL A. AIMONE, ASSISTANT DEPUTY CHIEF OF STAFF FOR LOGISTICS, INSTALLATIONS, AND MISSIONS SUPPORT, U.S. AIR FORCE, WASHINGTON, DC

Mr. AIMONE. Chairman Baucus, Senator Grassley, distinguished members, thank you for the opportunity to appear today and outline the Air Force's new strategy for energy in the 21st century and describe some of our recent achievements to improve Air Force energy use in our aviation operations, ground vehicle fleet, and the worldwide network of 166 installations.

I would also like to provide the preliminary results of our recent flights of a B–52 bomber using a blend of synthetic and crude oil-based jet fuel.

As stated, I am Mike Aimone, and I work in the Office of the Deputy Chief of Staff for Logistics, Installations, and Mission Support. With 37 years of experience working in the Air Force as a facilities engineer and logistician, I have had the opportunity to be part of the Air Force energy program since its inception in 1974.

Sir, you were at my change-of-command ceremony at Malmstrom Air Force Base as we stood up the 819th RED HORSE Squadron.

In the aftermath of the hurricanes that impacted the Gulf of Mexico 18 months ago, the Secretary of the Air Force directed extraordinary actions by all Airmen to help mitigate the resultant energy issues that faced the Air Force, and the Nation.

One of his first actions was to direct the Under Secretary to lead an aggressive energy strategy for the department. Dr. Sega, the Under Secretary, directed the stand-up of the senior focus group. This focus group has met 7 times and has developed an energy strategy. Its vision is to make energy a consideration in all we do, and its strategy is 3-fold.

First, ensure energy supply-side availability of fuel for our aircraft, ground vehicles, and equipment, as well as reliable utility services for our installations to meet our Combatant Commander's needs.

Second, implement aggressive demand-side fuel optimization and energy efficiency initiatives laser-focused on each of our sectors: aviation, ground transportation, and installations.

Then, third, and indeed the most important element of our energy strategy, is to ensure that our strategy transcends the present to create a lasting culture of change in all Airmen so that energy becomes a consideration in all we do.

To kick-start this cultural change, the Secretary released a letter to all Airmen, and in this letter communicated the goals of the energy conservation program. This letter was followed up with a robust communications program to all Airmen to raise their awareness on energy issues.

The Air Force has had an aggressive facilities energy program that has achieved an impressive 30-percent reduction in energy use over the last 20 years. However, we are challenged to do better.

The President, on the 24th of January this year, issued a new energy Executive Order directing agencies to reduce energy intensity by 3 percent annually through the end of fiscal year 2015, or an additional 30 percent across the Air Force in the next 10 years. So just to repeat, we achieved 30 percent across the Air Force in the last 20, and will do another 30 percent above and beyond that in the next 10.

Besides a new energy conservation goal, the Executive Order establishes new goals in renewable energy, greenhouse gas emission reductions, and water conservation.

We have established that goal and, in order to do this in our ground transportation, have right-sized the fleet. In fact, our goal in the vehicle world is to procure 30 percent of our vehicles in the future as what we call "low-speed" vehicles, or maybe better known in the industry as "neighborhood electric vehicles."

Sir, as you are familiar, our bases are very compact and would allow vehicles that only operated at 30 to 35 miles an hour to be efficiently used on the installation and have tremendous energy efficiency opportunities.

However, 80 percent of the Air Force energy bill, that $7 billion a year bill, goes to fueling our aircraft. Our new strategy is committed to root out waste and implement greater efficiencies in aviation operations. We have set an aggressive target to reduce aviation fuel use by 10 percent over the next 6 years.

We are accomplishing this aviation fuel optimization strategy through a series of operational changes by our pilots and aircraft mechanics. Some changes are as simple as reducing unneeded weight on the aircraft. For example, for every 100 pounds of weight removed off of a large strategic airlift aircraft in the Air Force, we will save 240,000 gallons of fuel over a year and the cost of carrying that fuel.

We have also implemented significant reductions. In fact we found over 2,000 pounds that we could remove off of a KC–135 without impacting most of its operations. So you can do the math yourself as a committee, but we in the Air Force are doing that across the entire aviation fleet, looking at how we can reduce weight on our aircraft.

We are looking at other initiatives in the aviation sector: increased use of simulators, better planning of our flights so that we take advantage of every hour of flight time that we use in training, and then, ultimately, establishing a culture that underpins the use of aviation fuel to optimize that fuel for every flight.

We have made some significant accomplishments, and I would like to offer you, the committee, some of these. The Air Force, in fiscal year 2006, remained the largest green power purchaser of electricity in the United States, over 990,000 megawatt hours. That leads us to be number three in the United States in green power purchases. Thirty-seven of our installations procure green power; three of those are 100-percent electric green.

We have installed over 7 megawatts of on-site wind energy and solar photovoltaic and landfill gas systems at a number of our bases. These systems provide renewable energy for our installations, but also provide for increased energy security in the event of loss of electric power from the grid due to natural disaster or potential enemy attack.

Nearly 8 percent of our diesel fuel use is B–20, which is a blend of 80 percent conventional diesel and 20 percent renewable biofuels. Our efforts to expand the use of E–85 for our flex fuel fleet is less successful. This is because E–85 and its infrastructure is not currently available at the majority of our installations in the United States or worldwide.

However, we are ready. We have over 4,479 flex-fuel vehicles in our fleet. Of that total, about 1,500 are sedans, or nearly 30 percent of our sedans are E–85-ready. Indeed, 58 percent of our Air Force bases dispense B–20 today, 16 dispense E–85.

Mr. Chairman and members of the committee, I assure you that you are probably most interested in our plans to test, certify, and fly a synthetic fuel B–52 bomber, and I would like to report on that today.

Last year, the Secretary directed us to a project to procure synthetic fuel, static ground test that fuel in fuel cells in Oklahoma City's Logistic Center at Tinker Air Force Base, and, if the ground tests were successful, to conduct an aviation flight demonstration at the Air Force Flight Test Center at Edwards Air Force Base, CA.

To ensure maximum crew safety on the first U.S. military jet aircraft powered by domestically manufactured synthetic hydrocarbons, the test was conducted using a 50/50 blend and also only one of the pods, or two engines out of the eight engines of the B–52, were serviced with that blend. We conducted three flights. They were successful.

We also conducted a fourth flight on December 15th. The commander of the Flight Test Center flew the flight and, in fact, all eight engines were powered by synthetic fuel.

The jet was then flown to Minot Air Force, ND. The weather succeeded to our greatest desire, because we desired to do a series of cold-weather engine starts in the month of January. Those tests are complete, and the jet is back at Edwards Air Force Base, going through inspection and rebuild.

The tests, to date, have shown that the synthetic fuel operates effectively in the engine. It has significant reductions in sulfur dioxide, as well as particulates. There is very little change with regard to the amount of carbon dioxide that is produced by the jet engine using synthetic fuel.

It should be pointed out, as we chose the domestic source for synthetic fuel for our first military aviation demonstration, that this was manufactured from natural gas. We recognize that gas-to-liquids do not assure the Air Force a dependable supply of jet fuel, since domestic natural gas production is insufficient to meet the Nation's needs.

The production of synthetic fuel from coal, oil shale, and biomass sources would solve this constraint; however, there are considerable technical, environmental, and economic issues that remain to be worked out.

In that effect, we are partnering with the Department of Energy and the Defense Logistics Agency, as well as the Task Force on Strategic Unconventional Fuels, mandated by section 369 of the Energy Policy Act, to explore what can be done in these areas.

Mr. Chairman, let me conclude that the Air Force appreciates the opportunity to provide an overview of our energy initiatives and the testing and certification of synthetic fuel for the fleet, and I look forward to answering your questions.

The CHAIRMAN. Thank you, Mr. Aimone.

[The prepared statement of Mr. Aimone appears in the appendix.]

The CHAIRMAN. Now I would like to turn to my good friend, Senator Salazar, to introduce the next witness.

Senator SALAZAR. Thank you very much, Chairman Baucus. Let me just say at the outset, to you, I congratulate you for holding this hearing, and to Chairman Grassley. I like the title: "America's Energy Future: Bold Ideas, Practical Solutions."

I think it is the kind of leadership that actually can bring about the bipartisan result that we are looking for here.

As you said, Chairman Bingaman of the Energy Committee is doing the same thing, and Senator Harkin in the Agriculture Committee with the farm bill as well. It gives us tremendous energy to get this thing done.

Now, the question becomes, how do we get there? That is why Dan Arvizu is here. Dr. Dan Arvizu is the Director of the National Renewable Energy Lab. We are very proud to host that in Colorado.

President Bush visited that facility about a year ago. I told the President then, and I have told many of my colleagues in the Senate, that the smartest person in terms of helping us get to the answers that we are seeking in this committee and in other committees is Dan Arvizu.

He has a long history that I will not go over, but let me just say that he received an appointment to be on the National Science Board in the National Science Foundation, and he truly, at the end of the day in his own mind and with all of the employees at the National Renewable Energy Lab, has the answers that we are looking for in terms of the technology fixes that are we looking for in this committee, and in other committees.

So, we are very, very proud of him and very proud of the fact that he is here in Washington today.

The CHAIRMAN. Thank you.

You may proceed.

STATEMENT OF DAN ARVIZU, Ph.D., DIRECTOR, NATIONAL RENEWABLE ENERGY LABORATORY, GOLDEN, CO

Dr. ARVIZU. Thank you, Mr. Chairman. I also want to acknowledge the tremendous support that I have gotten, and the laboratory has gotten, from Senator Salazar. He has been at our laboratory a number of times now and he is a regular visitor, so we do appreciate his support.

I am from New Mexico and live in Colorado, so I actually have great support and friends from two members of your committee. And Senator Bingaman's leadership in this area has also been very, very welcome.

Thank you for this opportunity to discuss important issues related to our Nation's energy policies. I am, as has been stated, the Director of the National Renewable Energy Laboratory in Golden, CO. We call ourselves NREL, so that is how I will refer to us.

NREL is the U.S. Department of Energy's primary laboratory for research and development of renewable energy and energy efficiency technologies. I am very much humbled and honored to get this opportunity to be before you today.

Landscape. Never before have we witnessed here such an intense interest and rapid growth in the renewable energy and energy efficiency technology areas. And while this is certainly very, very welcome, we have a lot of work to do. I want to make sure that people understand that we want the Nation to receive the full benefits that renewable energy and energy efficiency technologies can provide.

What we need, first and foremost, is a careful and balanced blend of new technology, market acceptance, and government policies. The specifics of policies in the Senate must be tailored to fit the unique requirements of the systems we seek to deploy. These are all in various stages of maturity.

At the same time, policies must be put in place with a long-term view in mind. They must be maintained and supported consistently to maximize their effectiveness. We have already witnessed what can happen if our commitment is inadequate or short-lived.

Over the past decade, Denmark, Germany and Spain have surpassed the U.S. in production and employment of wind turbines. Japan and Germany have surpassed the U.S. in the production of electric-producing solar photovoltaic panels.

They did so largely by adopting technologies that were developed here in this country, and many of those I worked on personally, and it is very frustrating. We came up with the right technologies but we failed to capitalize on these innovations with policies to help us adequately spur the deployment in this country.

New energy policy must be true to the realities of our growing economy and our natural environment. For instance, at the Department of Energy's National Laboratory System, including NREL, they have worked intensely on trying to develop new technologies for cellulosic ethanol, which I believe has tremendous promise.

I believe it has a number of attributes that are particularly compelling. It will help us relieve our dependence on foreign oil. At the same time, it is a resource that is distributed throughout the Nation and that many communities around the country can take full advantage of.

But what we are coming to understand is that, if we are to get to where we need to be, which is significant use of this technology, there are a number of other essential pieces of this important puzzle and a massive undertaking that must be addressed.

To achieve the potential of biofuels, in particular, we need to carefully examine such questions as, where will this new supply of biomass come from? It is a very distributed source and, with the platform that we are building on corn, there obviously is a lot more in terms of resource that goes beyond corn.

How will the vehicle fleet in our infrastructure evolve? Ultimately, what will the impacts be on our land, our water, and our air usage? I think these are all a number of issues that we need to address and must be considered as we talk about how we get to this ultimate point where we want to be.

Answers to these essential questions have profound implications. There is no simple academic exercise that gets us there. For this work to be lasting and useful, it must be done in close collaboration with industry and the private sector.

What is called for, then, is a comprehensive integrated program plan for biofuels development which identifies and plans for all the critical factors that are part of this massive undertaking.

Beyond advancing individual energy technologies, we as a Nation should, additionally, establish durable criteria and priorities to determine what our national energy landscape will look like in the future.

As we plot a course for the future and consider the range of energy, environmental, and economic choices that confront us, we must insist the decisions we make today are not only technologically defensible, but also practical, environmentally sound, and sustainable in the future.

The appropriateness of new technology and the sustainability over an entire life cycle must be the guiding forces in our decisionmaking. In addition, we must make new investments in our research capabilities. Adequate research facilities are essential to all of our other R&D goals.

The Nation's world-class laboratory system, in particular, and the leading academic institutions, I believe, need to be retooled and funded, beginning with this year's budget, at an adequate level and sustained and be consistent.

In conclusion, to address our near-term needs, we need a national strategy that promotes rapid deployment of renewable energy systems and processes that are all ready and able to serve us today. This is what I call "harvesting" the investments that we have made in the past.

At the same time, we need to address needs on the longer term. We must make major new commitments to the research required to deliver the next and subsequent generations of new technology.

I do believe we do need innovations to get us to the level of significance that I believe is ultimately available. This will not come without a cost, but recent experience suggests that investments in renewable energy technologies will provide significant economic energy security and environmental benefits. Thank you.

The CHAIRMAN. Thank you, Doctor.

[The prepared statement of Dr. Arvizu appears in the appendix.]

The CHAIRMAN. Dr. Socolow, I might say that Dr. Reicher is about 15 minutes out, so why don't you give your testimony? Then we will get to questions, and we will hear Dr. Reicher when he arrives.

Dr. SOCOLOW. I wondered if you were going to give me 15 minutes.

The CHAIRMAN. I knew you were thinking that. [Laughter.] That crossed my mind. Take as long as you want.

STATEMENT OF ROBERT SOCOLOW, Ph.D., CO-DIRECTOR, THE CARBON MITIGATION INITIATIVE, PRINCETON UNIVERSITY, PRINCETON, NJ

Dr. SOCOLOW. Chairman Baucus, Senator Grassley, and members of the committee, thank you for inviting me to testify today.

I am pleased to be here in my capacity as co-director of Princeton University's Carbon Mitigation Initiative, as a professor of mechanical and aerospace engineering at Princeton, and as an individual concerned about the future of U.S. and global energy policy. I commend you for these hearings.

In 2004, Steve Pacala and I published a paper in *Science* magazine called "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies." We argued for a portfolio of climate change mitigation strategies, each one an immense effort on its own, each involving the scaling up of what we already know how to do.

Among these strategies are the deepening of energy efficiency in buildings, transport, and industry, the deployment of renewable energy, nuclear power, and biofuels, and the capture and sequestration of carbon dioxide produced at coal power plants and coal-to-liquids plants.

Today I will focus my testimony on the strategy that has moved to near the top of the list from the perspective of urgency: carbon capture and sequestration, or CCS, for short.

Mr. Chairman, this really is a time of bad news and good news. The bad news is, the two trains are on a collision course. The good news is, there is still time to switch one of the trains onto a different track.

Train number one is the rush to coal power in the U.S., a consequence of changed expectations about the future natural gas price.

Train number two is the urgency of dealing with climate change, in my view none too soon. Climate change is high on the agenda for U.S. policy. A collision is imminent because burning coal as we have burned it in the past sends more carbon dioxide into the atmosphere for each unit of useful energy produced than any other energy source.

So the rush to coal makes the already-difficult challenge of climate change ever more challenging. The switch is carbon dioxide capture and sequestration, or CCS. Using CCS, when coal is burned, its carbon does not end up in the atmosphere. CCS is commercially mature. It uses proven technologies in new combinations.

Carbon dioxide has long been captured at natural gas-powered plants and coal-powered plants for use by the food industry. A 500-mile carbon dioxide pipeline built 20 years ago has brought carbon dioxide from across New Mexico from Southwest Colorado to the oil fields in Texas. There are no technological reasons to delay full-scale deployment of carbon capture and storage.

The best evidence I know for the readiness of CCS for full deployment in coal plants and coal-to-liquids plants is the 500-megawatt CCS project at BP's Carson refinery near Long Beach, CA. This project of BP and Edison Mission Group received investment tax credits under section 48(b) of the tax code for the 2005 Energy Policy Act.

The project will gasify 4,500 tons per day of petcoke, the bottom of the barrel at a refinery, petroleum coke, a negative-cost fuel. Four million tons of carbon dioxide will be sent off-site each year for enhanced oil recovery. So the entire Carson project is a demonstration to me that we have each of the components that are required, and they are being put together there.

There is another project that is also being developed in Colorado that is nearly as far along, in that case coal gasification, using hydrogen turbines for power, taking carbon dioxide below-ground at the end of the day.

Carbon dioxide capture and sequestration is likely to become a favorable economic strategy for a coal utility at a price of about $30 per ton of carbon dioxide. There is lots of uncertainty in that number, but it is a target number.

Prices on emissions in the same range should also enable other upstream carbon-saving strategies, ending flaring at the oil field and bringing new investments at oil refineries. Carbon dioxide policies should reach far upstream because the low-hanging fruit is upstream.

Efficiency in energy use is where the other low-hanging fruit is to be found. A low-tech air conditioner cooling a poorly-designed and poorly-instrumented office building is as out of place in a climate-constrained world as a coal plant without carbon dioxide capture and sequestration.

Carbon dioxide is the mischief molecule in the atmosphere, but the miracle molecule below ground. Used for enhanced oil recovery, carbon dioxide injects new life into old fields. Quantitatively, a new 1,000-megawatt coal plant will produce about 6 million tons of carbon dioxide per year.

If captured and used for enhanced oil recovery, this carbon dioxide should increase oil production at mature fields by about 30,000 to 80,000 barrels a day. Any carbon dioxide heading for the sky is domestic oil not produced, and more imported oil.

Your committee is considering subsidizing synthetic fuel from domestic coal, and that is why I am here. From a climate change perspective, unless SynFuels production is accompanied by carbon dioxide capture and sequestration, this is a big step backwards.

Burning coal-based synthetic fuel in a car engine instead of burning gasoline made from crude oil sends approximately twice as much carbon dioxide into the atmosphere when driving the same distance, unless CCS is incorporated into the SynFuels production process, in which case coal-to-liquids fuel, CTL fuel, is no worse for climate, no better, about the same, than petroleum fuel. “No CTL without CCS” is not the world’s most exciting bumper sticker, but it does carry a vitally important message.

Mr. Chairman, the sulfur trading you helped launch in the early 1990s has been a spectacular success and the template for every cap-and-trade proposal since then, but the launching of CCS will require a carbon trading system, plus.

I strongly recommend that your committee restrict the next investment tax credits only to coal power plants and coal SynFuels plants that capture and sequester carbon dioxide.

Moreover, I recommend that policies specify only that carbon dioxide must be sequestered, with penalties for failure, then leave it to the market to choose the specific capture and sequestration strategy for each circumstance.

Urgently needed for the current period are policies that give clear and persuasive signals that any new power plant without

CCS will be penalized, not rewarded, in whatever U.S. climate change mitigation policy emerges after the current planning period. No one should expect the grandfathering of the newborn.

I was one of many who were delighted by the news this past weekend that eight new coal plants with conventional technology proposed for rapid construction in Texas will not be built. I cannot prove it, of course, but it seems likely to me that the op-ed in the *Dallas News* last month from Senator Bingaman and Senator Boxer, warning investors and the TXU leadership that in effect there would be no grandfathering of the newborn, was instrumental in derailing the construction of these eight backward-looking plants.

Mr. Chairman and members of the committee, thank you for your attention.

The CHAIRMAN. Thank you, Doctor, very, very much.

[The prepared statement of Dr. Socolow appears in the appendix.]

The CHAIRMAN. I want to begin with Governor Schweitzer and ask you, Governor, just your thoughts on how to coordinate State and Federal efforts here as we become energy independent, and also address the climate change. You mentioned that many Governors here at the National Governors conference are trying to put together their own cap-and-trade system.

At the same time, as you know better than I, in Montana there are renewable portfolio standards which are required in the State. Of course, we in the Congress and at various levels, the Tax Committee, and also Senator Bingaman's committee, are trying to get some energy policy put together here.

But I am asking your thoughts on the relationship between States and the Federal Government. Where should we spend our efforts? Where can States better spend their efforts as we attempt to move in the same direction?

Governor SCHWEITZER. Well, let me just pat you on the back for the things that you have already done that have helped us. CREBS (Clean Renewable Energy Bonds) is a great step forward so that we have a bonding mechanism for people to put up wind turbines. Extending the tax credit on these renewable sources for 10 years will send a signal to the market that it is safe to manufacture and plan to manufacture for at least 10 years.

In Montana, we passed a renewable energy standard so that 15 percent of our electricity, by the year 2015, will be generated by renewable sources. In 2 years, we are already at 10 percent. In 2 years from now, we will be at 20 percent. It seems to be working.

We have an ethanol mandate in Montana so that, once we produce enough ethanol, 10 percent of all the gasoline in Montana will have ethanol in it. We hope to do the same thing with biodiesel. There are some concerns with biodiesel. I drive a biodiesel car.

The Colleges of Technology around Montana and the high school students all know that I drive this car, so wherever I go across Montana these kids will walk up to me with their home blend. They will have a gallon or two. It is like hooch. [Laughter.] They will pass me that bottle.

Senator BUNNING. Hooch?

Governor SCHWEITZER. It is different than Kentucky hooch. [Laughter.] So, I take that bottle of biodiesel home and I give it to my wife, and she dumps it in the car. Now, it has a computer on board and some of these kids make a blend that gets you about 43 miles per gallon, and it starts in cold weather; some down to about 37, and it coughs even in warm weather.

We do not have standards for biodiesel like we do with petroleum, so we are trying to pass those standards in Montana. But if I could ask you to do one thing, one thing that will profoundly affect the future of this country, Dr. Socolow talked about it, we have to have a cap-and-trade system that is national.

We cannot Balkanize cap-and-trade. The West Coast has one standard, the Midwest has another standard, West Virginia, of course, has their own. We cannot Balkanize this. So, please give us a standard that we can all live with and all utilities will be on the same standard.

The second is, help us with carbon sequestration. We will start, not by spending $30 a ton to pump it into the earth in our limestone formations, like our Madison limestone in Montana. It will start with enhanced oil recovery.

We have enough old oil fields in Montana that we could build about five coal gasification plants in Montana during the next 10 years and pump that carbon dioxide back into those old oil fields, and enhance oil recovery double or triple.

There is something called the Big Sky Sequestration Project. Department of Energy has funded it with $17 million, and we are studying the geologic structures in Montana and Wyoming. How much carbon can we store?

We have, between the two States, 40 percent of America's coal supply, and we are only spending $17 million to study the geology to develop effectively our ace in the hole. It is too little and it is too slow. Please help us develop carbon sequestration technology.

The CHAIRMAN. Let me ask about sequestration. Dr. Socolow, there is an article that we talked about before the hearing in today's *Wall Street Journal* which casts some doubt on the commercial viability of carbon sequestration. I just wondered if you had a chance to look at it, and your response.

Dr. SOCOLOW. Let me try. First of all, there is the capture part and the storage part. That particular article is quoting Jim Rogers of Duke Energy. It is a little ambiguous, what exactly he was saying. Capture is commercial technology. Licensing from various vendors, it seems to me, is not where the risk is. Storage is part of the world of the oil and gas world, which is full of dry holes and——

The CHAIRMAN. Is capture pretty well understood now? Are there various ways to capture?

Dr. SOCOLOW. There are going to be many ways of capturing. They are going to be competing with each other. That is why I argue that we should not be directing the subsidies, necessarily, to any particular technology. I think right now gasification is out in front, oxygen-blown gasification. There will be capture technologies in competition.

The CHAIRMAN. But storage is a bit of an issue?

Dr. SOCOLOW. Storage is the world of the below-ground wildcatting. You will have situations—and I think we have to be in a frame of mind—where occasional fields that turn out not to have the integrity for storage that one expected and that gradually lose some carbon dioxide are not show-stoppers, because you can have insurance, you can have various ways of accepting it, especially in the beginning.

If we take some risks—people do not say this in my field, I have to tell you that. This is the way I look at it—1 in 10 of the places where we think we are putting carbon dioxide away gradually leaks it out, and we cannot do anything about it.

We even add additional carbon dioxide because we were expending some energy on capturing the stuff in the first place. We go on from there, and we learn and we get better at it.

A slow leak of an underground formation is something no engineer wants to admit can happen, but if it does happen, it is not an abrupt leak that kills people, but a slow leak that vents the stuff. We just have to do more sequestration at the end of the day.

The CHAIRMAN. My time has expired. But just very briefly, what more do we need to do to better understand storage?

Dr. SOCOLOW. Do it. Do it. Do it at full scale.

The CHAIRMAN. Governor Schweitzer mentioned some geologic formation studies. Is that needed or not needed?

Dr. SOCOLOW. Well, here is how I think about it. And again, I am not a specialist. I am learning from the people who are in the business. The way you think of it is as a first, broad-brush scoping of where there are promising places.

Then there is a company that decides that, with its coal plant, it will go to such-and-such an area. Then they do an additional, much more detailed scoping of the specific field to see whether it is a good field, and then they will go ahead with that project. It will generally work. The expectation is, it almost always will work.

The first brush is, the Federal Government's role to probably get a sense of where the formations are on a broad scale, then a plant or location is picked and they have alternatives. They hire geologists to go figure out and detail whether a particular place is going to work.

The CHAIRMAN. All right. Thank you very much.

Dr. SOCOLOW. Is there some risk? Sure, there is some risk in that process.

The CHAIRMAN. Got you. Thank you.

Senator Grassley?

Senator GRASSLEY. Governor Schweitzer, in our State, renewables always come to people's minds, ethanol and biodiesel. In your State, you are trying to do some diversification in this area.

One thing you did not have time to mention that I would like to have you make a short comment on, is the crop "camelina." Would you tell us a little bit about that? Because I do not know anything about it.

Governor SCHWEITZER. What a beautiful name, "camelina." She is a Brassica, which means related to spinach, and canola, and flax. She is a crop that developed in Asia Minor, and she is adapted to grow in Montana from 2,000 feet to 6,000 feet of elevation.

She will yield from 75 to 150 gallons of diesel per acre. You can plant her in the middle of the winter and harvest her 30 days before a wheat crop. It is a wonderful rotation.

In over 100 trials across Montana, only one trial has found that camelina responds to any fertilizer. It is a low-input crop. It is a great rotation. It has a wonderful yellow flower. It produces an omega-3 oil, which is fish oil, a healthy oil. It may be too valuable as a food product to use as biodiesel.

We are in the early development processes with this. I have met with plant scientists as recently as last week who have one trigger they think can double that yield during the next couple of years.

There are many promising biodiesel crops. In Montana, our evenings are too cool to grow soybeans and, for the most part, corn. But we can grow camelina, and canola, and safflower, and some of the flax seeds.

I do not know that ethanol will produce a billion barrels eventually in this country, but I know between ethanol and biodiesel, it will. I know that you can grow a crop in every single State in this country that will produce a biofuel. It does not have to be corn and it does not have to be soybeans.

Senator GRASSLEY. Thank you.

Mr. Aimone, three questions, but give me short answers. Of the tactical vehicles, including Air Force jets, how many gallons of fuel does the Air Force consume per year? Of that amount, how much is consumed domestically, and what is the Air Force's plan to acquire alternative fuels made in the United States?

Mr. AIMONE. Thank you, Senator. The Air Force, in fiscal year 2006, consumed 2.6 billion gallons of fuel in all categories of liquid petroleum, so that is aviation as well as ground vehicles.

As I mentioned in my short statement, 80 percent of that is in the aviation sector, so the ground vehicle fleet is only about 2 percent of the total energy that we use. Of that 2.6 billion gallons of liquid product we use a year, about 65 to 70 percent of that is domestic. The remainder, of course, is overseas.

Then the third question, the Air Force has a very strong desire to proceed forward from the B–52 test that I described. Our vision is to be able to certify the B–52 for aviation use, unrestricted, by the end of this summer, and we are on track to do that assuming all the tear-down of the engine and systems that we are doing right now pans out. So, first, the B–52.

We actually have four steps that we would like to execute in our strategic plan for synthetic fuel. The first is cooperating with the commercial aviation Alternative Fuels Initiative, which is primarily an FAA- and industry-sponsored activity looking at the commercial aviation fleet and what they could do about synthetics. The goal of that group is to have a national standard, actually an ASTM standard, for synthetic fuels by 2009.

The second step, sir, would be to then continue the certification process of the Air Force's aviation fleet. I mentioned the B–52 this year, but continue that with both our strategic airlift, as well as our fighter aircraft, to have all aircraft certified for synthetic fuel use by 2010.

The third is invest strategically in the right kind of research and development to advance the processes, including production demonstrations. These would include, for example, aviation testing in mill spec support for a family of products beyond coal-to-liquids and natural gas-to-liquids, as I mentioned in my opening comments, but to include to include oil shale and biomass as means. We spent quite a bit of time this morning as a committee examining the subject of carbon sequestration.

Our goal is to find a way to make that carbon an asset, not a liability that has to be buried, that in fact ultimately may be part of a multi-feedstock gasification capability with coal and other biomass materials to provide a partial renewable feed.

Then finally, the fourth element of our strategy—the first of course, working with the commercial aviation industry; the second to get our aviation fleet certified for manned aviation use of synthetics; the third, strategic research and development investments and looking at how we might be able to look at an environmentally friendly kind of a plant that might meet the needs for jet fuel—the last piece, sir, is to seek long-term contracting authority for these kinds of products.

The Air Force, through its partner, the Defense Logistics Agency, is limited to 5-year procurements for commodities, and we think that part of what the Air Force needs to do is be able to enter, with our partner, the Defense Logistics Agency, into the longer-term contracts.

Senator GRASSLEY. The other two witnesses, I am going to have to submit a question in writing for answers from both of you. I would appreciate it if you would do that.

Senator GRASSLEY. Thank you, Mr. Chairman.

The CHAIRMAN. Thank you, Senator.

Now, to Senator Bingaman, chairman of the Energy Committee.

Senator BINGAMAN. Thank you very much. Thanks for having this hearing. It is very useful. Thanks to all the witnesses for being here.

I know Dan Reicher is not here, but he, in his written testimony, makes a strong argument in favor of establishing what is referred to as an energy efficiency resource standard.

He talks about, we should have both a renewable portfolio standard or renewable energy requirement which would be put on utilities, and then we should also have a provision, this energy efficiency resource standard, to require utilities to improve the efficiency with which they operate. He points to the fact that eight States have adopted something like that.

I wonder if any of you have looked at this issue and have an opinion on whether this makes sense as something for Congress to do. Do any of you know about this? I can wait and ask Dr. Reicher.

Dr. Socolow, did you have a view on this?

Dr. SOCOLOW. Well, it is, frankly, a new idea to me as a policy instrument. But what it is getting at is the fact that, in so many instances today, it is still the case that an electric utility is rewarded by the number of kilowatt hours it sells rather than what services it can accomplish, so it is very hard to get investments in the efficiency area.

If this policy will accomplish that, that is just terribly important. I also think the standard setting that pushes the air conditioners and the other major appliances forward, and the motors, is terribly important also. We can do so much more than we have been doing with efficiency.

Senator BINGAMAN. All right.

Let me ask Dr. Arvizu, one of the concerns that has been raised about us going forward in this aggressive effort to develop biofuels that the President outlined in his State of the Union speech, is the impact this will have on natural gas usage and what it might do to the price of natural gas that residential customers and others are having to pay if you have this additional use of natural gas in ethanol plants, in biodiesel plants throughout.

I guess the question is, do we need additional tax incentives to encourage these new plants to configure themselves so they can operate off of biomass some way or other so that you do not have this tremendous demand for additional natural gas usage? That is the question.

Dr. ARVIZU. Well, thanks for the question. I think it certainly is a piece of the point I was earlier making regarding, you need to think about the impacts that a very aggressive program in biofuels will ultimately have on our land use, water use, et cetera.

The use of fossil fuels in the ethanol production process is actually quite significant for corn ethanol, in particular. What I think we in the research community are advocating is a bio-refinery that is totally self-contained.

In other words, there is a part of the plant matter, the lignin in particular, that is not amenable to breaking into fermentable sugars that you can generate ethanol from. It is that piece of the plant that you can thermochemically use to create and generate power that will power the plant.

So, ultimately I think you want a self-contained bio-refinery that has both a thermochemical, perhaps a biochemical, process. It is very efficient in its use of water and does not require any additional fossil fuel usage.

Senator BINGAMAN. Do we have any of those bio-refineries, like you were just describing, in operation today?

Dr. ARVIZU. No, sir, we do not. I think that is where we can encourage and incentivize that kind of technology by putting in the things that I think you have already begun to do, certainly as part of EPACT (the Energy Policy Act) 2005, with loan guarantees that will help the investor community recognize and realize the return on investment that they are looking for when they make the kind of investments for these advanced technologies.

Senator BINGAMAN. We put a provision in EPACT 2005 for combined heat and power installations, a 10-percent tax incentive for combined heat and power, together including biomass, combined heat and power. Do you have any view as to whether that has been useful, needs to be continued, or needs to be increased?

Dr. ARVIZU. I think it certainly is useful. There are a lot of things in the EPACT 2005 legislation that are of tremendous value.

Senator BINGAMAN. I am corrected. We put it in the Senate bill and it was not in the final bill. Go ahead.

Dr. ARVIZU. All right. Let me make the point that I want to make, which is that we need a broad portfolio of policies that are both consistent and predictable. It is all about mobilizing private sector capital.

And the way in which you can get that money to start flowing—it is flowing now—is to have policies that are enduring and, at least, understandable and predictable from the perspective of those who are making investments.

Senator BINGAMAN. My time is up. Thank you, Mr. Chairman.

The CHAIRMAN. Thank you very much, Senator.

Next on the list is Senator Thomas.

Senator THOMAS. Thank you, Mr. Chairman.

Thank you all.

The CHAIRMAN. Oh, yes. I am sorry. If you could suspend.

Dr. Reicher, we are very glad that you were able to make it. We have been expecting your arrival.

Dr. REICHER. Thank you, Mr. Chairman.

The CHAIRMAN. Why don't you go ahead? We would very much like to hear from you first before we proceed.

Dr. REICHER. Thanks so much.

The CHAIRMAN. We want to hear from Senator Thomas, too, but we also want to hear from you.

Dr. REICHER. I have had a rather energy-inefficient morning, flying on the red-eye from California last night. Could not land at Dulles. We flew to BWI. Landed at BWI and sat on the runway there. Got back in the air, landed at Dulles and finally made it. But I am sure you have been through that many, many times.

The CHAIRMAN. It gives you a lot of time to think about all of this. [Laughter.]

Dr. REICHER. It does. It does. That nice, long red-eye.

The CHAIRMAN. Right.

STATEMENT OF DAN REICHER, J.D., DIRECTOR, ENERGY AND CLIMATE INITIATIVES, GOOGLE CORP., MOUNTAIN VIEW, CA

Dr. REICHER. Mr. Chairman, members of the committee, I am very pleased to be here and have the opportunity to make a few brief remarks. I will make these quite brief because I know I have already passed that point in the hearing when we give opening statements.

But I am with Google. I am the director of Energy and Climate Initiatives at Google. Google recently set aside many hundreds of millions of dollars to invest in energy and climate, poverty, and global health. My focus will be on both investment and on policy measures that can advance energy and climate.

Prior to that, I was president of a company called New Energy Capital. It is a private equity firm. Over the last several years, we invested significant sums of money in ethanol plants, biodiesel plants, co-generation facilities, wood-fired power plants, and a variety of facilities around the United States, so we have some experience in how to move capital.

I was in the Clinton administration for 8 years. I was Assistant Secretary of Energy for Energy Efficiency and Renewable Energy, Chief of Staff at DOE, and the Acting Assistant Secretary for Policy.

I want to focus specifically, in a couple of minutes, on energy efficiency. I can talk more broadly on other energy sources, but I think when all is said and done, energy efficiency, in many ways, is the lowest of the low-hanging fruit. Whether it is cars, factories, offices, buildings of all sorts, there is a significant amount of energy that we can wring out of current use.

This low-hanging fruit, Mr. Chairman, grows back. The incandescent light bulb that you replaced with a compact fluorescent one of these days will be replaced again with yet another technology.

The internal combustion engine that we are replacing with hybrids today, we are going to replace down the road again with plug-in hybrids running on biofuels. So, technology for efficiency is always developing, thus, low-hanging fruit can grow back.

McKinsey and Company did a study recently looking at the energy efficiency potential globally. Annual energy growth is over 2 percent. McKinsey and Company said, "Cost-effective investments in energy efficiency can bring that annual global growth in energy to below 1 percent annually," so we can cut greater than 2-percent energy growth to less than 1-percent energy growth through energy efficiency, and that is very, very significant.

If there is one message I want to leave today, it is that Federal policy—Federal policy—can truly stimulate private sector investment. And understand, this private sector investment has to be literally in the trillions of dollars over the next few decades if we are going to make the changes to our global energy system that will both meet demands for energy and deal with global climate change, energy security, economic competitiveness, poverty alleviation, and all the other things that we need to deal with in our energy system.

Federal policy is critical for stimulating private sector investment. You need only look at the success we have had with ethanol. We put Federal tax credits in place, we put a Federal mandate in place, lots of investment flowed. Of course, oil prices went up and that helped as well, but it was that Federal policy that gave quite a push.

The unfortunate thing is that energy efficiency has not enjoyed the same kind of Federal policy support, so I just want to tick through a list of things that I think you should consider to leverage greater private sector investment in energy efficiency.

First, is putting a price on carbon. We have to get to climate controls. We have to get to climate legislation. We can debate what the mechanisms are, but ultimately we have to internalize the price of carbon emissions. If we do that, that will send a very positive signal to the investment community in terms of energy investments in cleaner technologies.

Second, we do need to strengthen CAFE standards, the Corporate Average Fuel Economy standards. There is no doubt about it. That is a very, very significant energy-using component of our economy. CAFE itself is the single biggest step that the Federal Government has ever taken in terms of energy efficiency, it is just, we have not updated those standards in years.

Third, as you consider a Federal renewable portfolio standard, which I know the Senate adopted a year ago, consider a complement to that, what is called the Energy Efficiency Resource Standard. It has come up to Capitol Hill as a proposal recently, and it would be a wonderful complement to a renewable portfolio standard.

It would set a target for decreasing energy use, increasing energy efficiency, as it were, among utilities and gas suppliers over the period of 2008 to 2020. Essentially if you could put an RPS, Renewable Portfolio Standard, together with an Energy Efficiency Resource Standard, you could both decrease demand and begin to move cleaner sources of supply in. They are very complementary, and I strongly encourage you to consider them.

Fourth, I think tax credits are very, very helpful. The Energy Policy Act's tax credits that you adopted have been a great stimulus to investment. The building-related tax credits have been helpful, but they need to be extended. They need to be strengthened.

I know that Senators Snowe and Feinstein introduced legislation last year that would extend those important energy efficiency tax credits, and I urge you to take up that proposal.

Fifth, weatherization assistance. I think we are headed in the wrong direction when it comes to energy efficiency for the poor. In one sense, we are buying down poor people's energy bills through the LIHEAP program, a one-shot investment in their energy bills.

It is a critical thing to do, but it does not get to the heart of the matter, which is improving the energy efficiency of poor people's homes. That is what weatherization assistance does. Instead of that budget going up over time, it has been going down. In fact, the administration has proposed a $100-million cut.

We propose a major increase in weatherization to radically cut residential energy use, particularly among low-income people. With that will come vast energy savings, climate reductions, jobs, and we would propose trying to get to a point where we are weatherizing a million homes a year in the United States.

Lastly, one of the least-heralded energy efficiency success stories in the United States has been the appliance efficiency standards, boring old white goods that you sell in a store: refrigerators, freezers, air conditioners.

The good news has been, over the last couple of decades we have, for example, set standards which have taken the energy use of a refrigerator down by two-thirds. The same for air conditioners.

The unfortunate thing is, despite a lot of progress over many years in adopting these standards, in the last 6 years almost none have been adopted, and the administration is now under court order to adopt more than 20 standards in the next 4 years.

I urge you to move that process along, provide DOE with the funding that it needs to get those standards written, and ensure they are as strong as possible.

So with that, I just want to say that if you want to leverage private capital to change our energy systems, one of the best ways to do it is to focus on Federal policy related to clean energy. Thank you.

The CHAIRMAN. Thank you, Dr. Reicher. That was very, very helpful.

[The prepared statement of Dr. Reicher appears in the appendix.]

The CHAIRMAN. Senator Thomas, we have been waiting for you.

Senator THOMAS. Thank you, sir. I have been anxious to go.

Well, thank you very much for being here. I know this is a tough issue and we need to deal with it. I guess the thing that I have on my mind as we go along here is, we are going to go to alternatives one of these days, but it is going to be a while.

In the meantime, I think we have to focus a little more on where we are going to be in the next 10, 15 years, because we are not going to be in alternatives. We are not going to have wind energy to do all those things, I do not think, in that very short time.

Governor, you mentioned that we have not moved forward. I have to tell you that I think in Wyoming, we have moved forward quite a little bit, as a matter of fact, in energy, and we have moved forward on coal, and all those things.

In terms of clean coal technology, many of the major benefits come to the States. What do you think the States' role is in causing this to happen?

Governor SCHWEITZER. What we can do is work with the Federal Government to facilitate the sites. We will place those sites. The sites are most likely to be built mine-mouth, or even better, mine-mouth that is co-located with carbon sequestration zones. You can help us in financing or help us in bonding transmission lines. Wyoming and Montana have a great opportunity of delivering more electrons to the Southwest.

California alone is asking for 25,000 megawatts of electricity; Las Vegas needs 5,000; Phoenix needs about 5,000 just in the next 10 years. They are all looking to Montana and Wyoming to deliver those electrons.

We are kind of stuck in between right now in terms of technologies. If you build a pulverized coal plant today, you may be subjecting your rate payors for the next 30 years to pay a carbon tax.

If you say you want to build an integrated gas combined cycle coal plant and sequester the carbon dioxide, you immediately add 25 percent to the cost of the electricity for those rate payors.

If the Federal Government places a cap-and-trade system so we are playing on a level playing field, transmission lines will be built and companies will begin to build these IGCC plants.

In many ways, those private developers and the States are waiting for Congress to make those decisions of what the playing field will look like. When those decisions are made, believe me, the transmission lines will be built and the integrated gas combined cycle with coal will be built, and we will sequester the carbon dioxide. Thank you.

Senator THOMAS. We have made a number of those decisions, but the funding has not been made available to do some of those things.

Dr. Arvizu, your research seems to be all in the future, when the real challenge is in the short term. What kind of research are you doing to help us fill that vacancy between your long-term research and what we need in the next 5 to 10 years?

Dr. ARVIZU. Let me be clear. I have been in the renewable energy business pretty much all of my professional career, so I have actually seen it when it was strictly research and very much, I would think, in the demonstration mode. That has changed dramatically.

Today, the renewable energy industry, by some estimates, I think, coming out of the U.K., is over $70 billion worth of annual sales investment. The investment in new technology is also growing rapidly, but there is, in fact, an industry that is what I would call very much mainstream in other parts of the world. With public policies in Europe, and some now following that lead in Asia, you see technology going into the marketplace.

Senator THOMAS. So you think a lot of it is there and we have not given the incentives to use it. Is that it?

Dr. ARVIZU. We have technology today that can be used to actually make a significant dent in our energy use. The answer is yes. I think, long-term, if we are going to get to a large fraction of our energy from renewables, we need the continued investment in the R&D.

Senator THOMAS. Thank you.

Dr. Socolow, you seem to be very critical of coal. Coal is our greatest source for this rather short-term time. Now, we can do some different things with it, but it seems like it is a little tough to be negative on what is apparently our biggest source of energy for the next 5, 10 years.

Dr. SOCOLOW. More than for 10 years. And if I am critical, I am trying to be a friend of coal.

Senator THOMAS. Oh. Well, I did not recognize that.

Dr. SOCOLOW. Well, then I did not express myself well. It seems to me that the problem, if we take climate as a truly dominant concern, looking out decade after decade from here, there is a collision course between coal and climate unless we bring a whole set of new technologies to bear on coal.

The good news is, they exist and they can make coal and climate compatible. Without them, there really is a problem for coal internationally. The coal industry has a major opportunity here to start demonstrating that it is serious about the climate problem and will move forward. I am not talking about a world without coal.

Senator THOMAS. All right. Very good. And it is going to take an investment that I presume will end up being in the cost of energy, to some degree.

Dr. SOCOLOW. Absolutely.

Senator THOMAS. Yes. Thank you, sir.

The CHAIRMAN. Senator Stabenow?

Senator STABENOW. Thank you, Mr. Chairman. And thank you very much for an excellent hearing.

Governor, it is always good to see you. Mr. Aimone, I have to tell you, my husband is an Air Force veteran, so I am always glad to hear about the good things happening in the Air Force.

With another branch of the Armed Services, I was pleased to join Senator Levin and General Motors last fall with the Army, who is now field testing 100 hydrogen fuel-cell vehicles. So, I am glad to see the Armed Services really moving out aggressively in this very important area.

To each of you, welcome. I am very pleased, Mr. Reicher, to see you here as well. I want to say that we are very proud. Google is expanding in Ann Arbor, MI, and we are extremely excited about that, so we are proud to have you with us today.

Dr. REICHER. Thank you, Senator.

Senator STABENOW. When we look at this issue, which is so critical to us, I guess I see, number one, it is exciting to see now in the new Congress that we are acknowledging that global warming is real and aggressively moving forward on how we can work together to address it.

It is also a national security issue. Very clearly, our whole national security policy would change if we were not dependent on oil from the places in the world where we are.

It is also about jobs, though. I would say, coming from Michigan, not only making automobiles and moving quickly on alternatives fuels and so on, but we make the wind turbines, which I believe is closer than my colleague believes, we are doing it right now, and ethanol and biodiesel plants and all that, it is jobs. I think we can do both as we move forward.

My first question relates to the farm bill. The Chairman, the Ranking Member, myself, a number of us are on the Agriculture Committee, and we are writing a farm bill.

The last time in the farm bill, we put in an energy title for the first time. It was really a small—important, but small—effort that I know the chairman of the committee, I know our Chairman here, and Chairman Harkin, working with Chairman Bingaman, are looking at.

If you were to pick one or two things that we could do—and I would ask any of you to respond—within the context of the farm bill that would be most helpful as it relates to moving forward on biofuels, what would that be? Governor?

Governor SCHWEITZER. The most important thing that we can do is these emerging crops that will produce fuels. I mentioned camelina, but also crops like safflower and canola, non-traditional crops. Unfortunately, our insurance program is built around the existing crops.

So if you are a farmer who is willing to experiment and grow a new crop that has not been grown in your area, the Federal crop insurance will say, well, we are going to set these yield levels that are so low, that it is going to chase you back to growing corn, or wheat, or soybeans. So I think we have to be realistic and set yield levels so that farmers will try these new crops.

Senator STABENOW. So you are suggesting that crop insurance be expanded.

Governor SCHWEITZER. Crop insurance be expanded to these emerging crops, and set the levels that are high enough so that a farmer will try these new crops. If there is a crop failure due to climate, that they are going to be at least even as if they would have tried wheat, corn, or soybeans, their traditional crops.

There is another one. A State like Montana is not likely to be one who produces a lot of ethanol with a lot of plants. Our distances are too great. So in order to produce enough corn for a commercial-sized ethanol plant, or barley, or wheat, we end up trucking it 150 or 200 miles in a concentric ring around that plant.

Biodiesel is something else. We have farmers in Montana who are producing biodiesel on their own farms, 50 gallons a day. They can build their own plant for $10,000.

Twelve or fifteen farmers could come together and build a biodiesel plant, where only a few thousand acres are produced to go to that plant and they can produce that biodiesel very effectively and very efficiently with less trucking. They will use that crop at home.

Here is the beauty of this thing: whatever crop you have in your backyard that will produce a biofuel, produce it and use that biofuel at home so that we are not transporting oil clear across this continent in order to get it to a farmer to put in his tractor.

If you incent those farmers to grow the crops that will produce the biodiesel, and then you have a loan guarantee for them to build their own biodiesel plants, then they will begin using that biodiesel in their Case tractor, in their John Deere tractor, in their Caterpillar tractor.

And by the way, the manufacturers only allow up to 10 or 20 percent biodiesel in their engines in the United States; some of those same engines are up to 80 percent in Europe. So I would simply say to the manufacturers, do not expect a farmer to pay $300,000 for your tractor if you will not allow the farmer to use their own oil in your tractor. Thank you.

Senator STABENOW. Thank you.

Dr. Reicher?

Dr. REICHER. Senator, at New Energy Capital where I was previously, we developed and invested in three corn ethanol plants and the first biodiesel plant in the Northeast. So, based on that, I guess I would make several recommendations.

First, I do think alternative feedstocks, alternatives to corn and soybeans, are going to be important. Corn is the backbone of the ethanol industry, but everybody knows that we are going to get to a point where that corn supply cannot continue to provide the feedstocks we need to grow the ethanol industry. So, I think building on corn, but using the farm bill to encourage other feedstocks for both ethanol and biodiesel, is critical.

Secondly, I think cellulosic ethanol, which you have talked about this morning, making ethanol from waste and energy crops, and all sorts of things, makes an awful lot of sense. I think probably looking at a tax credit that goes beyond the regular tax credit for corn ethanol would make some sense.

One of the things that you put in the original energy title in the farm bill is a grant program for both renewables and energy efficiency, heavily over-subscribed. I would suggest you increase that grant program.

It has been very useful on the farm for people seeking to put up small farm-scale wind turbines, increase the efficiency of farming and agricultural processes, a whole variety of things. That has been a good program.

I also would suggest that we were the beneficiary of a USDA loan guarantee for our biodiesel plant in Delaware. It worked extremely well for us. But one thing to look at is potentially increasing the upper limit of those loan guarantees. They are capped, and it would be worth exploring whether those could be raised.

The CHAIRMAN. Thank you very much. I appreciate that. Thank you.

Senator STABENOW. Thank you.

The CHAIRMAN. Senator Salazar?

Senator SALAZAR. So much to talk about, Mr. Chairman, and so little time.

The CHAIRMAN. I was thinking the same.

Senator SALAZAR. Let me just say thank you to a stellar group of witnesses. I appreciate the dialogue. You were all great.

I have two questions, and they are to Governor Schweitzer, Dr. Arvizu, and to Dan Reicher. The first of those questions is, what in your mind—and you are going to have to each be very quick, like a 1-minute response—are the two or three most important incentives that we could create out of this Finance Committee to make the vision that has been outlined here on a bipartisan basis?

I look at the legislation that we already have, bipartisan legislation: renewable energy bonds, rural wind energy development, the Energy Efficiency Incentives Act, the Securing America's Energy Independence Act. There will probably be a thousand of those things that we will be dealing with here.

What are the top three that you think would be most instrumental for us to move this energy independence agenda forward? That is question number one.

Question number two: Renewable Portfolio Standards. I know, Brian, what you have done in Montana. It is exemplary. In Colorado, we started out at 10 percent by 2015. Yesterday, the legislature adopted a 20 percent by 2015 RPS. Doesn't it make sense to do a national RPS? If so, what is it that we ought to be aiming at with respect to the national RPS?

So let us start with you, Dr.—Governor Schweitzer, and then we will just move down the table.

Governor SCHWEITZER. Well, I thought that you had elevated me. As you know, I went to Colorado State University. But I only have a bachelor's degree, not a doctor's degree.

Senator SALAZAR. We can arrange an honorary doctorate any time you want to come back to Colorado. [Laughter.]

Governor SCHWEITZER. Even though I got "C"s? [Laughter.]

Senator SALAZAR. You are Governor. It does not matter what you did when you were in college.

Governor SCHWEITZER. Renewable tax credits are the most important thing. Give a signal to those who manufacture this equipment for at least 10 years. That is the most important thing that we can do here.

The other thing is, you actually, in the energy bill, have loan guarantee provisions, but the money has not been made available through the Finance Committee so that we can begin building some of these coal gasification plants.

Senator SALAZAR. So we have production tax credits and the loan guarantee programs. Now, RPS?

Governor SCHWEITZER. I have already signed on to 25 by '25. I was the first Governor to sign on; some of you Senators have also signed on, that by the year 2025 we will be at 25 percent. I think that we do need to have a national standard. I think we need a challenge to get to 20 percent soon, and I think that 25 by 2025 is reasonable.

Senator SALAZAR. Twenty-five by 2025 works.

Governor SCHWEITZER. That is right. Thank you.

Senator SALAZAR. Dr. Arvizu?

Dr. ARVIZU. Well, see, I am going to second this thing about the production tax credit. I think it is absolutely essential, even for the wind industry. The prices for wind turbines have increased over the last 18 months, primarily because of the commoditization kinds of things. The price of steel has gone up.

They are beginning to make a profit at some of these things, which I think is a good thing to be doing. As a result, the prices have gone from $1,000 a kilowatt to over $1,800 a kilowatt. So we need long-term credits to help shore up that industry.

I also think, certainly in the case of cellulosic biomass, the loan guarantee is actually a very good mechanism to help defray some of that financial risk that exists in building those first-of-a-kind type plants that are just now going into place.

Regarding the national RPS, I find that the RPSs that the States have implemented have been very positive and very valuable. I know that certainly Xcel has found that having that experience in Colorado is actually putting in a very positive business case for some of the things that they are doing.

It is problematic, I believe, to have a national RPS without recognizing the differences from region to region of the country. So my offering would be that some sort of an interstate renewable energy credit trading mechanism might be something to consider as we think about, how do we do that.

Senator SALAZAR. A question I will ask you later is, could you do an RPS, maybe the 25 by 2025, with a State implementation or regional implementation program, kind of like we do with a lot of the environmental programs that we already have?

But I only have another minute, so let me ask Dan Reicher.

Dr. REICHER. Very quickly, Senator. I think long-term extension of the production tax credits makes an awful lot of sense, at least 5 years. The problem in the investment world is, with a 2-year horizon, it makes it very difficult to make those kinds of investments to get projects on the ground, get them up and running.

Second, I think we should complement the production tax credits with aggressive energy efficiency tax credits. As I said, I think before you came in, efficiency and renewables work extremely well together, both lowering demand as we bring cleaner energy sources in.

Third, in terms of the RPS, I think we should push to 20 percent if we are looking at electricity; 25 by 2025 for a longer period of time also makes sense. But I think an aggressive RPS, I think we can figure out how to do it nationally. Not to say that there are not challenges, but we can implement it.

Also, again, I would complement the RPS with what I described briefly in my testimony as an energy efficiency resource standard. This is a standard that would——

Senator SALAZAR. Thank you very much. I appreciate your quick responses.

The CHAIRMAN. Thank you, Senator, very much.

Senator Bunning?

Senator BUNNING. Five minutes is awfully short.

First of all, I compliment you all on your testimony. Governor Schweitzer, I thank you for endorsing S. 155, the Coal-to-Liquid. In your testimony, you did that. I appreciate that because that is one way to get there in a hurry. If we would fund the 2005 Energy bill properly, we could get there in a hurry, because the technology is there.

Carbon sequestration is an absolute must, and we can use the byproducts, the carbon sequestration, to do exactly what the Governor has said in the oil fields, make sure that you put the plants where you can transfer into gasification, or put it into a big pipeline and send it to the oil fields, the carbon sequestration.

Mr. Aimone, in your testimony you said that coal-to-liquid fuel faces considerable technical, environmental, and economic issues. But there is significant evidence that suggests otherwise.

The Assistant Secretary of the Air Force, William Anderson, and I visited in our office. He talked to me about the testing of the B–52. There is significant evidence that suggests that South Africa has fueled jets for decades on coal-to-liquid fuel.

The Air Force is nearly finished, as you said, with successful B–52 certification. Users who replace conventional fuels with CTL fuel receive the environmental benefits of an ultra-clean, virtually zero sulfur fuel. While I agree that there are economic issues, they center on the government's incentives that this committee is exploring today.

If the Defense Logistics Agency expressed a preference for synthetic fuels, is anything stopping the Air Force from purchasing that fuel at market prices today?

Mr. AIMONE. No, sir. In fact, the Defense Logistics Agency has a pre-solicitation on the street for 200,000 gallons of synthetic fuel this year. The Department of Defense's Logistics Agency should put that out as a formal Request for Proposal towards the end of this week, seeking delivery within the June/July time frame.

Senator BUNNING. One of the big problems in the changes that we have put in our new Senate bill for coal-to-liquids, is the length of the contract. Five years is not a long enough contract for security for those who want to invest $2 billion, or $3 billion in a plant to produce that kind of a coal-to-liquid. So we have put in a 25-year window for the Army and the Air Force, and anyone who wanted to use that, in our bill. Would that be helpful?

Mr. AIMONE. Sir, I believe it would be helpful. Yes.

Senator BUNNING. So expanding the time. All right.

Dr. Socolow, there seem to be very, very strong feelings on coal one way or the other, but we have a 25-year supply of unbelievable amounts. Now, we can go both ways, but we have to secure the sequestration, as you suggested. If we do it properly, can we use coal efficiently, as you suggested?

Dr. SOCOLOW. Yes.

Senator BUNNING. We can?

Dr. SOCOLOW. Yes. I mean, I think——

Senator BUNNING. Well, see, I got the same feeling that Senator Thomas did in your testimony, that you were anti-coal. I maybe misunderstood you.

Dr. SOCOLOW. Well, the two of you got it wrong from my perspective.

Senator BUNNING. All right. We have the same ears.

Dr. SOCOLOW. Yes. I think it is because it is an unfamiliar message, frankly, which is, there is a technology—a whole class of technologies—that appears to have no show-stoppers. There is going to be a lot of learning. But the carbon capture and storage, combined with coal, gives you using coal for centuries within the climate constraints, which are very severe.

Senator BUNNING. For electric and for other fuels?

Dr. SOCOLOW. I think so. The question is, is there going to be sufficient pore space below ground? The question that the international R&D community asks, in looking at coal and carbon capture and storage, no other critical question, is ultimately how much storage capacity is there below ground internationally in formations that are typically ones that did not hold oil and gas? They will get us started, but the other ones are going to be the important ones over the century scale.

Senator BUNNING. But there are other uses, byproduct uses.

Dr. SOCOLOW. Byproduct uses are not going to be sufficient.

Senator BUNNING. In other words, there is going to have to be storage.

Dr. SOCOLOW. There is going to have to be storage. The judgments about pore space, we have not had enough of a survey. I could put in an argument here that one of the things important to do now is more of the surveying of the U.S. for the below-ground storage capacity.

Australia has done the best job so far of any country because they believe it is part of the future of coal. The U.S. Geological Survey is capable of doing a deeper survey. As I said, individual projects will be still deeper than that.

So the first question is, is there pore space below-ground for century-scale storage? I believe the answer is almost probably yes, or maybe I could say almost surely yes.

Senator BUNNING. What I am trying to get to is, we do not have to reinvent the wheel to advance this technology quickly. All we have to do is incentivize it properly.

Dr. SOCOLOW. I believe that is correct. I believe a strong cap-and-trade system that puts the carbon price in the range of $30 a ton of carbon dioxide in play will be a very important part of that, plus the subsidies for the early movers.

Senator BUNNING. Thank you very much.

Mr. AIMONE. Senator Bunning, if I could just offer one thought. Back in the 1980s, the Synthetic Fuels Corporation was created.

Senator BUNNING. We had a plant in Kentucky, I know.

Mr. AIMONE. There was a plant. But there was a book written in 1987 called, "The Unfulfilled Promise of Synthetic Fuels." It is an interesting book to read 30 years later. What is it that we have learned in the last 30 years? I encourage the committee to examine that a little bit. We do have coal gasification operations in this country today.

Senator BUNNING. But not on the scale of commercial use.

Mr. AIMONE. But at least they are there and answering some of those technical questions that I raised in my testimony, including, for example, scaling this up. Understanding an industry that can build to this technology, the economics of it and the like, all drive to, what have we learned?

The university system is 20-plus years in further understanding of this than both the engineering and sciences communities. We have modern plants operating in Qatar and Malaysia, and certainly some in China being built today to learn from. As you mentioned, SASIL has 30 years of operation. These are different than where the industry was in 1975 when the industry was attempting this.

Senator BUNNING. Thank you very much.

The CHAIRMAN. Thank you, Senator.

I am going to have to leave, if Senator Grassley has any questions. You have all been just terrific. I think this has been one of the best hearings this committee has had in a long, long time.

Governor, you clearly know what you are talking about. You have spent a lot of time thinking about this in our State, and talking all around the country, and many people deeply appreciate your energy, and also the depth of your knowledge on this subject.

Mr. Aimone, clearly the military—the Air Force especially—and all the energy it consumes is a huge part of this. Thank you so much for your contribution, a vitally important part of one of the big pieces of the puzzle here that you are helping to solve for us. Thank you so very much.

And Dr. Arvizu, Senator Salazar was right, you, too, know your stuff. I mean, it is clear that you have given deep thought about this and all the different aspects, and it is a real driver in getting this to move ahead with your agency and your organization you are working with.

Dr. Socolow, thanks so much for helping shed a lot more light on carbon sequestration. There is a lot of fog around it, but it is clear, in my judgment, that we have to move aggressively in that area.

I do have one question to ask you. That is, if all power plants were to sequester, is there enough underground storage capacity?

Dr. SOCOLOW. This is the kind of question that the IPCC (Intergovernmental Panel on Climate Change) deals with with climate, trying to state a probabilistic answer in terms of likely and more likely with various numbers. The answer, essentially, is likely, yes.

The CHAIRMAN. All right.

And Dr. Reicher, I am sorry for all the red-eye and all that you had to go through, but it is clear that that did not dim your thinking. You were very clear with your ideas, too.

We are going to have a lot more hearings on this subject in this committee. This is only the beginning. We may invite you back or figure out some way to make best use of your talents, your expertise, and your substance. I just cannot thank you enough for all the time and energy, if you will, that you have devoted in coming here, and I just thank you very, very, much.

Dr. REICHER. Thank you, Senator.

The CHAIRMAN. I will turn it over to Senator Grassley.

Senator GRASSLEY. Listen, I am not going to keep you long. I am going to ask the questions that I was going to ask you to answer in writing; it will save you some time as well.

So, I have just one question for the three people on the right-hand of the panel; I asked the other two earlier. For Dr. Socolow, the fertilizer industry has a long history of capturing carbon dioxide and selling it and using it to produce additional urea, combining carbon dioxide with ammonia.

In your testimony, you have said carbon dioxide capture is a mature technology. I know my farmers from Iowa use a lot of fertilizer. You mentioned that the fertilizer industry captures and uses a lot of carbon dioxide.

One of our energy problems is fertilizer production going offshore to countries with cheap natural gas. If our domestic fertilizer plants close because of high natural gas prices, will we not lose all the experience in carbon dioxide utilization?

Dr. SOCOLOW. The last part, I am really not sure about. The main point I was making in my testimony—I did not say it here in the hearing—was that it is the case that, in the process of making urea, almost all of the technologies that are above ground are in play, that are involved in capturing carbon dioxide in a natural gas or a coal-fired plant.

The same technologies used to make urea in China are based on coal, which is to say you gasify the fuel, you make carbon dioxide and hydrogen, you make the hydrogen into ammonia, and then you bring the carbon dioxide back to combine with the ammonia to make urea.

So you really have in that industry a demonstration of the commercial readiness of the carbon capture part of capture and storage. If it leaves offshore, I do not know if that is an intellectual property that one loses. I would not be sure of that.

Senator GRASSLEY. All right.

Then Dr. Arvizu, you said that Europe and Asia have grown to dominate a $40-billion international energy technology and equipment industry. What part of the market does the United States still have?

And a second question. You mentioned that, since the establishment of the National Renewable Energy Lab, and over the last decade, Denmark, Germany, and Spain have surpassed the United States in production and deployment of wind turbines, and Japan and Germany have surpassed the United States in the production of electricity-producing solar panels. What, in your opinion, should Congress do to turn those trade issues around?

I might partly answer your question, that just recently in Iowa we had Siemens decide to locate a plant in Madison, IA, and another company from Denmark is interested in locating something in Iowa. But beyond that, answer my questions.

Dr. ARVIZU. All right. On the first question, where do we still have, perhaps, dominance? I would say that is in the technology R&D world, both in the solar photovoltaics and, for that matter, I think some of the advanced concepts in wind energy and biofuels. I think the U.S. still enjoys technological leadership there.

What we have lost is the production capacity at this point. And again, those are primarily driven by these public policies in these other parts of the world.

What I think we can do to try to gain back a position of some level of prominence is, it really has to do with maintaining our technological lead. I think, wherever the innovation occurs, that is really where the opportunity for job creation and wealth creation really occurs.

So I think we have moved to the point now where I think the next big market in the world will be the U.S., and it would be certainly a shame to have us importing the technology that we spent so many taxpayer dollars to build.

So it is important, I think, that we try to localize our industry so that the innovation continues to occur here and the job creation occurs here. I think that is happening. The reason these foreign companies are moving into the U.S. is because this is where the markets are, and that is where the opportunity really is. I think public policy can help aid that in making certain that wealth creation and those jobs occur here.

Senator GRASSLEY. All right. Thank you.

And Dr. Reicher, my last question. Your specialty is structuring public/private financing for energy technology. Could you talk briefly about the roles of foundations, Wall Street, and the government in funding the next generation of domestic energy?

Dr. REICHER. Yes, Senator. I think the key is that most of the capital is going to come from the private sector. If we are, indeed, talking literally trillions of dollars that we are going to need over the next several decades, it is going to be private capital.

What the Federal Government can do is two things. One, is as Dr. Arvizu said, provide support for R&D to move technologies out of the lab. Second, the Federal Government can provide policy instruments that really drive this private capital to where it ought to go. So, standards, credits, a whole host of instruments that can really move private capital.

As you know well, it has made a huge difference in the ethanol industry, having both a tax credit and a renewable fuels standard. If we could move those sorts of instruments of policy, make them long-term—the problem, you know, with the production tax credit, is that it is an on again/off again incentive.

If we can make those long-term, if the investment world can rely on them, lots of things will happen, including, to your earlier point, locating more wind manufacturing, solar panel manufacturing in the U.S. The problem here is, companies look at the U.S. and they say, we just cannot make a bet on this market because it is so up and down. So that long-term, consistent Federal policy can help.

One more thing I would like to mention in the area of sequestration. We mostly talk about coal and sequestering the carbon dioxide from coal. There is an interesting twist on that. That is that we can also sequester the carbon dioxide from the use of biomass for power and fuels. The interesting thing about that is, it is the same carbon dioxide, so technically whatever we develop in terms of sequestration for coal we can apply to biomass.

The interesting thing about biomass, though, is it is what we call "carbon neutral." The plants take the carbon dioxide in when they grow and they release carbon dioxide when you produce energy, as opposed to the carbon dioxide having been underground for millions of years in the case of fossil fuels.

So what the sequestration of carbon dioxide from biomass would do is actually cause a net decrease in atmospheric carbon dioxide, because you have gone from a neutral carbon dioxide cycle to actually sequestering that carbon dioxide, and it would cause a net reduction in atmospheric carbon dioxide.

The National Academy of Sciences has talked about this, and others have looked at it. So we can piggy-back on this sequestration research from the biomass side. I think that is very exciting in farm country; I think that is very exciting in the forest products industry.

Black liquor gasification, ethanol, you name it: there is a whole host of things we can do with biomass. If we apply carbon sequestration technology to that, we are going to be that much further ahead.

Senator GRASSLEY. Thank you.

Senator, do you have a question?

Senator BUNNING. Yes. I have just a couple.

Senator GRASSLEY. Go ahead.

Senator BUNNING. I want to get back to the carbon sequestration globally. Because we can get it zeroed down in the United States of America, we can get it to nothing, and, if China and India do not do the same, we are going to have the same problems that we have right now.

Is it not necessary for everybody to get on the same page on that? Dr. Socolow, I would think that you would be——

Dr. SOCOLOW. I think a lot about this. You are absolutely right. China is investing in coal power and in coal-to-liquids at an incredible rate.

Senator BUNNING. Yes.

Dr. SOCOLOW. And we don't have the standing to say much to them.

Senator BUNNING. Well, we do. We have a big market for their products.

Dr. SOCOLOW. I am talking specifically in the industry, like people involved in the same jobs and marketing the same technologies. So if we move, it seems to me, then we have the credibility——

Senator BUNNING. The standing.

Dr. SOCOLOW. They are not as courageous as we are about new technology. I think it is unlikely that they would do something in this area first, although people say it might happen.

I think if we do what we are expected to do, we're the leaders in so many different ways and we move in this, then we go and say, look, it works and you have to do it, too. We also have the expectation, if they are capturing and storing carbon dioxide, there is going to be more of it going on there, in the early years, anyway.

Senator BUNNING. They have lots of room to store.

Dr. SOCOLOW. And we learn from each other because there is transferrable——

Senator BUNNING. Technology.

Dr. SOCOLOW. There is transferrable insights and information, and larger markets for the technologies, and so forth. So it really can be win-win, but it will not start if we do not start.

Senator BUNNING. Doctor, you mentioned in your testimony a base price of $40 per barrel. Was it not you who mentioned it?

Governor SCHWEITZER. I am guilty.

Senator BUNNING. You are guilty? I am sorry, Governor. Since you only have a what-you-call-it degree, a normal degree, all these other doctors, I thought maybe they had mentioned it, because I think that is essential, if we are going to advance this technology beyond speculation, for it to have a base price with new technologies like coal-to-liquids, like other technologies for fuel-based, whether they be from Iowa in ethanol, whether they be from the new different types of grasses that you were talking about, because that gives stability to the marketplace. Is that an accurate estimate?

Dr. ARVIZU. It very much is. For cellulosic ethanol, the price point is somewhere at $50 a barrel. Unless the price of oil stays above that, the investors are not going to get their turn, right?

Senator BUNNING. But if we had a base.

Dr. ARVIZU. But if you put a floor that says we are going to protect you if the price of oil drops below that, then certainly that would do that. The interesting thing is, I have met with oil companies and oil company executives, and certain ones which I will not name by name, but they have a very low price point.

In order for all companies to actually make investments, their price point is down around $25 to $30 a barrel, as opposed to what we think about in the R&D arena where I work, is in the $45 to $55 a barrel.

Senator BUNNING. Or the $61 a barrel like now.

Governor SCHWEITZER. Or greater. Exactly. But there is a large gap there, and that really needs to be something that needs to be addressed by, perhaps, folks on this committee.

Senator BUNNING. But that could be something that could be included as a national base, particularly for the military, if we used that as a base for the Air Force so they could go out and make sure long-term contracts are not going to get hammered if the oil price happens to hit $30, that we would be protecting them at $40, the Air Force, the Army, whoever it might be.

There is such a consumption gap. I mean, we consume so much in the military. If we could do something to make sure that we were off of the Middle Eastern production for our military, what a national security thing that would be for the United States of America. Do you disagree?

Mr. AIMONE. No, sir.

Senator BUNNING. No, sir. All right. Thank you, Mr. Vice Chairman.

Senator GRASSLEY. Thank you. I think the Chairman said it better than I can, but I would associate myself with his words, the outstanding panel we have, as well as the importance of this hearing that we have had now that I think he would say is the start of a dialogue to formulate policy, and we thank you very much for your contribution to that.

The hearing is adjourned.

[Whereupon, at 12:04 p.m., the hearing was concluded.]

APPENDIX

Additional Material Submitted for the Record

WITNESS STATEMENT OF MR. MICHAEL AIMONE, ASSISTANT DEPUTY CHIEF OF STAFF/ LOGISTICS, INSTALLATIONS & MISSION SUPPORT

Chairman Baucus, Senator Grassley, and distinguished members of the committee, I thank you for the opportunity to appear today to outline the Air Force Energy Strategy for the 21^{st} Century, and describe some of our recent achievements to improve Air Force energy use in our aviation operations, ground vehicle fleet, and worldwide network of 166 installations. I also will provide the preliminary results from our recent flights of a B-52 Stratofortress bomber using a blend of synthetic and crude-oil based jet fuel (SynFuel Blend).

I am Mike Aimone, and I work for the Deputy Chief of Staff for Logistics, Installations and Mission Support, Headquarters United States Air Force. I have 37 years of experience working for the Air Force as a facility engineer and logistician, and have had the opportunity to be part of the Air Force Energy Program since its inception in 1974.

In the aftermath of the hurricanes that impacted the Gulf of Mexico 18 months ago, the Secretary of the Air Force, the Honorable Michael W. Wynne, directed extraordinary actions by all Airmen to help mitigate the resultant energy issues that faced the Air Force and the Nation. One of his first actions was to direct the Under Secretary of the Air Force, Dr. Ron Sega, to create and oversee an aggressive new energy strategy for the Department.

Dr. Sega immediately directed the stand up of a Senior Focus Group on energy to address these concerns. The group, which consists of the General Officers, Senior Civilians, including the Chief Scientist of the Air Force, has met seven times and published an energy strategy to guide our Department's energy efforts.

The vision that drives the Air Force Energy strategy is to: "Make energy a consideration in all we do."

Our strategy is three-fold:

-- First, ensuring energy supply side availability of fuel for our aircraft, ground vehicles, and equipment, as well as reliable utility services to our installations to meet Combatant Commander requirements.

-- Second, implementing aggressive demand side fuel optimization and energy efficiency initiatives laser-focused on each of our three energy sectors: aviation operations, ground transportation and support equipment, and installations.

-- Third, and indeed the most important element in our energy strategy is to ensure that our strategy transcends the present to create a lasting culture of change in all Airmen so that energy becomes a consideration in all we do.

To kick-start this cultural change, the Secretary of the Air Force issued a Letter to all USAF Airmen communicating his goals on energy conservation. The Secretary summarized the myriad of energy initiatives underway, and charged every Airman to develop new ways to personally and organizationally use energy more efficiently. This letter was followed with a robust communications program to all airmen to raise their awareness of energy conservation during October, which is traditionally for the Air Force "Energy Awareness Month".

The Air Force has an aggressive facility energy conservation program that achieved an impressive 30% reduction in energy use over the past 20 years. However, we are challenged to do better. The President, on January 24, 2007, issued a new energy Executive Order (E.O. 13423), directing agencies to reduce energy intensity by '(i) 3 percent annually through the end of fiscal year 2015, or (ii) 30 percent by end of fiscal year 2015, relative to the baseline of the agency's energy use in fiscal year 2003.' E.O. 13423, sec. 2(a)."

Besides a new facility energy conservation goal, the Executive Order also establishes new goals on the use of renewable energy, greenhouse gas emission reductions, and water conservation. Our strategy has been adjusted to meet these mandates. We also have established a goal to have our ground general purpose vehicle fleet "right-sized." This includes the purchase of at least 30% of our new vehicle requirement as Low Speed Vehicles – a new class of vehicle sometimes referred as "Neighborhood Electric Vehicles."

Over 80% of the Air Force annual $7B energy bill goes to fueling our aircraft. Our new strategy is committed to root-out waste and implement greater efficiencies in aviation operations. We have set an aggressive target to reduce aviation fuel use by 10% over the next six years.

We will accomplish this aviation fuel optimization strategy through a series of operational changes by our pilots and aircraft maintenance specialists – some changes are as simple as reducing unneeded weight on aircraft. For example, every 100 pounds of excess weight removed from one of our strategic airlift aircraft results in an annual savings of 240,000 gallons of aviation fuel. In one recent Lean/6-sigma rapid improvement event, we identified nearly 2,000 pounds of excess weight that could be removed from a single KC-135 air refueling aircraft. We are also eliminating the practice of standard ramp (fuel) loads to reduce the amount of excess fuel planes land with. We will do this without reducing safety margins, while increasing consciousness of the "Cost-to-Carry" excess weight and fuel. Additional efforts to move training events to simulators, updating ground operation procedures, and establishing a culture of air crew awareness and fuel use accountability are just a small number of the efforts we are undertaking to optimize aviation fuel while simultaneously delivering air, space and cyberspace capabilities to the Combatant Commanders.

We have significant accomplishments I would like to share with the Committee today. Specifically:

-- The Air Force in Fiscal Year 2006 remained the largest green power purchaser of electricity – over 990,000 MWHrs -- in the Federal Government, and 3rd largest in the United States, according to a recently published Environmental Protection Agency Green Power Partnership report. Dyess AFB in Texas, Fairchild AFB in Washington, and

Minot AFB in North Dakota achieve nearly 100% of their electrical energy requirements from wind energy systems located near their installations. Thirty-seven Air Force Bases in the United States procure green power.

-- We have installed over 7 Megawatts of on-site wind energy and solar photovoltaic and landfill gas systems at a number of our bases These systems provide renewable energy for our installations, but also provide for increased energy security in the event of the loss of electric power from the grid due to natural disaster or enemy attack.

-- Nearly 8% of our diesel fuel is B20, which is a blend of 80% conventional diesel and 20% renewable bio-fuels. Our efforts to expand the use of E85 for our Flex Fueled Vehicle fleet is less successful. This is because E85, and its infrastructure, is not currently available at the majority of our installations. However, we are ready -- we have 4,479 FlexFuel vehicles in our fleet. Of that total, 1,547 sedans, or nearly 29% of our sedan fleet, is E85-ready. We continue to grow the fleet and convert our infrastructure to B-20 and E-85. Indeed, today, 58 Air Force Bases are dispensing B20, and 16 bases are dispensing E85. With our partners at the Defense Energy Support Center we have 26 biofuels infrastructure projects in the plans, or just recently completed -- the vast majority of these construction projects are for E85.

Mr. Chairman and members of the committee, I am sure you are most interested in the Air Force's plans to test, certify and fly using a Synfuel blend for the B-52 Stratofortress bomber powered partially by synthetic jet fuel produced from natural gas from a company in Tulsa, Oklahoma.

Last year the Secretary of the Air Force directed Air Force Materiel Command to take on a project to procure synthetic fuel, static ground test the fuel on engine test stands at the Oklahoma City Air Logistics Center at Tinker AFB, Oklahoma City, Oklahoma, and, if ground tests were successful, conduct an aviation flight demonstration at the Air Force Flight Test Center, Edwards Air Force Base, California. To ensure maximum crew safety in the first US military jet aircraft powered by domestically manufactured synthetic liquid hydrocarbons, the test was conducted using a 50/50 blend of conventional crude oil refined jet fuel and synthetically manufactured product. The first three flights were arranged for safety purposes so that only a single pod of two engines were powered by the SynFuel blend. The remaining six engines of the aircraft used conventional crude oil refined jet fuel.

The initial flight took place on September 19, 2006, and there have been a total of four flight tests, the most recent occurring on December 15, 2006. The last flight in the test series was flown by the Commander of the Air Force Flight Test Center with all eight engines fueled by the SynFuel blend, thus fully demonstrating the feasibility of using synthetic fuel for military aviation use.

In January, the jet was flown to Minot AFB, North Dakota for a series of cold weather engine starting tests. Those tests have been completed.

The jet has returned to the Air Force Flight Test Center, Edwards AFB, California, and the jet is being thoroughly inspected. We expect a full test report in the summer. Preliminary inspections have confirmed that there are no deleterious effects of using a Synthetic blend jet fuel in military aircraft. It is our plan, if the detailed analysis of the test results and physical inspections prove out, to certify the entire inventory of B-52s for unrestricted flight operations using a SynFuel blend by the end of the year.

It should be pointed out that we chose a domestic source of SynFuel for our first military aviation demonstration, and this SynFuel was manufactured from natural gas. We recognize that Gas-to-Liquids do not assure the Air Force a dependable supply of jet fuel, since domestic natural gas production is insufficient to meet the Nation's. needs. The production of SynFuel from coal, oil shale and biomass sources would solve this constraint; however, there are considerable technical, environmental, and economic issues that remain to be worked out. We are partnering with the Department of Energy and the Defense Logistics Agency, as well as the Task Force on Strategic Unconventional Fuels mandated by Section 369 of the 2005 Energy Policy Act to explore what can be done in these areas.

Mr. Chairman, and members of the Committee, the Air Force appreciates the opportunity to provide an overview of our energy initiatives and the testing and certification of Synfuel for our fleet. I look forward to answering your questions at this time.

DEPARTMENT OF THE AIR FORCE
WASHINGTON DC 20330-1000

OFFICE OF THE SECRETARY

MAR 2 2 2007

SAF/LL
1160 Air Force Pentagon
Washington, DC 20330-1160

The Honorable Max Baucus
Chairman, Committee on Finance
United States Senate
Washington, DC 20510-6200

Dear Mr. Chairman

Attached are the answers to Questions for the Record on energy you requested in your March 1, 2007, letter to the United States Air Force regarding the February 27, 2007, Committee hearing on "America's Energy Future: Bold Ideas, Practical Solutions."

Should your staff have any questions, please contact Lt Colonel Doug Cato of my staff at 703-693-9109.

Very respectfully

DANIEL J. DARNELL
Major General, USAF
Director, Legislative Liaison

Attachment:
AF Answers to Questions for the Record

Hearing Date: February 27, 2007
Committee: Senate Finance Committee
Member: Chairman Baucus
Witness: Mr. Aimone
Question: #1

America's Energy Future: Bold Ideas, Practical Solutions

Question: The technology for turning coal or natural gas into fuel has been around since the 1920s. Fifty years after its discovery, synfuel was championed by the Carter administration, before the price of oil collapsed. What is different today, compared to the 1970s, that would make synfuels' use in the US successful? What is the potential for non-military use of synfuels? Do you agree with Governor Schweitzer that synfuel use must be complemented with carbon sequestration?

Question 1a: What is different today, compared to the 1970's that would make synfuel's use in the US successful?

Answer: Unlike the 1970s, wherein the United States had to start its Synthetic Fuels initiatives from a "cold-start", today the United States has a strong foundation of university research and intellectual property in Synthetic Fuels science and technology. For example:

While the Synthetic Fuels Corporation shuttered its operations in 1986, top-flight US University energy centers have continuously maintained superior research programs, and educated the next generation of engineers and scientists on the chemical engineering issues associated with advanced energy conversion. The Department of Energy has supported research at universities from coast to coast to develop advanced processing technologies for a variety of synfuels. In addition, the Gas Technology Institute in Chicago, Illinois has provided a gasification test bed for university and commercial activities, and is currently updating their flexible test facility to include a Fischer-Tropsch unit.

Nearly 30 years of experience has been gained through continuous unit operations at the Great Plains Synfuels Plant in Beulah, North Dakota. Practical lessons have been learned from the Integrated Gasification Combined Cycle coal to electrical power plants operating in Indianapolis, Indiana and Tampa, Florida. Research efforts by the Department of Energy and their laboratories have led to advances in coal gasificiation, gasifier designs, and unit operation efficiencies. In 2003, the Syntroleum Corporation commenced operations of the Fischer-Tropsch Catoosa Demonstration Facility in Tulsa, Oklahoma and produced 100,000 gallons of synthetic fuel from natural gas for the Air Force. Rentech, Inc. has announced plans to operate a plant in East Dubuque, Iowa, and Baard Energy has similar plans for construction of a plant in Columbiana County, Ohio. Other plants are planned for Montana, Wyoming, Mississippi, Alabama and North Dakota. Modern gasification plants have been constructed, and are operational in Qatar and Malaysia, as well as planned expansion of the 150,000 bbl/day SASOL plant in South Africa. China has in planning, design, and construction, over US$128B in gasification plants.

One of the potential differences is that industry is now focused on the long term economic viability of the projects. While many projects in the 1970's were developed as a rapid response to a crisis, today's projects must be competitive for decades in a global market. Technical maturity, commercial experience, and market demand should be able to provide the synfuels industry with a stronger position than 30 years ago.

Question 1b: "What is the potential for non-military use of synfuels?"

Answer: There is broad application of synfuels in the commercial sector as a direct replacement for liquid hydrocarbons.

While much of the ground transportation sector can convert to ethanol-based fuels, conversion of jet aircraft to ethanol is economically prohibitive and nearly impossible technically at this time. The commercial aviation sector is very interested in synfuels derived through the Fischer-Tropsch process. They have recently formed the Commercial Aviation Alternative Fuels Initiative (CAAFI) to develop industry wide plans and roadmaps to evaluate synfuels for fleet certification by 2009.

Question 1c: "Do you agree with Governor Schweitzer that synfuel use must be complemented with carbon sequestration?"

Answer: Yes.

It is our intent to procure synfuels from new, domestic coal-to-liquids plants that have carbon capture and sequestration (CCS) technology and equipment in order to greatly reduce CO_2 emissions. The Air Force has a proven track record of being good environmental stewards. Our testing and certification of the Air Force fleet to use synthetic fuel has the potential of producing fewer greenhouse gases and nearly zero SOx and particulates from the tailpipe.

Hearing Date: February 27, 2007
Committee: Senate Finance Committee
Member: Senator Salazar
Witness: Mr. Aimone
Question: #2

America's Energy Future: Bold Ideas, Practical Solutions

Question: How do you propose to address the issue of CO_2 emissions from coal-to-liquid (CTL) projects, which are much higher than normal refinery-based production of liquid fuels?

Answer: The capture and sequestration of CO_2 in the coal-to-liquids (CTL) process is critical to the viability of this new industry in the United States.

The gasification process provides a concentrated CO_2 stream compared to conventional pulverized coal burners. During this process, CO_2 is removed before the Fischer Tropsch reactor. This CO_2 is a valuable resource for enhanced oil recovery (EOR). At this time, it is being captured and sold by the Dakota Gasification Plant in Beulah, ND and sent 250 miles by pipeline to Canada to extract additional oil sands. In addition to EOR, the CO_2 can be pumped into deep saline aquifers, coal seams or other geological formations.

The Department of Energy's National Energy Technology Laboratory has developed new technology that can capture 90% of the CO_2 produced by CTL. This technology is being tested this year at an IGCC plant in Ohio and next year at an IGCC plant in Wisconsin.

If biomass is mixed with coal and carbon capture and sequestration are utilized, the CO_2 footprint can be reduced to levels significantly below that of conventional petroleum. The AF has partnered with DOE to evaluate both sequestration technology and the co-conversion of biomass with coal to determine the reduction of CO_2 levels below conventional petroleum and the cost implications related to the CO_2 reductions.

The environment qualities of CTL synfuel produces a product that is virtually free of SOx and particulates. Based on results from the B-52 flight test the Air Force has determined that the CO_2 at the tailpipe also is reduced by 1.6%.

Hearing Date: February 27, 2007
Committee: Senate Finance Committee
Member: Senator Salazar
Witness: Mr. Aimone
Question: #3

America's Energy Future: Bold Ideas, Practical Solutions

Question: It is my understanding that 3 to 4 barrels of oil could be produced from enhanced oil recovery (EOR) projects for every barrel of liquids produced from CTL, if the CO_2 produced from the CTL project is used for EOR purposes. Do you agree?

Answer: According to the Department of Energy, the state-of-the-art enhanced oil recovery with carbon dioxide, is now recognized as a potential way of dealing with greenhouse gas emissions, could add 89 billion barrels to the recoverable oil resources of the United States, the Department of Energy has determined. Current U.S. proved reserves are 21.9 billion barrels.

The 89-billion-barrel jump in resources was one of a number of possible increases identified in a series of assessments done for DOE which also found that, in the longer term, multiple advances in technology and widespread sequestration of industrial carbon dioxide could eventually add as much as 430 billion new barrels to the technically recoverable resource.

Beginning efforts to develop the 89-billion-barrel addition to resources would depend on the availability of commercial CO_2 in large volumes. If this oil could be added to the category of proven reserves, the U.S. would have the fifth largest oil reserves in the world behind Iraq, which has 115 billion barrels, based on present estimates; and an additional 430 billion barrels would make it first, ahead of Saudi Arabia with 261 billion barrels. The capture of CO_2 from combustion in power generation and other industrial uses is the subject of other research and development programs sponsored by the Office of Fossil Energy, DOE.

Invited Testimony for the U.S. Senate Finance Committee

Prepared Statement of
Dr. Dan E. Arvizu
Director, National Renewable Energy Laboratory
Golden, CO

February 27, 2007

Mr. Chairman, thank you for this opportunity to discuss important issues related to the nation's energy policies as we move to reduce our dependence on foreign oil, maintain a healthy environment and fully meet the energy demands of the future. I am the director of the National Renewable Energy Laboratory in Golden, Colorado. NREL is the U.S. Department of Energy's primary laboratory for research and development of renewable energy and energy efficiency technologies. I am honored to be here, and to speak with you today.

For those of us who have devoted our careers to energy research, the era in which we find ourselves today is both exciting and challenging. Never before have we witnessed such intense interest in – and rapid growth of – renewable energy and energy efficiency technologies. The industries for solar, wind and biomass energy systems are expanding at rates exceeding 30 percent annually. While this is certainly a welcome development, much remains to be done to sustain our current momentum.

If we are to ensure the nation receives the full range of benefits that renewable energy technologies can provide, we will need a carefully balanced blend of new technology, market acceptance and government policies. It is not a question of whether to rely solely on the market, or on new research, or on government action, as we work to solve our energy problems. To accelerate deployment of renewable energy technologies effectively, we need to effectively combine all three.

It's also crucial that this mix of technology, markets and policies be crafted so that each works in conjunction with the others. The reality is that distinct renewable energy technologies – be they solar photovoltaic, solar thermal, wind, biomass power, biofuels or geothermal – are in different places in terms of their economics, technological maturity and market acceptance. While a broad range of policies are needed to spur on these varied technologies, the specifics of policies and incentives to be enacted ideally must be tailored to fit the unique requirements of each of the systems and devices we are seeking to deploy.

At the same time, policies must be put in place with a view to the long term, and maintained and supported consistently, to maximize their effectiveness. The Production Tax Credit for wind power is a case in point. The history of the PTC has been one of fits and starts – the tax credit has been on in some years, off in others. As a result, wind turbine manufacturers, developers, utilities and consumers who have wanted to see more of their energy come from renewable sources, have all endured the predictable boom-and-bust problems that come with on-again, off-again policies. While I can only imagine the challenges that confront those who deliberate and adopt a federal budget, anything we can do to move beyond a year-to-year approach, and chart a long term course for renewable energy policy, will provide us with lasting benefits.

Losing Global Renewable Energy Market Leadership

So, to be successful, any new policy commitment must be consistent and sustained. We have already witnessed what can happen if our commitment is inadequate or short-lived.

Over the last decade, Denmark, Germany and Spain have surpassed the U.S. in production and deployment of wind turbines, and Japan and Germany have surpassed the U.S in production of electricity-producing solar photovoltaic panels.

Ironically, they did so largely by adopting technologies that had been developed here in the United States. We came up with the right technologies, but we did not capitalize on these innovations with policies adequate to spur deployment. While the U.S. remains the technological leader for renewable energy, industries in Europe and Asia have grown to dominate this greater than $40 billion international business. Our foreign competition were able to leapfrog U.S. businesses because of public policy driven investment incentives, aggressive renewable energy targets and other bold national policies adopted in their home countries.

Given where our national markets and technologies stand today, a particular need exists for sound government policies and incentives – at the local, state and federal level – that stimulate smart domestic energy development within the framework of the marketplace. Such policies should support the mobilization of private sector capital and the fostering of robust competition. The competition of the marketplace drives improvements in technology and economic efficiencies. Market competition has been and should remain a vital ingredient in the successful evolution of renewable energy in the United States.

Energy policy must also take into account the realities and complexities of our growing economy, modern lifestyles and our natural environment. We risk much if we fail to grasp the totality of the energy landscape before us, and not plan for and address the full range of contingencies upon which the success of our new energy ventures depend.

Granted, gaining both a broad and detailed understanding of such a complex mission may be daunting – but resolving the issues therein is fundamental to all else that we do.

Opportunities and Challenges of Biofuels

The evolution of biofuels as a national priority provides a timely lesson. Researchers at NREL have been working on biofuel technologies since our laboratory was founded in 1977. However, it only has been recently that public policy has looked to biofuels as a way to supplant petroleum use in a near-term, meaningful way.

Recent studies have shown that there is sufficient biomass potential in the U.S., and worldwide, to produce significant amounts of transportation fuels – enough to displace a major portion of the petroleum we use today. Clearly, this is an area that has great promise; but it must be done correctly.

The Department of Energy, NREL and other national laboratories, have embarked upon a concerted effort to move beyond the use of corn grain for ethanol, and develop a new industry that will produce tens of billions of gallons of ethanol from corn stover, switch grass, wood chips, crop and forest residues and other forms of cellulosic biomass, over the next several decades.

As the enormity of this task is considered, a range of formidable challenges is coming into sharper focus. We understand that the research we are performing today to make cellulosic ethanol technologies more efficient and affordable is precisely the correct first step. But we also are coming to understand that there are a number of other essential pieces to this puzzle.

To achieve the unrealized potential of biofuels, we need to carefully examine such questions as: Where will this huge new supply of biomass come from? How will we achieve improvements in agricultural practices? How will massive new volumes of biomass get to refineries, and how will commensurately large volumes of fuels get to retail stations? Will new fuels be consistently energy dense and free of contaminants? How will vehicle fleets have to evolve? How will the value chain components and bi-products alter existing value chains? And perhaps most importantly, what are the ultimate impacts on our land use, water and air? And how will those who adopt these technologies affect the global environment? These are just a few of the factors in play.

Of equal concern are the longer-range needs of the biofuels industry itself. We should begin today to conduct the research that will be needed for a time in the future when industry and consumers will require new and better fuels, chemical feedstocks and a range of other products, we know we can make from biomass.

Answers to these essential questions have profound implications – this is no simple, academic exercise. For this work to be lasting and useful, it all must be done in close collaboration with industry. What is called for then is a comprehensive, integrated program for biofuels development, which identifies and plans for all the critical factors such a massive undertaking will entail.

Our Nation's Energy Future

Beyond advancing individual energy technologies, we as a nation should establish durable criteria and priorities to determine what our national energy landscape will look like in the future. You may have heard that we could meet all of our nation's electricity needs by building a giant solar power farm in the Nevada desert. Although that may indeed be a useful metaphor to illustrate the vast solar resource available to us, it isn't helpful at all in determining what our nation should actually do in any practical sense.

The same holds true for other energy choices as well. For instance, we know the U.S. has immense reserves of conventional and non-conventional fossil resources, and we know that technologies might be developed to turn those into fuels. But as we plot a course for the future, and consider the range of energy, environmental and economic choices that confront us, we must demand that the decisions we make today are not only technologically defensible, but also practical, environmentally sound and sustainable long into the future. The appropriateness of new technology, and sustainability over its entire life-cycle, must be guiding forces in decision making.

The Role of R&D in Advancing Renewable Energy

As for renewable energy technologies, we are at present confronted with something of a double-edged sword. On one side we have existing renewable energy systems that should be encouraged into the marketplace here and now – through a combination of viable technology, government policy and market mechanisms. On the other side, if we are to achieve "significance" in the level of contribution renewable energy can make to our future energy mix, we must make technological advances to make today's technology more efficient and less costly.

There has never been a greater need for new research into subsequent generations of renewable energy technologies, even though the drive to commercialize existing renewable energy technology has never been more brisk. We still need to make tomorrow's energy solutions more productive, economical and environmentally beneficial than those available today.

For renewable energy research, here again, a sustained, long-term commitment is required. Our Laboratory may provide a useful example. While we at NREL work with industry to perfect and deploy existing renewable energy systems, we also are working on new technologies that industry will be using, five, ten, twenty and perhaps even fifty years hence.

A melding of basic and applied science is essential in the energy research field. It is only through a sustained commitment to research that the nation will meet its long range energy needs. Researchers at NREL and elsewhere are closing the gap between basic science and applied research and development – all the while focusing a bright light on the valuable end uses of our work. The result is that we are shortening the time it takes to push new renewable energy technology off the lab bench and into the marketplace.

To guarantee this progress continues, we must make necessary new investments in our research capabilities now – because having adequate research facilities is essential to all other R&D goals. The nation's world-class laboratory system and its leading academic institutions must be re-tooled, and funded at an adequate level, so we have the necessary capabilities to see this vital mission to its successful conclusion.

Beyond the need to invest in research capabilities and facilities, we need to focus the resources and attention of universities and other academic institutions into renewable energy research. In the biofuel industry, we are already encountering a dearth of qualified engineers and scientists with the appropriate education and training to make the contributions that are needed in the field. Meanwhile, a looming shortfall of potential researchers in the undergraduate system will only be compounded as industry ramps up its hiring demands in the future.

Balancing R&D Investments, Short and Long Term

In conclusion, to address our near-term needs, we need a national strategy that promotes the rapid deployment of the renewable energy systems and processes that are ready and able to serve us today. At the same time, to address needs longer-term, we must make a major new commitment to the research required to deliver the next, and subsequent, generations of new technologies.

This will not come without cost, but recent experience suggests that investment in renewable energy technologies will produce significant economic benefits. And, by investing in technologies not tied to the unpredictable price of oil, we may very well pay less than we ultimately would have for more conventional sources of energy.

New research can and will make these technologies more practical, and more affordable. In the less than three decades since our laboratory was founded, the cost of producing energy from the sun, wind and biomass has been reduced by more than 80 percent – a favorable cost trajectory that continues today.

The good news is that the United States can take back the leadership it once had in the renewable energy field – what is likely to be one of the most important new industries of this century – through investing wisely now, and into the future. The timing is fortuitous, because by most all accounts, the next big market for global renewable energy growth is here in the United States.

Thank you.

Senate Finance Committee Hearing
"America's Energy Future: Bold Ideas, Practical Solutions"
February 27, 2007
Questions for the Record for Dr. Arvizu

Questions from Chairman Baucus

1. *Today the Department of Energy announced plans to invest $385 million in six biorefinery projects across the U.S. When fully operational, the plants are expected to produce more than 130 million gallons of cellulosic ethanol per year. Cellulosic ethanol holds tremendous progress, but so far has been limited by its high cost. What is the relative cost of constructing a cellulosic ethanol plant, compared to a corn based facility? Once the plant is built, what is the relative cost of producing these two types of fuel?*

Response

The table below compares a typical 50-million gallon corn ethanol facility with two different cellulosic ethanol plants. The 'Current SOT' plant refers to the state of technology of the R&D being performed and proven at the pilot scale at NREL. The 2012 plant is the DOE Office of Biomass Programs goal which has many R&D targets that must be met in order to reach.

All values are in 2007 $	Installed Capital ($/annual gallon EtOH)	Total Project Investment ($/annual gallon EtOH)	Operating Costs not including feedstock ($/gallon EtOH)	Feedstock Costs ($/gallon EtOH)	Minimum Ethanol Selling Price ($/gallon EtOH)
Current Corn Dry Mill[1]	$1.10	$1.53	$0.20	$1.06	$1.53
Current SOT Cellulosic Plant[2]	$2.95	$5.06	$0.74	$0.95	$2.63
2012 Cellulosic Plant[3]	$1.96	$3.40	$0.22	$0.49	$1.31

2. *Many electronic devices – such as cell-phone chargers – draw power when plugged in, even if they're turned off. Estimates for the costs of 'phantom electricity' are $8 billion per year to the American consumer, totaling 5% of all electricity we use. Are we making progress on reducing 'phantom electricity'? If not, does the answer lie in more research, better standards, or better technology from manufacturers?*

Response

Yes, we're making progress but additional work is needed in all three areas you cite. Let me explain.

In 2001, President Bush ordered all federal agencies to purchase energy efficient appliances and office equipment when possible. Since then, the purchasing power of the Federal Government has helped to influence manufacturers to make more efficient appliances and equipment.

The Federal government will save approximately $14 million in annual energy costs from the 2001 baseline. U.S. consumers will save approximately $300 million in annual energy costs, saving the equivalent electricity used in approximately 350,000 homes.

However, sufficient field testing has not been done in this area to be able to definitively answer the question, "what else do we need to be doing?". The good news is products are becoming more efficient in standby mode. The down side is we're increasing the number of electronics in each household.

The answer to reducing phantom electricity lies in several possible approaches. First, the Energy Policy Act (EPACT) requires that the Department of Energy review whether regulation of standby power usage for external power supplies and battery chargers is necessary. DOE is already examining the standby power used for battery chargers and external power supplies as part of its determination analysis prior to determining whether it will issue energy efficiency standards for these products.

Second, for appliances with internal power supplies, a review of standby power usage will be included in the process of developing new or updated efficiency standards for 24 categories of appliances or equipment over the next 5 years. For any of these products where standby power has energy saving potential, DOE will consider whether to incorporate standby mode into the test procedure and energy conservation standards, taking into account standby power consumption compared to overall product consumption, thereby encouraging the use of better technologies.

The third approach is future research possibilities in advanced power management. There are several possible research areas that could address this.

Additional research could be done to help product manufacturers innovate further in this area. At the outlet level, configured correctly, outlet controls could be developed to control and reduce standby power usage. At the whole building level, a wiring system or whole building controls could be used to minimize standby loads. Central control systems or central-system products (i.e. a single cable box instead of one box for each television) are also possibilities for reducing the load. Much can be done in this area to reduce not only standby power use, but the overall energy used in miscellaneous electric loads.

The fourth area is public awareness. Energy Star has made a good start at addressing this at the product level and has done an excellent job of showing companies will support voluntary efforts to reduce power usage in products. However, many more products on the market are capable of reduced energy usage. How many people know a television cable box is using nearly as much power when it's "off" as when it's on? Raising the awareness on electricity usage in household products could significantly reduce these loads as well.

<u>Question from Senator Kyl</u>

3. *Congress has repeatedly justified the extension and expansion of section 45 of the Internal Revenue Code based on the "success" of the credit. When section 45 was approved in the 1992 Energy Policy Act, the House report noted that "the credit is scheduled to sunset after June 30, 1999, to provide the committee with the opportunity to assess the effectiveness of the credit in encouraging utilization of renewable energy sources." Before Congress extends section 45 again, I believe we should conduct a serious review to determine how much longer taxpayers will be asked to subsidize wind and other renewable sources. Wind accounts for more than two-thirds of the cost of section 45. In a press release issued this month by the American Wind Energy Association it boasts that there were more wind turbines installed in the United States last year than in any other nation and the wind power has plunged from 45 cents per kilowatt-hour in 1980 to less than 3 cents today.*

    a. *Is wind energy competitive with other energy sources that do not enjoy a production tax credit?*
    b. *If wind is not yet competitive, when will it be?*

Response

The cost of wind generated electricity has dropped dramatically since 1980, as stated in the AWEA Press release. Cost data for some wind energy projects from public records shows that in 2006 the price paid for electricity generated in large wind farms, generally located in very good wind resource areas, was between 3 and 5 cents per kilowatt-hour, with an average of a little over 4 cents per kilowatt-hour. These figures represent the electricity price as sold by a wind farm owner to the utility. The price includes the benefit of the federal production tax credit, and any state incentives, as well as revenue from the sale of any renewable energy credits. The true cost of the delivered electricity would be higher by approximately 1.9 cents per kilowatt-hour, which is the value of the federal tax credit. Thus the unsubsidized cost for wind generated electricity for projects completed in 2006 – again, at the best resource sites - ranges from about 5 to 7 cents per kilowatt-hour. These wind energy costs are generally higher than the wholesale cost of other electricity generating sources.

Furthermore, the cost of wind turbines has been increasing in the last five years. The average cost per installed kilowatt for wind farms *proposed* in 2006 has risen by about 30% from 2002 to about $1680/kW. Conversations with wind farm project developers indicate that turbine prices are expected to be even higher for future projects. This means that the cost of wind generated electricity for projects installed in 2007 and beyond will likely be higher than the 5 to 7 cents per kilowatt hour given above for 2006.

The reasons generally offered for the increasing price of turbines after the long downward price trend of the last 25 years include:

- Turbine and component shortages due to the dramatic recent growth of the wind industry both in the U.S. and Europe.
- The weakening U.S. dollar relative to the euro, because many major turbine components are imported from Europe. There are relatively few wind turbine component manufacturers in the U.S.
- A significant rise in material costs such as steel and copper.
- The on-again and off-again cycle of the wind energy production tax credit. This uncertainty hinders investment in new turbine production facilities, and encourages hurried and expensive production, transportation and installation of projects when the tax credit is available.

In summary, wind energy is not yet competitive with other sources of generation and appears to be growing less competitive.

For the wind energy industry to become mature and competitive with other generating sources, the following issues need to be addressed:

- The policies employed to stimulate the introduction and use of advanced energy technologies, much like when advanced conventional technologies were introduced, need to be stable and predictable over several years to stimulate the needed private sector investment in research, development and manufacturing.

- The value of emission free and carbon free generation sources needs to be monetized to enable the transformation of the energy marketplace to low, or no, carbon technologies.
- There is a need to invest in research and development in order to reduce current wind turbine costs and increase energy capture to drive the unsubsidized cost of wind generated electricity down to about 4 cents per kilowatt-hour, which would be about a 40% improvement over today's technology.

Research progress is always difficult to predict; however, based on the cost reductions achieved over the past 25 years, land based wind technology could probably achieve this level of cost effectiveness in 7 to 10 years, with the appropriate policies and the needed research and development investments.

[1] This case assumes corn at $3.00/bu, natural gas = $7.25/MMBtu, and DDGS selling price = $80/ton
[2] This case assumes a delivered feedstock cost (corn stover) = $62/dry ton
[3] This case assumes a delivered feedstock cost (corn stover) = $44/dry ton

Testimony of Dan W. Reicher
Director, Climate Change and Energy Initiatives
Google.org
Before the
Senate Finance Committee
February 27, 2007

Mr. Chairman and members of the Committee, my name is Dan W. Reicher and I am pleased to testify today on federal policy measures that can enhance investment in clean energy, particularly energy efficiency. I recently joined Google where I serve as Director of Climate Change and Energy Initiatives for the company's new philanthropic venture called Google.org. Google.org has been capitalized with more than $1 billion of Google stock to make investments and advance policy in the areas of climate change and energy, global poverty and global health.

Prior to my position with Google, I was President and Co-Founder of New Energy Capital, a private equity firm funded by the California State Teachers Retirement System and Vantage Point Venture Partners to invest in clean energy projects. New Energy Capital has made equity investments and secured debt financing for ethanol and biodiesel projects, cogeneration facilities, and a biomass power plant. Prior to this position, I was Executive Vice President of Northern Power Systems, the nation's oldest renewable energy company. Northern Power has built almost one thousand energy projects around the world and also developed path-breaking energy technology.

From 1993 to 2001, I served in the Clinton Administration as Assistant Secretary of Energy for Energy Efficiency and Renewable Energy, Department of Energy Chief of Staff and Deputy Chief of Staff, and the Acting Assistant Secretary of Energy for Policy.

Mr. Chairman, we have a broad array of options for addressing the nation's energy challenges, as other witnesses demonstrate in their testimony today. The federal government, through Congressional and Presidential leadership, has a powerful role to play in moving these energy solutions to market. I am honored to share with you my views as an investor, former policymaker and most importantly, as a professional dedicated to ensuring our success in meeting today's energy-related challenges: climate change, national security, economic competitiveness and poverty alleviation.

There are several steps the federal government must take to drive massive private sector investment – measured in the trillions of dollars – that will be required to move the nation toward a more sustainable energy future:

- First, the federal government must put a price on greenhouse gas emissions in order to internalize the costs of climate change and move energy investments toward lower carbon and more efficient technologies.
- Second, we must remove barriers to cleaner and more efficient technologies and establish incentives and standards to move these technologies to market.
- Third, we must significantly increase public funding of research, development and deployment of advanced energy technologies.
- And fourth, the federal government must support fluid, transparent markets to monetize the environmental benefits that these technologies provide. The market needs clear definitions of and ownership rules for renewable energy certificates, carbon offsets, white tags, and other environmental assets created by regulation at the federal and state level.

Energy Efficiency – Our Cheapest, Cleanest and Fastest Energy Option

Today I have been asked to focus my attention on how to spur investment in what many see as our fastest, cheapest and cleanest opportunity to address our energy challenges – energy efficiency. Duke Energy CEO James Rogers has termed energy efficiency our "fifth fuel" and energy efficiency guru Amory Lovins measures it in "Negawatts". The federal government has the power to leverage vastly more private sector investment in energy efficiency thereby dramatically increasing U.S. competitiveness, improving our quality of life, and addressing climate change.

Energy efficiency is the real low-hanging fruit in the US and global economy. From cars and homes to factories and offices, we know how to cost effectively deliver vast quantities of energy savings TODAY. And the exciting fact is that this low hanging fruit grows back. The incandescent light bulb we replace today with a compact fluorescent, we will be able to replace again with an even more efficient bulb in the future. Similarly, we can trade our gas-guzzling SUV today for a more efficient full-featured hybrid gas-electric model. And down the road we will replace the hybrid with an advanced model that runs on ethanol or biodiesel and plugs into the electric grid.

We have made an important transition in this country away from a focus on "energy conservation" and toward the more recent concept of "energy efficiency" (or "energy productivity"). In the era of energy conservation in the 1970's and 1980's we were asked to "do less with less" – to lower the thermostat, turn off the lights, don a sweater and leave the car in the garage. Energy efficiency takes a different approach, offering the opportunity to "do more with less". As McKinsey and Company states in a 2006 report, "By looking merely in terms of shrinking demand, we are in danger of denying opportunities to consumers – particularly those in developing economies who are an increasingly dominant force in global energy-demand growth. Rather than seeking to reduce end-user demand – and thus the level of comfort, convenience and economic welfare demanded by consumers – we should focus on using the benefits of energy most productively."

The main finding of the 2006 McKinsey report is that while energy demand will continue to grow, "there are sufficiently economically viable opportunities for energy-productivity improvements that could keep global energy-demand growth at less than 1 percent per annum – or less than half of the 2.2% average growth to 2020 anticipated in our base-case scenario." According to McKinsey, "Energy-productivity improvements can come either from reducing the energy inputs required to produce the same level of energy services, or from increasing the quality or quantity of economic outputs." The report concludes that globally the largest untapped potential for cost-effective energy productivity gains (>10% Internal Rate of Return) lies in the residential sector (e.g. better building shells and more efficient water heating and lighting), power generation sector (e.g. more efficient power plants and electricity distribution) and industrial sector (e.g. less energy-intensive oil refineries and steel plants).

However, McKinsey concludes that capturing this vast potential will require a significant policy push. McKinsey says, "market-distorting subsidies, information gaps, agency issues, and other market inefficiencies all work against energy productivity. Furthermore, the small share of energy costs for most businesses and consumers reduces end-use response to energy-price signals. Therefore shifting global energy demand from its current rapid growth trajectory will require the removal of existing policy distortions; improving the transparency in the usage of energy; and the selective deployment of energy policies, such as standards."

As we consider this policy dimension we also need to consider how to harness an important and heartening new trend – the unprecedented flow of private capital toward clean energy. Who would have thought even a few years ago that Goldman Sachs, Citigroup, John Hancock Insurance, General Electric, Morgan Stanley, the Carlyle Group, Kleiner Perkins and other titans of Wall Street and Silicon Valley would be major investors in clean energy technologies and projects? In fact, in just the last year we have seen literally billions of dollars invested in companies commercializing advanced energy technologies and tens of billions of dollars invested in building clean energy projects. "CleanTech" has recently become the hottest new area of venture capital investing, while clean energy projects have become an important new element of the project finance world.

At the same time, most of this increasing investment in technologies and projects has been on the supply side involving key technologies like solar, wind, and biofuels. However, little investment has found its way to commercializing or deploying energy efficiency technologies despite their cost-effectiveness and reliability. Explanations for this range from the simple to the arcane: for example, the less "sexy" nature of efficiency technologies, the often more disaggregated nature of their deployment, the greater challenge of financing "savings" measured in Negawatts than production measured in Megawatts, and weaker policy support.

Regarding the last point, aggressive federal policy can make a major difference in the development and deployment of energy technology. In the case of ethanol, for example, Congress has enacted both a significant federal tax credit and major federal mandate which have helped stimulate massive new investment in production plants as well as new technologies. Energy efficiency has simply not enjoyed this kind of policy support and the investment that it generates. Below I address how federal policy can enhance private sector investment in energy efficiency, as it now supports critical investment in renewable energy.

I should emphasize that by moderating demand growth through energy efficiency, and at the same time increasing clean generation using renewable sources, we can slow and begin to decrease carbon emissions while we work to adopt and implement a comprehensive approach to addressing climate change. Congress should pay careful attention to this complementary strategy involving both energy efficiency and renewable energy as an important down payment on reducing carbon emissions, while it deliberates the more complex issues entailed in enacting and implementing an economy-wide climate policy.

Federal Policies to Increase Investment in Energy Efficiency

There are an array of federal policy instruments that can enhance investment in energy efficiency including standards, tax credits, and RD&D funding.

- *Automobile Fuel Efficiency*

The single most effective energy efficiency policy ever adopted by the federal government is the Corporate Average Fuel Economy requirement (CAFE). Since its adoption in 1975, CAFE has cut U.S. oil consumption by over 1 billion barrels each year. Even with this progress, passenger vehicles today consume approximately 40% of the petroleum in the United States – with the transportation sector projected to generate 89 percent of the growth in petroleum demand through 2020. And the federal government has not significantly strengthened the CAFÉ standards in years, further diminishing their effectiveness. Raising fuel economy performance to 40 mpg over the next 10 years – through revision of the CAFE standards –could alone cut passenger vehicle oil demand by about one-third or 4 million barrels per day by 2020 -- about twice current daily imports from Saudi Arabia and Kuwait.

Existing technologies – hybrid electric automobiles, drive train improvements, lighter weight materials – can today get us to roughly double the mileage of our current passenger fleet. Perhaps the most exciting technological development has been the recent emergence of plug-in hybrids – a technology that will enable us to exceed any fuel economy proposals under consideration at this time. Plug-in hybrids have a more powerful battery than traditional hybrids and are designed to be connected to the electric grid for recharging. This allows the vehicle to cut gasoline use and, if charged at night, use lower cost and cleaner off-peak electricity. These cars can also benefit electric utilities when plugged in during the day by sending power back to the grid to meet peak power needs, thereby supplanting some of the most costly and often most polluting power generation. According to analysts, this benefit to utilities could be worth thousands of dollars per year per car, a value that could rapidly exceed the incremental cost of the vehicle's more powerful battery if shared with consumers.

By increasing vehicle use of electricity over liquid fuels, we should have an easier time improving the environmental profile of our automotive fleet. This is because lowering emissions from hundreds of power plants will likely be a more rapid and straight forward task than influencing the fuel purchases and driving behavior of millions of individuals. Even charged with electricity from coal dominated parts of our electric grid, a plug-in hybrid is generally cleaner than a gasoline powered car. In addition, plug-in hybrid vehicles enabled to run on biofuels can reduce greenhouse gasoline emissions up to 80%, and oil consumption by as much as two thirds.

The multiple benefits provided by plug-in hybrids call for significant federal actions to move this technology to market as quickly as possible. In addition to controls on greenhouse gas emissions and increased CAFE standards, the federal government can partner with the private sector to address outstanding technological barriers such as battery cost and performance. Even more importantly, the federal government should support deployment of plug-in hybrid vehicles through tax incentives and federal fleet procurement.

- *Energy Efficiency Resource Standard (EERS)*

Just as the Senate has voted in favor of a Renewable Portfolio Standard, it should strongly consider a similar - and highly complementary - mechanism called the Energy Efficiency Resource Standard (EERS). The EERS sets efficiency resource targets for electricity and gas suppliers over the period of 2008-2020. It builds on policies now in place in eight states – California, Texas, Vermont, Connecticut, Nevada, Hawaii, Pennsylvania, and Colorado – designed to cut the growth in electricity demand through energy efficiency. The Texas and Vermont policies have been implemented for several years and have been very successful. Texas utilities, for example, are required to meet 10% of their load growth needs through efficiency programs. Utilities are easily exceeding this target, resulting in current consideration of raising the standard to as high as 50% of load growth. Vermont created an energy efficiency utility that has helped the state in recent years meet more than two thirds of load growth (typically 1.5 to 2% per year) through energy efficiency and the state is on a path to avoid all load growth in the near future.

Under the proposed federal EERS, suppliers are required to obtain energy savings from customer facilities and distributed generation installations in amounts equal to at least 0.75% of base year energy sales for electricity, and 0.50% for natural gas. This requirement is phased in over three years and cumulates during the compliance period. The requirement applies to retail suppliers, be they local distribution utilities or competitive energy suppliers, who sell annually at least 800,000 megawatt hours of electricity or 1 billion cubic feet of natural gas.

Eligible energy savings measures include efficiency improvements to new or existing customer facilities, distributed energy technologies including fuel cells and combined heat and power systems, and recycled energy from a variety of defined commercial and industrial energy applications. Savings are determined using evaluation protocols that can be defined by the Department of Energy (DOE), with state protocols available that the Department can build upon.

Suppliers may obtain and trade credits for energy savings under procedures to be defined by DOE. This will enable suppliers with energy savings beyond the requirements of the standard to sell them to suppliers unable to obtain sufficient savings from their customers within a given compliance period.

The EERS is a compelling complement to a Renewable Portfolio Standard (RPS), which the Senate has passed before and will consider again this year. EERS moderates demand growth so that RPS targets can actually reduce fossil fuel consumption. The RPS provision the Senate supported in 2005 calls for 10% of US electricity generation to be generated from non-hydro renewable energy sources in 2020. However, the Energy Information Administration forecasts electricity demand to grow more than 22% by 2020. Unless we bring down demand growth, the RPS will not likely reduce fossil energy consumption or carbon emissions. The EERS proposal, as analyzed by the American Council for an Energy Efficient Economy would reduce 2020 peak electricity demand by about 10% or about 133,000 MW -- equivalent to almost 450 power plants at 300 MW each. This would bring demand growth down to a level where a 10% RPS could meet all new electricity generation needs. ACEEE also estimates that by 2020, this provision will reduce natural gas needs by about 2 billion cubic feet, reduce CO2 emissions by more than 340 million metric tonnes, and result in cumulative net savings to electricity and natural gas consumers of about $29 billion. Moving to a 15% or 20% RPS level, as proposed in recent bills, would further accelerate the move to a less carbon-intensive electricity system.

These two policies, EERS and RPS, figure prominently in a forthcoming report, prepared by the American Council for an Energy Efficient Economy and the American Council on Renewable Energy and supported by the Rockefeller Brothers Fund, that explores the synergies between energy efficiency and renewable energy. These two energy sources offer a highly complementary approach to managing the challenges of the U.S. power sector in the coming decades.

By moderating demand growth through an EERS and increasing clean generation through an RPS, we can slow and begin to decrease carbon emissions in the utility sector, while we work to adopt and implement a comprehensive cap-and-trade system. Congress should give strong consideration to this EERS-RPS approach as a straightforward down payment on reducing carbon emissions, while it deliberates the more complex issues entailed in enacting and implementing an economy-wide climate policy.

- *Utility Revenue Decoupling*

The recent National Action Plan for Energy Efficiency (http://www.epa.gov/cleanrgy/actionplan/eeactionplan.htm) provides joint recommendations from federal agencies, states, the utility industry and environmental groups regarding energy efficiency. One area of focus in the report is the concept of "revenue decoupling". This approach, first instituted in California, decouples sales from profits, so that electric and gas utilities do not have a disincentive to promote energy efficiency. The current "throughput" incentive (the more electricity or gas a utility sells, the more it earns) is a significant impediment to energy efficiency. As state utility commissions work to advance decoupling, Congress and the Administration (especially FERC and DOE) should consider further incentives to promote energy efficiency. One important federal role would be to promote "best practices" and provide technical assistance to interested parties to facilitate energy efficiency.

- *Tax Credits for Efficient Buildings*

Thanks in part to the efforts of this Committee, the Energy Policy Act of 2005 provided important tax incentives for efficient buildings and equipment, in addition to significant support for renewable energy and other advanced energy technologies. Legislation introduced last year by Senators Snowe and Feinstein, called the EXTEND Act, extends and expands these building-related incentives to enhance investment in energy efficiency. The principal purpose of the bill is to extend the temporary 2005 EPACT tax incentives for a sufficient length of time so that the business community can invest in complying with the significant requirements for the incentives.

Commercial buildings and large residential subdivisions have lead times for planning and construction of 2-4 years, so many businesses will refrain from making investments to qualify for tax incentives if the duration of the incentive is only 2 years. The EXTEND Act provides four years of assured incentives for most situations, and some additional time for projects with particularly long lead times, such as commercial buildings.

The EXTEND Act also makes an important modification to the 2005 EPACT incentives so as to phase out incentives based on the cost incurred in saving or producing energy and replace them with incentives based on the actual performance (measured by on-site ratings for whole buildings and factory ratings for products like air conditioners, furnaces, and water heaters.) The legislation provides a new home retrofit tax incentive for ambitious levels of energy savings that are verified by a third-party rater.

A goal of this bill is to provide a transition from the EPACT 2005 retrofit incentives, which are based partially on cost and partially on performance, to a new system that provides greater financial incentives based on performance. These larger incentives should not cost the Treasury more because the ambitious requirement of a minimum 20 percent savings will effectively eliminate free ridership, which is the problem that caused the current EPACT incentives to be scored as high as they were.

The Snowe-Feinstein bill also extends the applicability of the EPACT incentives so that the entire commercial and residential building sectors are covered. The current EPACT incentives for new homes are limited to owner-occupied properties or high rise buildings. The Snowe-Feinstein bill extends these provisions to rental property and offers incentives whether the owner is an individual taxpayer or a corporation. This extension does not increase costs significantly, but it does provide greater fairness and clearer market signals to builders and equipment manufacturers.

- *Public- Private Partnership on Low Income Weatherization*

Across the nation, poor families often increasingly face the choice between heating and eating as prices for natural gas, heating oil, propane and electricity have skyrocketed and millions of poor Americans have found themselves spending more than one-quarter of their income to run their furnaces, air conditioners and keep the lights on. In a survey of low income families – before the energy price spike in 2005-2006 -- 32% went without medical or dental care, 24% failed to make a rent or mortgage payment, and 22% went without food for at least one day due to energy bills.

Congress continues to debate the traditional fix for this problem: additional funding for the Low Income Home Energy Assistance Program (LIHEAP). But we need to recognize the serious limitations of the roughly $2 billion we spend annually on federal fuel assistance, particularly as Congress considers the Fiscal Year 2008 budget. LIHEAP is essentially a one-shot buy-down of energy bills that covers only a modest percentage of eligible families – an absolutely critical but in no way sufficient answer to the energy woes of the poor. Together, federal and state fuel assistance funds provided less than 10% of the total energy costs for low income households in 2006.

The longer-term answer for the poor is home weatherization. By upgrading a home's furnace, sealing leaky ducts, fixing windows, and adding insulation we can cut energy bills by 20-40% -- for years – and the substantial savings accrue with summer air conditioning as well as winter heating. And by adding energy efficient appliances and lighting the savings are even greater. Replacing a 1970's vintage refrigerator with a new energy efficient model will cut an average home electricity bill by 10-15%. Weatherizing low-income homes also improves comfort, reduces illness, and creates jobs.

Unfortunately, we have taken a penny-wise pound-foolish approach to low-income weatherization with less than $245 million in the 2006 Department of Energy weatherization budget, enough for only about 100,000 U.S. homes. And while the nation has weatherized about 5.5 million low-income homes since 1976, more than 28 million remain eligible. While the Bush Administration has supported increases in the weatherization program in the past, the 2008 budget proposes only $144 million, a cut of about $100 million that will have serious consequences for the nation's poor.

Instead of cutting weatherization funding, the President and Congress should make a national commitment to weatherize at least one million low-income homes each year for the next decade. This program would go a long way toward helping the most vulnerable among us—something the nation pledged it would do after Hurricane Katrina emphasized the extent of American poverty. The price tag for retrofitting 10 million low-income homes is relatively modest – about $2 billion annually when fully implemented.

With such a commitment there would be other benefits that directly address our current energy and environmental challenges. Stresses we are seeing today on the U.S. energy system – from blackouts to natural gas shortages --will be dampened with every additional home weatherized. For example, weatherizing all the low-income homes that heat with natural gas would cut residential U.S. use of this clean-burning fuel by about 5%, dampen its price volatility and reduce the call on federal fuel assistance funds.

The advanced technologies pioneered in the federal low income weatherization program can also be readily applied to the U.S. housing stock at large, with even greater energy savings. One technology developed in the Department of Energy weatherization program uses a pressurization device and a simple infrared sensor to pinpoint leaks down to the size of a nail hole for about $100 per home. With this information insulation can be installed in the right places with the least amount of waste.

As we cut energy demand we also cut air pollution. An Ohio study showed that weatherizing 12,000 homes not only cut the average consumer bill by several hundred dollars each year but overall avoided annual emissions of 100,000 pounds of sulfur dioxide as well as 24,000 tons of carbon dioxide – the primary global warming gas. As Congress and the Administration consider changes to the Clean Air Act and how to address climate change we ought to create an effective way to encourage power plant owners to invest in weatherization and other "downstream" pollution reduction opportunities. This could leverage substantial additional private sector capital for low-income weatherization and avoid the need for new power plants.

More broadly, we believe there are a variety of potential mechanisms to spur private sector investment in weatherization and we are currently exploring these within the financial community. One approach would:

- aggregate thousands of homes eligible for weatherization in a locality
- establish a base-line of energy use as well as associated greenhouse gas and other emissions across the portfolio of homes
- install advanced metering to monitor post-investment savings as well as provide utility load control
- secure federal and state funding as well as carbon off-set, pollution credits, and utility capacity payments
- leverage private sector investment in the aggregated portfolio through a "shared savings" approach or other financial mechanism
- benchmark the investment to enhance replication

There may also be an opportunity to provide an extra incentive or credit in the Energy Efficiency Resource Standard for investment by an electricity or gas supplier in low income home weatherization.

- *State Building Codes*

California has demonstrated the significant efficiency gains that can be achieved through state building codes that are well designed and implemented. Title 24 of the California Code has been the national model, helping the state avoid thousands of Megawatts of new generation capacity. Despite this impressive track record in California, many states have inadequate state building codes or none at all. Section 128 of the 2005 Energy Policy Act authorizes $25 million per year for FY2006-FY2010 ($125 million total) for states that have adopted, and are implementing, both residential and commercial building energy-efficiency codes that meet or exceed specific standards. For states where there is no statewide code, the money will be allocated to local governments that have implemented codes that meet the above standards. Unfortunately, the funding authorized in the 2005 EPACT for state building codes was never appropriated by Congress and therefore this important incentive for adoption of state building codes has not been implemented. Congress should appropriate the funds authorized in the 2005 EPACT.

- *Appliance Efficiency Standards*

One of America's least-heralded energy success stories involves federal appliance efficiency standards. In the last 15 years, Congress and the Department of Energy have set new standards for dozens of products. Refrigerators sold since 2001 in the U.S. use just one-third the energy of comparable models sold in 1980. Home air conditioners are nearly twice as efficient as those sold at the start of the Reagan administration.
Standards in place today will save American families and businesses about $200 billion cumulatively by 2020, cutting electricity demand and carbon emissions substantially. The 16 products in the Energy Policy Act of 2005 will save another $50 billion, and will cut carbon emissions by another 16 million tons in 2020.

Unfortunately, DOE has issued only two new appliance efficiency standards during the tenure of the current Administration. In the settlement of recent litigation brought by states and environmental groups, DOE agreed to issue 22 overdue standards in the next four years. Congress should ensure that DOE has the funds to conduct the necessary analysis, that the Department stays on schedule, and that it adopts rigorous final standards.

Section 124 of EPACT 2005 authorizes a new program to encourage deployment of high efficiency appliances, based on a successful New York program. The program, however, has not been funded. Congress should appropriate the authorized funds.

- *Federal RD&D Funding*

Research and development is essential to supplying the "technology pipeline" we need to provide this century's clean energy solutions. Unfortunately, R&D on energy efficiency, as well as other energy technologies, has been falling. The Bush Administration's 2008 request for efficiency R&D is 18% below the FY 2006 levels, and more than a third lower than the 2002 budget. Total federal spending remains far below the peak of investment that occurred in the 1970s. And the private sector has not yet picked up the slack; efficiency funding in the electricity and gas industries has fallen even faster than federal investment. Some states, like California, Iowa, Wisconsin, and New York, are trying to pick up the slack, but their work is no substitute for federal support. Congress should ensure that adequate funds are appropriated in Fiscal Year 2008 and beyond to advance critical clean energy R&D.

Beyond R&D there are a number of deployment-oriented programs that Congress authorized in EPACT 2005 but has either not funded or has provided insufficient funds. These cut across many areas including buildings, appliances, energy codes, state energy programs, low income programs, public information and education, public buildings, and pilot projects. Also, the loan guarantee program authorized by Congress in EPACT 2005, which could be a significant help in energy efficiency projects, has yet to back any loans. All of these deployment programs help ensure that the technologies developed in the national laboratories or nurtured by federal R&D funding, actually get to the marketplace.

Conclusion

Mr. Chairman and members of the Committee I am confident that a concerted policy push by the federal government, as outlined above, can greatly increase private sector investment in energy efficiency, resulting in many benefits for the nation. I look forward to working with the Senate to develop, enact and implement legislation that will stimulate this much needed investment.

Statement of U.S. Senator John D. Rockefeller IV on Senate Finance Committee hearing on "America's Energy Future: Bold Ideas; Practical Solutions"

February 27, 2007

Thank you, Mr. Chairman, for calling this hearing and for bringing together this distinguished panel of experts to discuss an issue of utmost importance to the nation.

A discussion of our "Energy Future" could just as easily be thought of as one to discuss our "Economic Future" or our "Foreign Policy Future." There may be nothing we do in this Committee, or possibly in this entire Congress, with as many far-reaching impacts as a frank and honest discussion leading to a comprehensive and responsible national energy policy.

When I go home to my state of West Virginia, I am often asked what can be done to lower the price of gasoline, and I am frequently asked in West Virginia and in Washington what can be done to increase our domestic supply of natural gas and alternatives. Each of us has ideas on the best ways to tackle these problems, but even if the prices our constituents are paying for various energy products were not of concern, we should still be engaging in a program similar to the Apollo program to find our way to greater energy independence: Since the Administration of the President's father, we have twice put American soldiers, sailors, airmen, and Marines in harm's way to defend, among other things, foreign sources of the energy we use.

If price was of no concern, our dependence on foreign sources of energy – which has only grown since I came to the Senate 22 years ago – would still have to be seen as a ticking time bomb for our nation, our economy, and our way of life. It is imperative that we take action as a Congress, hopefully with the cooperation of this Administration, to address our dependence on foreign sources of energy.

How do we do that? For me and many members of this committee, one part of the answer has been to diversify our energy choices by diversifying the fuels that power our economy. I have long advocated for a broad-based program to increase the use of alternative fuels and alternative fuel vehicles. We should look at the success of Brazil, which has embraced ethanol from sugar cane, and see if we can increase our production of bio-based fuels beyond corn-producing states. We should push for greater use of our other renewable sources of energy. We should look at what we have, and find better ways to use these resources.

We have only scratched the surface in doing all that we can with all or our domestic energy resources. As a Senator proud to represent a coal state, I will continue to fight for greater use – and more innovative use – of an abundant domestic resource that absolutely dwarfs the Btu value of all the oil in the Persian Gulf. I know Governor Schweitzer and some of the other witnesses today will discuss clean coal and coal-to-liquids conversion, and I look forward to what they have to say. If our demand for electricity increases as projected, and this country is going to be proactive in addressing its rate of carbon emissions, we have no choice but to dramatically increase our use of advanced clean coal and carbon capture technologies. We made some strides with our work on this issue in the 2005 energy bill, but we must do more.

As important as coal is to our electricity supply, I believe the coalfields of Appalachia and elsewhere can be just as great a source of energy for the transportation sector. Coal-to-liquids conversion, or CTL, is proven science, not some theoretical construct we hope to be able to count on several decades hence. There are challenges with CTL, as with any energy production, but they are challenges we understand and which we can overcome.

I look forward to working with my colleagues on these important uses of coal, as well as other energy measures to be considered by this Committee in the months to come, and I look forward to the testimony of our witnesses.

Opening Statement of U.S. Senator Ken Salazar
Committee on Finance
America's Energy Future: Bold Ideas, Practical Solutions
February 27, 2007

Thank you, Mr. Chairman and Ranking Member Grassley. I want to thank you for the leadership you've shown in supporting extensions of the production tax credits, and passage of Clean Renewable Energy Bonds. I also want to thank you for holding today's hearing on this important topic of our country's energy future.

All Americans should be alarmed at how our country's rising dependence on foreign oil is undermining our security at home and abroad. We must champion a new ethic and goal of setting America free from its overdependence on foreign oil, including the development of alternative and renewable energy sources, and new technologies to utilize fossil fuels in a more efficient and environmentally sound manner.

Our country is extremely rich in renewable energy resources, such as solar, wind, biofuels, and biomass. As I have spent time in places like Prowers County or Alamosa County in Colorado, I have seen a clean energy revolution beginning to develop in our heartland. In these small rural communities, like so many others across the country, people are banding together to build small biofuels plants that will fuel our cars, and solar and wind farms that will produce electricity for our homes. We have some of the most productive farmers, ranchers, entrepreneurs, and engineers in the world. If we give them the right tools, they can use our country's renewable resources to build a new, clean energy economy.

Many of these renewable energy technologies are available for wide-scale deployment today, but a national commitment that includes effective policy measures is necessary if these renewable energy technologies are going to be able to reach their full potential. That's why I have worked to develop four bills that will provide important incentives to spur rural communities to build a renewable, clean energy economy.

The first bill, the Renewable Energy Bonds Act (S. 673), introduced with Senator Smith, provides incentives for investment in wind and other renewable energy projects by giving private developers access to tax-exempt bond markets. Currently, the federal tax code only allows municipal and public entities access to tax-exempt bond markets for wind and other renewable energy projects. Private developers, who are more likely to invest in smaller projects and who are currently responsible for nearly 75% of current renewable energy development, are not eligible to use these federally tax-exempt bonds. This is unfortunate because these are the same small developers who don't benefit much from the production tax credit, as their federal tax liabilities usually aren't big enough to reap the tax credit's benefits.

Renewable energy bonds make sense for these small developers, and because they cost the federal government less than the production tax credit, they also make sense from a fiscal perspective. This bill may actually save the government money.

The second bill I introduced with Senators Smith, Dorgan and Craig, the Rural Wind Energy Development Act (S. 672), would extend the production tax credit to include small wind systems. We have made great strides in wind development over the last few years, a fact that is demonstrated by wind energy's growing availability to Colorado consumers.

Unfortunately, the existing production tax credit only benefits larger producers that build wind farms with million-dollar turbines. Small businesses, towns, farms, and families aren't given the same incentive to produce their own renewable power from smaller, more affordable turbines.

This simply doesn't make sense. The National Renewable Energy Lab in Golden, Colorado, and others are making great strides in the development of small wind systems that can be installed on homes and businesses. The systems that are currently available cost around $50,000 for 10 kilowatts of capacity. That's a steep investment for any family or business. My bill, by providing a tax incentive for their purchase, would not only reduce the cost, it would also create more market certainty for manufacturers of small wind systems. With more systems in production, costs will fall even further, and small wind will be a real option for more people.

The Rural Wind Energy Development Act is simple; it creates a five-year tax credit of $1,500 per half kW. There is no cap for the purchase and installation of small wind systems, so long as they are smaller than 100kW. It will put more small wind systems on the market, and it will give consumers more choices of how to power their homes and businesses.

I will also co-sponsor legislation soon to be introduced by Senators Snowe and Feinstein – the Extend the Energy Efficiency Incentives Act. This legislation will extend the temporary tax incentives for energy-efficient buildings established in the Energy Policy Act (EPAct) of 2005 for a sufficient length of time in order to allow the business community to make rational investments in complying with the ambitious requirements of the Act.

I have also co-sponsored, along with Senator Smith, the Securing America's Energy Independence Act (S. 590), which will extend for eight years the investment tax credit for qualified fuel cell property and solar energy property.

Finally, I strongly support extending the production tax credit for electricity produced from renewable sources of energy as a way to encourage greater use of renewables. Specifically, I support a five- to ten-year extension of the existing production tax credit for electricity produced from renewables.

The Senate Committee on Finance has a key role to play in providing incentives that are needed to build a new energy economy, and that is why today's hearing is so timely. I believe it is imperative that this Congress be bold in putting in place energy tax policies that will encourage and speed the development of our nation's renewable resources.

Mr. Chairman, I thank you again for holding this important hearing. I look forward to hearing from our witnesses today on their ideas for creating a new, clean energy economy.

US Senate, Committee on Finance

Montana Governor Brian Schweitzer

February 27, 2007

Chairman Baucus and Ranking Member Grassley—a very sincere thanks for inviting me to address this important committee and allowing me the opportunity to share my ideas about America's energy future. I can't conceive of a more pressing issue for the country, and appreciate the Senate Finance Committee sharing that concern.

As Governor of the State of Montana I have been very aggressive in positioning the state to assist in helping the country address energy independence while capitalizing on emerging energy markets. This includes promoting renewable energy development and conservation, as well as the development of coal-to-liquids facilities as a bridge to new, sustainable energy development. During the last two years Montana has adopted new energy policies and completed and announced an amazing array of energy projects—from wind farms to refinery upgrades to interstate transmission projects to coal gasification and liquefaction plants.

The context for my efforts to develop domestic energy can be found halfway across the globe. If you look at a map of the Middle East, and place at the center of it the country of Kuwait, you can see that this tiny country is the most strategic place in the region, and possibly on the entire planet. A circle around Kuwait with a radius of 1,000 nautical miles encompasses or touches upon Russia, Turkey, Kazakhstan, Uzbekistan, Turkmenistan, Afghanistan, Pakistan, Iran, Saudi Arabia, the Emirates, and Egypt, and all of it is accessible on the ground.

As a comparison, place tiny Kuwait in Kansas, and draw that same 1,000-mile circle. It reaches well into both Manitoba and Mexico, and into California and the Carolinas. We could indeed move massive military or other resources to any of these places—thousands of troops, along with tanks and humvees, on the ground. How long would it take? Thirty-six hours? Forty-eight? The scenario is the same for logistical movements from the center of the circle at Kuwait.

I lived in Saudi Arabia for a half-dozen years, developing large irrigation projects from the Iraqi border to the Yemeni border. While there, I had a chance to observe Iran's situation in the Gulf. The oil in the region floats on supertankers through the Strait of Hormuz, which at its narrowest point is 20 or 30 miles wide. So Iran, at a time of its choosing, can stop as much as 20% of the world's oil supply from getting to Asia, Europe and North America. Even though only about 17% of U.S. oil comes from the Middle East, the effect of such an act would be devastating. It is conceivable that the price of oil could move rapidly from $100 to $200 to $300 a barrel, and gasoline could move from $4 to $8 to $12 a gallon.

That is why our troops, unless we develop alternatives, will be in Kuwait for the rest of our lives, and until the end of our children's lives. Consider that we still have 30,000 troops in Korea, 50 years after that war, because it is a strategic location. We still have thousands of troops in Central Europe, 60 years after WWII, for the same reason.

In the last two years, Montana was one of only two states in the nation to appreciably increase its oil production, and we will increase it again this year. I hope that can continue for some time, but our nation's dependence on foreign oil ensures that we will be involved not only in the Middle East, but also in places like Venezuela, Nigeria, and Angola. It demands that we continue to send our soldiers—and their children, and their grandchildren—into harm's way, to ensure that we have boots on the ground for the protection of our strategic interests.

Americans use 6.5 billion barrels of oil each year. We only produce 2.5 billion barrels ourselves. We import 4 billion from some of the world's most unstable regions. America needs a plan to get out of this mess.

We can save 1 billion barrels of oil a year through conservation—things like more efficient cars, homes, businesses, and appliances. We've done this before. We reduced our energy use by a similar percentage during the oil crisis of the late 1970's, when President Carter asked us to sacrifice. During the period from 1975 to 1983, we decreased our consumption of oil by 17%, while we grew our economy by 27%. Through informed consumers and the use of existing technology, we can do it again. That leaves us with a 3 billion barrel a year deficit to conquer.

Another part of the solution is biofuels. A year ago, in his State of the Union address, President Bush recognized our addiction to oil. In his address to the nation just a few weeks ago, he talked about conservation and alternative fuels, and of setting a goal of producing 35 billion gallons of ethanol by 2017. That's almost a billion barrels—about 15% of our entire annual consumption of petroleum. I'm an agronomist by training, so over the last few years I've been crunching the numbers on biofuels.

I do think we can produce a billion barrels of biofuels, but they won't be just ethanol. Some of the biofuels we produce will be biodiesel from crops like canola, safflower, soybeans, and camelina, which is my personal favorite, because it is particularly well-suited to Montana's arid climate. And the net energy ratio of biodiesel is more favorable than with ethanol.

So after we produce a billion barrels a year of biofuels and add it to the billion barrels gained through conservation, our 4 billion barrel oil deficit has been reduced to 2 billion barrels a year.

What do we do to cover that remaining 2 billion barrels? In Montana we have a lot of coal—as much as 120 billion tons of it. That is 28% of the nation's reserves, and 8% of the world's coal, just in Montana. It is located close to the surface, and it represents some of the least expensive BTU's available in the world. Over a year ago representatives from Sasol, the South African coal liquefaction giant, came to visit. We toured Montana's coal country.

On maps and from the air, I was able to show them our resources and infrastructure: our three varieties of coal; oil and gas resources; oil shale; railroads; transmission lines; pipelines, and so on. Especially notable were the two significant oil fields in Montana, where they eagerly await carbon dioxide for enhanced oil recovery. As I told Sasol about our great work force and our work ethic, and pointed out the distant towns and trade centers from the air, I mentioned that a facility built in this part of Montana is a very safe asset—we don't have hurricanes or major tornadoes or earthquakes. That was in August, just before Hurricane Katrina hit and reminded us all of the importance of safe geography.

I informed Sasol that Montana has the greatest crack spread for fuels. All three of the oil refineries in Billings, Montana are some of the most profitable in the country for their parent companies, because the value of the crude oil they buy is low and the value of the refined product is high.

When I began to talk about the numbers related to coal, these representatives thought I was off by a factor of ten. I then repeated that the lignite was indeed worth about 18 cents a ton in the ground, and about $4.50 a ton mined. They didn't seem convinced, but then we flew down to Colstrip, Montana. It really is one of the most impressive coal developments in the world. And they were impressed. We landed and showed them the value of this sub bituminous coal, the way we mine it, the way we reclaim it, and the four coal-fired plants where we generate electricity, mostly for export from the state. Sasol became intrigued.

Since then, plants have been announced. At the Bull Mountain Mine near Roundup, Montana, a partnership involving Arch Coal, the 2nd largest coal company in America, has said they are going to develop a 300 megawatt IGCC power plant and a 20,000 barrel a day coal-to-diesel plant. It will be a $2 billion project. Peabody Energy, the world's largest private coal company, and the technology company Rentech have agreed to move forward to assess the feasibility of a coal-to-liquids facility at the Big Sky Mine near Colstrip.

But America is not going to develop coal in Montana or in other parts of the country if we continue the ways of the past. Development of coal the way we have in the past simply won't be financable in the future. That is because, as a nation, we are finally coming to grips with the risks of climate change.

We need to use better ways of extracting energy from coal, and put the carbon back into the earth where it came from. To do so, we need to perfect geologic sequestration of carbon dioxide. We must identify geologic structures where we can store great quantities of carbon dioxide. In Montana, we have what we call the Big Sky Sequestration Partnership at Montana State University, working with the Department of Energy. We have identified some of these geologic zones, but there is much more work to be done. We need measuring devices and monitoring protocols, and we need to work out liability provisions. We clearly cannot be doing this haphazardly.

Back to our 4 billion barrel oil deficit. A billion barrels a year can be met through conservation and efficiency, and another billion from biofuels. It is my hope that Americans can produce the final 2 billion barrels a year from our enormous coal reserves—developing a clean-burning fuel for about $1.20 a gallon. We could do this, and over the next thirty years only touch a small fraction of our domestic coal reserves.

Beyond the challenge of imported oil and its impact on our foreign policy and the lives of our young soldier heroes, we face a challenge in producing enough electricity to meet our growing demand—and doing so in a way that does not contribute further to global warming. Part of the solution is in wind power generation. In Montana, we have class 4, 5, 6, and 7 wind—first in the nation in those combined categories. So we have some of the most robust wind potential in America, but only in the last two years has significant wind power development occurred in Montana. Over $300 million has been invested in wind power recently, but in just the projects now proposed there will be another billion dollars invested in Montana wind energy over the next few years.

Wind power must become a more significant part of our energy portfolio in this country. But the wind does not blow all the time and backup power sources are needed to ensure transmission system stability. It's impossible to use wind power as a significant source of new electrical energy to supply growing markets like California, southern Nevada, and Arizona unless we have additional transmission capacity. Without it, we won't be able to use wind power for much more than 15% of our portfolio.

So I am excited that TransCanada's proposed Northern Lights project is moving forward with a 3500MW DC transmission line. It will originate in Montana, and deliver clean and green electricity to the Southwestern U.S. In addition, the Montana Alberta Tie Line now under permitting will deliver 300MW of wind power to Canada for movement to the Pacific Northwest.

Combined with power from wind generation and clean, green coal projects coming on-line, this added transmission will help to stimulate energy production in Montana. Frankly, if we had enough redundant transmission capacity in this country we could run a good portion of our portfolio on wind alone, because at any given moment the wind is blowing in a number of places in America.

There are other opportunities for firming wind power. We have begun to assess underground compressed air storage sites. Typically, we can only generate electricity when the wind is blowing, whether we can use it at that moment or not. But with underground compressed air, we can use some of this wind power to run compressors, store that air underground, and then release it to run turbines when the wind is not blowing. Some of the same types of geological formations that are suitable for storage of carbon dioxide are suitable for storing compressed air.

Once more, please visualize that map of the Middle East. If we don't get conservation right, if we don't start utilizing our wind resources more effectively, and if we don't develop biofuels and coal-derived fuels, then the next generation and the one after that will be even more familiar with the countries of the Middle East.

We need to make a very real national commitment to domestically produced energy. We have the inherent energy resources, and we can develop the technologies to use them. We can perfect the sequestration of carbon dioxide. Through these efforts we can create tens of thousands of new jobs right here in America.

Yes, we can achieve energy independence in America, but only if we have a true vision for the energy future of America. We must have a plan to get there, and the political will to bring it to reality.

Senate Finance Committee Hearing
"America's Energy Future: Bold Ideas, Practical Solutions"
February 27, 2007
Questions for the Record for Governor Brian Schweitzer

Questions From Senator Salazar:

1. How do you propose to address the issue of CO_2 emissions from coal-to-liquid (CTL) projects, which are much higher than normal refinery-based production of liquid fuels?

Producing coal-derived fuels does indeed result in greater CO_2 emissions than those from petroleum-derived fuels. As I stated in my testimony, unless we develop carbon sequestration technologies to store carbon subsurface, I do not believe coal will be part of the future of America's portfolio. The principle applies whether energy production involves petroleum refining, pulverized coal, coal gasification, or CTL. That is why I suggested both a national cap-and-trade structure for carbon and a commitment to fund extensive research and development related to carbon sequestration.

More specific to CTL, I understand from my discussions with Dr. Socolow's colleague Dr. Robert Williams at Princeton that CTL carbon emissions can be made on-par with refined fuels by adding approximately 10% biomass to dry-feed gasifiers, and in fact CTL can be made carbon-neutral by adding approximately 20% biomass.

2. It is my understanding that 3 to 4 barrels of oil could be produced from enhanced oil recovery (EOR) projects for every barrel of liquids produced from CTL, if the CO_2 produced from the CTL project is used for EOR purposes. Do you agree?

I am not familiar with information suggesting the 3 or 4-to-1 EOR oil-to-CTL fuel ratio, although on a tons-of-CO_2-basis, that ratio appears plausible. What I do understand is that EOR using carbon dioxide can increase oil production by a factor of 2 to 5, depending on the geologic situation and the remaining potential of the oil field.

3. If Congress offers incentives for the use of CO_2 for EOR, should these apply only to CO_2 from CTL, or should they apply to the use of CO_2 from any source?

If incentives are offered, they should apply to the use of CO_2 for EOR from any man-made source, whether from pulverized coal, IGCC, or CTL. However, under a carbon-cap scenario, EOR using CO_2 should only be credited with the actual carbon that remains stored following oil field depletion.

Question From Senator Bunning:

4. You are an avid proponent of coal-to-liquid fuels and I have watched your proposals in Montana with great interest. I recently reintroduced my coal-to-liquid bill in this committee, which would provide tax incentives to develop this technology. Specifically, it would extend the fuel excise tax credit, expand the investment tax credit, and create a new credit for carbon capture and sequestration. Are there other federal tax policies that are needed to develop domestic coal-to-liquid fuel?

The tax policy front is fairly well covered, although those policies need to be extended to provide for predictability—probably until at least the year 2020. I believe, however, that we can have a much greater impact if we think bigger. If we institute a carbon cap-and-trade system, put a floor price on all domestically-produced fuels, and make a real commitment to fund carbon sequestration research and development, we incentivize a much more rapid response from the energy industry.

The Challenge of Managing U.S. Coal in a Climate-Constrained World

Testimony for the Record
Submitted to the Senate Finance Committee

Professor Robert Socolow
Princeton University
February 27, 2007

Mr. Chairman, Senator Grassley, and members of the Committee: Thank you for inviting me to testify today on "America's Energy Future: Bold Ideas, Practical Solutions." I am pleased to be here in my capacity as co-director of Princeton University's Carbon Mitigation Initiative; as a Professor of Mechanical and Aerospace Engineering at Princeton; and as an individual concerned about the future of U.S. and global energy policy. We have tremendous challenges before us when it comes to energy policy. But I firmly believe those challenges can be met, and I commend you for your efforts to that end.

When William Shakespeare took a breath, 280 molecules out of every million entering his lungs were carbon dioxide. Each time you draw breath today, about 380 molecules per million are carbon dioxide. That portion climbs about two molecules per million every year. In my view, we already know enough about the negative impacts on human civilization and the natural environment that lie ahead to warrant taking action now to cut CO_2 emissions.

In 2004 Stephen Pacala and I published a paper in *Science* magazine called "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies." Our article's thesis was that, when it comes to energy policy and climate change, there's no silver bullet. Rather, a portfolio of strategies must be implemented to address this issue. Each strategy uses technologies that have passed beyond the laboratory bench and demonstration project and have already been implemented somewhere at full industrial scale. Among these strategies are the deepening of energy efficiency in buildings, transport, and industry; the replacement of coal plants with renewable energy and nuclear power; the use of biofuels; and the capture and sequestration of carbon dioxide produced at coal power plants and coal-to-liquids plants. A portfolio is needed because none of these elements is a credible candidate for doing the entire climate mitigation job, or even half the job, by itself.

Today, I will focus my testimony on the strategy that has moved to near the top of the list from the perspective of urgency: carbon capture and sequestration, or CCS for short.

Two trains are on a collision course, but there is a switch.

Mr. Chairman, this really is a time of Bad News and Good News. The Bad News is that two trains are on a collision course. The Good News is that there is still time to switch one of the trains onto a different track.

Only a few years ago, the U.S. saw very few new coal plants in its near future. The coal industry was pleading for regulatory relief so as not to be completely dismissed from the scene in favor of natural gas. I remember hearing comments like: "Watch out, you may not need us now, but you will need us later." All this has changed. Train Number One is the rush to coal power in the U.S., a consequence of a much higher natural gas price than had been anticipated even quite recently.

Train Number Two is the urgency of dealing with climate change. Here too, a few years ago not many Americans saw our country dealing aggressively with climate change in this decade. Now, appropriately in my view, and none too soon, climate change is high on the agenda for U.S. policy.

The collision is simple to explain. Coal, burned as we have burned it in the past, sends more CO_2 into the atmosphere for each unit of useful energy produced than any other energy source. About twice as much CO_2 goes into the sky for each kilowatt-hour of electricity produced, when the electricity is produced at a conventional coal power plant, compared with a conventional natural gas power plant.

So, the rush to coal makes the already difficult challenge of climate change even more challenging.

But I said there was a switch that can prevent this collision. There are ways to burn coal so that the CO_2 produced by oxidizing its carbon does not end up in the atmosphere. The switch is called CO_2 capture and storage, or CO_2 capture and sequestration, or CCS.

CO_2 capture and sequestration is ready right now for full-scale deployment.

Relative to energy efficiency, renewable energy, and nuclear power, CCS is new on the scene. But nonetheless it is mature. If Congress enacts legislation that enables CCS, the technology will spread rapidly.

How could CCS be both new on the scene and commercially mature? The answer is that CCS uses proven technologies in new combinations. CO_2 has long been captured at natural-gas power plants and coal power plants for use by the food industry. At nitrogen fertilizer plants CO_2 is also captured and combined with ammonia to make urea. Many of the components required for CO_2 capture have long been used at full scale where hydrogen is made at refineries and where natural gas is upgraded between the wellhead and the pipeline. A 500-mile carbon dioxide pipeline built 20 years ago has brought carbon dioxide from across New Mexico from southwest Colorado to oil fields in west Texas. Ever since then CO_2 has been pumped into those fields and managed there for enhanced oil recovery.

I cannot emphasize strongly enough that from a technological perspective *CCS is ready for full-scale deployment.* Some technology strategies that may contribute to mitigating climate change in a decade or two are *not* ready for full-scale deployment today; an example is the hydrogen fuel-cell car, which awaits further work on hydrogen storage and on fuel cells. By contrast, there are no technological reasons to delay full-scale deployment of CCS. Industry leaders will tell you that once supportive policies are in place the industry will move ahead, learning as it goes, steadily improving the many component technologies with which it is already familiar, and lowering costs through experience and R&D.

The best evidence I know for the readiness of CCS for full-scale deployment is the project at BP's Carson refinery, near Long Beach, California. BP and Edison Mission Group (a power company) announced this project a year ago, and it is one of the projects that has received investment tax credits under Section 48B of the tax code, per the 2005 Energy Policy Act. The project is expected to gasify 4500 tons per day of petcoke, a negative-cost fuel that is the solid residue left behind at the refinery when all the marketable products are extracted from crude oil. After processing the petcoke, 800 tons per day of hydrogen will be burned in turbines for 510 MW of power, and four million tons of CO_2 will be sent off-site each year for enhanced oil recovery (EOR).

From the perspective of gasification, petcoke and coal are essentially identical. The gasifier, shift reactor, gas cleaning technology, gas separation technology, CO_2 compressor, and hydrogen turbine are exactly the systems one envisages for coal power with CCS. The Carson project is a testament to the readiness of the whole CCS approach.

At a new coal plant, CO_2 capture and sequestration is likely to break even, relative to CO_2 venting, at a CO_2 emissions price somewhere near $30 per U.S. ton of CO_2.

CO_2 capture and sequestration is likely to become a favorable economic strategy for a coal utility at a price for CO_2 emissions of $30 per U.S. ton of CO_2, approximately[2]. Prices on emissions in the same range should also bring an end to flaring at the oil field and should enable other "upstream" carbon-saving strategies, such as investments at oil refineries. CO_2 policy should reach far upstream, because the low-hanging fruit is upstream.

Efficiency in energy use is where the other low-hanging fruit are to be found. Approximately 70% of U.S. electricity is consumed in buildings. Mandatory federal standards for household and commercial lights, motors, air conditioners and other appliances are the most important policy legacy resulting from the attention to energy efficiency in the 1970s and 1980s. Whatever package of climate-change policies emerges from this Congress must contain a new set of mandatory standards assuring much higher efficiency in the use of electricity. Advances in modern electronics and materials can be incorporated in a new generation of efficient energy-using devices and systems, thereby bringing into the market energy-efficiency achievements considerably more impressive than the best we used to be able to do. A low-tech air-conditioner cooling a poorly designed and poorly instrumented office building is as out of place in a climate-constrained world as a coal plant without CO_2 capture and sequestration.

Any CO_2 policy restricted to creating a price for CO_2 emissions can be expected to have more effect on technological decisions in the energy industries than on consumer behavior. This is because any price on CO_2 emissions to the atmosphere will be a much higher percent of the wholesale price of energy than of the retail price of energy. This is exactly like a tax on copper, which affects the owner of the copper mine more than the buyer of copper wire. Overheads

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[2] The estimate that $30 dollars per U.S. ton of CO_2 is the incremental cost of CCS is uncertain for at least four reasons. 1) It pertains to the "Nth" plant, where N may be about 10, with the assumption that the incremental CCS cost will fall steeply before the Nth plant is built, but slowly after that. 2) It describes the least expensive CO_2 capture strategy now known, which is capture at an integrated gasification combined-cycle (IGCC) coal power plant running on bituminous coal. The incremental cost may be twice as high for capture from a modern pulverized-coal steam plant. 3) It does not take into account the likely fall in costs as new technology becomes available. 4) It assumes that permitting is not a costly process with long delays, so that the costs of sequestration are well approximated by the costs of CO_2 pipelines and wells.

accumulate as the material progresses along the value chain, lowering the percentage impact on the price. As a result, federal policy can induce a large amount of carbon mitigation activity in the energy industries (including CCS deployment) at a price on CO_2 emissions that induces only small changes in the behaviors of energy consumers. The price of $30 per U.S. ton of CO_2 cited above as probably sufficient to elicit the deployment of CCS at new coal plants will increase in the cost of gasoline at the pump by only 25 cents per gallon. (See the Table at the beginning of the Second Supplement at the end of this document.)

Enhanced oil recovery connects CO_2 capture and sequestration to national energy security.

Carbon dioxide is the mischief molecule in the atmosphere, but the miracle molecule below ground. In the atmosphere, the gas traps the Earth's infrared radiation heading to outer space, thereby impeding the Earth's dominant cooling strategy and raising the Earth's average surface temperature. Below ground, injected into the porous rocks where crude oil is trapped and hard to recover, CO_2 combines with the oil to produce a fluid that flows more easily, increasing the amount of oil recovered – an industrial strategy called enhanced oil recovery (EOR). Carbon dioxide injects new life into old fields.

Quantitatively, a new one-thousand-megawatt coal plant will produce about six million tons per year of CO_2. If captured and used for EOR, this CO_2 should increase oil production at mature fields by between 30,000 and 80,000 barrels per day. Domestic oil production is less than six million barrels per day, so the incremental oil production from even 20 new coal power plants would have a significant positive effect on vexing domestic and international oil problems. Any CO_2 heading for the sky is domestic oil not produced – and more imported oil.

In one plausible model, the coal industry will hand CO_2 to the oil and gas industry at the power plant gate, and the oil and gas industry will put it under ground. The coal industry and the oil and gas industry have little history of cooperation. Your committee has hard work ahead as it figures out the policies that can promote this cooperation.

"No CTL without CCS": Any plant built in the U.S. that produces synthetic fuels from coal must capture and sequester the CO_2 that would otherwise be emitted at the plant.

In response to the growing demand for imported oil to fuel vehicles, your committee is considering subsidizing synthetic gasoline and diesel fuel from domestic coal. From a climate change perspective, unless synfuels production is accompanied by CO_2 capture and sequestration, this is a big step backward.

In synthetic fuels (synfuels) production from coal, only about half the carbon in the coal ends up in the fuel, later to be emitted as CO_2 at the tailpipe. The other half of the carbon originally in the coal is emitted as CO_2 at the synfuels plant. As a result, burning a coal-based synthetic fuel in a car engine, instead of burning gasoline made from crude oil, sends approximately twice as much carbon dioxide to the atmosphere when driving the same distance, *unless CCS is incorporated into the synfuels production process*. Engineers can modify the design of a coal-to-liquids (CTL) plant to capture its CO_2 emissions rather than venting them, and to send the captured CO_2 below ground. A fuels system based on synfuels produced only at plants where CCS is deployed is no less bad for climate than a fuels system based on petroleum fuels.

"*No CTL without CCS*" isn't the world's most exciting bumper sticker, but it carries a vitally important message.

To produce a million barrels per day of synthetic fuel from coal requires transforming about 100 million tons per year of coal into synfuels. CO_2 is produced at these plants at a rate of about 150 million tons of CO_2 per year. This is the approximate rate of CO_2 production at 25 one-thousand-megawatt coal power plants.

"Carbon Price, Plus": For CCS to take off, cap-and-trade policy must be supplemented with policies specifically supportive of CCS.

The day will come when the CO_2 emissions price trajectory established in legislation is regarded as nearly free of political risk. This time has already arrived for sulfur trading, brought into being in the early 1990s – a spectacular success from the perspective of environmental policy and the template for every cap-and-trade proposal since then. (I understand that our chairman is one of the architects of that policy, and I welcome this opportunity to congratulate him personally.) But during the early years of a carbon management regime, this credibility will be missing. Moreover, the price will be low, relative to where it is heading.

These considerations militate in favor of putting in place, in parallel with a schedule governing CO_2 emissions, strong technology-forcing sectoral policies. Examples of sectoral CO_2 policies include appliance efficiency standards, renewable portfolio standards, and many of the investment tax credits that this committee has added to our laws. The deployment of CCS will require its own supplemental policies in the early years. For example, laws modeled on the renewable portfolio standard can require the early costs of CCS deployment to be widely shared among ratepayers. Especially important are the next investment tax credits. *I strongly recommend that your committee restrict the next investment tax credits only to coal power plants and coal synfuels plants that capture and sequester carbon dioxide.*

There are dozens of variants of CCS, and therefore one should anticipate that CCS will develop along many tracks at once. The optimal CCS strategy may depend on the details of the coal; the best way to capture CO_2 appears for now to be via gasification with oxygen, but there are many kinds of gasifiers, many capture technologies, and alternatives to gasification. There are also many different sequestration destinations. I recommend that policies specify only that CO_2 must be sequestered, with penalties for failure, but then leave it to the market to discover, for each circumstance, the cheapest alternative.

Policy must distinguish industrial from natural CO_2.

There are some remarkable gas fields in nature where the trapped gas is nearly pure CO_2. Several federal and state energy policies in the 1980s promoted the development of these fields, sending into the atmosphere CO_2 that otherwise would have remained trapped below ground millions of years into the future. This adverse impact on climate was inadvertent; the purpose of these policies was to subsidize domestic oil production by subsidizing enhanced oil recovery. Existing policy that does not distinguish natural from anthropogenic CO_2 should be repealed, and no further policy of this kind should be legislated.

Needed immediately are binding policies that encourage early good action and penalize early bad action.

Some of those currently planning new coal-fired power plants apparently have expectations of receiving a windfall from these plants. For example, they imagine that emissions permits will be granted to these plants when a cap-and-trade system for CO_2 emerges. Such grandfathering of the newborn would be extraordinary.

Often, policy makers seek ways to "encourage early action" during the period when policy is being constructed, with the assumption that early action will be good action. In this instance, early action is perverse. Urgently needed for the current period, during which the U.S. is evaluating alternative climate-change mitigation policies, are policies that give clear and persuasive signals to those contemplating the construction of new conventional coal plants, carrying the message that all such plants will be penalized, not rewarded, no matter what the climate-change mitigation policy that emerges.

I was one of many who were delighted by the news this past weekend that eight new coal plants with conventional technology proposed for rapid construction in Texas will not be built. I can't prove it, of course, but it seems likely to me that the op ed in the Dallas News last month from Senators Bingaman and Boxer, warning investors and the TXU leadership that, in effect, there would be *no* grandfathering of the newborn, was instrumental in derailing the construction of these eight backward-looking plants.

Supplement One. Thoughts about economy-wide CO_2 policy.

"Mitigation Lite" must be avoided.

The political process will need to resist the temptation to settle for "Mitigation Lite," a CO_2 strategy with the right words but with the wrong numbers. Mitigation Lite leads to very little investment in CO_2-saving technology. Under Mitigation Lite, the CO_2 emissions price is internalized, especially by the coal power industry, as just another cost of business. Mitigation Lite results in a revenue stream flowing to the government that is compromised by being unrelated to the intended function of the policy. To avoid the pathologies of Mitigation Lite, CO_2 policies must be technology-forcing – in other words, CO_2 policies must be stringent enough to lead to significant investments that reduce CO_2 emissions within the energy industries.

A low safety valve in a Cap and Trade System is a sure-fire way to arrive at Mitigation Lite.

A ramp from zero to $30 per ton of CO_2 over 10 years is probably strong enough to avoid Mitigation Lite.

For purposes of encouraging discussion of specifics, consider a trajectory for the CO_2 price which is a ramp that grows over ten years from zero to 30 dollars per U.S. ton of CO_2 in ten equal increments of 3 dollars per U.S. ton of CO_2. Thus, after five years, the price will be 15 dollars per U.S. ton of CO_2.

Very roughly, a CO_2 emissions price of $30 dollars per U.S. ton of CO_2 is the breakeven cost where building a coal plant that vents its CO_2 costs the same as building a coal plant that captures its CO_2 and paying for sequestration. (See footnote 2, above.) Such a price places distinctly different pressure on the coal producer, the power plant operator and the home owner who consumes the electricity. A coal producer sees a charge of about $70 per ton of coal, roughly tripling the cost of the coal delivered to an electric utility customer. The owner of a new coal power plant faces a 50 percent rise in the cost of the power the coal plant puts on the grid, about two cents per kilowatt-hour (kWh) on top of a base cost of around four cents per kWh. The home owner buying only coal-based electricity and paying a retail price of 10 cents per kWh experiences one-fifth higher electricity costs – provided that the extra two cents per kWh cost for capture and sequestration is passed on without increases in the charges for transmission and distribution.

CO_2 policies must soon become prescriptive for a decade or more.

It is essential to develop the credibility of any legislated trajectory for the CO_2 emissions price – whether it be the trajectory of the shrinking size of the cap in a cap-and-trade system or the trajectory for the rising emissions price in a tax system Probably, a shake-out period lasting two or three years is a good idea. Even after the shake-out period, periodic revision, such as every five years, is probably desirable, allowing new information about climate change science, about technology, and about the workings of the mitigation system itself to be incorporated. But policy design should not be built on "foot in the door" assumptions: low emissions prices for only a few years, followed by unspecified ratchets.

Supplement Two: Further observations

1. A Table of Costs expressing the same CO_2 emissions price in different ways suggests that price policy will modify the practices of energy producers more than energy consumers.

Form of Energy	Price increment at \$100/tC, or \$27/tCO_2 ("t" is metric ton; 1 metric ton = 1.1 U.S ton)
Natural gas	**\$1.50/1000 standard cubic feet**
Crude oil	**\$12/barrel**
Coal	**\$65/U.S. ton**
Gasoline	**25¢/gallon (ethanol subsidy: about 50¢/gallon)**
Electricity from coal	**2.2¢/kWh (wind and nuclear subsidies: 1.8 ¢/kWh)**
Electricity from natural gas	**1.0¢/kWh**

Notes to Table

Gasoline:	1 m^3 = 264.2 U.S. gals; 630 kgC/m^3 gasoline.
Crude oil:	1 bbl = 42 U.S. gals; 730 kgC/m^3 crude oil
Coal:	1 U.S. ton = 907 kg; 0.71 kgC/kg coal
Natural gas:	1 Nm^3 = 37.24 scf; 0.549 kgC/ Nm^3 natural gas
Electricity from coal:	29.3 GJ/t coal (12,600 Btu/pound); 40% conversion.
Electricity from natural gas:	55.6 GJ/t natural gas; 0.75 kgC/kg natural gas; 50% conversion.

2. Enhanced oil recovery is a CO_2 emissions reduction policy, even though it produces hydrocarbons.

EOR traps some CO_2 below ground. The baseline for thinking about the oil produced by EOR is oil produced without EOR. Thus, EOR is a CO_2 emissions reduction strategy. There is another perspective, technically correct but misguided, which observes that, for EOR as practiced today, more carbon atoms come out as oil than are tucked away as CO_2. The reason this argument is misguided is that for most oil production, *no* carbon atoms are tucked away. Some is better than none.

With a high price on CO_2 emissions, EOR will be different. The field operator's strategy today is to leave behind as little as possible of the CO_2 brought to the field, because buying the CO_2 is costly and releasing it to the atmosphere is cost-free. Once there is a substantial price on CO_2 emissions, the same operator will leave behind and sequester as much CO_2 as possible. The industry will be transformed into one with two commercial purposes instead of one.

3. Sequestration capacity will grow, much as any other non-renewable reserve grows, as technology develops.

Space below ground for CO_2 sequestration in geological formations ("pore space"), already large, will be subject to the same logic as oil or a metal or any other non-renewable energy or mineral reserve. The quantity of pore space available will increase as exploration is extended, experience with sequestration increases, and technologies improve.

4. Slow leakage of CO_2 from sequestration sites is not a catastrophe, only a loss of money.

Safe sequestration has two very different meanings. Safe sequestration requires absolutely preventing fast and sudden release of CO_2 that could result in serious hazards to humans. For a sequestration operation to earn a license, regulators will need to be satisfied that sudden leakage is virtually certain not to occur. But safe sequestration is compatible with very occasionally losing the CO_2 slowly, in spite of best intentions. Gradual leakage of carbon dioxide merely returns some of the greenhouse gas to the air. The risks of safe sequestration in the second sense can be managed by carrying insurance to reimburse whoever paid for the sequestration. Slow loss of CO_2 is far from a catastrophe, and regulatory regimes should reflect this.

5. Clean coal must be clean upstream.

CCS technology has the potential to transform the image of the coal industry into one that commercializes cutting edge, environmentally friendly, jobs generating, and profitable technology. But this can happen only if the coal industry makes significant social and environmental investments at the coal mine as well as at the coal power plant.

6. US leadership should accelerate the development of CO_2 policy in China and elsewhere.
China is now building coal power plants at a faster rate than we ever will. A coherent U.S. CO_2 policy should result in gaining some influence on China's construction program. Benefits to both parties include reductions in overall costs resulting from shared learning about new technology (including CCS technology), harmonized rules, and new markets for specific technologies. Levers producing influence over China and other countries may be hard to find. What is certain is that there is no point looking for such levers until the U.S. embarks on its own vigorous climate-change mitigation policies. We must practice before we preach.

Mr. Chairman and members of the Committee, thank you for your attention.

A FEATURE ARTICLE FROM ... SEPTEMBER 2006

SCIENTIFIC AMERICAN

A Plan to Keep *Carbon* in Check

Getting a grip on greenhouse gases is daunting but doable. The technologies already exist. But there is no time to lose

BY ROBERT H. SOCOLOW AND STEPHEN W. PACALA

OVERVIEW

- Humanity can emit only so much carbon dioxide into the atmosphere before the climate enters a state unknown in recent geologic history and goes haywire. Climate scientists typically see the risks growing rapidly as CO_2 levels approach a doubling of their pre-18th-century value.
- To make the problem manageable, the required reduction in emissions can be broken down into "wedges"—an incremental reduction of a size that matches available technology.

Retreating glaciers, stronger hurricanes, hotter summers, thinner polar bears: the ominous harbingers of global warming are driving companies and governments to work toward an unprecedented change in the historical pattern of fossil-fuel use. Faster and faster, year after year for two centuries, human beings have been transferring carbon to the atmosphere from below the surface of the earth. Today the world's coal, oil and natural gas industries dig up and pump out about seven billion tons of carbon a year, and society burns nearly all of it, releasing carbon dioxide (CO_2). Ever more people are convinced that prudence dictates a reversal of the present course of rising CO_2 emissions.

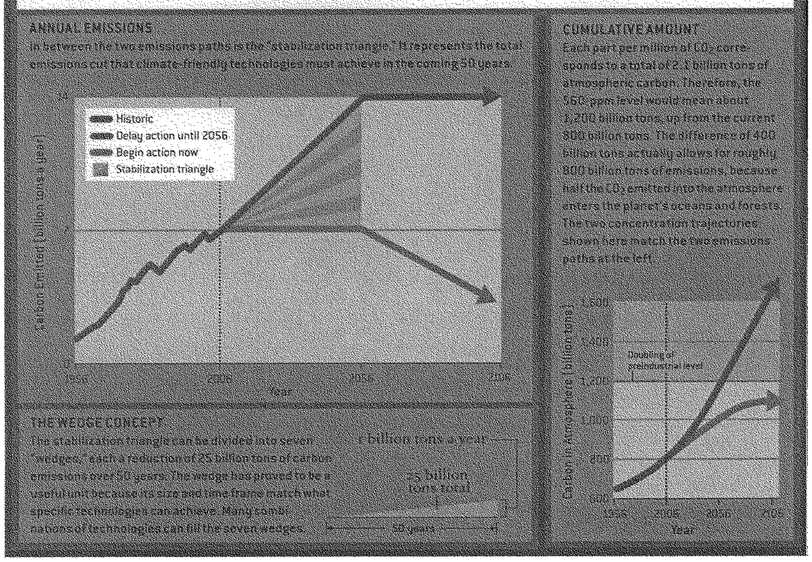
The boundary separating the truly dangerous consequences of emissions from the merely unwise is probably located near (but below) a doubling of the concentration of CO_2 that was in the atmosphere in the 18th century, before the Industrial Revolution began. Every increase in concentration carries new risks, but avoiding that danger zone would reduce the likelihood of triggering major, irreversible climate changes, such as the disappearance of the Greenland ice cap. Two years ago the two of us provided a simple framework to relate future CO_2 emissions to this goal.

We contrasted two 50-year futures. In one future, the emissions rate continues to grow at the pace of the past 30 years for the next 50 years, reaching 14 billion tons of carbon a year in 2056. (Higher or lower rates are, of course, plausible.) At that point, a tripling of preindustrial carbon concentrations would be very difficult to avoid, even with concerted efforts to decarbonize the world's energy systems over the following 100 years. In the other future, emissions are frozen at the present value of seven billion tons a year for the next 50 years and then reduced by about half over the following 50 years. In this way, a doubling of CO_2 levels can be avoided. The difference between these 50-year emission paths—one ramping up and one flattening out—we called the stabilization triangle [*see box on opposite page*].

To hold global emissions constant while the world's economy continues to grow is a daunting task. Over the past 30 years, as the gross world

MANAGING THE CLIMATE PROBLEM

At the present rate of growth, emissions of carbon dioxide will double by 2056 [*below left*]. Even if the world then takes action to level them off, the atmospheric concentration of the gas will be headed above 560 parts per million, double the preindustrial value [*below right*]—a level widely regarded as capable of triggering severe climate changes. But if the world flattens out emissions beginning now and later ramps them down, it should be able to keep concentration substantially below 560 ppm.



product of goods and services grew at close to 3 percent a year on average, carbon emissions rose half as fast. Thus, the ratio of emissions to dollars of gross world product, known as the carbon intensity of the global economy, fell about 1.5 percent a year. For global emissions to be the same in 2056 as today, the carbon intensity will need to fall not half as fast but fully as fast as the global economy grows.

Two long-term trends are certain to continue and will help. First, as societies get richer, the services sector—education, health, leisure, banking and so on—grows in importance relative to energy-intensive activities, such as steel production. All by itself, this shift lowers the carbon intensity of an economy.

Second, deeply ingrained in the patterns of technology evolution is the substitution of cleverness for energy. Hundreds of power plants are not needed today because the world has invested in much more efficient refrigerators, air conditioners and motors than were available two decades ago. Hundreds of oil and gas fields have been developed more slowly because aircraft engines consume less fuel and the windows in gas-heated homes leak less heat.

The task of holding global emissions constant would be out of reach, were it not for the fact that all the driving and flying in 2056 will be in vehicles not yet designed, most of the buildings that will be around then are not yet built, the locations of many of the communities that will contain these buildings and determine their inhabitants' commuting patterns have not yet been chosen, and utility owners are only now beginning to plan for the power plants that will be needed to light up those communities. Today's notoriously inefficient energy system can be replaced if the world gives unprecedented attention to energy efficiency. Dramatic changes are plausible over the next 50 years because so much of the energy canvas is still blank.

To make the task of reducing emis-

JEN CHRISTIANSEN

sions vivid, we sliced the stabilization triangle into seven equal pieces, or "wedges," each representing one billion tons a year of averted emissions 50 years from now (starting from zero today). For example, a car driven 10,000 miles a year with a fuel efficiency of 30 miles per gallon (mpg) emits close to one ton of carbon annually. Transport experts predict that two billion cars will be zipping along the world's roads in 2056, each driven an average of 10,000 miles a year. If their average fuel efficiency were 30 mpg, their tailpipes would spew two billion tons of carbon that year. At 60 mpg, they would give off a billion tons. The latter scenario would therefore yield one wedge.

Wedges

IN OUR FRAMEWORK, you are allowed to count as wedges only those differences in two 2056 worlds that result from deliberate carbon policy. The current pace of emissions growth already includes some steady reduction in carbon intensity. The goal is to reduce it even more. For instance, those who believe that cars will average 60 mpg in 2056 even in a world that pays no attention to carbon cannot count this improvement as a wedge, because it is already implicit in the baseline projection.

Moreover, you are allowed to count only strategies that involve the scaling up of technologies already commercialized somewhere in the world. You are not allowed to count pie in the sky. Our goal in developing the wedge framework was to be pragmatic and realistic—to propose engineering our way out of the problem and not waiting for the cavalry to come over the hill. We argued that even with these two counting rules, the world can fill all seven wedges, and in several different ways [*see box on opposite page*]. Individual countries—operating within a framework of international cooperation—will decide which wedges to pursue, depending on their institutional and economic capacities, natural resource endowments and political predilections.

To be sure, achieving nearly every one of the wedges requires new science and engineering to squeeze down costs and address the problems that inevitably accompany widespread deployment of new technologies. But holding CO_2 emissions in 2056 to their present rate, without choking off economic growth, is a desirable outcome within our grasp.

Ending the era of conventional coal-fired power plants is at the very top of the decarbonization agenda. Coal has become more competitive as a source of power and fuel because of energy security concerns and because of an increase in the cost of oil and gas. That is a problem because a coal power plant burns twice as much carbon per unit of electricity as a natural gas plant. In the absence of a concern about carbon, the world's coal utilities could build a few thousand large (1,000-megawatt) conventional coal plants in the next 50 years. Seven hundred such plants emit one wedge's worth of carbon. Therefore, the world could take some big steps toward the target of freezing emissions by not building those plants. The time to start is now. Facilities built in this decade could easily be around in 2056.

> Holding carbon dioxide emissions constant for 50 years, without choking off economic growth, is within our grasp.

Efficiency in electricity use is the most obvious substitute for coal. Of the 14 billion tons of carbon emissions projected for 2056, perhaps six billion will come from producing power, mostly from coal. Residential and commercial buildings account for 60 percent of global electricity demand today (70 percent in the U.S.) and will consume most of the new power. So cutting buildings' electricity use in half—by equipping them with superefficient lighting and appliances—could lead to two wedges. Another wedge would be achieved if industry finds additional ways to use electricity more efficiently.

Decarbonizing the Supply

EVEN AFTER energy-efficient technology has penetrated deeply, the world will still need power plants. They can be coal plants but they will need to be carbon-smart ones that capture the CO_2 and pump it into the ground [see "Can We Bury Global Warming?" by Robert H. Socolow; SCIENTIFIC AMERICAN, July 2005]. Today's high oil prices are lowering the cost of the transition to this technology, because captured CO_2 can often be sold to an oil company that injects it into oil fields to squeeze out more oil; thus, the higher the price of oil, the more valuable the captured CO_2. To achieve one wedge, utilities need to equip 800 large coal plants to capture and store nearly all the CO_2 otherwise emitted. Even in a carbon-constrained world, coal mining and coal power can stay in business, thanks to carbon capture and storage.

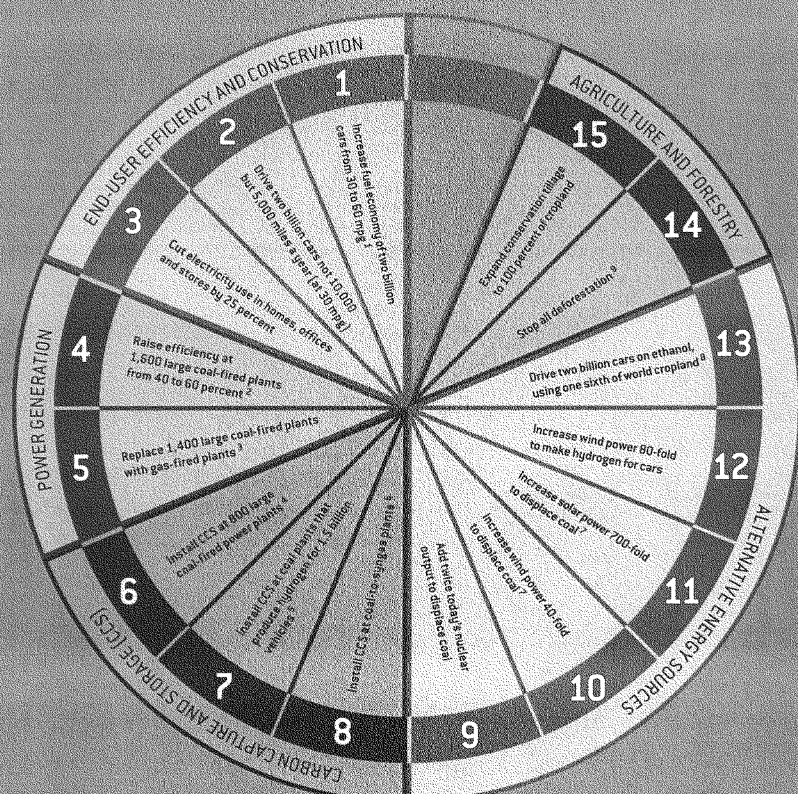
The large natural gas power plants operating in 2056 could capture and store their CO_2, too, perhaps accounting for yet another wedge. Renewable and nuclear energy can contribute as well. Renewable power can be produced from sunlight directly, either to energize photovoltaic cells or, using focusing mirrors,

THE AUTHORS

ROBERT H. SOCOLOW and STEPHEN W. PACALA lead the Carbon Mitigation Initiative at Princeton University, where Socolow is a mechanical engineering professor and Pacala an ecology professor. The initiative is funded by BP and Ford. Socolow specializes in energy-efficient technology, global carbon management and carbon sequestration. He was co-editor (with John Harte) of *Patient Earth*, published in 1971 as one of the first college-level presentations of environmental studies. He is the recipient of the 2003 Leo Szilard Lectureship Award from the American Physical Society. Pacala investigates the interaction of the biosphere, atmosphere and hydrosphere on global scales, with an emphasis on the carbon cycle. He is director of the Princeton Environmental Institute.

15 WAYS TO MAKE A WEDGE

An overall carbon strategy for the next half a century produces seven wedges' worth of emissions reductions. Here are 15 technologies from which those seven can be chosen (taking care to avoid double-counting). Each of these measures, when phased in over 50 years, prevents the release of 25 billion tons of carbon. Leaving one wedge blank symbolizes that this list is by no means exhaustive.



Notes:

[1] World fleet size in 2056 could well be two billion cars. Assume they average 10,000 miles a year.
[2] "Large" is one-gigawatt (GW) capacity. Plants run 90 percent of the time.
[3] Here and below, assume coal plants run 90 percent of the time at 50 percent efficiency. Present coal power output is equivalent to 800 such plants.
[4] Assume 90 percent of CO_2 is captured.
[5] Assume a car (10,000 miles a year, 60 miles per gallon equivalent) requires 170 kilograms of hydrogen a year.
[6] Assume 30 million barrels of synfuels a day, about a third of today's total oil production. Assume half of carbon originally in the coal is captured.
[7] Assume wind and solar produce, on average, 30 percent of peak power. Thus replace 2,100 GW of 90-percent-time coal power with 2,100 GW (peak) wind or solar plus 1,400 GW of load-following coal power, for net displacement of 700 GW.
[8] Assume 60-mpg cars, 10,000 miles a year, biomass yield of 15 tons a hectare, and negligible fossil-fuel inputs. World cropland is 1,500 million hectares.
[9] Carbon emissions from deforestation are currently about two billion tons a year. Assume that by 2056 the rate falls by half in the business-as-usual projection and to zero in the flat path.

JANET CHAO

to heat a fluid and drive a turbine. Or the route can be indirect, harnessing hydropower and wind power, both of which rely on sun-driven weather patterns. The intermittency of renewable power does not diminish its capacity to contribute wedges; even if coal and natural gas plants provide the backup power, they run only part-time (in tandem with energy storage) and use less carbon than if they ran all year. Not strictly renewable, but also usually included in the family, is geothermal energy, obtained by mining the heat in the earth's interior. Any of these sources, scaled up from its current contribution, could produce a wedge. One must be careful not to double-count the possibilities; the same coal plant can be left unbuilt only once.

Nuclear power is probably the most controversial of all the wedge strategies. If the fleet of nuclear power plants were to expand by a factor of five by 2056, displacing conventional coal plants, it would provide two wedges. If the current fleet were to be shut down and replaced with modern coal plants without carbon capture and storage, the result would be *minus* one-half wedge. Whether nuclear power will be scaled up or down will depend on whether governments can find political solutions to waste disposal and on whether plants can run without accidents. (Nuclear plants are mutual hostages: the world's least well-run plant can imperil the future of all the others.) Also critical will be strict rules that prevent civilian nuclear technology from becoming a stimulus for nuclear weapons development. These rules will have to be uniform across all countries, so as to remove the sense of a double standard that has long been a spur to clandestine facilities.

Oil accounted for 43 percent of global carbon emissions from fossil fuels in 2002, while coal accounted for 37 percent; natural gas made up the remainder. More than half the oil was used for transport. So smartening up electricity production alone cannot fill the stabilization triangle; transportation, too, must be decarbonized. As with coal-fired electricity, at least a wedge may be available from each of three complementary options: reduced use, improved efficiency and decarbonized energy sources. People can take fewer unwanted trips (telecommuting instead of vehicle commuting) and pursue the travel they cherish (adventure, family visits) in fuel-efficient vehicles running on low-carbon fuel. The fuel can be a product of crop residues or dedicated crops, hydrogen made from low-carbon electricity, or low-carbon electricity itself, charging an onboard battery. Sources of the low-carbon electricity could include wind, nuclear power, or coal with capture and storage.

Looming over this task is the prospect that, in the interest of energy security, the transport system could become *more* carbon-intensive. That will happen if transport fuels are derived from coal instead of petroleum. Coal-based synthetic fuels, known as synfuels, provide a way to reduce global demand for oil, lowering its cost and decreasing global dependence on Middle East petroleum. But it is a decidedly climate-unfriendly strategy. A synfuel-powered car emits the same amount of CO_2 as a gasoline-powered car, but synfuel fabrication from coal spews out far more carbon than does refining gasoline from crude oil—enough to double the emissions per mile of driving. From the perspective of mitigating climate change, it is fortunate that the emissions at a synfuels plant can be captured and stored. If business-as-usual trends did lead to the widespread adoption of synfuel, then capturing CO_2 at synfuels plants might well produce a wedge.

39 percent
U.S. share of global carbon emissions in 1952

23 percent
U.S. share in 2002

The U.S. share of global emissions can be expected to continue to drop.

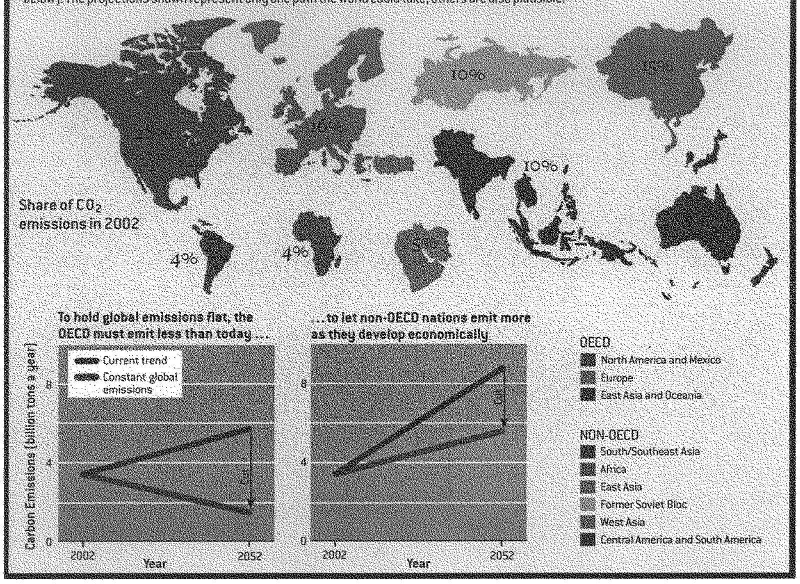
Not all wedges involve new energy technology. If all the farmers in the world practiced no-till agriculture rather than conventional plowing, they would contribute a wedge. Eliminating deforestation would result in two wedges, if the alternative were for deforestation to continue at current rates. Curtailing emissions of methane, which today contribute about half as much to greenhouse warming as CO_2, may provide more than one wedge: needed is a deeper understanding of the anaerobic biological emissions from cattle, rice paddies and irrigated land. Lower birth rates can produce a wedge, too—for example, if they hold the global population in 2056 near eight billion people when it otherwise would have grown to nine billion.

Action Plan

WHAT SET OF POLICIES will yield seven wedges? To be sure, the dramatic changes we anticipate in the fossil-fuel system, including routine use of CO_2 capture and storage, will require institutions that reliably communicate a price for present and future carbon emissions. We estimate that the price needed to jump-start this transition is in the ballpark of \$100 to \$200 per ton of carbon—the range that would make it cheaper for owners of coal plants to capture and store CO_2 rather than vent it. The price might fall as technologies climb the learning curve. A carbon emissions price of \$100 per ton is comparable to the current U.S. production credit for new renewable and nuclear energy relative to coal, and it is about half the current U.S. subsidy of ethanol relative to gasoline. It also was the price of CO_2 emissions in the European Union's emissions trading system for nearly a year, spanning 2005 and 2006. (One ton of carbon is carried in 3.7 tons of carbon dioxide, so this price is also \$27 per ton of CO_2.) Based on carbon content, \$100 per ton of carbon is \$12 per barrel of oil and \$60 per ton of coal. It is 25 cents per gallon of gasoline and two cents per

RICH WORLD, POOR WORLD

To keep global emissions constant, both developed nations (defined here as members of the Organization for Economic Cooperation and Development, or OECD) and developing nations will need to cut their emissions relative to what they would have been (*arrows in graphs below*). The projections shown represent only one path the world could take; others are also plausible.



JEN CHRISTIANSEN; SOURCE: "GLOBAL, REGIONAL, AND NATIONAL FOSSIL FUEL CO_2 EMISSIONS," BY G. MARLAND, T. A. BODEN AND R. J. ANDRES, IN *TRENDS: A COMPENDIUM OF DATA ON GLOBAL CHANGE*. CARBON DIOXIDE INFORMATION ANALYSIS CENTER, OAK RIDGE NATIONAL LABORATORY, 2006

kilowatt-hour of electricity from coal.

But a price on CO_2 emissions, on its own, may not be enough. Governments may need to stimulate the commercialization of low-carbon technologies to increase the number of competitive options available in the future. Examples include wind, photovoltaic power and hybrid cars. Also appropriate are policies designed to prevent the construction of long-lived capital facilities that are mismatched to future policy. Utilities, for instance, need to be encouraged to invest in CO_2 capture and storage for new coal power plants, which would be very costly to retrofit later. Still another set of policies can harness the capacity of energy producers to promote efficiency—motivating power utilities to care about the installation and maintenance of efficient appliances, natural gas companies to care about the buildings where their gas is burned, and oil companies to care about the engines that run on their fuel.

To freeze emissions at the current level, if one category of emissions goes up, another must come down. If emissions from natural gas increase, the combined emissions from oil and coal must decrease. If emissions from air travel climb, those from some other economic sector must fall. And if today's poor countries are to emit more, today's richer countries must emit less.

How much less? It is easy to bracket the answer. Currently the industrial nations—the members of the Organization for Economic Cooperation and Development (OECD)—account for almost exactly half the planet's CO_2 emissions, and the developing countries plus the nations formerly part of the Soviet Union account for the other half. In a world of constant total carbon emissions, keeping the OECD's share at 50 percent seems impossible to justify in the face of the enormous pent-up demand for energy in the non-OECD countries, where more than 80 percent of the world's people live. On the other hand, the OECD member states must emit *some* carbon in 2056. Simple arithmetic indicates that to hold global emissions rates steady, non-OECD emissions cannot even double.

One intermediate value results if all OECD countries were to meet the emissions-reduction target for the U.K. that was articulated in 2003 by Prime Minister Tony Blair—namely, a 60 percent reduction by 2050, relative to recent levels. The non-OECD countries could then emit 60 percent more CO_2. On average, by midcentury they would have one half the per capita emissions of the OECD countries. The CO_2 output of every country, rich or poor today, would be well below what it is generally projected to be in the absence of climate policy. In the case of the U.S., it would be about four times less.

Blair's goal would leave the average American emitting twice as much as the world average, as opposed to five times as much today. The U.S. could meet this goal in many ways [*see illustration at right*]. These strategies will be followed by most other countries as well. The resultant cross-pollination will lower every country's costs.

Fortunately, the goal of decarbonization does not conflict with the goal of eliminating the world's most extreme poverty. The extra carbon emissions produced when the world's nations accelerate the delivery of electricity and modern cooking fuel to the earth's poorest people can be compensated for by, at most, one fifth of a wedge of emissions reductions elsewhere.

Beyond 2056

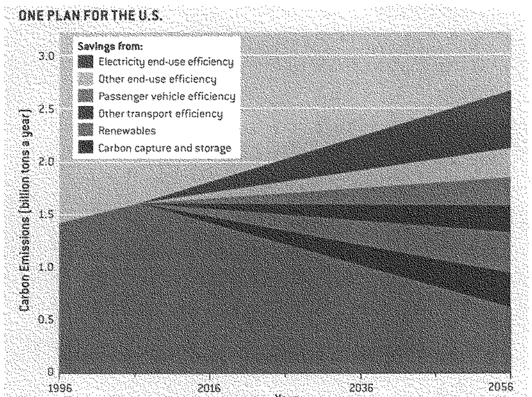
THE STABILIZATION triangle deals only with the first 50-year leg of the future. One can imagine a relay race made of 50-year segments, in which the first runner passes a baton to the second in 2056. Intergenerational equity requires that the two runners have roughly equally difficult tasks. It seems to us that the task we have given the second runner (to cut the 2056 emissions rate in half between 2056 and 2106) will not be harder than the task of the first runner (to keep global emissions in 2056 at present levels)—provided that between now and 2056 the world invests in research and development to get ready. A vigorous effort can prepare the revolutionary technologies that will give the second half of the century a running start. Those options could include scrubbing CO_2 directly from the air, carbon storage in minerals, nuclear fusion, nuclear thermal hydrogen, and artificial photosynthesis. Conceivably, one or more of these technologies may arrive in time to help the first runner, although, as we have argued, the world should not count on it.

As we look back from 2056, if global emissions of CO_2 are indeed no larger than today's, what will have been accomplished? The world will have confronted energy production and energy efficiency at the consumer level, in all economic sectors and in economies at all levels of development. Buildings and lights and refrigerators, cars and trucks and planes, will be transformed. Transformed, also, will be the ways we use them.

The world will have a fossil-fuel energy system about as large as today's but one that is infused with modern controls and advanced materials and that is almost unrecognizably cleaner. There will be integrated production of power, fuels and heat; greatly reduced air and water pollution; and extensive carbon capture and storage. Alongside the fossil energy system will be a nonfossil energy system approximately as large. Extensive direct and indirect harvesting of renewable energy will have brought about the revitalization of rural areas and the reclamation of degraded lands. If nuclear power is playing a large role, strong international enforcement mechanisms will have come into being to control the spread of nuclear technology from energy to weapons. Economic growth will have been maintained; the poor and the rich will both be richer. And our descendants will not be forced to exhaust so much treasure, innovation and energy to ward off rising sea level, heat, hurricanes and drought.

Critically, a planetary consciousness will have grown. Humanity will have learned to address its collective destiny—and to share the planet. ■

ONE PLAN FOR THE U.S.



▲ U.S. share of emissions reductions could, in this Natural Resources Defense Council scenario, be achieved by efficiency gains, renewable energy and clean coal.

JEN CHRISTIANSEN; SOURCE: DANIEL A. LASHOF AND DAVID G. HAWKINS *Natural Resources Defense Council*

MORE TO EXPLORE

Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. S. Pacala and R. Socolow in *Science*, Vol. 305, pages 968–972; August 13, 2004.

The calculations behind the individual wedges are available at www.princeton.edu/~cmi

Energy statistics are available at www.eia.doe.gov, www.iea.org and www.bp.com; carbon emissions data can also be found at cdiac.esd.ornl.gov

Princeton University

CMI Graphics by Douglas Jakobsen

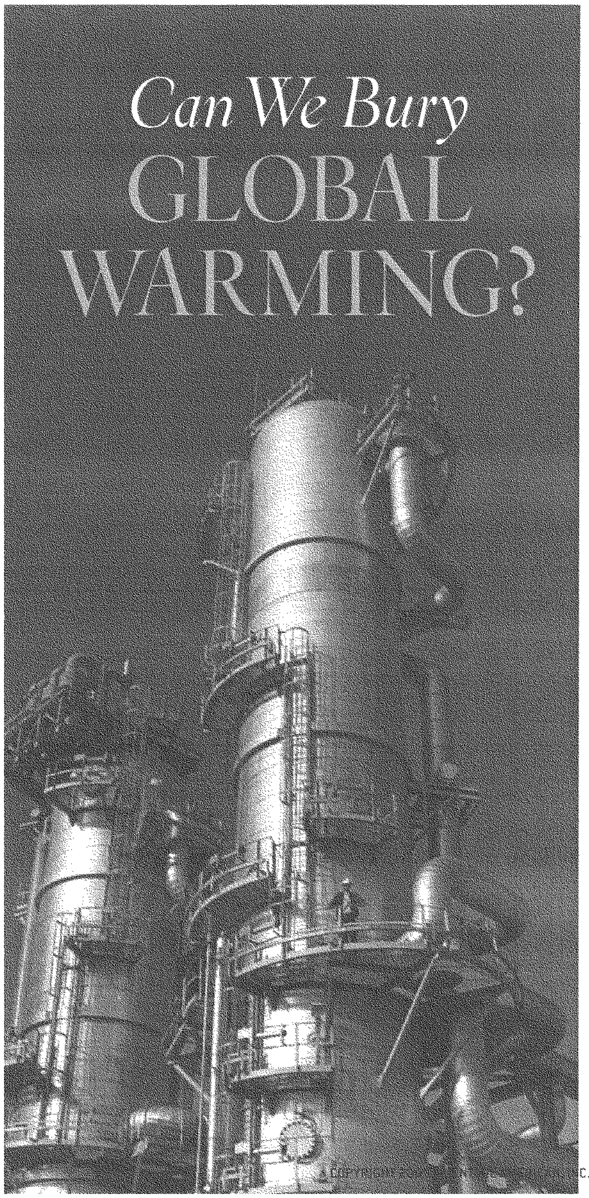
Carbon Mitigation Initiative

Carbon Mitigation Initiative
Princeton Environmental Institute
Princeton University
www.princeton.edu/~cmi

Three percentages on the map on p. 6 in this reprint differ slightly from those in the September 2006 issue on p. 56.
The percentages in this reprint are correct. An erratum will appear in a later issue of *Scientific American*.

SEPTEMBER 2006 • VOL. 295, NO. 3 • PAGES 50 THRU 57 •

Can We Bury GLOBAL WARMING?



Pumping carbon dioxide underground to avoid warming the atmosphere is feasible, but only if several key challenges can be met

By Robert H. Socolow

When William Shakespeare took a breath, 280 molecules out of every million entering his lungs were carbon dioxide. Each time you draw breath today, 380 molecules per million are carbon dioxide. That portion climbs about two molecules every year.

No one knows the exact consequences of this upsurge in the atmosphere's carbon dioxide (CO_2) concentration nor the effects that lie ahead as more and more of the gas enters the air in the coming decades—humankind is running an uncontrolled experiment on the world. Scientists know that carbon dioxide is warming the atmosphere, which in turn is causing sea level to rise, and that the CO_2 absorbed by the oceans is acidifying the water. But they are unsure of exactly how climate could alter across the globe, how fast sea level might rise, what a more acidic ocean could mean, which ecological systems on land and in the sea would be most vulnerable to climate change and how these developments might affect human health and well-being. Our current course is bringing climate change upon ourselves faster than we can learn how severe the changes will be.

If slowing the rate of carbon dioxide buildup were easy, the world would be getting on with the job. If it were impossible, humanity would be working to

STRIPPER TOWERS at an Algerian gas-extraction facility deep in the Sahara Desert chemically separate carbon dioxide from natural gas bound for European markets. The CO_2 is then pumped two kilometers below ground.

adapt to the consequences. But reality lies in between. The task can be done with tools already at hand, albeit not necessarily easily, inexpensively or without controversy.

Were society to make reducing carbon dioxide emissions a priority—as I think it should to reduce the risks of environmental havoc in the future—we would need to pursue several strategies at once. We would concentrate on using energy more efficiently and on substituting noncarbon renewable or nuclear energy sources for fossil fuel (coal, oil and natural gas–the primary sources of manmade atmospheric carbon dioxide). And we would employ a method that is receiving increasing attention: capturing carbon dioxide and storing, or sequestering, it underground rather than releasing it into the atmosphere. Nothing says that CO_2 must be emitted into the air. The atmosphere has been our prime waste repository, because discharging exhaust up through smokestacks, tailpipes and chimneys is the simplest and least (immediately) costly thing to do. The good news is that the technology for capture and storage already exists and that the obstacles hindering implementation seem to be surmountable.

Carbon Dioxide Capture

THE COMBUSTION of fossil fuels produces huge quantities of carbon dioxide. In principle, equipment could be installed to capture this gas wherever these hydrocarbons are burned, but some locations are better suited than others.

If you drive a car that gets 30 miles to the gallon and go 10,000 miles next year, you will need to buy 330 gallons—about a ton—of gasoline. Burning that much gasoline sends around three tons of carbon dioxide out the tailpipe. Although CO_2 could conceivably be caught before leaving the car and returned to the refueling station, no practical method seems likely to accomplish this task. On the other hand, it is easier to envision trapping the CO_2 output of a stationary coal-burning power plant.

It is little wonder, then, that today's capture-and-storage efforts focus on those power plants, the source of one quarter of the world's carbon dioxide emissions. A new, large (1,000-megawatt-generating) coal-fired power plant produces six million tons of the gas annually (equivalent to the emissions of two million cars). The world's total output (roughly equivalent to the production of 1,000 large plants) could double during the next few decades as the U.S., China, India and many other countries construct new power-generating stations and replace old ones [*see illustration on page 52*]. As new coal facilities come online in the coming quarter of a century, they could be engineered to filter out the carbon dioxide that would otherwise fly up the smokestacks.

Today a power company planning to invest in a new coal plant can choose from two types of power systems, and a third is under development but not yet available. All three can be modified for carbon capture. Traditional coal-fired steam power plants burn coal fully in one step in air: the heat that is released converts water into high-pressure steam, which turns a steam turbine that generates electricity. In an unmodified version of this system—the workhorse of the coal power industry for the past century—a mixture of exhaust (or flue) gases exits a tall stack at atmospheric pressure after having its sulfur removed. Only about 15 percent of the flue gas is carbon dioxide; most of the remainder is nitrogen and water vapor. To adapt this technology for CO_2 capture, engineers could replace the smokestack with an absorption tower, in which the flue gases would come in contact with droplets of chemicals called amines that selectively absorb CO_2. In a second reaction column, known as a stripper tower, the amine liquid would be heated to release concentrated CO_2 and to regenerate the chemical absorber.

The other available coal power system, known as a coal gasification combined-cycle unit, first burns coal partially in the presence of oxygen in a gasification chamber to produce a "synthetic" gas, or syngas—primarily pressurized hydrogen and carbon monoxide. After removing sulfur compounds and other impurities, the plant combusts the syngas in air in a gas turbine—a modified jet engine—to make electricity. The heat in the exhaust gases leaving the gas turbine turns water into steam, which is piped into a steam turbine to generate additional power, and then the gas turbine exhaust flows out the stack. To capture carbon from such a facility, technicians add steam to the syngas to convert (or "shift") most of the carbon monoxide into carbon dioxide and hydrogen. The combined cycle system next filters out the CO_2 before burning the remaining gas, now mostly hydrogen, to generate electricity in a gas turbine and a steam turbine.

The third coal power approach, called oxyfuel combustion, would perform all the burning in oxygen instead of air. One version would modify single-step combustion by burning coal in oxygen, yielding a fuel gas with no nitrogen, only CO_2

Overview/*Entombing CO_2*

- A strategy that combines the capture of carbon dioxide emissions from coal power plants and their subsequent injection into geologic formations for long-term storage could contribute significantly to slowing the rise of the atmospheric CO_2 concentration.
- Low-cost technologies for securing carbon dioxide at power plants and greater experience with CO_2 injection to avoid leakage to the surface are key to the success of large-scale CO_2 capture and storage projects.
- Fortunately, opportunities for affordable storage and capture efforts are plentiful. Carbon dioxide has economic value when it is used to boost crude oil recovery at mature fields. Natural gas purification and industrial hydrogen production yield CO_2 at low cost. Early projects that link these industries will enhance the practitioners' technical capabilities and will stimulate the development of regulations to govern CO_2 storage procedures.

COURTESY OF BP plc (*preceding page*)

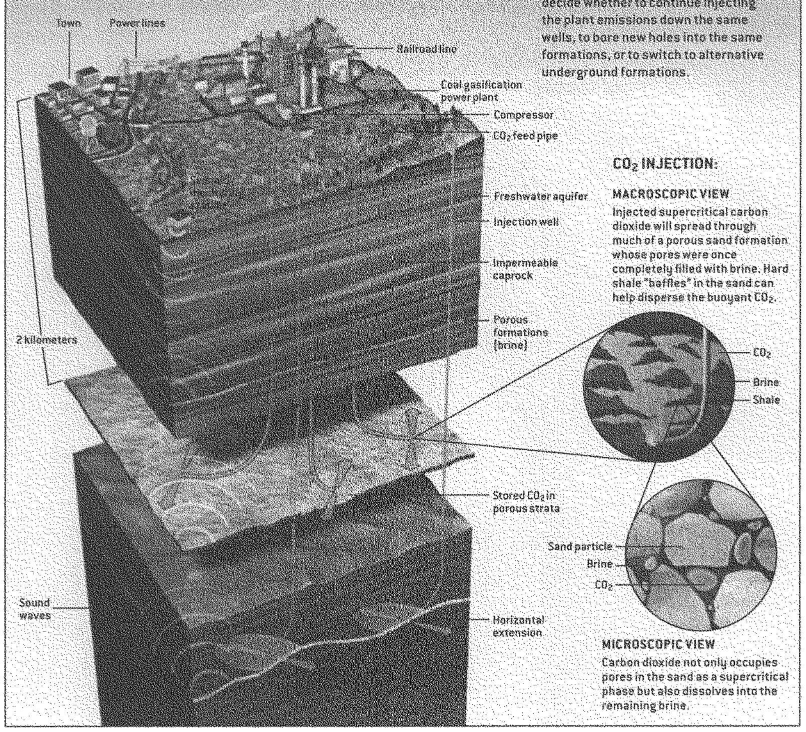
FUTURE FOSSIL-FUEL POWER PLANT

Consider a hypothetical town near a future 1,000-megawatt coal gasification power plant that has been sequestering carbon dioxide for 10 years. The town receives water from a shallow aquifer, unaffected by the CO_2 injection. The rail line transports coal to the plant, and the power lines carry away the electricity it generates.

Some 60 million tons of CO_2 have been captured during the plant's first 10 years of operation, and by now very large pancake-shaped deposits of CO_2 sit in the porous subterranean strata. The carbon dioxide was injected through horizontal wells into two deep brine (saltwater) formations, each located under impermeable caprock more than two kilometers below the surface. At seven tenths the density of water, the high-pressure "supercritical" CO_2 occupies almost 90 million cubic meters. In both formations, 10 percent of the volume is pore space, and a third of the pores are filled with CO_2 (*see insets for detailed views of the porous strata*). Two thirds of the injected gas has been pumped into the 40-meter-thick upper formation, and one third has been sent into the 20-meter-thick lower formation. As a result, the total (horizontal) area of porous rock soaked with supercritical carbon dioxide in each formation is about 40 square kilometers.

Note that the horizontal and vertical scales depicted here differ. The depth of each injection well and the length of their horizontal extensions are really about equal in length, around two kilometers. Nor are the building structures to scale.

Technicians at a seismic monitoring station keep track of the CO_2 locations by beaming sound waves into the ground. During the power station's initial decade of operation, utility managers learned many details about the local geology by observing how the CO_2 spread through the area. This information will help them decide whether to continue injecting the plant emissions down the same wells, to bore new holes into the same formations, or to switch to alternative underground formations.

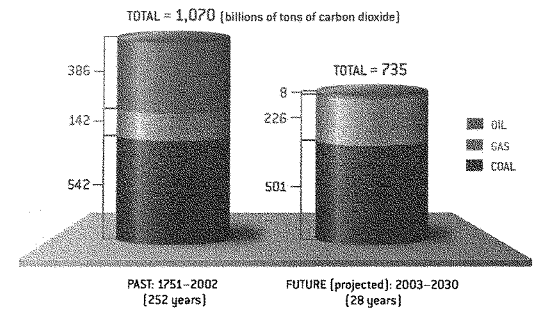


CO_2 INJECTION:

MACROSCOPIC VIEW
Injected supercritical carbon dioxide will spread through much of a porous sand formation whose pores were once completely filled with brine. Hard shale "baffles" in the sand can help disperse the buoyant CO_2.

MICROSCOPIC VIEW
Carbon dioxide not only occupies pores in the sand as a supercritical phase but also dissolves into the remaining brine.

ILLUSTRATION BY DAVID FIERSTEIN; CONCEPT BY JULIO FRIEDMANN *Lawrence Livermore National Laboratories*



LIFETIME FOSSIL-FUEL EMISSIONS from power plants projected to be built during the next quarter of a century will be comparable to all the emissions during the past 250 years. The left column shows the cumulative carbon dioxide emissions produced by burning coal, oil and natural gas for all uses (including transportation and building heating) from 1751 to 2002, whereas that on the right depicts the lifetime CO_2 emissions from fossil-fuel power generation plants projected by the International Energy Agency to come online between 2003 and 2030. Coal-fired power plants are assumed to operate for 60 years and gas-fired power stations for 40 years.

and water vapor, which are easy to separate. A second version would modify the coal gasification combined-cycle system by using oxygen, rather than air, at the gas turbine to burn the carbon monoxide and hydrogen mixture that has exited the gasifier. This arrangement skips the shift reaction and would again produce only CO_2 and water vapor. Structural materials do not yet exist, though, that can withstand the higher temperatures that are created by combustion in oxygen rather than in air. Engineers are exploring whether reducing the process temperature by recirculating the combustion exhaust will provide a way around these materials constraints.

Tough Decisions

MODIFICATION FOR carbon dioxide capture not only adds complexity and expense directly but also cuts the efficiency of extracting energy from the fuel. In other words, safely securing the carbon by-products means mining and burning more coal. These costs may be partially offset if the plant can filter out gaseous sulfur simultaneously and store it with the CO_2, thus avoiding some of the considerable expense of sulfur treatment.

Utility executives want to maximize profits over the entire life of the plant, probably 60 years or more, so they must estimate the expense of complying not only with today's environmental rules but also with future regulations. The managers know that the extra costs for CO_2 capture are likely to be substantially lower for coal gasification combined-cycle plants than for traditional plants. Removing carbon dioxide at high pressures, as occurs in a syngas operation, costs less because smaller equipment can be employed. But they also know that only a few demonstration gasification plants are running today, so that opting for gasification will require spending extra on backup equipment to ensure reliability. Hence, if the management bets on not having to pay for CO_2 emissions until late in the life of its new plant, it will probably choose a traditional coal plant, although perhaps one with the potential to be modified later for carbon capture. If, however, it believes that government directives to capture CO_2 are on their way within a decade or so, it may select a coal gasification plant.

To get a feel for the economic pressures the extra cost of carbon sequestration would place on the coal producer, the power plant operator and the home owner who consumes the electricity, it helps to choose a reasonable cost estimate and then gauge the effects. Experts calculate that the total additional expense of capturing and storing a ton of carbon dioxide at a coal gasification combined-cycle plant will be about $25. (In fact, it may be twice that much for a traditional steam plant using today's technology. In both cases, it will cost less when new technology is available.)

The coal producer, the power plant operator and the home owner will perceive that $25 cost increase quite differently. A coal producer would see a charge of about $60 per ton of coal for capturing and storing the coal's carbon, roughly tripling the cost of coal delivered to an electric utility customer. The owner of a new coal power plant would face a 50 percent rise in the cost of power the coal plant puts on the grid, about two cents per kilowatt-hour (kWh) on top of a base cost of around four cents per kWh. The home owner buying only coal-based electricity, who now pays an average of about 10 cents per kWh, would experience one-fifth higher electricity costs (provided that the extra two cents per kWh cost for capture and storage is passed on without increases in the charges for transmission and distribution).

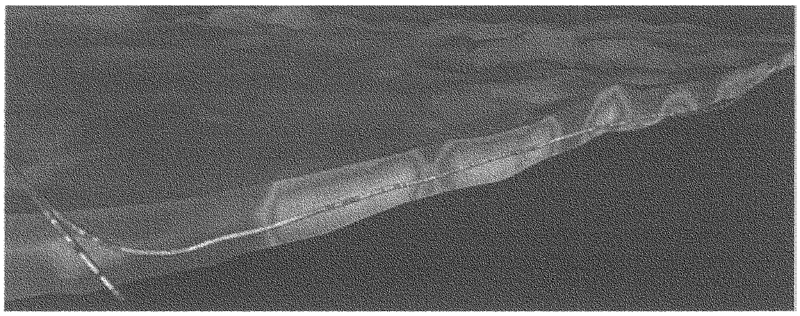
First and Future Steps

RATHER THAN WAITING for the construction of new coal-fired power plants to begin carbon dioxide capture and storage, business leaders are starting the process at existing facilities that produce hydrogen for industry or purify natural gas (methane) for heating and power generation. These operations currently generate concentrated streams of CO_2. Industrial hydrogen production processes, located at oil refineries and ammonia plants, remove carbon dioxide from a

THE AUTHOR

ROBERT H. SOCOLOW is professor of mechanical and aerospace engineering at Princeton University. He teaches in both the School of Engineering and Applied Science and the Woodrow Wilson School of Public and International Affairs. A physicist by training, Socolow is currently co-principal investigator (with ecologist Stephen Pacala) of the university's Carbon Mitigation Initiative, supported by BP and Ford, which focuses on global carbon management, the hydrogen economy and fossil-carbon sequestration. In 2003 he was awarded the Leo Szilard Lectureship Award by the American Physical Society.

ILLUSTRATION BY ALISON KENDALL; CONCEPT BY DAVID HAWKINS *Natural Resources Defense Council*; PAST DATA FROM GREGG MARLAND *Oak Ridge National Laboratory*



POROSITY OF A GEOLOGIC FORMATION near a carbon dioxide injection well (*thin tubing*) at the Krechba field in the Algerian desert was revealed by two sets of measurements. (Red and yellow represent high porosity regions of the 20-meter-thick reservoir; blue indicates low porosity areas.) BP engineers used the coarse mapping of the geologic layers, which was derived from seismic echolocation soundings, to determine where best to place the well. A down-hole electric sensor probe, which gave a finer depiction of porosity (looking like colored beads), revealed porosity within a few centimeters of the well. Engineers employed these more accurate readings to hunt for and steer the drilling apparatus toward regions of high porosity.

COURTESY OF BP plc

high-pressure mix of CO_2 and hydrogen, leaving behind carbon dioxide that is released skyward. Natural gas purification plants must remove CO_2 because the methane is heading for a liquefied natural gas tanker and must be kept free of cold, solid carbon dioxide (dry ice) that could clog the system or because the CO_2 concentration is too high (above 3 percent) to be allowed on the natural gas distribution grid.

Many carbon dioxide capture projects using these sources are now under consideration throughout the oil and gas industry. Hydrogen production and natural gas purification are the initial stepping-stones to full-scale carbon capture at power plants; worldwide about 5 percent as much carbon dioxide is produced in these two industries as in electric power generation.

In response to the growing demand for imported oil to fuel vehicles, some nations, such as China, are turning to coal to serve as a feedstock for synthetic fuels that substitute for gasoline and diesel fuel. From a climate change perspective, this is a step backward. Burning a coal-based synthetic fuel rather than gasoline to drive a set distance releases approximately double the carbon dioxide, when one takes into account both tailpipe and synfuels plant emissions. In synthetic fuels production from coal, only about half the carbon in the coal ends up in the fuel, and the other half is emitted at the plant. Engineers could modify the design of a coal synfuels plant to capture the plant's CO_2 emissions. At some point in the future, cars could run on electricity or carbon-free hydrogen extracted from coal at facilities where CO_2 is captured.

Electricity can also be made from biomass fuels, a term for commercial fuels derived from plant-based materials: agricultural crops and residues, timber and paper industry waste, and landfill gas. If the fossil fuels used in harvesting and processing are ignored, the exchanges between the atmosphere and the land balance because the quantity of carbon dioxide released by a traditional biomass power plant nearly equals that removed from the atmosphere by photosynthesis when the plants grew. But biomass power can do better: if carbon capture equipment were added to these facilities and the harvested biomass vegetation were replanted, the net result would be to scrub the air of CO_2. Unfortunately, the low efficiency of photosynthesis limits the opportunity for atmospheric scrubbing because of the need for large land areas to grow the trees or crops. Future technologies may change that, however. More efficient carbon dioxide removal by green plants and direct capture of CO_2 from the air (accomplished, for example, by flowing air over a chemical absorber) may become feasible at some point.

Carbon Dioxide Storage

CARBON CAPTURE is just half the job, of course. When an electric utility builds a 1,000-megawatt coal plant designed to trap CO_2, it needs to have somewhere to stash securely the six million tons of the gas the facility will generate every year for its entire life. Researchers believe that the best destinations in most cases will be underground formations of sedimentary rock loaded with pores now filled with brine (salty water). To be suitable, the sites typically would lie far below any source of drinking water, at least 800 meters under the surface. At 800 meters, the ambient pressure is 80 times that of the atmosphere, high enough that the pressurized injected CO_2 is in a "supercritical" phase—one that is nearly as dense as the brine it replaces in geologic formations. Sometimes crude oil or natural gas will also be found in the brine formations, having invaded the brine millions of years ago.

The quantities of carbon dioxide sent belowground can be expressed in "barrels," the standard 42-gallon unit of volume employed by the petroleum industry. Each year at a 1,000-megawatt coal plant modified for carbon capture, about 50 million barrels of supercritical carbon dioxide would be secured—about 100,000 barrels a day. After 60 years of operation, about three billion barrels (half a cubic kilometer) would be sequestered below the surface. An oil field with a capacity to produce three billion barrels is six times the size of the smallest of what the industry calls "giant" fields, of which some 500 exist. This means that each large modified coal plant would need to be associated with a "giant" CO_2 storage reservoir.

Alternative CO_2 Storage Schemes

Captured carbon dioxide might be stored not only in depleted oil and gas reservoirs and subterranean brine formations but also in minerals that form carbonate compounds, in coal seams and in the deep ocean.

Minerals that can become carbonates could potentially sequester even more carbon dioxide on the earth's surface than brine formations could store underground. The magnesium oxide in two abundant iron-magnesium minerals, serpentine and olivine, combines with CO_2 to produce highly stable magnesium carbonate. The big challenge is to get CO_2 to react quickly with bulk quantities of these rocks, perhaps by grinding them into fine powders to increase the surface area at which the chemical reactions occur.

The pore surfaces within coal formations adsorb methane. During mining, some of this methane can be released, too often causing underground explosions and, consequently, the deaths of miners. Pressurized carbon dioxide could be introduced into unexploited coal seams where it would replace the adsorbed methane, which could then be recovered and sold as fuel.

Ocean injection of carbon dioxide is controversial. Advocates of storage in the deep ocean point out that atmospheric CO_2 passes continuously into the ocean surface, as the air and ocean system seeks chemical equilibrium. Slowing the increase of CO_2 levels in the air will reduce the amount dissolving into the surface water. Thus, deep-ocean injection would shift some CO_2 from the surface waters to the lowest layers, reducing environmental impacts near the surface, where most marine life is found. Opponents of ocean storage cite international law that protects the oceans from certain kinds of industrial uses and the difficulties of monitoring carbon dioxide transport after injection. In many parts of the world, opponents tap into a strong cultural preference for leaving the oceans alone. *—R.H.S.*

About two thirds of the 1,000 billion barrels of oil the world has produced to date has come from these giant oil fields, so the industry already has a good deal of experience with the scale of the operations needed for carbon storage.

Many of the first sequestration sites will be those that are established because they can turn a profit. Among these are old oil fields into which carbon dioxide can be injected to boost the production of crude. This so-called enhanced oil recovery process takes advantage of the fact that pressurized CO_2 is chemically and physically suited to displacing hard-to-get oil left behind in the pores of the geologic strata after the first stages of production. In this process, compressors drive CO_2 into the oil remaining in the deposits, where chemical reactions result in modified crude oil that moves more easily through the porous rock toward production wells. In particular, CO_2 lowers crude oil's interfacial tension—a form of surface tension that determines the amount of friction between the oil and rock. Thus, carbon dioxide injects new life into old fields.

In response to British government encouragement of carbon dioxide capture and storage efforts, oil companies are proposing novel capture projects at natural gas power plants that are coupled with enhanced oil recovery ventures at fields underneath the North Sea. In the U.S., operators of these kinds of fields can make money today while paying about $10 to $20 per ton for carbon dioxide delivered to the well. If oil prices continue to rise, however, the value of injected CO_2 will probably go up because its use enables the production of a more valuable commodity. This market development could lead to a dramatic expansion of carbon dioxide capture projects.

Carbon sequestration in oil and gas fields will most likely proceed side by side with storage in ordinary brine formations, because the latter structures are far more common. Geologists expect to find enough natural storage capacity to accommodate much of the carbon dioxide that could be captured from fossil fuels burned in the 21st century.

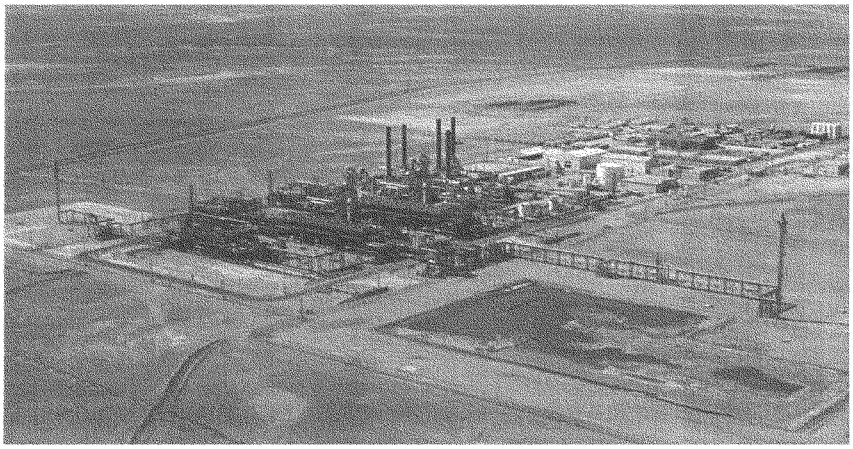
Storage Risks

TWO CLASSES of risk must be addressed for every candidate storage reservoir: gradual and sudden leakage. Gradual release of carbon dioxide merely returns some of the greenhouse gas to the air. Rapid escape of large amounts, in contrast, could have worse consequences than not storing it at all. For a storage operation to earn a license, regulators will have to be satisfied that gradual leakage can occur only at a very slow rate and that sudden leakage is extremely unlikely.

Although carbon dioxide is usually harmless, a large, rapid release of the gas is worrisome because high concentrations can kill. Planners are well aware of the terrible natural disaster that occurred in 1986 at Lake Nyos in Cameroon: carbon dioxide of volcanic origin slowly seeped into the bottom of the lake, which sits in a crater. One night an abrupt overturning of the lake bed let loose between 100,000 and 300,000 tons of CO_2 in a few hours. The gas, which is heavier than air, flowed down through two valleys, asphyxiating 1,700 nearby villagers and thousands of cattle. Scientists are studying this tragedy to ensure that no similar man-made event will ever take place. Regulators of storage permits will want assurance that leaks cannot migrate to belowground confined spaces that are vulnerable to sudden release.

Gradual leaks may pose little danger to life, but they could still defeat the climate goals of sequestration. Therefore, researchers are examining the conditions likely to result in slow seepage. Carbon dioxide, which is buoyant in brine, will rise until it hits an impermeable geologic layer (caprock) and can ascend no farther.

Carbon dioxide in a porous formation is like hundreds of helium balloons, and the solid caprock above is like a circus tent. A balloon may escape if the tent has a tear in it or if its surface is tilted to allow a path for the balloon to move sideways and up. Geologists will have to search for faults in the caprock that could allow escape as well as determine the amount of injection pressure that



UNDERGROUND STORAGE of carbon dioxide is being performed today at the In Salah gas project in the Algerian desert. The raw natural gas produced at this site by BP, Statoil and Sonatrach contains too much CO_2 for commercial use, so the excess is removed by chemical absorbers (*two pairs of stripper towers at center of plant*), compressed and then injected under pressure into a brine formation two kilometers below the surface. Subterranean injection proceeds at a rate that is only about six times less than what would be required at a 1,000-megawatt coal gasification plant fitted for CO_2 capture and storage.

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could fracture it. They will also evaluate the very slow horizontal flow of the carbon dioxide outward from the injection locations. Often the sedimentary formations are huge, thin pancakes. If carbon dioxide is injected near the middle of a pancake with a slight tilt, it may not reach the edge for tens of thousands of years. By then, researchers believe, most of the gas will have dissolved in the brine or have been trapped in the pores.

Even if the geology is favorable, using storage formations where there are old wells may be problematic. More than a million wells have been drilled in Texas, for example, and many of them were filled with cement and abandoned. Engineers are worried that CO_2-laden brine, which is acidic, could find its way from an injection well to an abandoned well and thereupon corrode the cement plug and leak to the surface. To find out, some researchers are now exposing cement to brine in the laboratory and sampling old cements from wells. This kind of failure is less likely in carbonate formations than in sandstone ones; the former reduce the destructive potency of the brine.

The world's governments must soon decide how long storage should be maintained. Environmental ethics and traditional economics give different answers. Following a strict environmental ethic that seeks to minimize the impact of today's activities on future generations, authorities might, for instance, refuse to certify a storage project estimated to retain carbon dioxide for only 200 years. Guided instead by traditional economics, they might approve the same project on the grounds that two centuries from now a smarter world will have invented superior carbon disposal technology.

The next few years will be critical for the development of carbon dioxide capture-and-storage methods, as policies evolve that help to make CO_2-emission reduction profitable and as licensing of storage sites gets under way. In conjunction with significant investments in improved energy efficiency, renewable energy sources and, possibly, nuclear energy, commitments to capture and storage can reduce the risks of global warming. ■

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Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies

S. Pacala[1]* and R. Socolow[2]*

Humanity already possesses the fundamental scientific, technical, and industrial know-how to solve the carbon and climate problem for the next half-century. A portfolio of technologies now exists to meet the world's energy needs over the next 50 years and limit atmospheric CO_2 to a trajectory that avoids a doubling of the preindustrial concentration. Every element in this portfolio has passed beyond the laboratory bench and demonstration project; many are already implemented somewhere at full industrial scale. Although no element is a credible candidate for doing the entire job (or even half the job) by itself, the portfolio as a whole is large enough that not every element has to be used.

The debate in the current literature about stabilizing atmospheric CO_2 at less than a doubling of the preindustrial concentration has led to needless confusion about current options for mitigation. On one side, the Intergovernmental Panel on Climate Change (IPCC) has claimed that "technologies that exist in operation or pilot stage today" are sufficient to follow a less-than-doubling trajectory "over the next hundred years or more" [(*1*), p. 8]. On the other side, a recent review in *Science* asserts that the IPCC claim demonstrates "misperceptions of technological readiness" and calls for "revolutionary changes" in mitigation technology, such as fusion, space-based solar electricity, and artificial photosynthesis (*2*). We agree that fundamental research is vital to develop the revolutionary mitigation strategies needed in the second half of this century and beyond. But it is important not to become beguiled by the possibility of revolutionary technology. Humanity can solve the carbon and climate problem in the first half of this century simply by scaling up what we already know how to do.

What Do We Mean by "Solving the Carbon and Climate Problem for the Next Half-Century"?

Proposals to limit atmospheric CO_2 to a concentration that would prevent most damaging climate change have focused on a goal of 500 ± 50 parts per million (ppm), or less than double the preindustrial concentration of 280 ppm (*3*–*7*). The current concentration is ~375 ppm. The CO_2 emissions reductions necessary to achieve any such target depend on the emissions judged likely to occur in the absence of a focus on carbon [called a business-as-usual (BAU) trajectory], the quantitative details of the stabilization target, and the future behavior of natural sinks for atmospheric CO_2 (i.e., the oceans and terrestrial biosphere). We focus exclusively on CO_2, because it is the dominant anthropogenic greenhouse gas; industrial-scale mitigation options also exist for subordinate gases, such as methane and N_2O.

Very roughly, stabilization at 500 ppm requires that emissions be held near the present level of 7 billion tons of carbon per year (GtC/year) for the next 50 years, even though they are currently on course to more than double (Fig. 1A). The next 50 years is a sensible horizon from several perspectives. It is the length of a career, the lifetime of a power plant, and an interval for which the technology is close enough to envision. The calculations behind Fig. 1A are explained in Section 1 of the supporting online material (SOM) text. The BAU and stabilization emissions in Fig. 1A are near the center of the cloud of variation in the large published literature (*8*).

The Stabilization Triangle

We idealize the 50-year emissions reductions as a perfect triangle in Fig. 1B. Stabilization is represented by a "flat" trajectory of fossil fuel emissions at 7 GtC/year, and BAU is represented by a straight-line "ramp" trajectory rising to 14 GtC/year in 2054. The "stabilization triangle," located between the flat trajectory and BAU, removes exactly one-third of BAU emissions.

To keep the focus on technologies that have the potential to produce a material difference by 2054, we divide the stabilization triangle into seven equal "wedges." A wedge represents an activity that reduces emissions to the atmosphere that starts at zero today and increases linearly until it accounts for 1 GtC/year of reduced carbon emissions in 50 years. It thus represents a cumulative total of 25 GtC of reduced emissions over 50 years. In this paper, to "solve the carbon and climate problem over the next half-century" means to deploy the technologies and/or lifestyle changes necessary to fill all seven wedges of the stabilization triangle.

Stabilization at any level requires that net emissions do not simply remain constant, but eventually drop to zero. For example, in one simple model (*9*) that begins with the stabilization triangle but looks beyond 2054, 500-ppm stabilization is achieved by 50 years of flat emissions, followed by a linear decline of about two-thirds in the following 50 years, and a very slow decline thereafter that matches the declining ocean sink. To develop the revolutionary technologies required for such large emissions reductions in the second half of the century, enhanced research and development would have to begin immediately.

Policies designed to stabilize at 500 ppm would inevitably be renegotiated periodically to take into account the results of research and development, experience with specific wedges, and revised estimates of the size of the stabilization triangle. But not filling the stabilization triangle will put 500-ppm stabilization out of reach. In that same simple model (*9*), 50 years of BAU emissions followed by 50 years of a flat trajectory at 14 GtC/year leads to more than a tripling of the preindustrial concentration.

It is important to understand that each of the seven wedges represents an effort beyond what would occur under BAU. Our BAU simply continues the 1.5% annual carbon emissions growth of the past 30 years. This historic trend in emissions has been accompanied by 2% growth in primary energy consumption and 3% growth in gross world product (GWP) (Section 1 of SOM text). If carbon emissions were to grow 2% per year, then ~10 wedges would be needed instead of 7, and if carbon emissions were to grow at 3% per year, then ~18 wedges would be required (Section 1 of SOM text). Thus, a continuation of the historical rate of decarbonization of the fuel mix prevents the need for three additional wedges, and ongoing improvements in energy efficiency prevent the need for eight additional wedges. Most readers will reject at least one of the wedges listed here, believing that the corresponding deployment is certain to occur in BAU, but readers will disagree about which to reject on such grounds. On the other hand, our list of mitigation options is not exhaustive.

[1]Department of Ecology and Evolutionary Biology, [2]Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544, USA.

*To whom correspondence should be addressed. E-mail: pacala@princeton.edu (S.P.); socolow@princeton.edu (R.S.)

What Current Options Could Be Scaled Up to Produce at Least One Wedge?

Wedges can be achieved from energy efficiency, from the decarbonization of the supply of electricity and fuels (by means of fuel shifting, carbon capture and storage, nuclear energy, and renewable energy), and from biological storage in forests and agricultural soils. Below, we discuss 15 different examples of options that are already deployed at an industrial scale and that could be scaled up further to produce at least one wedge (summarized in Table 1). Although several options could be scaled up to two or more wedges, we doubt that any could fill the stabilization triangle, or even half of it, alone.

Because the same BAU carbon emissions cannot be displaced twice, achieving one wedge often interacts with achieving another. The more the electricity system becomes decarbonized, for example, the less the available savings from greater efficiency of electricity use, and vice versa. Interactions among wedges are discussed in the SOM text. Also, our focus is not on costs. In general, the achievement of a wedge will require some price trajectory for carbon, the details of which depend on many assumptions, including future fuels prices, public acceptance, and cost reductions by means of learning. Instead, our analysis is intended to complement the comprehensive but complex "integrated assessments" (*1*) of carbon mitigation by letting the full-scale examples that are already in the marketplace make a simple case for technological readiness.

Category I: Efficiency and Conservation

Improvements in efficiency and conservation probably offer the greatest potential to provide wedges. For example, in 2002, the United States announced the goal of decreasing its carbon intensity (carbon emissions per unit GDP) by 18% over the next decade, a decrease of 1.96% per year. An entire wedge would be created if the United States were to reset its carbon intensity goal to a decrease of 2.11% per year and extend it to 50 years, and if every country were to follow suit by adding the same 0.15% per year increment to its own carbon intensity goal. However, efficiency and conservation options are less tangible than those from the other categories. Improvements in energy efficiency will come from literally hundreds of innovations that range from new catalysts and chemical processes, to more efficient lighting and insulation for buildings, to the growth of the service economy and telecommuting. Here, we provide four of many possible comparisons of greater and less efficiency in 2054. (See references and details in Section 2 of the SOM text.)

Option 1: Improved fuel economy. Suppose that in 2054, 2 billion cars (roughly four times as many as today) average 10,000 miles per year (as they do today). One wedge would be achieved if, instead of averaging 30 miles per gallon (mpg) on conventional fuel, cars in 2054 averaged 60 mpg, with fuel type and distance traveled unchanged.

Option 2: Reduced reliance on cars. A wedge would also be achieved if the average fuel economy of the 2 billion 2054 cars were 30 mpg, but the annual distance traveled were 5000 miles instead of 10,000 miles.

Option 3: More efficient buildings. According to a 1996 study by the IPCC, a wedge is the difference between pursuing and not pursuing "known and established approaches" to energy-efficient space heating and cooling, water heating, lighting, and refrigeration in residential and commercial buildings. These approaches reduce mid-century emissions from buildings by about one-fourth. About half of potential savings are in the buildings in developing countries (*1*).

Option 4: Improved power plant efficiency. In 2000, coal power plants, operating on average at 32% efficiency, produced about one-fourth of all carbon emissions: 1.7 GtC/year out of 6.2 GtC/year. A wedge would be created if twice today's quantity of coal-based electricity in 2054 were produced at 60% instead of 40% efficiency.

Category II: Decarbonization of Electricity and Fuels

(See references and details in Section 3 of the SOM text.)

Option 5: Substituting natural gas for coal. Carbon emissions per unit of electricity are about half as large from natural gas power plants as from coal plants. Assume that the capacity factor of the average baseload coal plant in 2054 has increased to 90% and that its efficiency has improved to 50%. Because 700 GW of such plants emit carbon at a rate of 1 GtC/year, a wedge would be achieved by displacing 1400 GW of baseload coal with baseload gas by 2054. The power shifted to gas for this wedge is four times as large as the total current gas-based power.

Option 6: Storage of carbon captured in power plants. Carbon capture and storage (CCS) technology prevents about 90% of the fossil carbon from reaching the atmosphere, so a wedge would be provided by the installation of CCS at 800 GW of baseload coal plants by 2054 or 1600 GW of baseload natural gas plants. The most likely approach

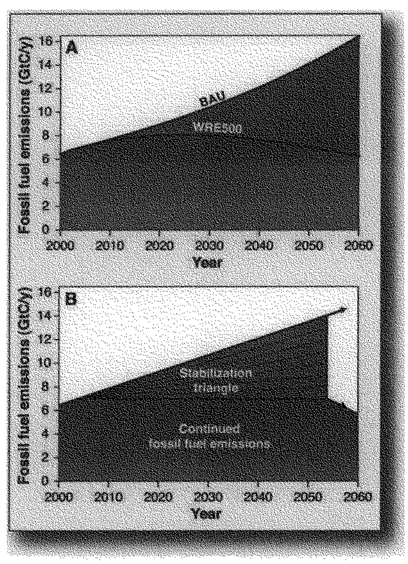

Fig. 1. **(A)** The top curve is a representative BAU emissions path for global carbon emissions as CO_2 from fossil fuel combustion and cement manufacture: 1.5% per year growth starting from 7.0 GtC/year in 2004. The bottom curve is a CO_2 emissions path consistent with atmospheric CO_2 stabilization at 500 ppm by 2125 akin to the Wigley, Richels, and Edmonds (WRE) family of stabilization curves described in (*11*), modified as described in Section 1 of the SOM text. The bottom curve assumes an ocean uptake calculated with the High-Latitude Exchange Interior Diffusion Advection (HILDA) ocean model (*12*) and a constant net land uptake of 0.5 GtC/year (Section 1 of the SOM text). The area between the two curves represents the avoided carbon emissions required for stabilization. **(B)** Idealization of (A): A stabilization triangle of avoided emissions (green) and allowed emissions (blue). The allowed emissions are fixed at 7 GtC/year beginning in 2004. The stabilization triangle is divided into seven wedges, each of which reaches 1 GtC/year in 2054. With linear growth, the total avoided emissions per wedge is 25 GtC, and the total area of the stabilization triangle is 175 GtC. The arrow at the bottom right of the stabilization triangle points downward to emphasize that fossil fuel emissions must decline substantially below 7 GtC/year after 2054 to achieve stabilization at 500 ppm.

has two steps: (i) precombustion capture of CO_2, in which hydrogen and CO_2 are produced and the hydrogen is then burned to produce electricity, followed by (ii) geologic storage, in which the waste CO_2 is injected into subsurface geologic reservoirs. Hydrogen production from fossil fuels is already a very large business. Globally, hydrogen plants consume about 2% of primary energy and emit 0.1 GtC/year of CO_2. The capture part of a wedge of CCS electricity would thus require only a tenfold expansion of plants resembling today's large hydrogen plants over the next 50 years.

The scale of the storage part of this wedge can be expressed as a multiple of the scale of current enhanced oil recovery, or current seasonal storage of natural gas, or the first geological storage demonstration project. Today, about 0.01 GtC/year of carbon as CO_2 is injected into geologic reservoirs to spur enhanced oil recovery, so a wedge of geologic storage requires that CO_2 injection be scaled up by a factor of 100 over the next 50 years. To smooth out seasonal demand in the United States, the natural gas industry annually draws roughly 4000 billion standard cubic feet (Bscf) into and out of geologic storage, and a carbon flow of 1 GtC/year (whether as methane or CO_2) is a flow of 69,000 Bscf/year (190 Bscf per day), so a wedge would be a flow to storage 15 and 20 times as large as the current flow. Norway's Sleipner project in the North Sea strips CO_2 from natural gas offshore and reinjects 0.3 million tons of carbon a year (MtC/year) into a non-fossil-fuel–bearing formation, so a wedge would be 3500 Sleipner-sized projects (or fewer, larger projects) over the next 50 years.

A worldwide effort is under way to assess the capacity available for multicentury storage and to assess risks of leaks large enough to endanger human or environmental health.

Option 7: Storage of carbon captured in hydrogen plants. The hydrogen resulting from precombustion capture of CO_2 can be sent offsite to displace the consumption of conventional fuels rather than being consumed onsite to produce electricity. The capture part of a wedge

Table 1. Potential wedges: Strategies available to reduce the carbon emission rate in 2054 by 1 GtC/year or to reduce carbon emissions from 2004 to 2054 by 25 GtC.

Option	Effort by 2054 for one wedge, relative to 14 GtC/year BAU	Comments, issues
	Energy efficiency and conservation	
Economy-wide carbon-intensity reduction (emissions/$GDP)	Increase reduction by additional 0.15% per year (e.g., increase U.S. goal of 1.96% reduction per year to 2.11% per year)	Can be tuned by carbon policy
1. Efficient vehicles	Increase fuel economy for 2 billion cars from 30 to 60 mpg	Car size, power
2. Reduced use of vehicles	Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5000 miles per year	Urban design, mass transit, telecommuting
3. Efficient buildings	Cut carbon emissions by one-fourth in buildings and appliances projected for 2054	Weak incentives
4. Efficient baseload coal plants	Produce twice today's coal power output at 60% instead of 40% efficiency (compared with 32% today)	Advanced high-temperature materials
	Fuel shift	
5. Gas baseload power for coal baseload power	Replace 1400 GW 50%-efficient coal plants with gas plants (four times the current production of gas-based power)	Competing demands for natural gas
	CO_2 Capture and Storage (CCS)	
6. Capture CO_2 at baseload power plant	Introduce CCS at 800 GW coal or 1600 GW natural gas (compared with 1060 GW coal in 1999)	Technology already in use for H_2 production
7. Capture CO_2 at H_2 plant	Introduce CCS at plants producing 250 MtH_2/year from coal or 500 MtH_2/year from natural gas (compared with 40 MtH_2/year today from all sources)	H_2 safety, infrastructure
8. Capture CO_2 at coal-to-synfuels plant	Introduce CCS at synfuels plants producing 30 million barrels a day from coal (200 times Sasol), if half of feedstock carbon is available for capture	Increased CO_2 emissions, if synfuels are produced without CCS
Geological storage	Create 3500 Sleipners	Durable storage, successful permitting
	Nuclear fission	
9. Nuclear power for coal power	Add 700 GW (twice the current capacity)	Nuclear proliferation, terrorism, waste
	Renewable electricity and fuels	
10. Wind power for coal power	Add 2 million 1-MW-peak windmills (50 times the current capacity) "occupying" 30×10^6 ha, on land or offshore	Multiple uses of land because windmills are widely spaced
11. PV power for coal power	Add 2000 GW-peak PV (700 times the current capacity) on 2×10^6 ha	PV production cost
12. Wind H_2 in fuel-cell car for gasoline in hybrid car	Add 4 million 1-MW-peak windmills (100 times the current capacity)	H_2 safety, infrastructure
13. Biomass fuel for fossil fuel	Add 100 times the current Brazil or U.S. ethanol production, with the use of 250×10^6 ha (one-sixth of world cropland)	Biodiversity, competing land use
	Forests and agricultural soils	
14. Reduced deforestation, plus reforestation, afforestation, and new plantations.	Decrease tropical deforestation to zero instead of 0.5 GtC/year, and establish 300 Mha of new tree plantations (twice the current rate)	Land demands of agriculture, benefits to biodiversity from reduced deforestation
15. Conservation tillage	Apply to all cropland (10 times the current usage)	Reversibility, verification

would require the installation of CCS, by 2054, at coal plants producing 250 MtH_2/year, or at natural gas plants producing 500 MtH_2/year. The former is six times the current rate of hydrogen production. The storage part of this option is the same as in Option 6.

Option 8: Storage of carbon captured in synfuels plants. Looming over carbon management in 2054 is the possibility of large-scale production of synthetic fuel (synfuel) from coal. Carbon emissions, however, need not exceed those associated with fuel refined from crude oil if synfuels production is accompanied by CCS. Assuming that half of the carbon entering a 2054 synfuels plant leaves as fuel but the other half can be captured as CO_2, the capture part of a wedge in 2054 would be the difference between capturing and venting the CO_2 from coal synfuels plants producing 30 million barrels of synfuels per day. (The flow of carbon in 24 million barrels per day of crude oil is 1 GtC/year; we assume the same value for the flow in synfuels and allow for imperfect capture.) Currently, the Sasol plants in South Africa, the world's largest synfuels facility, produce 165,000 barrels per day from coal. Thus, a wedge requires 200 Sasol-scale coal-to-synfuels facilities with CCS in 2054. The storage part of this option is again the same as in Option 6.

Option 9: Nuclear fission. On the basis of the Option 5 estimates, a wedge of nuclear electricity would displace 700 GW of efficient baseload coal capacity in 2054. This would require 700 GW of nuclear power with the same 90% capacity factor assumed for the coal plants, or about twice the nuclear capacity currently deployed. The global pace of nuclear power plant construction from 1975 to 1990 would yield a wedge, if it continued for 50 years (*10*). Substantial expansion in nuclear power requires restoration of public confidence in safety and waste disposal, and international security agreements governing uranium enrichment and plutonium recycling.

Option 10: Wind electricity. We account for the intermittent output of windmills by equating 3 GW of nominal peak capacity (3 GW_p) with 1 GW of baseload capacity. Thus, a wedge of wind electricity would require the deployment of 2000 GW_p that displaces coal electricity in 2054 (or 2 million 1-MW_p wind turbines). Installed wind capacity has been growing at about 30% per year for more than 10 years and is currently about 40 GW_p. A wedge of wind electricity would thus require 50 times today's deployment. The wind turbines would "occupy" about 30 million hectares (about 3% of the area of the United States), some on land and some offshore. Because windmills are widely spaced, land with windmills can have multiple uses.

Option 11: Photovoltaic electricity. Similar to a wedge of wind electricity, a wedge from photovoltaic (PV) electricity would require 2000 GW_p of installed capacity that displaces coal electricity in 2054. Although only 3 GW_p of PV are currently installed, PV electricity has been growing at a rate of 30% per year. A wedge of PV electricity would require 700 times today's deployment, and about 2 million hectares of land in 2054, or 2 to 3 m^2 per person.

Option 12: Renewable hydrogen. Renewable electricity can produce carbon-free hydrogen for vehicle fuel by the electrolysis of water. The hydrogen produced by 4 million 1-MW_p windmills in 2054, if used in high-efficiency fuel-cell cars, would achieve a wedge of displaced gasoline or diesel fuel. Compared with Option 10, this is twice as many 1-MW_p windmills as would be required to produce the electricity that achieves a wedge by displacing high-efficiency baseload coal. This interesting factor-of-two carbon-saving advantage of wind-electricity over wind-hydrogen is still larger if the coal plant is less efficient or the fuel-cell vehicle is less spectacular.

Option 13: Biofuels. Fossil-carbon fuels can also be replaced by biofuels such as ethanol. A wedge of biofuel would be achieved by the production of about 34 million barrels per day of ethanol in 2054 that could displace gasoline, provided the ethanol itself were fossil-carbon free. This ethanol production rate would be about 50 times larger than today's global production rate, almost all of which can be attributed to Brazilian sugarcane and United States corn. An ethanol wedge would require 250 million hectares committed to high-yield (15 dry tons/hectare) plantations by 2054, an area equal to about one-sixth of the world's cropland. An even larger area would be required to the extent that the biofuels require fossil-carbon inputs. Because land suitable for annually harvested biofuels crops is also often suitable for conventional agriculture, biofuels production could compromise agricultural productivity.

Category III: Natural Sinks

Although the literature on biological sequestration includes a diverse array of options and some very large estimates of the global potential, here we restrict our attention to the pair of options that are already implemented at large scale and that could be scaled up to a wedge or more without a lot of new research. (See Section 4 of the SOM text for references and details.)

Option 14: Forest management. Conservative assumptions lead to the conclusion that at least one wedge would be available from reduced tropical deforestation and the management of temperate and tropical forests. At least one half-wedge would be created if the current rate of clear-cutting of primary tropical forest were reduced to zero over 50 years instead of being halved. A second half-wedge would be created by reforesting or afforesting approximately 250 million hectares in the tropics or 400 million hectares in the temperate zone (current areas of tropical and temperate forests are 1500 and 700 million hectares, respectively). A third half-wedge would be created by establishing approximately 300 million hectares of plantations on nonforested land.

Option 15: Agricultural soils management. When forest or natural grassland is converted to cropland, up to one-half of the soil carbon is lost, primarily because annual tilling increases the rate of decomposition by aerating undecomposed organic matter. About 55 GtC, or two wedges' worth, has been lost historically in this way. Practices such as conservation tillage (e.g., seeds are drilled into the soil without plowing), the use of cover crops, and erosion control can reverse the losses. By 1995, conservation tillage practices had been adopted on 110 million hectares of the world's 1600 million hectares of cropland. If conservation tillage could be extended to all cropland, accompanied by a verification program that enforces the adoption of soil conservation practices that actually work as advertised, a good case could be made for the IPCC's estimate that an additional half to one wedge could be stored in this way.

Conclusions

In confronting the problem of greenhouse warming, the choice today is between action and delay. Here, we presented a part of the case for action by identifying a set of options that have the capacity to provide the seven stabilization wedges and solve the climate problem for the next half-century. None of the options is a pipe dream or an unproven idea. Today, one can buy electricity from a wind turbine, PV array, gas turbine, or nuclear power plant. One can buy hydrogen produced with the chemistry of carbon capture, biofuel to power one's car, and hundreds of devices that improve energy efficiency. One can visit tropical forests where clear-cutting has ceased, farms practicing conservation tillage, and facilities that inject carbon into geologic reservoirs. Every one of these options is already implemented at an industrial scale and could be scaled up further over 50 years to provide at least one wedge.

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13. The authors thank J. Greenblatt, R. Hotinski, and R. Williams at Princeton; K. Keller at Penn State; and C. Mottershead at BP. This paper is a product of the Carbon Mitigation Initiative (CMI) of the Princeton Environmental Institute at Princeton University. CMI (www.princeton.edu/~cmi) is sponsored by BP and Ford.

Supporting Online Material
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SOM Text
Figs. S1 and S2
Tables S1 to S5
References

Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies

S. Pacala and R. Socolow

(Science V305, 5686, pp 968-972)

SUPPORTING ON-LINE MATERIAL

Table of Contents

SUPPORTING ON-LINE MATERIAL

SECTION 1. EMISSIONS TRAJECTORIES FOR BUSINESS AS USUAL AND STABILIZATION BELOW DOUBLING

The Stabilization Triangle is bounded on two sides by a "ramp" scenario and a "flat" scenario, each departing from the present world. The ramp scenario is intended to be an abstraction of carbon emissions for Business As Usual (BAU), and the flat scenario is intended to be an abstraction of stabilization below doubling. In this section, we discuss each in turn.

Carbon Emissions for Business As Usual and the "Ramp" Scenario

Our Business As Usual (BAU) carbon emissions (or, equivalently, CO_2 emissions) simply continue to grow for the next fifty years with the 1.5%/y average growth rate of the past three decades. The corresponding emissions path, shown in Fig. S1(A), starts at 7.0 GtC/y in 2004 and rises at 1.53%/y to 15.0 GtC/y in 2054. A carbon emissions trajectory that increases linearly with the same cumulative emissions (525 GtC) rises to 14.0 GtC/y in 2054. This linear-increase scenario, or "ramp" scenario, conceptually easier to work with, is our BAU emissions scenario in all subsequent sections of the Supporting On-Line Material.

Looking backward, according to the International Energy Agency (IEA), carbon emissions rose 51% from 1973 to 2001 or 1.5%/y (S1). According to the Energy Information Agency of the U.S. Department of Energy (EIA), emissions growth averaged 1.6%/y from 1970-2001, 1.3%/y from 1980-2001, and 1.0%/y from 1990-2001 (1.5%/y if the former Soviet Union is omitted) (S2). The IPCC (S3) reports that emissions averaged 5.4 GtC/y in the 1980s and 6.3 GtC/y in the 1990s, which works out to an average increase of 1.5%/y. Finally, the BP statistical review (S4) reports 1.0%/y growth during the 1990s, but 1.6%/y if China and the former Soviet Union are omitted.

A growth in carbon emissions of 1.5%/y is bracketed by the emissions forecasts of the International Energy Agency and U.S. Department of Energy, and it is similar to the mean and median of the 40 IPCC SRES future emissions scenarios over the next fifty years (S1-S5). The IEA predicts 1.3%/y growth in carbon emissions through 2030 (S1). The EIA predicts 1.9%/y growth through 2025 (S2). The IPCC (S5) has compiled a set of 40 future emissions scenarios called the SRES scenarios. The mean and median 2054 emissions for the SRES scenarios are both approximately 15 GtC/y, with half the scenarios between 12 and 18 GtC/y. With 2004 emissions in these scenarios at approximately 7 GtC/y, the average 50-year growth rate for carbon emissions works out to 1.5%/y for the mean and median of the scenarios, and 1.1%/y - 1.9%/y for the range covered by the central 20 scenarios.

Assuming a carbon emissions growth of 1.5%/y over the period 2004-2054, cumulative emissions are 525 GtC/y for the 50 years. For growth rates of 1.2%/y and 1.8%/y, 2004-2054 cumulative emissions are smaller and larger by about 50 GtC, or approximately 2 wedges.

Primary Energy Consumption and Gross World Product

The approach taken in this paper's analysis is to specify as little as possible of BAU and to concentrate on the activities ("wedges") required to alter emissions dramatically, whatever the details of a full-blown BAU. Specifically, we do not need to specify the BAU growth rates of primary energy or gross world product. The many self-consistent, highly disaggregated analyses of BAU primary energy and BAU gross world product are nonetheless useful, because they provide insight into the level of conservation and energy decarbonization likely to be undertaken over the next 50 years, even in the absence of a specific concern for carbon emissions.

The EIA, IEA and BP report the following historical annual growth rates of primary energy consumption:

> EIA (S2): 1.9% for 1970-2001, with 3.2% during the 70's, 2.0% during the 80's and 1.4% during the 90's.
>
> IEA (S1): 1.9% for 1973-2001.
>
> BP (S4): 1.5% for 1977-2002, with 2.0% during the 80's and 1.2% during the 90's.

The EIA predicts 1.9%/y growth in primary energy through 2020 (S2). This is the same as the predicted growth rate in carbon emissions. Thus, the EIA is predicting a departure from the historic decarbonization of the energy system that, in recent years, has resulted from larger market shares for natural gas and nuclear power. For the past 100 years, each decade has seen a fall in the carbon intensity of the energy system, with annual emissions growth, on average, 0.3-0.5% slower than annual energy growth (S5).

The IEA predicts 1.8%/y growth in primary energy through 2020. This prediction is from their 2002 assessment; the most recent IEA handbook predicts 1.6%/y growth in the primary energy through 2030 (S1). The median annual growth rate of primary energy from the 40 SRES scenarios is 1.8% from 2004 to 2054, while the 25% and 75% bounds are 1.2% and 2.0% (S5).

Gross World Product grew at 3.1%/y from 1970 to 2001. The EIA predicts 3.1%/y growth through 2025 (S2), and the IPCC predicts approximately 3% /y growth for the next half century (S5). The SRES are divided into four "families" labeled A1, A2, B1 and B2. From 1990 to 2050, the ranges of predicted annual percent growth rates for the scenarios in each family are, respectively: 2.9-3.7, 1.7-2.3, 2.9-3.5, and 2.1-2.9.

Carbon Emissions for Stabilization Below Doubling and the "Flat" Scenario.

The "flat" emissions scenario, constant emissions at 7 GtC/y for 50 years, is presented for simplification of discussion in the body of the paper as a representative emissions scenario for stabilization below doubling of the pre-industrial concentration of 280 ppm. Here, we relate the "flat" trajectory to traditional analysis of the connection of emissions and concentrations. This analysis requires, first of all, models of the future net land sink and future ocean sink and an understanding of current uncertainty about these sinks.

The Net Land Sink

Terrestrial ecosystems were a net sink of 0.2±0.7 GtC/y during the 1980's and 1.3±0.8 GtC/y during the 1990's (S6, as modified by S7), or 0.7±1.1 GtC/y over the combined period[1]. Our BAU scenario for land use is simply that the net terrestrial sink will continue at 0.5 GtC/y for the next fifty years, or at approximately the level of the last 20 years. The terrestrial biosphere thus supplies one wedge of reduced net emissions to the atmosphere in the BAU scenario.

Estimates of the net terrestrial flux are best constrained by the more certain estimates of fossil emissions, atmospheric inventory and oceanic uptake (fossil emissions minus atmospheric increase minus oceanic uptake). The sink is partially the result of land use change in the temperate zone that causes a sink of ~1.5 GtC/y, roughly half of which is due to forest regrowth and management (S8, S9, S10). This sink is offset by a tropical source, due to deforestation.

The size of the deforestation sink is controversial. Houghton (S10 and references therein) uses FAO data and a model of the effect of land use on terrestrial carbon fluxes to estimate a tropical source of 2.0±0.8 GtC/y in the 1980's and 2.2±0.8 GtC/y in the 1990's, or 2.1±1.1 GtC/y over the combined period. However, Houghton's model does not reproduce the relatively well-constrained values for U.S. forests from the U.S. Forest Service Inventory (S8, S10). Two recent satellite surveys put the tropical source at 0.9±0.5 GtC/y and 1.3 GtC/y in the 1990's (S11, S12, as modified by Houghton in S10).

If Houghton's estimate of a tropical source of 2.1 GtC/y were correct, then there would be a "missing" carbon sink of approximately 1.3 GtC/y. (The tropical source of 2.1 GtC/y minus the temperate sink of 1.5 GtC/y gives a net *source* of 0.6 GtC/y, whereas the average net terrestrial flux in the 1980s and 1990s was actually a *sink* of 0.7 GtC/y.) A missing sink this large is usually explained, as in the models of the IPCC Third Assessment, by CO_2 fertilization of the terrestrial biosphere (S6). In contrast, if the S11 satellite survey is correct and also applies to the 1980s, then temperate land use minus tropical deforestation yields a net sink of 0.4 GtC/y, which is within 0.3 GtC/y of the actual net terrestrial flux over the last 20 years. Thus, if the S12 estimate is correct, then both the missing sink and the effect of CO_2 fertilization must be small. The difference between the tropical deforestation estimates in (S10) and (S12) is important for our purposes here, because it implies two different futures for the terrestrial sink. A sink caused by CO_2 fertilization will increase in the future as CO_2 builds up in the atmosphere, whereas a sink caused solely by recovery from past land use will diminish as the affected ecosystems approach full recovery (S13).

How big is this difference? The six global vegetation models included in the carbon cycle chapter of the IPCC Third Assessment (S6) provide a guide. These models were run with an emissions scenario very similar to our BAU scenario of 1.5% fossil emissions growth, and they included climate-induced carbon cycle feedbacks. Their mean prediction was for a sink of 1.7 GtC/y in 2000 that rose to 4.5 GtC/y in 2050. Using the same proportional change over fifty years , the CO_2 fertilization sink of 1.3 GtC/y implied by Houghton's deforestation estimate would grow to 3.4 GtC/y by 2054 and produce a total of ~5 wedges' worth of carbon sink. In contrast, we can expect the temperate land-use sink to decay over time with a time constant of roughly 100 years (S13). Thus, the ~1.5 GtC/y temperate land use sink should diminish to ~0.9 in fifty years, producing a cumulative sink of 58 GtC over the period, or roughly 2 wedges.

[1] Ranges preceded by ± are plus or minus one standard deviation.

Putting all this together, Houghton's large tropical deforestation estimate implies a total terrestrial sink of ~7 wedges over the next 50 years, whereas the smaller estimate in (S12) implies a sink of ~2 wedges. Evidence continues to accumulate that the models of CO_2 fertilization in (S6) drastically overstate the likely benefits of CO_2 fertilization (see for example S14, S15 and the discussion in S10). For this reason, we adopt the conservative course of accepting the estimate of ~1 GtC/y for the current tropical deforestation source, and that the terrestrial sink will provide only 2 wedges' worth of benefits over the next half century.

To complete the BAU scenario for terrestrial ecosystems, we must specify a 50-year future for tropical deforestation. The 40 SRES scenarios (S5) are of some use here, because most predict diminished deforestation. The land use fluxes in the SRES scenarios are normalized at a source of 1 GtC/y in 2000 (tropical deforestation plus temperate sink), and they thus imply a "missing" sink of ~1.7 GtC/y (because the average net terrestrial flux in the period 1980-1999 was a sink of 0.7 GtC/y). The 1 GtC/y net source from land use in the scenarios diminishes to a mean of 0.5 GtC/y in 2054 with a range for the central 50% of scenarios of 0.0-0.9 GtC/y, and a full range for all 40 scenarios of –0.7 GtC/y to +1.2 GtC/y. Thus, nearly all predict a decrease in tropical deforestation.

Together, the decreased tropical deforestation predicted by the SRES scenarios and our prediction of a decreasing temperate land-use sink and no CO_2 fertilization, provide a simple rationale for our BAU scenario. Again, we propose a BAU land sink that for 50 years is constant at 0.5 GtC/y, approximately the average net terrestrial flux in the 1980's and 1990's of 0.7 GtC/y. Our BAU land sink thus provides one wedge. Note that this is consistent with the philosophy of simple extrapolation of current trends that was used for fossil emissions, energy and GDP. It is also consistent with a tropical source and a temperate sink that both diminish by ~0.5 GtC/y over 50 years, or with an infinite number of other combinations of trajectories for tropical deforestation, temperate land use and the missing sink that add up to a net sink of one wedge.

At the same time, it is important to keep in mind how uncertain our BAU land use sink is. If the mean of the SRES land use scenarios and the mean of the IPCC Third Assessment terrestrial ecosystem models were correct, then the terrestrial biosphere would supply a net sink totaling almost five wedges. In contrast, if Houghton's estimate were correct for tropical deforestation and were to persist, if the missing sink were suddenly to disappear, and if the temperate land use sink were to decay away as in our BAU scenario, then the terrestrial biosphere would be a net source of two wedges.

The Ocean Sink

Carbon uptake by the oceans is much better constrained by observations than uptake by the land. From 1980-2000, the oceans were a net sink of 1.9 ± 0.7 GtC/y (S16). Predictions of ocean models also exhibit relatively high consistency. For example, (S6) used seven ocean models to predict carbon uptake under fossil fuel emissions very similar to those in our BAU scenario of 1.5% growth, and observed a range of ± 0.5 GtC/y in 2000 and ± 0.8 GtC/y in 2050.

Here, we use the HILDA ocean model to calculate the ocean sink. HILDA, a multi-box ocean model (S17), calibrated with measurements of natural and bomb-produced $^{14}CO_2$, has been shown to predict carbon uptake over time scales of a century or less with the accuracy of a general circulation model (S18). The mean ocean uptake from 1980-1999 calculated using HILDA is 2.4 GtC/y, within the uncertainty of the observations. Following the WRE500 atmospheric concentration scenario (see below), HILDA predicts an ocean uptake of 2.82 GtC/y in 2004, rising to 3.92 GtC/y in 2054, with a cumulative uptake of 180 GtC. Accepting the stated uncertainty in the observations (approximately ±40%) as our estimate for future uncertainty in ocean uptake, we obtain ±72 GtC in 50 years, or ±3 wedges. An additional wedge is at stake in the difference between the 1980-1999 observed uptake of 1.9 GtC/y and HILDA's 2.4 GtC/y calculation (0.5 GtC/y x 50 years), giving an overall uncertainty of approximately 1±3 wedges.

Future changes in ocean CO_2 uptake due to climate change feedbacks are also uncertain. In the first half of the century, they are dominated by reduced CO_2 solubility and increased stratification that result from warming of the surface ocean. Ocean models predict a reduction in cumulative ocean uptake between 1990 and 2050 of 6 to 25% (S3). The HILDA model does not include any climate-driven feedback effects; therefore, based on the estimated range stated above, it could overestimate ocean uptake by between 10 and 45 GtC, or approximately 1±1 wedges.

Assuming these two sources of uncertainty are independent, the ocean sink may be weaker than we have estimated by 2±3 wedges.

Construction of Stabilization Emissions Scenarios

To locate the "flat" emissions scenario of the Stabilization Triangle among traditional emissions scenarios for stabilization below doubling, we consider six stabilization emissions scenarios and their corresponding stabilization concentration trajectories (S19). The six emissions scenarios are shown in Fig. S1(A), and the corresponding concentration trajectories are shown in Fig. S1(B).

We consider three stabilization targets: 450, 500 and 550 ppm. For each target, we construct a pair of concentration trajectories, one leading to a "delayed reduction" scenario and one leading to an "early reduction" scenario. The delayed reduction scenarios have higher emissions in the first decades and lower emissions later, relative to the early reduction scenarios with which they are paired. The increase in effort required by early action in the first fifty years translates into a more permissive emissions schedule later. Such trade-offs must, of course, be analyzed in a full economic framework to assess costs and benefits properly.

Each fossil fuel emissions scenario in Fig. S1(A) is the sum of 1) the rate of increase in atmospheric carbon, 2) the net land sink, and 3) the ocean sink. The rate of increase in atmospheric carbon is the derivative of the corresponding concentration trajectory. The net land sink is assumed to be constant at 0.5 GtC/y. The ocean sink is found from the HILDA model.

The delayed reduction scenarios are similar to the "WRE" scenarios (S20, S21) used in the IPCC Third Assessment (S3), which depart from Business As Usual emissions between 2005 and 2010. But our concentration trajectories have been updated to reflect recent atmospheric CO_2 growth. In addition, the specified atmospheric concentration in 2050 has been lowered by 5 ppm (for the 450 ppm scenario) or 10 ppm (for the 500 and 550 ppm scenarios) in order that future emissions do not exceed those of the Business As Usual scenario.

The early reduction scenarios are similar to the "S" series scenarios used in the IPCC Second Assessment (S22), which departed from historical emissions in 1990. These have been updated to follow historical and Business As Usual emissions through 2004. The 2004-2054 average emissions from these scenarios differ from those which depart from BAU in 1990 by less than 2%.

The "flat" emissions scenario, measured by 2004-2054 cumulative emissions, is bracketed by the 450 ppm and 500 ppm delayed reduction scenarios and also by the 500 ppm and 550 ppm early reduction scenarios.

How different are the six emissions scenarios from one another? We measure these differences by the difference in the size of the corresponding 50-year stabilization triangle. These triangles are bounded by our BAU emissions scenario and the particular stabilization emissions scenario, for 2004-2054. Since a "wedge" is 25 GtC, the size of such a triangle can be expressed alternatively as a number of 25 GtC "wedges." The sizes of the six emissions scenario triangles, in GtC and "wedges," are given in Table S1.

From Table S1, we see that the 500 ppm delayed reduction scenario requires two more wedges than the 550 ppm delayed reduction scenario, but the 500 ppm early reduction scenario requires only one more wedge than the 550 ppm early reduction scenario. This is a reflection of the greater divergence of the delayed emissions scenarios than the early reduction emissions scenarios seen in Fig. S1(A). Furthermore, the early reduction scenarios require 1-3 more wedges, relative to the delayed reduction scenarios, for the same stabilization level.

In the period 2054-2104, the average rate of decline in CO_2 emissions is steeper in all six scenarios, relative to 2004-2054. As Fig. S1(A) shows, the maximum rate of decline in 2054-2104 in the early reduction scenarios is significantly smaller, and occurs later, than in the delayed reduction scenarios.

Eventually, to achieve stabilization of the atmospheric concentration, the rate of emissions falls to a rate equal to the total net uptake rate of CO_2 by the ocean and land, so that there is no further atmospheric build-up. In Table S2, the time when this happens is called the "Stabilization Year." For stabilization below doubling, we see that atmospheric build-up ends in the first half of the 22nd century.

SECTION 2. CONSERVATION AND EFFICIENCY

The Carbon Intensity of the Economy

Economy-wide (societal, macroeconomic) energy efficiency is measured by the energy intensity of the economy – the ratio of global primary energy production to gross global economic product. Today's roughly 350 EJ/y throughput of fossil energy and 35 trillion dollar per year global economy result in a global *fossil energy intensity* of approximately 10 MJ (fossil)/$. The full "energy intensity" includes non-fossil energy, approximately 15 to 25% of the total; the amount of non-fossil energy cited varies from reference to reference, depending on whether non-commercial energy (firewood, charcoal, dung) is included and depending on conventions about hydropower (S23, S24).

From a carbon perspective, the carbon intensity of the economy – the ratio of atmospheric carbon emissions to gross global economic product – is the crucial ratio. The global value today, roughly 7 GtC/y divided by $35T/y, is about 200 gC/$. The economy is decarbonizing at the same time as it is becoming more energy efficient, as discussed in Section 1 of the Supporting On-Line Material.

The Bush administration has chosen to frame the U.S. contribution to mitigating climate change in terms of national carbon efficiency (carbon emissions per unit GNP). Specifically, the goal is to reduce national carbon intensity by 18% over the next decade, or 1.96%/y. Continuing this pace for 50 years would reduce the U.S. carbon intensity by 62.9%. Following a faster pace of decline for 50 years, namely declining 2.11% per year, would reduce U.S. carbon intensity by 19.2% in ten years and 65.6% in 50 years. The U.S. carbon emissions would be reduced an additional one part in 14 from this toughening of the goal by 0.15%/y and staying the course for 50 years. It turns out that toughening *any* such goal by the same increment, 0.15%/y, and staying the course for 50 years, will result in reduction of carbon emissions by one part in 14. Thus, if every country were to toughen whatever target it started with by 0.15% per year, the result would be carbon emissions down by 1/14, which is a wedge (1 GtC/y) relative to a BAU of 14 GtC/y.[2]

An economy-wide focus on carbon intensity helps to remind us that reduced carbon intensity is achieved not only by more efficient devices. An economy decarbonizes when less carbon-intensive sectors grow more rapidly than more carbon-intensive sectors. The faster growth of services than primary materials in advanced industrial societies is an example.

In our BAU emissions scenario, carbon emissions grow 1.5%/y and double in 50 years. If, as well, the economy were to grow at 3%/y, then, in 50 years, the economy would quadruple, and its carbon intensity would fall to half its original value. Some complex combination of structural

[2] If the Bush targets are continued for 50 years, U.S. carbon emissions after 50 years are 37.1% of what they would have been had there been *no* change in carbon intensity. With the tougher target, 0.15%/y more stringent, they are 34.4% of what they would have been had there been no change in carbon intensity, which is almost exactly 13/14 of what they would have been with the more lenient target. (Compare 0.344/0.371 = 0.927, with 13/14 = 0.929.) So, U.S. 2054 carbon emissions with the tougher target would be reduced by one part in 14. The absolute toughening of *any* carbon intensity goal by 0.15%/y will always produce a level of carbon consumption that is down by one part in 14, as long as the original goal is not more than a few percent per year. This is because the fraction which, raised to the 50th power, gives 13/14 is 0.9985; multiplying a number close to 1.00 by 0.9985 will give the same number minus 0.0015.

changes and improved efficiency in specific devices would have brought this about. No one can foresee exactly how and where in the economy improvements in carbon intensity will be achieved, and, therefore, where further improvements are and are not available. The best we can do is to admit for consideration *all* the major opportunities for improved energy efficiency, and to acknowledge that an unknowable subset of these opportunities are wedges.

Wedges from Specific Carbon-Emitting Activities

A complementary perspective on reducing carbon emissions is provided by examining where fossil-fuel carbon enters the atmosphere, as opposed to where it comes out of the ground. Analyses of global emissions from this perspective are very difficult to do, because national data are usually not organized in these categories. One comprehensive review from this perspective is available, performed by Working Group III (Mitigation) of the Intergovernmental Panel on Climate Change (S25). Of a total of 5.5 GtC/y emissions in 1995, this report associates 1.73 GtC/y with buildings (31.5%); 1.21 GtC/y with transport (22.1%); 2.34 GtC/y with industrial uses (42.5%); and 0.22 GtC/y with agricultural uses (3.9%) (S25, Table S3)[3].

Here, instead, we choose five categories, combining industry and agriculture and splitting out two categories to describe carbon emissions associated with energy production, distribution, and conversion.

1. Sites involved in bringing fossil fuels to users, including sites of extraction, distribution, and refining.
2. Electric power plants.
3. Vehicles.
4. Buildings.
5. Direct use of fuel at the factory and farm.

Upstream carbon overheads The first category of sites are the sites where upstream "carbon overheads" are incurred, for *all* energy sources. The carbon overheads of fossil fuels are incurred at sites such as wells and mines; tankers, pipelines, and railroads; refineries; trucks delivering fuel oil and gasoline; and compressors of propane and LPG. The carbon overheads of other energy sources are incurred at sites such as uranium isotope enrichment plants and factories making fertilizer for the fields where biofuel is grown. A portion of this overhead is called "transformation, own use, and losses" in IEA accounts. (S24, p. 410. See also Table S4 in Section 3, Energy Supply, of the Supporting On-Line Material). For the sake of argument, we imagine that in 2054, carbon emissions associated with production, upgrading, refining, and distributing energy are 2 GtC/y under BAU (an overhead rate of 2/12, or 17%). In 2054, oil will be extracted from what we today call non-conventional sources (tarsands, shales), a much larger fraction of gas will be transported by LNG, some coal will be converted to liquid fuels, and as a reflection of greater world trade the average distance between extraction and use of fuel will grow. All of these developments of the energy system will increase carbon overheads. Because our BAU is a world oblivious to carbon concerns, we assume that it does not deploy substantial amounts of carbon capture and storage, which would raise overheads even more.

[3] A different but similar disaggregation among final users, for 2000, from the International Energy Agency's *World Energy Assessment 2002* (S24) is presented in the Supporting On-Line Material, Section 3.

Thus, in our BAU, of the 14 GtC/y in 2054, 2 GtC/y is emitted during production and delivery, and 12 GtC/y is emitted at the points of use (specifically including power plants). Halving this overhead to 1 GtC/y achieves a wedge. Targets of recent attention in this category include flaring and venting at oil fields, the CO_2 present in natural gas as an impurity, and methane emissions from coal fields. The management of carbon emissions in this category is usually presumed to be the responsibility of the fossil fuel industries themselves.

Electric power plants Emissions from power plants can be reduced both by changing the fuel and by converting the fuel to electricity more efficiently at the power plant. We treat more efficient conversion here, and changing the fuel in Section 3 of the Supporting On-Line Material. More efficient conversion results at the plant level, for example, from better turbines, from high-temperature fuel cells, and from combining fuel cells and turbines. At the system level, more efficient conversion results from load leveling, from cogeneration (the co-production of electricity and useful heat), and from polygeneration (the co-production of chemicals and electricity).

Restricting the discussion here to 2054 coal power plants, we choose a reference baseload coal plant that operates at 50% lower-heating value efficiency, and hence emits 25.80 kgC for each one-half GJ of output electricity. 1 kWh is 3.6 MJ, so the carbon intensity of electricity from such plants is 186 gC/kWh.

To develop a wedge from the efficiency of coal power, we note that 40% and 60% efficient coal plants have carbon intensities of 232 gC/kWh and 155 gC/kWh, respectively, and thus a difference in carbon emissions of 77 gC/kWh. Hence, a wedge is achieved when 13,000 TWh (13 trillion kWh) are produced per year in 2054 at 60% instead of 40% efficiency. By comparison, global electricity output from coal in 2000 was 6000 TWh, according to the World Energy Outlook (S24, p. 411). Thus, a wedge is achieved if, in 2054, roughly twice today's output of coal power is produced at 60% instead of 40% efficiency.

All the carbon intensities considered here for coal plants in 2054 exceed the current average carbon efficiency. Year 2000 carbon in and electricity out for coal-based power plants were, respectively, 1712 MtC/y and 5989 TWh/y, resulting in a carbon intensity of 290 gC/kWh (S24, p. 411 and p. 413).

Electricity production is already more decarbonized than non-electric end uses of energy. Only about 20% of all primary energy comes from sources other than fossil fuels, but for electricity production the share from other than fossil fuels is 40%[4]. The difference in share is the result of non-carbon primary energy (dominated by hydropower and nuclear energy) being used almost exclusively in the electricity sector. This trend is likely to continue. Wind and other renewables will also have their primary impact, for the foreseeable future, as sources of electricity. To decarbonize the fuel supply system, in contrast to the electricity supply system, there are fewer options available, as discussed in Section 3 of the Supporting On-Line Material. This is why wedges available from improved efficiency of fuel use are especially important.

[4] The share of primary energy from non-fossil sources varies across data sources, depending on whether traditional energy sources are included and on how hydropower is treated. According to the IPCC Mitigation Report, the share of electricity from non-fossil sources in 1995 was 38%, 5000 TWh out of 13,200 TWh (S25, Table 3.29, p. 238).

Vehicles A light-duty vehicle ("car") consumes 330 gallons of gasoline per year if it goes 10,000 miles with a fuel economy of 30 mpg. The carbon content of a gallon of gasoline is about 2.4 kg (specific gravity = 0.74; 85% carbon by weight), leading to 3 kg of carbon emissions per gallon of gasoline when one adds about 25% carbon "overheads" incurred at production, at the refinery and further downstream (S26). Thus, a typical car emits a ton of carbon into the air each year. Then, accepting 30 mpg and 10,000 miles per year as the baseline, a world with two billion cars on the road offers two wedges if the fuel can be totally decarbonized and one wedge if the fuel is unchanged but the fuel efficiency is doubled.

Note that the improved fuel efficiency required to achieve a wedge is strongly dependent on the average fuel economy assumed in the BAU. Assuming 24 mpg, a wedge is available from fuel efficiency by achieving 40 mpg instead. Assuming a 36 mpg baseline, a wedge is available from fuel efficiency by achieving 90 mpg instead.

Note also that the assumption of 10,000 miles of driving per year for the average car is only slightly larger than the 14,000 km/y (8700 miles/y) value used by the U.S. Energy Information Agency as a world average today (S23). The assumption of two billion light-duty vehicles in 2054 is consistent with the 530 million cars in 1999 (S23), if the growth rate in number of cars is 2.4% per year.

The decarbonization of freight transport presents challenges similar to those for personal transport. It is widely agreed, however, that the decarbonization of aviation will be more difficult. And aviation is the fastest growing component of transportation.

Buildings When energy is examined comprehensively from the end-use perspective, the buildings sector stands out as particularly promising. The buildings sector is traditionally subdivided into residential and commercial buildings. The largest savings are in space heating and cooling, water heating, lighting, and electric appliances.

The 2001 "Mitigation" report of the Intergovernmental Panel on Climate Change (IPCC) contains historical data and projections across all economic sectors and levels of industrial development. The report cites a 1996 paper commissioned by the IPCC that judges the buildings sector as a whole to have the "technological and economic potential" to cut emissions in half, relative to a particular base case, from 3.9 GtC/y to 2.0 GtC/y. Thus, two wedges are achieved. One wedge is achieved in residential and another in commercial buildings. In the base case, two-thirds of the carbon emissions are from residential buildings, but the carbon savings achievable from commercial buildings are judged to be larger than from residential buildings (65% vs. 45%). In both the residential and commercial buildings, almost half of the savings are achieved in the buildings of developing countries (S25, Table 3.5, p. 189). The paper cautions, however, that only "between 35% and 60% of the efficiency measures that are technically and economically feasible… could be adopted in the market through known and established approaches (S25, p. 188, fn. 13)."

We can read this observation in either of two ways, depending on how we view Business As Usual. 1) We can judge the savings available using "known and established" approaches as sufficiently difficult to achieve that they would not occur as part of Business As Usual. Then, one wedge would be available through implementing these approaches, and a second wedge would be available if unknown and not yet established approaches could be implemented to bring about the second half of the identified technical potential for carbon savings. 2) We can view the savings through "known and established" approaches to be part of Business As Usual, and thus very likely to occur without a focus on carbon. In that case, only the second wedge above would be available.

Carbon savings from space water heating will come from synergisms between end-use efficiency strategies, like wall and roof insulation, and renewable energy strategies, like solar water heating and passive solar design. These synergisms are further discussed in Section 3 of the Supporting On-line Material.

There are often critical interactions between two strategies that diminish the combined effect, relative to the sum of the two activities acting independently. Consider household lighting and the decarbonization of electricity. A wedges calculation could distinguish two 2054 worlds, one with half and one with full displacement of incandescent bulbs (IBs) with compact fluorescent bulbs (CFBs). About 10 kgC/y is at stake for each fixture, if we assume: 1) the bulbs are on 4 hrs/day; 2) a 15W CFB replaces a 60W IB, providing the same light output; and 3) the carbon intensity of electricity is 160 gC/kWh, the same as in recent years[5]. If we imagine 50 billion light fixtures in 2054 (there are about 10 billion today), half versus full penetration would be one-fourth of a wedge (25 billion fixtures where 10 kgC/y is saved). But, less than one-fourth of a wedge will be available, to the extent that the carbon intensity of electricity falls by 2054 from its current value. The carbon intensity of electricity fell 28% over the 29 years between 1971 and 2000, from 204 gC/kWh to 159 gC/kWh, or 0.9%/y (S24, p. 411 and 413). One would expect substantial further reductions in the carbon intensity of electricity in a world where global carbon is taken very seriously.

Direct use of fuel at the factory and farm The abundant literature on energy efficiency (S27-S32) provides grist for numerous estimates of opportunities for carbon emissions saving in all sectors of the economy. In the area of energy use in industry and agriculture, the identification of wedges is work for the future. The best we can do is to provide a template for such calculations, using vehicle fuel efficiency as an example. There are two steps to the identification of a wedge:

> 1) Invent a plausible baseline level of activity and carbon intensity in 2054, consistent with little attention being paid at that time to the global carbon problem. Take into account that many carbon intensities (like the analogous *energy* intensities) have been falling steadily and that many measures of level of activity have been growing with the economy. For vehicle fuel, the level of activity is the total vehicles miles traveled, or VMT, 20 trillion miles per year; and the carbon intensity is 0.10 gC/mile.
>
> 2) Invent either a lower level of activity, or a lower carbon intensity, or some combination of the two, that is a plausible representation of a world in 2054 that takes the global carbon problem very seriously.

Note that some (level of activity)-(carbon intensity) pairs will introduce the time dimension via the level of activity; an example is (tons of steel produced *per year*)-(carbon emissions per ton of

[5] In 1995, according to IPCC Working Group III, 13,200 TWh of global electricity were produced with the emission of 2.09 GtC, or 158 gC/kWh (S25). In 2000, according to the IEA World Energy Outlook tables for its Reference Scenario, 15,400 TWh were produced with the emission of 2.44 GtC, or 159 gC/kWh.

steel). Other pairs will introduce the time dimension via the carbon intensity; an examples is: (hectares planted in some crop)-(carbon emissions *per year* per hectare planted in that crop).

SECTION 3. THE DECARBONIZATION OF ENERGY SUPPLY

The Stabilization Triangle reduces carbon emissions from fossil fuel in 2054 to 7 GtC/y from 14 GtC/y. In addition to the energy efficiency strategies discussed in the previous section that can bring about such emissions reductions, there are also many supply strategies.

In recent years, fossil fuel extraction and use has resulted in the transfer of between six and seven billion metric tons of carbon per year (GtC/y) from fossil fuels to the atmosphere. At the next level of detail, where data are disaggregated in various ways (by part of the world, fuel, end-use, etc.), disagreements among available references reflect a variety of uncertainties in the data. Such uncertainties arise from poor reporting from some countries, variable and unknown carbon content of fuels (especially, across coals), and incomplete knowledge of the timing of the delayed carbon emissions from the world's many long-lived petrochemical products, like plastics and asphalt (the "non-energy uses" of fossil fuels). Unless otherwise noted, we use CO_2 emissions data from the International Energy Agency's *World Energy Outlook 2002* (S32, p. 413). We also use the energy-to-carbon conversion ratios recommended at the BP website (these are lower heating values); for natural gas, oil, and coal, in units of kgC /GJ, these are, respectively: 15.29, 20.07, and 25.80[6].

In Table S3, a 3x3 matrix, we display a disaggregation of the 6.2 GtC/y global carbon emissions in 2000 (S33). The columns of the matrix are fuels (gas, oil, coal), and the rows are category of use (power, transportation, direct fuel use)[7]. The same information is also shown in Fig. S2, top. Coal dominates the electricity market. Coal and gas compete in markets for electricity and process heat. A significant amount of coal is used directly for space heat in developing countries. Oil emissions account for almost all transportation emissions. Almost half of oil emissions come from sectors other than transportation.

In 2054, it is reasonable to assume that natural gas, oil, and coal will all continue to be produced, and that many current features of energy demand will be intact. In keeping with the spirit of our analysis, where we seek to specify as little as possible of BAU, we adopt a deliberately oversimplified view of BAU carbon emissions in 2054, in the form of another 3x3 matrix, with the same structure as the 2000 matrix. It is shown in Table S4 and Fig. S2, bottom left.

The BAU in Table S4 is deliberately rough hewn, but it is consistent with general expectations and it can help guide our thinking. We have confined ourselves to integer emissions, in units of GtC/y. The total of 14 GtC/y emissions in the baseline is split: 5 GtC/y natural gas, 3 GtC/y crude oil, and 6 GtC/y coal[8]. All crude oil is used in the transport sector. To promote attention to the potential for competition in 2054 in the transport sector between fuels derived from crude oil and from coal, emissions for transport from oil-derived fuels and coal-derived synfuels are 3 GtC/y and 1 GtC/y, respectively. The power sector emissions are 2 GtC/y from natural gas and 3

[6] The BP Tables (S34) state the conversion units in tC/toe: 0.64, 0.84, and 1.08, respectively. We use 1 toe = 41.86 GJ (10 Gcal).

[7] What we are calling Direct Fuel Use is the sum of two categories in *World Energy Outlook – 2002*: "Industry" and "Other" (S33). Industry will be dominated by process heat, since electricity is accounted for separately. "Other" will be dominated by space and water heating in buildings.

[8] A substantial fraction of the natural gas and oil will be what is today called, "unconventional," (tar sands, for example). The use of lower quality oil and gas resources may not alter the deep structure of energy markets expressed in our 2054 matrix.

GtC/y from coal. Emissions associated with direct use of fuel elsewhere than in transport are 3 GtC/y from natural gas and 2 GtC/y from coal; these fuels are used largely for industrial process heat and residential and commercial building space and water heating. Carbon emissions arise about equally, as today, from providing electricity, transportation, and heat for industry and buildings.

To cut 2054 carbon emissions by half, both the power system and the fuels system must be aggressively decarbonized. Below, we examine the decarbonization of power first, then the decarbonization of fuel.

I. The Decarbonization of Power

To decarbonize electricity production the principal target will be the coal power plant, and the secondary target will be the natural gas power plant. How much coal electric power is associated with 1GtC/y entering the atmosphere?

As in Section 2 of the Supporting On-Line Material, we choose a reference baseload coal plant, for 2054, that operates at 50% lower-heating-value efficiency, and hence with a carbon intensity of 186 gC/kWh. We now add that it has a capacity of 1 GW and operates with 90% capacity factor. Each year, therefore, it produces 8 TWh of electricity and emits 1.5 MtC. Our answer, then, is that 700 GW_e of vintage 2054 baseload coal capacity emits 1 GtC/y.

A carbon-emission rate from coal plants of 1 GtC/y is accompanied by coal consumption, in energy units, of 40 EJ per year, and 5400 TWh per year of electricity[9]. The electricity output is nearly as large as (90% of) today's total electricity output from coal, 6000 TWh in 2000, according to the World Energy Outlook (S33, p. 411). The coal input is about 60% of total coal input to power plants in 2000, 65 EJ (S33, p. 410). The second percentage is smaller, because the average efficiency of coal plants today is considerably less than the efficiency we are assuming for 2054.

Because we make much use of the equivalence of 700 GW of coal power plant capacity and 1 GtC/y of carbon emissions, it is important to understand the underlying assumptions. The carbon intensity we assume for the coal plants in 2054 far exceeds the average carbon efficiency today: Combining a 50% lower-heating-value efficiency with our lower-heating-value carbon intensity for coal, 25.80 kgC/GJ, yields an average carbon intensity of coal plants in 2054 of 185 gC/kWh, compared to 290 gC/kWh in 2000[10]. Combining these assumptions with a plant assumed to run 90% of the year, the emissions from each plant are 1.47 MtC/y, and therefore 1 GtC/y is emitted from 680 plants, which we round off to 700 plants.

A smaller number of 1 GW coal plants will emit 1 GtC/y when the efficiency is less, and a larger number when the plant runs less often. Combining two data one year apart, 1.712 GtC/y emissions from coal plants in 2000 and 1056 GW of installed coal capacity in 1999 (S33, p.413 and p. 412), one finds that 620 GW of recent coal plant capacity is associated with 1 GtC/y of recent emissions; evidently, the effects of much lower efficiency and much lower capacity factor nearly cancel.

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[9] 1 TWh = 10^9 kWh.

[10] Year 2000 carbon in and electricity out for coal-based power plants were, respectively, 1712 MtC/y and 5989 TWh/y (S33, p. 411 and p. 413).

The average carbon intensity of electric power from natural gas in 2000 was 172 gC/kWh,[11] about 60% of the average carbon intensity of electric power from coal in 2000, 290 gC/kWh, just cited. The average efficiencies of conversion of natural gas and coal to electricity are both about 32%[12]. Much of the natural gas is consumed in peaking plants, which are not as efficient as baseload plants. Correcting for this by assuming 60% lower-heating-value efficiency for the reference 2054 baseload natural gas plant, natural gas in 2054 will emit about half as much carbon per kWh as baseload coal plants.

It follows that a strategy that builds the capability, by 2054, to avoid the production of electricity from 1400 GW of baseload natural gas plants is a wedge. Equivalently (referencing the output instead of the capacity), a strategy that builds the capability to avoid the production of 10,800 TWh of electricity from vintage 2054 natural-gas-based power plants is a wedge. A wedge of natural-gas-based electricity avoided is approximately equal to four times the Year 2000 global production of electricity from natural gas (2700 TWh) (S33, p.411).

Four distinct approaches to the decarbonization of power will compete with one another:

A) Fuel shifting: Coal can be displaced by natural gas.

B) Carbon capture and storage: The CO_2 in the coal or natural gas can be captured and stored instead of vented to the atmosphere.

C) Nuclear energy: Coal or natural gas can be replaced by nuclear energy.

D) Renewable energy: Coal or natural gas can be replaced by renewable energy

We discuss each of these four options below.

A. Fuel Shifting: Substituting Natural Gas Power for Coal Power

From the data just presented, it follows that a wedge is available from using natural gas instead of coal at 1400 GW of baseload power plants by 2054. The pace associated with this wedge is 28 GW of new natural gas power displacing 28 GW of new coal power every year. Equivalently, a wedge results from producing10,800 TWh of electricity from natural gas instead of coal by 2054. At these power plants, 1 GtC/y will be emitted from natural gas instead of 2 GtC/y from coal. The 3x3 matrix for 2054 above would read, after one such wedge: 1 GtC/y from coal to electricity and 3 GtC/y from natural gas to electricity, for a total 2054 emission of 4 GtC/y associated with electricity production, instead of 5 GtC/y. A full second wedge of this kind would not be available.

[11] Year 2000 carbon in and electricity out for natural-gas-based power plants were, respectively, 461 MtC/y and 2676 TWh/y (S33, p. 411 and p. 413).
[12] Inputs of coal and natural gas to electricity in 2000 were, respectively, 1555 Mtoe/y (65.1 EJ/y) and 725 Mtoe/y (30.3 EJ/y) (S33, p. 410), resulting in average Year 2000 efficiencies (electricity out/fuel in) of 33% for coal and 32% for natural gas.

Materials flows equivalent to one billion tons of carbon per year are huge. We assume a reference coal which is 70.7% carbon[13]. Then, a flow of 1.4 billion tons of coal per year carries 1 GtC/y. The flow of natural gas, which is about 75% carbon (since natural gas is mostly methane, and methane is CH_4), is 1.3 billion tons per year. However, flows of natural gas are usually measured as volume flows, for example in units of billions of standard cubic feet per day (Bscfd). We find that 1 GtC/y is a flow of 190 Bscfd of natural gas.[14] Therefore, 1 wedge is a program of development of natural-gas-based power that displaces coal and grows from zero to 190 Bscfd in 50 years, emitting 1 GtC/y, but backing out coal that is twice as carbon intensive in producing electricity, and so would have emitted 2 GtC/y.

We can relate a wedge of natural gas to flows through specific large pipelines and LNG tankers:

> The Alaska natural gas pipeline currently under negotiation is to carry about 4 Bscfd. A wedge of flowing natural gas (190 Bscfd, or 1 GtC/y) is equivalent to bringing one Alaska pipeline on line every year for 50 years[15].
>
> A wedge of flowing natural gas (190 Bscfd, or 1 GtC/y) is equivalent to 50 large LNG tankers docking and discharging every day[16]. Current LNG shipments create about one-tenth as large a flow of carbon.

B. Electricity with Carbon Capture and Storage (Carbon Sequestration)

When energy is extracted from fossil fuels or biofuels by oxidizing its carbon to CO_2, there is no fundamental reason why that CO_2 should end up in the atmosphere. It is possible to capture the CO_2 at the energy conversion facility instead of venting it, and to store the captured CO_2 to prevent it from reaching the atmosphere for a long period of time. This strategy, carbon capture and storage (CCS), also known as fossil carbon sequestration, is being widely studied as a carbon mitigation strategy. The 2002 National Academy of Engineering symposium proceedings (S36) is a good source of introductory essays on many of the major issues; for more detailed information, we recommend the collection of papers prepared for a 2002 international conference in Kyoto, in two volumes (S37). The website of the International Energy Agency's Greenhouse Gas R&D Programme, www.ieagreen.org.uk, is particularly useful.

A wedge is CCS applied by 2054 to 800 GW of baseload coal power or 1600 GW of baseload natural gas power – when we take into account less than perfect capture and storage (both CO_2 not captured and extra energy to power the capture and storage). Biomass can also be used with CCS, leading to a net withdrawal of CO_2 from the atmosphere. Biomass may be able to be used

[13] "70.7 percent carbon describes coal equivalent within +/- 2%," according to G. Marland, et. al. (S35) . This percentage is consistent with the bituminous coal atomic ratios of $CH_{0.8}O_{0.1}$, if the coal is 85%($CH_{0.8}O_{0.1}$) and 15% "other", by weight. "Other" might be ash.

[14] We assume that the volumetric carbon content of natural gas is 538 gC/Nm^3, where Nm^3 is "normal cubic meter." We use the equivalence of two gas volumes, both defined at atmospheric pressure, but defined at different temperatures: 1 Nm^3 = 37.24 scf, where scf is "standard cubic foot." (The scf is at 60 degrees F, and the Nm3 is at 0 degrees C.) The arithmetic, then, is that 1 GtC/y is $37.24/(538*10^{-6}*365)$ Bscf/d = 190 Bscf/d. Here, both G and B are one billion, or 10^9.

[15] Another large natural gas pipeline is being built across China, from Kovyktinskoye, "Kovykta," in eastern Siberia, to Beijing. It is similar in size to the Alaska pipeline.

[16] We assume the LNG tanker has 200,000m^3 capacity. The density of LNG is 610 times the density of standard natural gas.

in dedicated facilities, and it also can be "co-fired" with coal, followed by CCS, increasing the mitigation effect of CCS per kWh.

To achieve the objectives of CCS, several commercial technologies must be combined in new ways. Key carbon capture technologies are well known from their use in industrial hydrogen production at refineries and ammonia plants. Key carbon storage technologies are well known from their use for enhanced oil recovery (EOR). We consider carbon capture and carbon storage separately.

Carbon capture Carbon capture is possible as end-of-pipe technology ("post-combustion capture"): CO_2 is separated from the flue gases exiting a power plant or other industrial facility, for example by chemical absorption or adsorption. Alternatively, CO_2 may be captured at an early stage, prior to most of the energy generation ("pre-combustion capture"). Post-combustion capture is less disruptive of already established technological practice. However, in many cases, pre-combustion capture is less costly, because the key step of separating CO_2 from other gases may be accomplished at much higher partial pressure.

Pre-combustion CO_2 capture shares many technologies with the gasification of solid fuels (coal, petroleum coke, and various biofuels). The synthetic gas (syngas) exiting the gasifier contains, principally, CO and H_2, at high temperature and pressure, but it also contains impurities, like sulfur. For a gasification plant to become a pre-combustion capture plant, the CO and H_2 mixture must be converted to a CO_2 and H_2 mixture, via a shift reactor ($CO + H_2O \rightarrow CO_2 + H_2$). The technologies to remove impurities from syngas are similar to the technologies to remove CO_2 from a mixture of CO_2 and H_2.

When gasification is the first step in power production, if there is no CO_2 capture, the CO-plus-H_2 syngas goes to a turbine, whereas if there is CO_2 capture, a much more H_2-rich syngas goes to the turbine. The incremental cost of CO_2 capture in power production, if gasification becomes established as the power conversion system of choice, is relatively low. Thus, the competition within coal-based power between steam power and power from gasification strongly affects and is affected by any requirement for carbon mitigation. The more gasification-based power is competitive, the less costly CO_2 capture will be, and the greater the societal demand for CO_2 capture, the more competitive gasification-based power will be.

Pre-combustion CO_2 capture also shares many technologies with H_2 production from coal or natural gas. Here, both a shift reactor to produce a mixture of CO_2 and H_2, and subsequent separation of the H_2 from the CO_2, are necessary to obtain a high-purity H_2 stream. The current scale of production of H_2, therefore, provides useful reference values for the task required to produce the "capture" part of a wedge of "capture and storage."

Hydrogen is currently produced from fossil fuels at a rate of about 40 million tons per year. Most production is associated with two industries, ammonia fertilizer and petroleum refining, and, in both cases, H_2 is produced and used in the same complex. At 120 GJ/t (lower heating value) for H_2, the flow of secondary energy as H_2 is approximately 5 EJ/y. As a result, taking into account losses in conversion of primary energy to H_2, roughly two percent of the 400 EJ/y of global primary energy is used to make H_2. Since, at any plant where H_2 is produced from fossil fuels, a nearly pure stream of CO_2 can be captured at some stage, we estimate that 0.1 GtC/y of capturable CO_2 is generated at H_2 production plants (S38). Today, in every case, this CO_2 is vented, but only small changes could lead to capture. The scale of H_2 production today is only ten times smaller than the scale of a wedge of carbon capture in 2054.

We return to H_2 production later in this section, when we consider the decarbonization of fuels and the hydrogen economy.

Carbon storage The capture part of "capture and storage" results in a stream of relatively pure CO_2 at a plant gate, ready to be taken away. The CO_2 must be at high pressure, if it is to leave via gas pipeline, and the compression step is often the most expensive and energy-intensive step in the whole process. But, where can it be stored, and in what chemical form? Many novel proposals are receiving much attention, including storage in minerals and storage in the deep ocean, but, in the spirit of this paper, we consider only "geological storage," because this is the one storage strategy for which there is already substantial relevant experience. The oil industry moves large quantities of CO_2 into underground formations for enhanced oil recovery (EOR), by far the largest industrial use of CO_2. The CO_2 is injected as a supercritical fluid, and much has been learned via EOR about migration of the fluid, dissolution into hydrocarbons and brine, and chemical interaction with host rock. The scale of current EOR provides useful reference values for the task required to produce the "storage" part of a capture-and-storage wedge.

In EOR, much of the CO_2 injected into a hydrocarbon formation reemerges with the oil it has helped produce, and it is then separated and reinjected. We choose to describe EOR experience with CO_2 in terms of the total flow of new CO_2 brought to EOR sites, rather than the total flow of CO_2 injected at EOR sites, which includes recycled CO_2. About 10 MtC/y is brought to EOR sites in the U.S. today. Most of these sites are in the Permian Basin, West Texas, and most of the world's EOR is in the U.S. Therefore, a wedge of the storage part of capture-and-storage is a flow of CO_2 about 100 times larger than the current flow of CO_2 to EOR sites.

EOR today only rarely uses CO_2 captured from fossil fuels. Rather, most of the CO_2 used in EOR is drawn from *natural* CO_2 reservoirs. A large part of the CO_2 used for EOR in the Permian Basin is tied to the huge McElmo CO_2 reservoir in southwest Colorado via a 800-km-long CO_2 pipeline that runs across New Mexico. This pipeline carries somewhat more than 1 billion standard cubic feet per day (Bscfd) of CO_2, or about 5 MtC/y[17]. Thus, a wedge is an activity that, during each of the next 50 years, adds a flow of carbon equal to the flow through four pipelines like the pipeline from McElmo Dome to the Permian Basin.

Much work remains to be done before there are good estimates of the total storage capacity for geological storage of CO_2, and before storage integrity and leakage are well understood. The storage part of a capture-and-storage wedge requires the storage of 25 GtC over the next 50 years. The global storage capacity in oil and gas reservoirs is estimated at 10 to 20 wedges. Estimates of the global storage capacity in large unconfined saline aquifers range from only four wedges to one hundred (S39).

Carbon storage has not been the objective of EOR. In the past ten years, however, demonstration projects designed to gain experience with geological sequestration have begun to come on line.

[17] Note that, as a manifestation of the universal properties of gases at low pressure, a flow of 190 billion standard cubic feet of gas per day (Bscfd) is a carbon flow of 1 GtC/y, the carbon flow associated with a wedge, *whether the gas is* CH_4 *or* CO_2.

The first three of these are: 1) the Sleipner project, offshore Norway; 2) the Weyburn project, Saskatchewan, Canada; and 3) the In Salah project, Algeria. The Sleipner project demonstrates storage in a huge unconfined aquifer; the Weyburn project demonstrates storage associated with EOR; and the In Salah project demonstrates storage in the water leg beneath the same natural gas field from which the natural gas is being produced. All three projects involve approximately the same storage rate: one million tons of carbon dioxide per year (0.3 MtC/y). Thus, a wedge of storage is 3000 Sleipners, or 3000 Weyburns, or 3000 In Salahs.

It is possible that storage of CO_2 will be routinely accompanied by the storage of pollutants, like sulfur, as a single fluid mixture. For the past 15 years, "acid gas" (a mixture of CO_2 and hydrogen sulfide, or H_2S, obtained from the desulfurization of "sour gas," or gas with high sulfur content) has been disposed of in geological media in Western Canada. This method, which we call co-capture and co-storage, is being adopted increasingly as the preferred strategy for sulfur management for many sour natural gas fields in western Canada and the U.S. The 2003 injection rate, summed over 41 active sites, was about 0.45 $MtCO_2$/y (0.12 MtC/y) and 0.55 MtH_2S/y. The cumulative storage through 2002 was 2.5 $MtCO_2$ (0.7 MtC) and 2.0 MtH_2S (S40).

Natural gas is stored in geologic reservoirs to buffer demand, providing further relevant experience in moving gases into and out of reservoirs below ground. In the U.S. alone, total gas in storage in 1999-2002 ranged, approximately, between five and seven trillion standard cubic feet, the minimum in March and the maximum in October (S41). The six-month-average flow in and out, therefore, is about 10 billion standard cubic feet per day (Bscfd). As noted above, a carbon flow of 1 GtC/y, whether as methane or CO_2, is a flow of 190 Bscfd. Therefore, ramping up the gas flow currently associated with seasonal natural gas storage in the U.S. to twenty times its current rate over the next fifty years is the storage part of a wedge of CO_2 capture and storage.

C. Nuclear Power

A wedge from nuclear power is power production by 2054 at a rate of 5400 TWh/y that displaces electricity from coal or 10,800 TWh/y that displaces electricity from natural gas. Assuming that 2054 nuclear plants have the same 90% capacity factor as we earlier assumed for 2054 coal and natural plants, a wedge is 700 GW of additional installed nuclear capacity by 2054 that displaces coal, or 1400 GW that displaces natural gas.

In 1999, 351 GW of nuclear capacity were installed, and in 2000, the rate of production of nuclear electricity was 2586 TWh/y, for an average capacity factor (neglecting the one-year interval) of 84% (S33). Assuming that the wedge envisioned here is added to existing capacity which remains unchanged, we see that a wedge of nuclear power displacing coal requires approximately tripling, by 2054, both the installed nuclear capacity (adding 700 GW to 350 GW) and nuclear power output (adding 5400 TWh/y to 2600 TWh/y). The current challenge of nuclear waste disposal, in terms of mass of fission products, also grows by a factor of three.

The world's nuclear capacity today is far below what was expected in the 1960s, when nuclear power's promise as a substitute for coal was most highly regarded. Round numbers were used to project an installed nuclear capacity in 2000 of 1000 GW in the U.S. and 1000 GW in rest of the world. Problems of plant siting, uranium resource availability, and waste management were all addressed in that period, and no technical obstacles were identified. The U.S. currently has about ten times less nuclear capacity than then envisioned and the world as a whole has about six times less. Were the incremental 1600 GW to be built through steady construction over the next 50 years and be credited against baseload coal, this would account for roughly two wedges. Nuclear fusion reactors could account for some of this capacity, if fusion were to arrive on the scene faster than is now anticipated.

Nuclear fission power generates plutonium, as neutrons are absorbed by U^{238}. The rate of generation of plutonium depends on the reactor type and its operation. A light water reactor running on low-enriched uranium (the dominant reactor today) generates about 35 kg Pu per TWh of electricity[18], or 250 kgPu/y per installed GW, at 80% capacity factor. If our 2054 reactor has the same plutonium production rate per unit of thermal energy, but 50% efficiency and 90% capacity factor, it generates 180 kgPu/y. A wedge from nuclear power (700 GW) generates, in 2054, 130 tPu per year[19].

To estimate the quantity of plutonium produced over the fifty years by the nuclear power plants that fill the wedge, we assume a linear ramp, so that, each year, 14 GW of new nuclear capacity are installed. Over 50 years, there are 17,500 GW-years of nuclear reactor operation. We can bracket the Pu produced while filling the wedge by observing that if all the reactors generated plutonium at today's estimated rate of 250 kgPu/GW-year, 4400 tPu would be produced, and if all the reactors generated plutonium at the rate we are estimating for reactors built in 2054, 180 kgPu/GW-year, 3200 tPu would be produced[20]. This addition of several thousand tons of plutonium to the world's stock can be compared with: 1) 1000 tPu, the current inventory in all the world's spent fuel; 2) 100 tPu, the current inventory in U.S. weapons; and 3) 10 kgPu, the critical mass of plutonium.

D. Power from Renewables

The list of renewable power sources is long. It includes power from renewable energy in the form of heat that is then converted to electricity in a power cycle, as well as power that has been generated directly from an organized renewable energy source. In the first category, the heat may originate in focused sunlight or geothermal energy or the combustion of biomass. It is possible for such heat to supplement the heat from the combustion of fossil fuels, as in the co-firing of biomass and coal, mentioned briefly earlier under carbon capture and storage. In the second category, organized renewable energy, capable of being converted to electricity without an intervening thermal power cycle, can take the form of hydropower, photovoltaics (PV), wind, waves, and tides.

Here, we arbitrarily focus on the displacement only of coal and only by wind or PV. Given the assumptions in this paper, a wedge of wind must displace 700 GW of baseload coal (5400

[18] We estimate this production rate from two inputs: 1) a ton of enriched uranium fuel generates about 35 GW_t-days of *thermal* energy before replacement (this is the "burn-up" of the fuel, expressed in its usual units), and 2) at replacement the spent fuel is about 1.0% plutonium (S42, Table 7.1, p. 109). Thus, the production of 10 kg Pu accompanies the production of 0.84 TW_th of thermal energy. At 32% efficiency converting thermal energy to electricity, the plutonium generation rate is 37 kgPu/TWh of electricity.
[19] Such a calculation is at best illustrative, because reactors in 50 years are unlikely to resemble today's light water reactors. They could produce either substantially more or substantially less plutonium than we have estimated.
[20] One way to model our conjectured improvements in nuclear reactor efficiency and capacity factor would be to assume that the plutonium production per reactor-year depends linearly on the year that the reactor begins operation, falling linearly from 250 kgPu/GW-year to 180 kgPu/GW-year over the 50 years. For this simple model, 3500 tPu are produced while filling the wedge – indeed bracketed by 4400 tPu and 3200 tPu.

TWh/y). Assuming a linear ramp, an increment of 100 TWh/y of either new wind energy or new PV each year for 50 years would be a wedge.

But wind blows intermittently, and PV cannot be collected at night; both are intermittent energy sources. The capacity of intermittent renewable energy to displace fossil fuel power depends on the availability of stand-alone storage and hybrid storage. A wedge is sufficiently large that it will require the wind or PV energy to be embedded in a system with sufficient storage to compensate for intermittency.

An example of hybrid storage is compressed-air wind-energy storage for remote wind farms, where the challenge is to gain maximum value from transmission lines by keeping them full. On very windy days, instead of spilling the wind at the site, the excess wind is stored in some geological formation as compressed air. Then, when winds are low, supplementary turbine power is produced by the compressed air, after its enthalpy is boosted by the burning of natural gas (S43).

For both wind and PV, deployment is measured in peak watts (W_p), a measure of the power output at the cutoff wind speed for wind and in direct sun normal to the surface for PV. We are assuming a present wind capacity of 40 GWp, based on data showing that at the end of 2002, the global installed wind capacity was 32 GW_p and had increased 29%, or 7.2 GW_p, over 2001. In 2002, 65 TWh were produced from wind, 0.4 % of total global electricity consumption (S44). Assuming the same 26% capacity factor relative to peak capacity in 2001 as in 2002,[21] wind energy in 2002 exceeded wind energy in 2001 by 16 TWh, one-sixth of the linear rate of increase required for 50 years for a wedge of wind-for-coal.

A simple way to estimate intermittency, for both wind and PV, is to match peak watts to baseload watts by dividing by three. (As we have just seen, a typical capacity factor for wind or PV is about one quarter, as compared to somewhat more than three-quarters for a baseload plant. In 2054, we imagine a 30% capacity factor for PV and wind and a 90% capacity factor for baseload plants.) Thus, a wedge is about 2000 GW_p of peak wind or PV power displacing coal by 2054, or 4000 GW_p displacing natural gas. The rate of deployment, for a linear ramp, is 40 GW_p per year if coal is displaced and 80 GW_p per year if natural gas is displaced. The current global deployment of PV is about 3 GW_p. For the past several years, installed global PV capacity, like wind capacity, has been growing at 30% per year (say, 0.7 GW_p/y). Thus, a wedge of PV-for-coal requires increasing the deployment of PV by a factor of 700 by 2054, or increasing the current deployment rate by a factor of 60.

To estimate the spatial demands of future wind farms on land or in the sea, we use data for Denmark's new 160 MW Horns Rev wind farm off the west coast of Jutland (S45). This offshore wind farm has 80 turbines in an 8x10 rectangular array, each with 80m-diameter blades and 2-MW_p output. The turbines are seven blade-diameters apart both in the prevailing wind direction and transverse to it. Thus, each of the inner 2-MW_p turbines "occupies" 310,000 m^2, and its power density is 6 W_p/m^2, from the perspective of surface area required[22]. A wedge in the form

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[21] To produce 65 TWh from wind in 2002 would require 2300 hours of operation at peak capacity, or operation for 26% of the year, assuming 28 GW_p average installed peak wind capacity.

[22] The area occupied by the entire Horns Rev wind farm is reported as 20 km^2 (S45), which results in a ratio of peak-power production to wind farm area of 8W_p/m^2. The area reported is equal to nine times seven inter-windmill spacings, rather than ten times eight, as if no surface were "occupied" beyond the perimeter of the wind farm.

of 2000 GW_p of wind-for-coal would then require 30 million hectares of surface. If all were on land, this would be between one and two percent of the world's 1800 million hectares of land estimated to have winds of Class 4 and above (S46). Thirty million hectares is also 3% of the land area of the United States. Land from which wind is harvested can be used for many other purposes, notably for crops or pasture.

The land demand for PV is inversely related to the conversion efficiency of sunlight. Here we choose 100 W_p/m^2 for the peak power output from PV divided by the area of the collection site[23], 15 times greater than for wind. Then, a wedge in the form of 2000 GW_p of PV-for-coal requires two million hectares, or 20,000 km^2, of site surface, either dedicated land or multiple-use surfaces such as the roofs and walls of buildings.

Note that in quantifying the wedges of renewable electricity, here, we have not needed to take into account the mix of centralized and distributed generation. Hundred-square-kilometer regions devoted to arrays of photovoltaics or wind farms have been treated as equivalent to large numbers of rooftop PV units or isolated wind turbines.

Greater Electrification as a Consequence of Decarbonization

In searching for wedges, it is important to keep in mind that, in a carbon-constrained world, electricity may displace fluid fuels, especially in distributed uses of energy. Today, when electricity competes as a secondary energy carrier with hydrocarbons in distributed energy markets, such as the markets for vehicle fuel and space heating, it does poorly. Distributed hydrocarbons offer portability in the first instance and thermodynamic efficiency in the second. The electric battery car has not displaced the car powered by gasoline or diesel fuel. The electric resistive heater has not displaced the natural gas furnace. In the future, however, distributed hydrocarbons will carry new costs associated with carbon emissions to the atmosphere: once hydrocarbons are distributed to small users, their carbon cannot be captured and stored. It should become more attractive to charge the battery on a hybrid vehicle at home from the grid between uses. The electric heat pump should become competitive in a larger range of climates.

We judge that, overall, the alternatives for the decarbonization of electricity discussed in this section will enter the market under a weaker carbon constraint than the alternatives for the decarbonization of fuel discussed in the next section. The result will be accelerated electrification: a greater fraction of primary energy used to produce electricity under a carbon constraint than in its absence.

II. The Decarbonization of Fuel

To decarbonize fuels production, there are major targets at both large and small unit scale. At large unit scale, fossil fuels today are used directly to provide industrial high-temperature heat. Under a carbon constraint, fossil fuels may continue to provide this service, while CO_2 is captured and stored. Or, carbon-free or low-carbon hydrogen, produced at large scale, may substitute for fossil fuels.

[23] On a clear day, the flux of sunlight is 1kW/m^2. Assuming 10% site conversion efficiency (inevitably less than device conversion efficiency), the peak power output per unit of site area is 100 W_p/m^2, and, using our factor-of-three approximation, average power output is 33 W/m^2.

At small unit scale, the principal targets are fuels for transportation and fuels to provide low-temperature heat to buildings. In 2000, as we saw in Table S3, about 3.6 GtC/y of CO_2 emissions were associated with fuels production, and 2.6 GtC/y of CO_2 emissions were associated with electricity production. Of the 3.6 GtC/y, 1.4 GtC/y was associated with oil for transportation. The remaining 2.2 GtC/y, divided remarkable equally between emissions from coal, oil and gas, is associated with direct uses of fuel, but we do not know how much is associated with centralized use by industry and how much with decentralized use in buildings. If we assume that two-thirds is associated with buildings, then on-site dispersed use (buildings and transportation) would account for almost half of carbon emissions. Continuing to use fossil fuels for such uses, but capturing and storing the carbon, is almost surely too costly. Carbon mitigation, instead, is likely to take the form, principally, of the distribution of carbon-free and low-carbon fuels, or the substitution of electricity.

Not only does fuels use come at large and small unit scale, but so, too, does fuels production. This leads to three possibilities: 1) large unit scale in both fuels production and fuels use, as in a steel plant; 2) small unit scale in both fuels production and fuels use, as in home heating from local woodlots; and 3) large unit scale in fuels production connected via infrastructure to small unit scale consumption, as in gasoline for vehicles and natural gas for home heating. The same four approaches that we explored while searching for wedges in the decarbonization of power also span the options for the decarbonization of fuels:

A) Fuel shifting: Natural gas can replace coal as a source of industrial and domestic heat.

B) Carbon capture and storage: There is a large quantity of residual carbon when coal or natural gas is transformed into hydrogen fuel, or when coal is transformed into hydrocarbons. In both cases, the residual carbon can be captured and stored as CO_2.

C) Nuclear energy: Fuels derived from fossil fuels can be replaced by nuclear hydrogen.

D) Renewable energy: Fuels derived from fossil fuels can be replaced by biofuels, renewable electrolytic hydrogen, or solar heat.

All four options compete to provide decarbonized fuels for centralized and decentralized use, but only the fourth option can provide dispersed fuel without an elaborate infrastructure.

Much of what we have written above about decarbonization of electricity in each of these categories applies to fuels as well. Below, for each of these four options we introduce only supplementary material.

A. Fuel shifting: Substituting Natural Gas for Coal in Domestic Heating and Industrial Processes

Coal is widely used for space heating and cooking in many developing countries. Although the extent of this direct use of coal is poorly documented, here may be one of the most important opportunities to have a large positive impact on carbon mitigation and to attack other environmental and public health problems at the same time. Both the indoor pollution associated with poorly ventilated combustion and the outdoor pollution in villages, towns, and cities associated with low-efficiency decentralized coal burning are notorious. Burning the coal more efficiently, more cleanly, and with better ventilation can improve the situation, as can burning coal-derived liquids and gases (synfuels). Given time for natural gas networks to develop, it is also possible to displace coal with natural gas. There may well be a wedge available in the displacement of decentralized coal burning by natural gas in the cities and towns of the developing world, though it may be hard to argue that the wedge is available as a difference between two credible scenarios. A wedge is not available if, over the next 50 years, the elimination of decentralized coal burning is regarded as near certain, even in a world where global carbon does not become a pressing concern.

Coal is also used directly in large centralized applications, notably in steel plants and other metallurgical plants. Displacing such coal is likely to be one focus of decarbonization. Available savings available may well be of the scale of a wedge, through a combination of remaining with coal but capturing and storing the CO_2 produced on the site, substituting hydrogen for coal, and substituting natural gas for coal.

The potential for carbon mitigation via modifications of the energy system where coal is used directly, as best we can determine, is largely unexplored.

B. Synfuels Production and Hydrogen Production with Carbon Capture and Storage:

We discuss two topics in this subsection. We first contend with the possibility that by 2054 oil no longer dominates the transportation sector, presumably for a combination of geophysical and geopolitical reasons, and that coal becomes a substantial source of synthetic carbon-bearing fuels. The impact of such a change in the global energy system for carbon emissions is inherently negative, but we will see that carbon capture and storage offers the promise of undoing some, if not all, of this impact. We then introduce hydrogen, first in general and then with specific reference to hydrogen as a vehicle fuel. This material is intended to serve the two subsequent subsections as well: nuclear hydrogen and renewables hydrogen. We conclude this subsection with a discussion of hydrogen vehicle fuel produced from fossil fuels, with the capture and storage of the accompanying CO_2.

Synfuels with Carbon Capture and Storage

Looming over the 2054 energy scene is the possibility that liquid fuels from petroleum will have become substantially more costly than today, not because of imperfect markets but because of geophysical factors: the cheaper oil may have been largely extracted. For each 100 GtC of carbon emissions from oil, 860 billion barrels of oil are extracted from the ground. By 2000, the world had extracted almost exactly this amount. Estimates of ultimately recoverable conventional oil currently still in the ground are in the range of 2000 ± 1000 billion barrels[24].

It is therefore likely that by 2054 a significant fraction of the fuels used at small unit scale in vehicles and buildings will not come from conventional oil, but from unconventional oil and coal. We specifically identify synthetic fuels (synfuels) from coal here. A synfuel, chemically,

[24] A good discussion of oil reserve estimates can be found in reference S47, chapter 3. Cumulative consumption by 2000 is estimated as "close to 900" billion barrels (S47, p. 43).

can be any of the current fuels produced from crude oil and natural gas, or a new "tailored" fuel. If large-scale synfuels production from coal occurs, the challenge of global carbon management will become more difficult, because obtaining fuels from coal is significantly more carbon intensive than obtaining fuels from crude oil. However, CCS provides a way to cancel much of the extra carbon intensity of coal-based-fuels, relative to oil-based-fuels (S48). The reason is that in the conversion of coal to synfuels, abundant CO_2 will be produced.

In a modern plant, we estimate that, for each two carbon atoms in coal, one will appear as CO_2 and one in the synfuels. Given that assumption, how much synfuels production is associated with a wedge, when one considers the alternatives of CCS and its absence? A flow of 23.56 mbd of reference crude oil carries a carbon flow of 1 GtC/y.[25] If we assume that synfuels and reference crude oil have approximately the same carbon content and specific gravity, then 1 GtC/y is also 23.56 mbd (rounding off, say, to 25 mbd) for synfuels. We make the rough assumption that, at a 2054 synfuels plant, carbon will leave in equal amounts as vented CO_2 and as product. In that case, a carbon flow of 1 GtC/y in synfuels leaves behind at the coal-to-synfuels plant an equal 1 GtC/y flow of capturable and storable carbon. It follows that applying CCS rather than venting the CO_2 emitted at 25 mbd of synfuels plants is a wedge, if the CCS captures all the carbon, and a wedge is more like CCS deployed at 30 mbd of synfuels plants with less than perfect capture.

Currently, Sasol produces 165,000 barrels per day of synfuels and chemicals from coal in Secunda, South Africa, east of Johannesburg (S49). This is the world's largest synfuels facility, and it is similar in scale to a typical large refinery. Assuming the average specific gravity and carbon content of these synfuels is the same as reference crude oil, there is a carbon flow of 7 MtC/y in the synfuels leaving the Sasol plant. The Sasol plant is the largest point source of atmospheric CO_2 emissions in the world.

Comparing 165,000 barrels per day synfuels production from Sasol's plants with our estimate that 1 GtC/y will be available for capture in 2054 from 30 mbd of coal-to-synfuels production, a wedge is an activity that, over 50 years, achieves the ability to capture the CO_2 emissions from 180 Sasol-scale coal-to-synfuels plants.

A synfuels plant can be designed to "polygenerate" both electricity and synfuels from coal, and, as well, to capture and store as CO_2 the carbon not in the synfuels product. Over time, polygeneration could evolve to include a greater proportion of hydrogen production (S48).

An orientation to hydrogen fuel

Today, the two-way competition between electricity and secondary hydrocarbon fuels plays out in arenas as disparate as the home water heater and the steel furnace. It is plausible that this two-way competition will become a three-way competition, with the inclusion of hydrogen fuel. Like electricity, hydrogen is a *secondary* fuel. It has to be made from something else, and it can be made from everything else. Much work is being done to examine how hydrogen may enter the

[25] The equality of these two carbon flows, 1 GtC/y and 23.56 million barrels of reference crude oil per day (mbd) links the unit of our carbon discussion with perhaps the world's most widely used unit of bulk energy flow. This equality requires only two assumptions about reference crude oil: Its specific gravity is assumed to be 0.860 (API° = 33.0°), and it is assumed to be 85.0% carbon by weight. Also, 1 barrel = 42 gallons = 159 liters. Multiplying by 365.24 days per year, an alternate form of this equality is that 1 GtC is the carbon in 8.605 billion barrels of reference crude oil.

energy economy. A recent reference is the National Research Council (NRC) report, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs* (S38).

Hydrogen is already in widespread use, but as a chemical, not a fuel. Adding hydrogen at a petroleum refinery improves the product mix, and making hydrogen is a necessary first step in making ammonia (NH_3) and nitrogen fertilizer. Currently these two uses, between them, elicit an annual production of 40 MtH_2. Almost all this hydrogen is made from fossil fuels, because it is cheaper than hydrogen produced from nuclear energy or renewable energy; production from fossil fuels does not require the costly intermediate step of electrolysis of water.

The second output when hydrogen is produced from fossil fuels is CO_2. In a carbon constrained world, this will disadvantage fossil fuels as the source of hydrogen, relative to hydrogen produced from nuclear or renewable energy. Currently, at least 100 MtC is vented annually as CO_2, often at high purity, at H_2 production sites (S38, Chapter 7). Hydrogen produced with capture and storage of CO_2 (CCS hydrogen), discussed above because of the overlap with low-carbon coal-based power via gasification and CO_2 capture, will compete with nuclear hydrogen and renewable hydrogen. A 1 GtC/y carbon flow to the atmosphere in hydrogen production from fossil fuels is associated with only a ten-fold increase, relative to today, in hydrogen production. And the technology exists to capture and store this carbon.

CCS hydrogen and nuclear hydrogen can only be produced at large unit scale. Hydrogen produced at large scale can serve distributed users, like light-duty vehicles and buildings, only if there is a hydrogen infrastructure connecting the large with the small. Such an infrastructure does not now exist, and it may be more difficult to create than many other infrastructures. The reason is that a hydrogen infrastructure to provide fuel to dispersed users is in competition with small-scale hydrogen production downstream from two other already existing infrastructures: 1) the electricity infrastructure that facilitates local hydrogen production in small electrolyzers, and 2) the natural gas infrastructure that facilitates local hydrogen production in small methane reformers. If the second of these – the small methane reformer – dominates hydrogen production, the CO_2 generated at such dispersed sites is unlikely to be captured and stored, because of the diseconomies of CCS at small scale, and hydrogen production will not serve the goals of carbon mitigation.

An orientation to hydrogen vehicles

As we already saw in Section 2 of the Supporting On-Line Material (Energy Efficiency and Conservation), a wedge is available from more efficient light-duty vehicles. Specifically, we considered cars on the road in 2054, driven 10,000 miles per year, and achieving either 60 mpg or 30 mpg. As in Section 2 of the Supporting On-Line Material, we attribute 3 kgC of carbon emissions to each gallon of conventional fuel, thereby including a 25% overhead on a fuel carbon intensity of 2.4 kgC/gallon. Then, these cars emit, annually, either half a ton of carbon (at 60 mpg) or a full ton of carbon (at 30 mpg). A strategy that puts on the road in 2054 two billion 60 mpg cars, instead of two billion 30 mpg cars, is a wedge. Clearly, a second wedge can be obtained if these two billion 60-mpg cars run on hydrogen, as long as the carbon emissions associated with the hydrogen production are negligible.

Let us first assume that the substitution of energy as hydrogen for energy as gasoline is one-for-one. Invoking the useful fact that the energy content (lower heating value) of 1 U.S. gallon of gasoline and 1 kg of hydrogen are both almost exactly the same (120 MJ), the one-for-one assumption, therefore, means one ton of hydrogen fuel backs out three tons of carbon emissions at the tailpipe. The hydrogen vehicle gets 60 miles per gallon of gasoline equivalent and is driven 10,000 miles per year, so it requires 170 kg of hydrogen fuel per year and backs out 500 kg of carbon per year in conventional fuels. Two billion cars require 330 million tons of hydrogen per year and back out 330 billion gallons of gasoline or diesel fuel (containing 1 GtC) per year.

Treating the energy stored in hydrogen and stored in gasoline as equivalent leaves out many critical issues. Hydrogen scores less well than gasoline from the perspective of safety and storage. Hydrogen scores better than gasoline, if the full promise of fuel cells can be realized. The NRC Report postulates that fuel cells deliver a 67% premium in energy efficiency for hydrogen, relative to hybrid vehicles running on hydrocarbons (S38, Chapter 4); 100 mpg-equivalent fuel cell cars would displace 60 mpg gasoline or diesel cars, for example[26]. Then, each kilogram of hydrogen fuel backs out five kilograms of carbon in conventional fuel, and each 100-mpg-equivalent hydrogen car requires 100 kgH_2 per year and prevents 500 kgC/y of tailpipe emissions. Where two billion 60-mpg-equivalent cars required 330 million tons of hydrogen per year, two billion cars with a fuel economy of 100-mpg-equivalent require 200 million tons of hydrogen per year.

For the remainder of this section, we will assume the hydrogen fuel cell cars achieve 100 mpg-equivalent, and we will identify several wedges, each associated with a different way of producing, annually, 200 MtH_2 of carbon-free hydrogen, or an appropriately larger amount of low-carbon hydrogen.

CCS hydrogen and CCS-hydrogen vehicles

The NRC report provides flow sheets for a "current" coal-to-hydrogen plant without and with CCS. For each ton of hydrogen produced, if CO_2 is not captured, 5.1 tons of carbon as coal flow through the plant and are vented; if CO_2 *is* captured, 5.2 tons of carbon as coal flow through the plant, of which 4.4 tons of carbon are captured and 0.8 tons of carbon (16%) are vented (S38, Appendix E). Thus, if over the next 50 years, we move to a hydrogen economy with coal as the workhorse for hydrogen production, for each ton of hydrogen produced, the venting of 4.3 tons of carbon is at stake in the decision to deploy CCS technology, rather than to vent the CO_2, at coal-to-hydrogen plants. For each 230 million tons of hydrogen produced from coal in 2054, a wedge is at stake in the decision to deploy CCS technology. The NRC plants are large: the hydrogen production rate is 1200 tH_2/day. A wedge is at stake in the decision to deploy CCS at 500 of these plants.

The NRC report also provides flow sheets for "current" natural-gas-to-hydrogen plants without and with CCS. The NRC data can be anticipated knowing only that half as much CO_2 is produced per unit of energy from natural gas as from coal: For each ton of hydrogen produced, if CO_2 is not captured, 2.5 tons of carbon as coal flow through the plant and are vented; if CO_2 *is* captured, 2.8 tons of carbon as coal flow through the plant, of which 2.3 tons of carbon are captured and 0.4 tons of carbon (16%) are vented (S38, Appendix E). Continuing the reasoning of the previous paragraph, if over the next 50 years, we move to a hydrogen economy with *natural gas* as the workhorse for hydrogen production, for each ton of hydrogen produced, the

[26] The fuel economies of the NRC hybrid and fuel cell vehicles in 2050 are somewhat less: 50 and 83 mpg, respectively (S38, Chapter 4).

venting of 2.1 tons of carbon is at stake in the decision to deploy CCS technology, and for each 480 million tons of hydrogen produced, a wedge is at stake in the decision to deploy CCS technology. The NRC natural-gas-to-hydrogen plants also have a 1200 tH_2/day capacity. A wedge is at stake in the decision to deploy CCS at 1100 of these plants.

Although, under the assumptions above, 200 MtH_2 of *carbon-free* hydrogen can create a wedge by backing out conventional hydrocarbon vehicle fuel in two billion 60-mpg cars in 2054, how much more hydrogen needs to be produced, for how many additional vehicles, when one takes into account that CCS hydrogen is not completely carbon free?

Annually, each 100 mpg car requires 100 kgH_2, and 80 kgC is emitted at the coal plant when this hydrogen is produced. Then, the net atmospheric carbon emissions reduction in displacing a 60 mpg gasoline car with a 100 mpg-equivalent hydrogen is 420 kgC/y. To eliminate 1 GtC/y of emissions, therefore, requires changing not two billion, but 2.4 billion cars. A flow to the atmosphere at tailpipes of 1.2 GtC/y is replaced by a flow of carbon into CCS coal plants of 1.4 GtC/y, a flow into the atmosphere at CCS coal plants of 0.2 GtC/y, and a flow from the CCS coal plants into storage of 1.2 GtC/y. The net flow to the atmosphere is 1 GtC/y less.

The objective of hydrogen production from fossil fuels is to transfer as much of the energy content of the fossil fuel to the hydrogen as is consistent with optimizing the plant economics. Adding the objective of CO_2 capture complicates the optimization and increases the costs. However, most of the plant components required to capture CO_2 are already required to produce hydrogen. For example, the shift reactor (see Section IB, above) required for CCS is needed for hydrogen production without CCS, but not for power production without CCS. As a result, the fractional cost increment for CCS is substantially smaller in hydrogen production than in electricity production (S38, Chapter 8 and Appendix E).

C. Nuclear electrolytic hydrogen

An orientation to carbon-free hydrogen, applicable to both nuclear and renewable primary sources

Non-carbon energy offers opportunities to carve wedges out of the 2054 carbon economy not only by producing electricity that displaces fossil-energy-based electricity (discussed earlier), but also by producing hydrogen that displaces fossil-energy-based fluid fuels. The non-carbon energy can be either nuclear energy or renewable energy. In both cases, there are two ways of producing hydrogen: 1) via chemical cycles that require high-temperature heat, after first producing that high temperature heat, and 2) by the electrolysis of water, after first producing electricity.

The nuclear power plant capable of delivering heat at sufficiently high temperatures to run the chemical cycles identified thus far (roughly, 900°C) is not yet proven, nor has high-temperature heat from focusing solar collectors been shown to lead to competitive hydrogen. A good, recent review of nuclear hydrogen, including hydrogen via high-temperature cycles, is available (S38, Chapter 8). If high-temperature nuclear reactors can be developed, they will be capable of producing hydrogen at higher efficiency (hydrogen out divided by nuclear power in) than the route to hydrogen via electrolysis.

Like CCS hydrogen, nuclear thermal hydrogen will be produced only at large unit scale. By contrast, if hydrogen is to be made electrolytically from electricity on the grid, the unit scale of the electricity generator does not determine the unit scale of production of hydrogen. Instead, the unit scale of production of hydrogen will be determined by the unit scale of the electrolyzer. The scale for which the NRC Report develops flow sheets for electrolysis is 480 kilograms of hydrogen per day, 2500 times smaller than the scale of production of hydrogen from coal plants with CCS.

The "present" electrolyzer in the NRC Report is assumed to produce 1 kg of hydrogen from 52.5 kWh of electricity, or 19 grams of hydrogen per kWh, an efficiency of 75% based on the higher heating value of hydrogen, or 63.5% based on its lower heating value. Then, in the vehicle substitution strategy that we have been considering where 1 kg of carbon-free hydrogen backs out 5 kg of carbon, each 1 kWh of carbon-free electricity backs out 95 g of carbon.

Given carbon-free electricity, can carbon emissions be reduced more by directly backing out coal in a power plant or by making hydrogen and backing out gasoline or diesel?

The same kWh of carbon-free electricity just considered, which we directed toward hydrogen production for a fuel-cell car, instead could have backed out coal power. Which strategy backs out more carbon: Using a carbon-free kWh to make hydrogen for a 100 mpg fuel-cell car that removes a 60 mpg vehicle from the road, or using a carbon-free kWh to make electricity that keeps a coal power plant from running?

Suppose the same carbon-free kWh had been used to back out a kWh produced in one of the reference 50%-efficient coal power plants discussed above. Earlier, we worked out that each kWh at the coal plant produced 186 g of carbon emissions, so each carbon-free kWh used to produce electricity avoids 186 g of carbon emissions that would have been emitted at a coal plant. Here, we just worked out, each carbon-free kWh used to produce hydrogen avoids 95 g carbon that would have been emitted by a gasoline engine. Thus, we have the intriguing result that carbon-free electricity reduces carbon emissions twice as effectively when directed toward the displacement of coal-based electricity than when directed toward the displacement of gasoline fuel via electrolytic hydrogen.

The factor of two advantage of the coal-substitution strategy over the gasoline-substitution strategy for carbon-free electricity is the result of three assumptions: coal power plant lower-heating-value efficiency (C), electrolyzer lower-heating-value efficiency (E), and premium for hydrogen fuel, expressed as the number of kg C displaced by 1 kg H (R), all dimensionless numbers. The relative advantage of the coal strategy over the gasoline strategy in reducing carbon emissions – let's call it, the "electricity preference factor" – turns out to be 3.1/(CxExR). For our particular assumptions, C = 0.5, E = 0.635, and R = 5, the electricity preference factor is 1.9, or, approximately, two.

The electricity preference factor is *more* than a factor of two, if either C or E or R is less, relative to our inputs, while the other two are unchanged. The electricity preference factor is more than two, if C is less than 0.5, i.e., if the coal plant is less than 50% efficient, because then more coal is backed out. The electricity preference factor is more than two, if E is less than 0.635, because, with a less efficient electrolyzer, less hydrogen fuel is made. The electricity preference factor is more than two, if the multiplier is less than five for hydrogen in a fuel-cell vehicle relative to a gasoline vehicle, which would result, for example, if the fuel cell car is less spectacular.

We turn this comparison into a comparison of alternative wedges. We have considered three wedges that could be achieved starting from carbon-free electricity: 1) a wedge via carbon-free electricity displacing coal-based electricity; 2) a wedge via carbon-free electricity displacing natural-gas-based electricity; and 3) a wedge via carbon-free electrolytic hydrogen displacing conventional vehicle fuel. The first wedge is the most effective, requiring 5400 TWh/y. The second and third wedges are about equally demanding: the second wedge requires 10,800 TWh/y. The third wedge requires 100 kgH_2 per car per year in two billion cars, or 200 MtH_2/y. To produce such a wedge using our electrolyzer requires about 10,000 TWh/y of carbon-free electricity.

Nuclear electrolytic hydrogen is carbon-free hydrogen, except to the extent that fossil energy is used in the nuclear fuel cycle, in plant construction, etc. Assuming such "net carbon" issues can be neglected, all of the calculations above for carbon-free hydrogen apply. A wedge via nuclear electrolytic hydrogen used in very efficient fuel cell cars requires 10,000 TWh of annual nuclear power by 2054. This is four times the rate of production of nuclear power in 2000, 2600TWh/y, a statistic quoted earlier (S33, p. 411). Assuming nuclear plants with 90% capacity, a wedge requires the hydrogen produced from 1300 1 GW plants.

Compare with our earlier result that a wedge is 700 1 GW nuclear plants displacing coal power. We see the factor of two advantage of coal displacement relative to gasoline displacement at work here: it takes twice as much nuclear power to achieve a wedge via electrolytic hydrogen for fuel cell cars as via direct substitution for coal power.

Carbon emissions when grid-based electricity produces hydrogen

One can make hydrogen from coal either by the thermochemical processes discussed above or by electrolysis. The thermochemical route from coal to hydrogen yields 1 kgH_2 from 5 kgC in coal. The electrolysis route from coal to hydrogen produces 1 kWh from 186 gC in coal, and then requires 52.5 kWh for the electrolyzer to produce 1 kgH_2; as a result, the electrolytic route yields one kg H_2 from 10 kgC in coal. Thus, the thermochemical route from coal to hydrogen is twice as efficient as the electrolysis route.

Suppose we use grid electricity, rather than carbon-free electricity, to power the electrolyzer. Grid electricity averages over *all* sources. In 2000, 15,400 TWh of electricity were produced from all sources, and a total of 2.36 GtC was emitted to the atmosphere from all plants with fossil fuel sources (S33, pp. 410 and 411), resulting in an average carbon intensity for the current grid of 153 gC/kWh. Our electrolyzer, which uses 52.5 kWh to produce 1 kgH_2, results in the emission of 8.0 kgC when it produces 1 kgH_2 from grid electricity. This is *more* carbon than the 5 kg of tailpipe carbon displaced by 1 kg H_2 as fuel (for our strategy where 100 mpg-equivalent hydrogen fuel cell cars replace 60 mpg gasoline cars). Globally averaged grid electricity at present is too carbon rich to be a source of carbon savings via electrolytic hydrogen and fuel cell cars. Of course, there will be many local situations where completely carbon-free or relatively carbon-free electricity is available.

D. Renewable Fuel: Renewable Hydrogen, Solar Heat, Sustainable Biofuels

We discuss three ways in which renewable energy can produce wedges by decarbonizing fuel. Hydropower, wind power, and photovoltaic electricity can produce hydrogen via electrolysis. Direct sunlight can provide heat that backs out fossil fuels used for space and water heating in buildings. And, plant matter (biomass) can be converted into fuels.

Electrolytic hydrogen from renewables

Electrolyzers producing hydrogen do not know the difference between renewable electricity, nuclear electricity, and other sources of electricity. Thus, the result above, that 1 kg of hydrogen can be produce from 52.5 kWh of electricity, based on the NRC electrolyzer, holds for renewable energy as well. A wedge from our car substitution strategy requires 10,000 TWh/y of renewable electricity. This may be compared to the 2002 global rate of production of electricity from hydropower, 2650 TWh/y, four times less and almost exactly the same as the rate of production of electricity from nuclear energy (S33, p. 411).

While nuclear electricity comes only at large unit scale and must be grid-connected, renewable electricity comes at all scales. It can produce distributed power, and it can produce grid-independent power. A wedge from 10,000 TWh/y of renewable electricity making hydrogen that eliminates tailpipe carbon emissions could be produced by four million 1 MW_p windmills or four hundred million 10 kW_p photovoltaic arrays, operating at 30 percent capacity factor.

Solar heat

One can associate each use of fuel with a temperature required to meet the need that the fuel is serving. Two of the most important uses of fuel, from the standpoint of carbon emissions, are heating of living spaces and heating of water, and both involve supplying heat at a temperature not very different from nearby "ambient" temperatures (the temperatures of nearby outside air or ground water, for example)[27]. The jobs of space heating and water heating rarely involve boosting the temperature, relative to ambient temperature, more than 50°C. Thermodynamics identifies the combustion of fuels for such purposes as intrinsically inefficient (S50). Wedges are available from displacing carbon emissions from the chimney, just as they are available from displacing carbon emissions from the tailpipe.

We commented earlier in this section that the heat pump, in principle, offers significant carbon savings in space and water heating. We noted in Section 2 of the Supporting On-Line Material that the insulation of buildings offers similarly large savings. Here we note that still a third strategy is to pursue passive and active solar energy management, the domain of solar architecture, to heat buildings in winter and to heat water year round. A full wedge is probably available from judicious combinations of solar design, careful construction, substantial insulation, and broad use of efficient heat pumps. Detailed estimates remain to be done.

Sustainable biofuels

[27] To quantify how "different" one temperature is from another temperature, one must introduce the concept of absolute temperature, which is 273 degrees higher than Celsius temperature. The transfer of heat from outside air at 0°C to hot water at 50°C is a fractional increase in its absolute temperature of 50/273, or 18%.

At least one wedge is probably available from each of two distinctly different strategies involving changes to vegetation. One can enlarge the stock of carbon in vegetation (enlarging the carbon stored in forests, for example), thereby drawing down the stock of carbon in the atmosphere. This topic will be addressed in Section 4 on the Supporting On-Line Material (Forests and Agricultural Soils). It is also possible to replace fossil fuels with fluid fuels produced directly from plant matter (biomass) that is grown sustainably. In the latter case, the use of "biofuels" makes no net addition of CO_2 to the atmosphere; the biofuels oxidized for energy deliberately through technology would have decayed (oxidized) elsewhere anyway (wood on the forest floor, for example). A sustainable biofuel is one obtained from plants that are replaced by new plants at the same rate as they are used.

A hectare of land used to produce biofuels has the potential to have a larger effect on the atmospheric carbon balance than a hectare of land used as a carbon sink. There are two reasons: 1) Most of the new carbon fixed by vegetation each year is allocated to construct short-lived and fast–decomposing tissue, such as leaves and fine roots. Because of its short residence time in ecosystems, such tissue cannot contribute substantially to a carbon sink, but it can be collected and used to produce biofuels. 2) A hectare of land dedicated to biofuels can produce these fuels indefinitely, displacing a stream of fossil carbon indefinitely, whereas a hectare of land used as a carbon sink has a certain capacity to store carbon and then its contribution to carbon accounts "saturates."

Examples of biofuels crops include switchgrass, sugarcane, and corn (S51). A good yield from such annually harvested species is 15 dry tons (dt) per hectare per year. Dry biomass is about 50% carbon by weight, so the carbon yield is 7.5 tC/ha-y, and the yield from 130 million hectares (Mha) dedicated to such biofuels (biofuels plantations) is 1 GtC/y. This is 10 percent of today's 1500 Mha of total cropland.

The energy content of biomass fuel is between 15 and 20 GJ/dt. (The lower value is appropriate for crops, the higher value for wood.) Thus, a good energy harvest is about 200 to 300 GJ/ha-y. This harvest may be restated as 0.7 W/m^2 to 1.0 W/m^2. Comparing this harvest with annually averaged incident sunlight, typically 250 W/m^2, the harvest is seen to convert 0.3 to 0.4 percent of incident sunlight. Such a low conversion rate, even for a high-yield species, is confirmation that the conversion of incident sunlight via photosynthesis has been only one of many objectives of green-plant evolution. Accordingly, there is considerable headroom for genetic engineering to improve substantially on such yields with organisms designed to convert sunlight efficiently into fuel (artificial photosynthesis), greatly reducing the land demands for a future wedge from artificial biofuels, relative to biofuels from nature's plants.

How are biofuels likely to be used? The current energy economy demonstrates clearly that liquid and gaseous fuels that contain carbon are the most valuable forms of energy. We should anticipate that biomass will be transformed preferentially into biofuels, rather than into electricity or hydrogen. As discussed earlier in this Section, biomass conversion into electricity could also become significant, via distributed production and via co-firing with coal. But biomass conversion to hydrogen is unlikely to become important. Hydrogen is not an intrinsically desirable fuel. Its virtue, from a climate perspective is that it does not contain fossil carbon and can be produced with relatively low fossil-carbon emissions. Biofuels already share this virtue[28].

The International Energy Agency estimates that the total energy in biomass providing "primary energy" for human needs in 2000 was 45 EJ, roughly 10% of that year's total primary energy (420 EJ). It further estimates that the non-OECD countries accounted for 85% of this bioenergy (S33, p.411). Most non-OECD bioenergy consumption is "traditional biomass," including firewood, crop wastes, dung, and charcoal. In both the OECD and non-OECD countries, there is a substantial contribution from wood waste in commercial forestry.

Currently, the principal "modern" biofuel is ethanol. In 2002, global fuel ethanol production was 22 billion liters/y, or 380,000 barrels per day, 95% of which was produced in two large national programs: by Brazil (from sugarcane) and by the U.S. (from corn). In both cases, the ethanol is used as automobile fuel, backing out petroleum products. The production rate in Brazil in 2002 for fuel ethanol was 12.6 billion liters/y, or 220,000 barrels per day (S52), about equally in anhydrous and hydrated forms (S53)[29]. The production rate in the U.S. in 2002 was 8.2 billion liters/y (S52), or 140,000 barrels per day[30]. In the U.S., ethanol accounted for about one percent of the energy content of vehicle fuels (S55); it was used in 12 percent of fuel at 10% blend.

Taking 21.1 MJ to be the energy available in a liter of ethanol[31], 0.46 EJ/y is the primary energy production associated with 2002 global ethanol production, which is 1% of all primary biomass energy, and 0.1% of all primary energy. Since ethanol is 52% carbon, a liter of ethanol contains 0.41 kgC,[32] and a gallon of ethanol contains 1.55 kgC, about two-thirds of the volumetric carbon content of gasoline or diesel fuel. The current ethanol flow of 22 billion liters per year is a renewable carbon flow of 9 MtC/y, not much larger than the non-renewable carbon flow in Sasol's coal-derived synfuels (7 MtC/y, see above). The 2002 renewable carbon flows in Brazil's and the U.S.'s ethanol programs were 5.2 and 3.4 MtC/y, respectively.

Ethanol is currently the principal modern biofuel, because in the natural world there are bacteria that can produce ethanol by fermentation with high selectivity. A world with extensive biofuels production can be expected to produce a wide range of biofuels, including methanol, dimethyl ether (DME), and "biodiesel" fuels[33].

What amount of land produces a wedge, when its harvest of fast-growing biomass is converted to ethanol that backs out conventional vehicle fuels? We assume that ethanol is produced from

[28] Another "driver" of the energy economy toward hydrogen in many countries is hydrogen's ability to reduce dependence on imported oil and gas, when hydrogen is made from domestic energy sources. Biomass shares this advantage too.

[29] Brazil's 2002-2003 total rate of consumption of ethanol, 12.5 billion liters/y, is the sum of: 1) 5.6 billion liters/y as hydrated ethanol, blended into all gasoline sold in Brazil at a percentage in the low 20s, and 2) 7.0 billion liters/y as anhydrous ethanol, used in engines adapted for pure ethanol (S53).

[30] A different source reports that in 2003 U.S. fuel ethanol production was 10.6 billion liters/y (S54), or 180,000 barrels per day.

[31] The lower heating value (LHV) heat of combustion of liquid ethanol is 26.8 MJ/kg, and its specific gravity is 0.789. Then, the heat released (LHV) in the ethanol combustion 21.1 MJ/liter; equivalently, the combustion of 48 liters of ethanol release 1 GJ.

[32] We again use the specific gravity of ethanol, 0.789.

[33] The term "biodiesel" is confined to esters of natural vegetable oils. Biodiesel production is expanding rapidly in Europe. An annual biodiesel production capacity of 1.4 billion liters in Europe and 1.5 billion liters globally was in place in 2002 (S52).

biomass with 50% energy conversion efficiency. Then, 100 to 150 GJ of ethanol, or 5000 to 7000 liters of ethanol, are produced per hectare[34]. We further assume that engines designed for ethanol, taking advantage of its high octane rating, can convert fuel energy into energy for driving 25% more efficiently than engines designed for conventional fuel, at the same level of engine engineering. Our reference fuel-efficient conventional vehicle, again, is driven 10,000 miles per year with 60 mpg fuel economy, and so uses, annually, 167 gallons of gasoline. The energy content of this gasoline is 20 GJ. Then, annually, the ethanol car will use 16 GJ of ethanol, produced from 32 GJ of biomass. Assuming an average value of 250 GJ biomass yield per hectare, one-eighth of a hectare of dedicated land will be required for each car[35].

Using, as above, 3 kgC/gallon for conventional fuels (which includes 25% carbon overheads in fuels production), the carbon saved annually per car is half a ton. A wedge is the replacement, by 2054, of a fleet of 2 billion reference cars running on conventional fuels by cars fueled by ethanol. The ethanol for a wedge is produced from high-yield energy crops grown on 250 million hectares, an area equal to one-sixth of the world's cropland. It is an ethanol program producing 1000 billion liters of ethanol per year, which is roughly 100 times larger than the current Brazilian or U.S. program, or 50 times larger than the total global program.

Much of the land that would have to be dedicated to annually harvested biofuels crops to gain a wedge would also be suitable for conventional agriculture. Land resources can be stretched by obtaining biofuels from residues of commercial crops (examples include bagasse from sugarcane, corn stover, and rice husks) and from harvest and mill residues of forest plantations.

Not included here are CO_2 emissions associated with fossil-carbon inputs accompanying ethanol production (inputs for feedstock production and for conversion of feedstock to ethanol). The ratio of fossil fuel input to ethanol output currently ranges from about 10% for Brazilian sugar to near unity for U.S. corn (S52).

Biofuels production has one special feature often mentioned in connection with carbon management: If biomass is co-fired with coal in coal power plants with CCS or in coal-to-hydrogen plants with CCS, the carbon removed from the atmosphere during biomass growth ends up below ground. Via biomass, the atmosphere is scrubbed of CO_2. Atmospheric scrubbing via biomass conversion with CCS is likely to remain a small activity, however, if one accepts that biofuels, not electricity or hydrogen, are the preferred products of biomass production, and that most biomass energy conversion is likely to be at a smaller scale than is required for CCS.[36]

Large-scale scrubbing of CO_2 from the atmosphere may be feasible someday, not via storage of CO_2 containing the carbon "captured" by biomass, but via storage of CO_2 captured directly from

[34] This value of ethanol production per hectare per year is similar to Brazil's today from sugarcane, and twice the value in the U.S. today from corn (S52).
[35] The annual carbon flow per car is as follows: one-eighth of a hectare of biomass is, equivalently, 30 GJ, 2 tons, or 800 kgC. From the 800 kgC in biomass we produce 300 kgC in ethanol which backs out 400 kgC in gasoline. Including carbon overheads on the gasoline, 500 kgC of gasoline-related fossil-carbon are not emitted to the atmosphere. (Here, gasoline is 85% carbon, its LHV heat of combustion is 43 GJ/t, and its specific gravity is 0.74.)
[36] If the biomass feedstock has a higher C/H ratio than the biofuel product, there may be a CO_2 coproduct. For example, the C/H ratio of biomass – approximately, CH2O – is 0.50, which is higher than the C/H ratio of ethanol (C_2H_5OH), which is 0.33. A simplified ethanol production reaction produces excess CO_2: 3 $CH_2O \rightarrow C_2H_5OH$ + CO_2 + H_20. Therefore, biofuels production at very large scale could provide be an opportunity for carbon capture and storage.

the air at large dedicated chemical absorption facilities (S56, S57). Such air scrubbing technology, like nuclear fusion electricity, nuclear thermal hydrogen, and artificial photosynthesis, may provide "second-period wedges" in the second half of the century. All of these technologies have the potential to reduce 2104 carbon emissions by 1 GtC/y or more, and to reduce carbon emissions over the interval 2054-2014 by 25 GtC or more, relative to some plausible BAU for 2054-2104. But they probably do not have the potential to provide "first-period wedges" in 2004-2054, the subject of this paper. Assigning technologies to "first-period wedges" and "second-period wedges" may be a fruitful exercise.

Putting It All Together

The emissions profile of any specific carbon-responsive global economy can be described by a 3x3 carbon emission matrix for 2054 (three fuels, three sectors of the energy economy), like the two matrices presented at the beginning of this section (Tables S3 and S4). In particular, if the Business As Usual world in 2054 is chosen to be the 14 GtC/y matrix displayed in Table S4, then the carbon-responsive world is found by removing seven GtC/y from the entries in that matrix. The sum of the entries in the new matrix (all in GtC/y) will be seven[37].

We have introduced a large number of wedges that might be developed over the next fifty years as global carbon mitigation strategies. The number of different ways of choosing the seven wedges to fill the stabilization triangle is very large. Some strategies capable of providing one wedge may be able to provide two wedges. Some wedges included in one person's Stabilization Triangle will be considered part of Business As Usual by another person.

To stimulate discussion, we introduce a carbon-responsive matrix here, displayed in Table S5 and in Figure S2, bottom right. Here, as before, we restrict ourselves to integer entries. Relative to Table S4, of the three fuels, it is coal whose emissions we have most sharply reduced. Of the three sectors, it is transportation whose emissions we have least sharply reduced. Natural gas continues to provide fuel for high-value distributed uses, where carbon emissions are at too small a unit scale to be captured and stored. The extensive use of decentralized coal in developing countries for space heating has come to an end.

Many combinations of wedges to decarbonize the electricity sector are compatible with the top row of this 3x3 matrix. From the entries in the first row, one cannot infer the relative contributions of end use efficiency, nuclear power, renewable power, and CCS technology. Similarly, from the entries in the third row, one cannot discern the relative roles of efficiency, solar architecture, and industrial hydrogen in reducing carbon emissions from direct fuel use.

One can easily argue the merits of a transfer of one unit of emissions from one matrix element to another in Table S5. We note in particular that by placing a *1* where coal intersects transportation we are asserting that synfuels will be used extensively for transportation. Here, we are being consistent with the 14 GtC/y 3x3 BAU matrix proposed at the beginning of this section, where the same assumption was made. A world where synfuels from coal are not a significant source of

[37] An exception arises if one wedge or more is obtained by the storage of carbon in the biosphere, as discussed in the Supporting On-Line Material, Section 4. In this case, the sum of the entries in the matrix of 2054 carbon emissions can be more than seven. Each wedge of carbon storage in the biosphere allows an additional 1 GtC/y of emissions in 2054.

vehicle fuel would have a *3* where oil and transportation intersect and a blank entry where coal and transportation intersect.

Table S5, and any corresponding table the reader may propose, says nothing about *how* such wholesale decarbonization is to be accomplished. Industrial structures, carbon policies, targeted subsidies, international relationships, geophysical realities, research and development priorities, changes in behavior and values, and other crucial factors remain unspecified.

SECTION 4: FORESTS AND AGRICULTURAL SOILS

When evaluating methods of biological carbon sequestration, it is important to remember that ecological carbon reservoirs are dynamic. Each carbon atom taken from the atmosphere by the growth of a newly planted forest will eventually return to the atmosphere when the tissue that contains it dies and decomposes. Thus, biological sequestration occurs only if the size of an ecological carbon pool is permanently increased by a net transfer of carbon from the atmosphere to an ecosystem. For example, suppose that a region of cropland is converted into a mosaic of periodically harvested plantation forests, with an even age distribution of forest stands ranging from those newly harvested to those just before harvest. This conversion will remove carbon from the atmosphere because the total mass of carbon (living and undecomposed organic matter) in a mosaic of plantation forests is larger than the mass of carbon in cropland. The difference in carbon mass (plantation mosaic minus cropland) represents a one-time net transfer of carbon from the atmosphere to the land, even though each patch of forest in the plantation mosaic is periodically harvested.

The dynamic nature of ecological carbon pools also implies that options of biological sequestration cannot be relied upon indefinitely, simply because the sizes of ecological carbon pools cannot be increased forever.

Reduced Tropical Deforestation

The 1.5 billion hectares of tropical forests contain 7-10 wedges worth of carbon in living trees and another 5-9 wedges in soils (S10, S58-S61). When primary forest (forest that has never been logged) is converted to permanent cropland, all of the 120-165 tC/ha in living trees (S10, S59, S60) and up to one third of the 83-150 tC/ha in the top 1 meter of soil is emitted to the atmosphere (S10, S59, S60, S62, S63). Conversion to pasture emits the carbon in trees, but may actually increase soil carbon by up to 10% (S64).

Section 1 of the Supporting On-Line Material and (S10) review the current controversy about the size of the carbon source caused by tropical deforestation. Briefly, a recent satellite survey concludes that a net of ~ 6 million hectares of tropical forest were lost per year in the 1990's (S11 and see S12), whereas surveys based on FAO statistics (S65) conclude that loss rates were twice this high. This leads to a factor of two difference in emissions to the atmosphere: ~1 vs. ~2 GtC/y (S10).

We make the conservative assumption that deforestation emissions are ~1GtC/y and that they will decrease linearly by one half in fifty years (see Section 1, above). Thus, half a wedge could be achieved by cutting deforestation to zero in fifty years. On the other hand, if deforestation losses were 2 GtC/y, then elimination of deforestation by 2054, relative to elimination of half of deforestation by 2054, would create a full wedge. Previous studies that rely on relatively large estimates of deforestation losses (S62, S63) have also concluded that approximately one wedge could be filled by reduced tropical deforestation by 2050.

Approximately 40% of current tropical deforestation is in Latin America, and approximately 30% each in Africa and Asia (S63). According to S66, the primary causes of deforestation differ among the continents, with pasture for cattle dominating in Latin America, fuel wood and cropland co-dominating in Africa, and cropland dominating in Asia. Thus, future decreases in deforestation would imply reduced future land area in food production.

Temperate and Boreal Forest Sink

Forest clearance, primarily for cropland, was responsible for 87% of the net of 136±55 GtC transferred from the terrestrial biosphere to the atmosphere from 1850 to 1998 (S62). A small portion of these net emissions is now being reclaimed because of changes in land use in the temperate and boreal zones. The forest sink in the United States, Canada, Russia, and Europe is approximately 0.7 GtC/y, but with wide uncertainty (S8). The largest contributor is the United States (0.3 GtC/y), where the sink is caused primarily by land use change (S14, S67, S68). For example, over the last 50 years in the eastern United States, the annual increase in above-ground carbon in wood (0.3 GtC/y) was larger than harvest by 0.1 GtC/y (S67). Growth rates do not appear to have increased because of CO_2 fertilization in these forests (S14). Even if models of CO_2 fertilization were correct (see S69), the few percent increase in growth predicted because of CO_2 fertilization would not be enough to overturn the conclusion that the sink is caused overwhelmingly by agricultural abandonment and harvest practices. Although increasing growth rates are observed in some European forests, these are also probably due to changes in management (S70).

There are three ways to increase the northern forest sink. One could increase the carbon gain rate of existing forests, decrease the carbon loss rates, or increase forest area. The IPCC (S62, S63) proposes all three, and estimates that 60% of a wedge could be obtained from northern forests. However, a large fraction of this increase would come from controlling fire and insect pests to decrease carbon loss rates (see Figure 4.8 in S63). Although it is feasible to increase carbon storage in this way, the option is unusual, in that fire and pest control would have to continue effectively forever. By simply relaxing effort, all of the newly stored carbon would return to the atmosphere. (Other options, such as reforestation, could also be reversed, but only if an action, clear-cutting, were taken.) For this reason, we do not include pest and fire management in our analysis, and we conclude that substantially less than a wedge is available from changing the management of temperate and boreal forests, at least using technology that is already deployed at large scale today.

The half wedge mentioned in the text from reforestation or afforestation is calculated from the following simple model of the build-up of carbon in forests after planting:

$$C'(t) = S - C(t)/R,$$

where $C(t)$ [tC/ha] is the wood carbon stored per forest area at a time t [years] after planting, $C'(t)$ [tC/ha-y] is its rate of change, S [tC/ha-y] is the rate of wood carbon gain per forest area, and R [years] is the residence time of carbon in the ecosystem. We assume the forest gains carbon at a constant rate, so S is independent of time. Then, the wood carbon climbs to a plateau, $C(t) \sim RS$, after many multiples of R. The net increase in stored wood declines steadily:

$$C'(t) = Se^{-t/R}.$$

We define the sink at the end of the period of interest, T [years], to be K [tC/y]. (For a half wedge, $T = 50$ years and $K = 0.5$ GtC/y.) We further define $A(t)$ [ha] to be the amount of land in forest at time t, and $P(t)$ [ha/year] to be the rate of planting: $P(t) = A'(t)$. We find the rate of planting by requiring the total sink to grow linearly at all intermediate times: at time t, the sink is $(K/T)t$.

Equating the total sink at time t to the integral over the contribution to the sink from all previous times of planting (y):

$$Kt/T = \int_0^t [P(y) \times C'(t-y)]dy,$$

or, $$(K/ST)te^{t/R} = \int_0^t [P(y) \times e^{y/R}]dy,$$

Differentiating both sides yields the planting rate at time t:

$$P(t) = (K/ST)[1 + t/R]$$

The planting rate increases, to compensate for the older average age of the forests already established. The planting rate increases linearly. The total area planted by time T is:

$$A(T) = \int_0^T P(t)dt = (K/S)[1 + T/(2R)]$$

Typical values for the tropics are R = 50 years and S = 3 tC/ha-y; typical values for the temperate zone are R = 100 years and S = 1.5 tC/ha-y. Inserting T = 50 years and K = 0.5 GtC/y, we find that a half-wedge can be obtained by reforestation and afforestation of 250 Mha of tropical forest by 2054: the initial planting rate is 3.3 Mha/y, by 2054 the planting rate is 6.7 Mha/y, and over the 50 years the average planting rate is 5 Mha/y. A half-wedge can also be obtained by reforestation and afforestation of 417 Mha of temperate forest by 2054: the initial planting rate is 6.7 Mha/y, by 2054 the planting rate is 10 Mha/y, and over the 50 years the average planting rate is 8.3 Mha/y.

The half wedge mentioned in the text from storage of carbon on new plantations is calculated as follows. We assume that plantations gain carbon at a roughly constant rate, Z, [tC/ha-y], from planting through harvest, and that the number of years between harvests is r [y]. We assume a mosaic of plantations of area A [ha], with a uniform age distribution, so the mosaic contains a $AZr/2$ tons of carbon. By 2054, these plantations need to store 12.5 GtC to contribute half a wedge. This requires $25/Zr$ billion hectares of new plantations to be established by 2054. Note that the product, Zr, is simply the yield at harvest. If the yield at harvest is 80 tC/ha, then 313 million hectares of plantations have to be established by 2054 to achieve the half wedge. The current rate of formation of new plantations, 3.2 million hectares per year (S62), if continued for 50 years on previously unforested land, is already sufficient to create one quarter of a wedge. Also, 313 million hectares is approximately five times larger than the current 61 million hectares in plantations (S62, S65).

Agricultural Soils

Conversion of natural vegetation to annually tilled cropland results in the loss, on average, of one third of the soil carbon if the land was formerly forested, and of one half of the soil carbon if the land was formerly in grassland or pasture (S62, S64). Over historical time, approximately 55 Gt of carbon has been lost on the 1600 million hectares of cropland (S58, S63).

Soil carbon loss can be reversed by techniques that increase the rate of carbon input into agricultural soils or decrease the rate of carbon loss. The former include techniques to reduce the period of bare fallow and the planting of cover crops. The latter include conservation tillage practices that reduce aeration of the soil, such as no till, ridge till, or chisel plow planting (S62, S71). Experiments have shown that it is possible to reverse the loss of soil carbon on croplands with these techniques (S71- S73) and to store carbon at an average rate of 0.3-0.6 t/ha-y over a period of several decades (S62, S72-S74). The lower storage rate, if it could be continued for 50 years, would store the 25 GtC required to contribute a wedge if it were applied to all cropland.

Soil management strategies that increase soil carbon are already widely adopted. Conservation tillage alone had been adopted on 110 million hectares by 1995 (S74). The IPCC estimated that up to a wedge (up to 22-29 GtC) could be filled by management of existing agricultural soils (S63, S75).

Figure S1 (A)

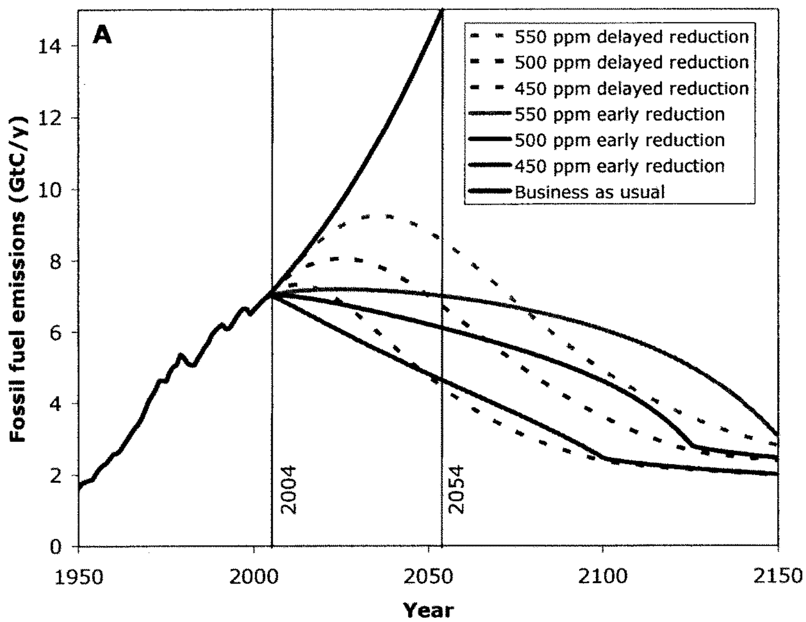

Figure S1 (B)

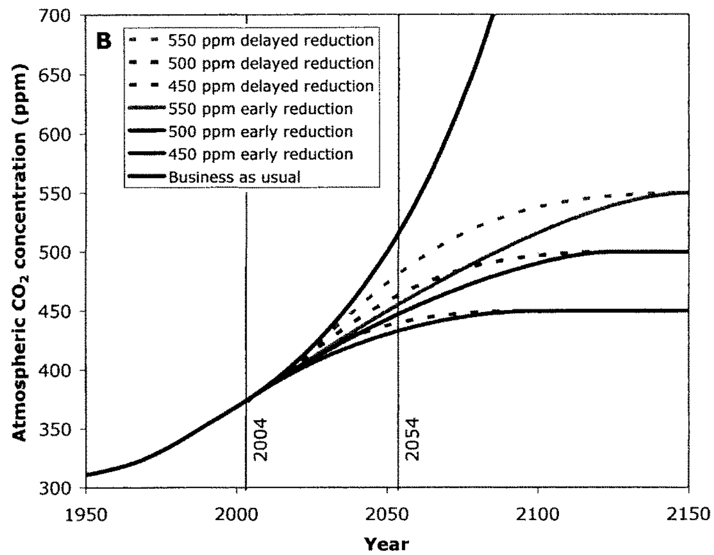

Figure S1. (A) The six stabilization emissions scenarios, and the Business As Usual (BAU) emissions scenario used in this study. The "delayed reduction" scenarios depart from BAU emissions between 2005 and 2010; they are identical to the "WRE" series stabilization scenarios (S19-S21) except that they follow historical and BAU emissions that have been updated since those scenarios were constructed, and the imposed atmospheric CO_2 concentrations in 2050 have been lowered by 5 ppm (for the 450 ppm scenario) or 10 ppm (for the 500 and 550 ppm scenarios), in order to keep emissions below those of the BAU scenario. The "early reduction" scenarios depart from historical emissions starting in 2004; they are otherwise identical to the "S" series stabilization scenarios described in (S21), which departed from historical emissions in 1990. The delayed reduction (WRE) 500 ppm scenario has been selected from this set to appear in Fig. 1A as an example stabilization emissions scenario. **(B)** Atmospheric CO_2 concentration trajectories corresponding to the six stabilization scenarios and the Business As Usual (BAU) emissions scenario.

Figure S2

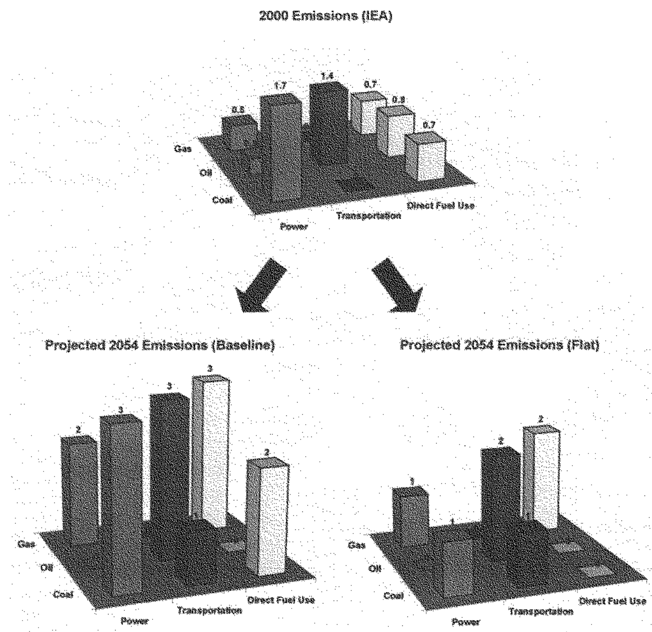

Figure S2. Graphical representations of Table S3 (top), Table S4 (bottom left), and Table S5 (bottom right). Carbon emissions are disaggregated by fuel and end use. In 2000, fossil-fuel-based global emissions of carbon to the atmosphere as CO_2 were 6.2 GtC/y (top, Ref. S33). The challenge of global carbon management is idealized by displaying a pair of worlds in 2054, one with 14 GtC/y emissions (bottom left), the other with 7 GtC/y emissions (bottom right). The difference between these two worlds is seven wedges of carbon-mitigation activity. The specific pair of 2054 worlds shown here is arbitrary; many other pairs are consistent with the wedges analysis.

TABLE S1. The six stabilization emissions scenarios and Business As Usual (BAU).

Scenario	Stabilization target (ppm)	Cumulative emissions from 2004-2054 (GtC)	Cumulative avoided emissions from BAU 2004-2054 (GtC)	Number of wedges	Emissions in 2054 (GtC/y)	Emissions rate of change in 2054 (%/y)
Business As Usual	–	525	–	–	15.0	+1.5
Delayed reduction	450	315	210	8.4	4.4	–1.7
(similar to IPCC	500	382	143	5.7	6.7	–1.1
"WRE" series)	550	433	92	3.7	8.6	–0.8
Early reduction	450	294	231	9.2	4.6	–1.0
(similar to IPCC	500	335	189	7.6	6.1	–0.4
"S" series)	550	359	166	6.6	7.0	–0.2

TABLE S2. Parameters used to generate the stabilization atmospheric CO_2 concentration curves in Fig. S1(B). See S21 for more information.

Scenario timing	Stabilization concentration (ppm)	Stabilization year	Departure year from BAU	Departure concentration (ppm)	Departure rate of change (ppm/y)	Tie-point year	Tie-point concentration (ppm)
Delayed reduction	450	2100.5	2005.5	377.9	1.74	2050.5	438.0
(similar to IPCC	500	2125.5	2008.0	382.4	1.83	2050.5	454.0
"WRE" series)	550	2150.5	2010.5	387.1	1.92	2050.5	475.0
Early reduction	450	2100.5	2004.5	376.1	1.71	2051.0	431.0
(similar to IPCC	500	2125.5	2004.5	376.1	1.71	2061.0	455.6
"S" series)	550	2150.5	2004.5	376.1	1.71	2071.0	480.2

Table S3: Allocation of emissions in 2000 among fuels and end-use sectors
Source: S33, p. 413.

		FUEL			
		Gas	Oil	Coal	*Total*
END-USE SECTOR	Power	0.5	0.3	1.7	*2.6*
	Transportation	--	1.4	--	*1.4*
	Direct Fuel Use	0.7	0.8	0.7	*2.2*
	Total	*1.3*	*2.5*	*2.4*	*6.2*

Note: 0.3 GtC/y for "transformation, own use and losses" has been distributed in proportion to the magnitude of each end use, for each fuel, and 0.1 GtC/y for non-energy uses has been distributed among the fuels within "Direct Fuel Use."

Table S4: Allocation of 14 GtC/y emissions in 2054 among fuels and end-use sectors in Baseline Scenario. Unit of Table entries: GtC/y.

		FUEL			
		Gas	Oil	Coal	*Total*
END-USE SECTOR	Power	2	--	3	*5*
	Transportation	--	3	1	*4*
	Direct Fuel Use	3	--	2	*5*
	Total	*5*	*3*	*6*	*14*

Table S5: One possible allocation of 7 GtC/y emissions in 2054 among fuels and end-use sectors. Unit of Table entries: GtC/y.

		FUEL			
		Gas	Oil	Coal	*Total*
END-USE SECTOR	Power	1	--	1	*2*
	Transportation	--	2	1	*3*
	Direct Fuel Use	2	--	--	*2*
	Total	*3*	*2*	*2*	*7*

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Statement of Senator Olympia J. Snowe
Senate Finance Committee Hearing
"America's Energy Future: Bold Ideas, Practical Solutions"
February 27, 2007

I want to thank the Chairman for holding this hearing, which I trust is the beginning of this Committee's comprehensive review of our nation's energy policy. This hearing comes at a time when the manifestations of our failed energy policy are discernible in the most significant issues facing the United States.

In trade, the importation of nearly 14.5 million barrels of oil per day exacerbates the annual US trade deficit by nearly $70 billion dollars. In foreign policy, Thomas Friedman has extensively written about the correlation between despotism and the price of oil. Referring to what he calls, "petroauthoritarianism," Friedman has stated that "as oil has moved to $60 to $70 a barrel, it has fostered a counterwave - a wave of authoritarian leaders who are not only able to ensconce themselves in power because of oil profits but also to use their oil wealth to poison the global system." The United States is the largest market for petroleum, consuming roughly 25% of the global supply.

Furthermore, the persisting high prices of energy has a dramatic effect on the budgets of families, especially in rural states. In aggregate, the repercussions of our current energy policy should invoke our country to develop an undertaking on the scale of our nation's great 20th Century missions like the Apollo Project . The leadership in this country needs to outline a bold challenge to the entrepreneurs and researchers and provide the resources to achieve this goal.

As the price of energy increases, the cost of inefficiency grows. As the price of oil remains over $60 a barrel, we clearly need to reassess how we use energy and improve our energy efficiency. Currently technology exists that dramatically improves the energy efficiency of residences and commercial buildings, which accounts for 70% of the electricity use in the country. Specifically, by making investments into energy efficient infrastructure, new buildings can reap energy savings of more than 50%. This is critical because, on average, residential buildings have life spans of 100 years and commercial buildings have life spans of 50 years. Making the initial investment into an energy efficient building, as opposed to standard infrastructure, pays dividends for decades.

Accordingly, I plan on reintroducing legislation that would extend and improve the energy efficiency provisions in the Energy Policy Act of 2005 and I am pleased that Dan Reicher, former Assistant Secretary for Energy for Energy Efficiency and Renewable Energy at DOE has urged Finance Committee members to support a sufficient length of time of assured incentives for efficient buildings and equipment so that the business community can realize the benefits in making investments. In total, experts have calculated that, if fully implemented, my EXTEND Act will by 2010 save 7 trillion cubic feet of natural gas. To put this figure in context, the United States imported 4.3 trillion cubic feel of natural gas in 2005.

It is critical that we creatively address our energy policy. With energy prices at their current rates, other technologies have become cost effective. For instance, extracting virgin materials, processing it, and making it into a final product is significantly more energy intensive than using recycled product. Taken together, the amount of energy wasted from not recycling aluminum, paper, printed materials, glass, and plastic equals the annual output of 15 medium sized power plants.

And the reality is that fossil fuel-burning power plants are responsible for over 40% of the global warming carbon dioxide that is spewed into the atmosphere and I am pleased that Montana Governor Schweitzer in his testimony today called on the federal government to put in place a national carbon cap and trade system in place to limit US CO2 emissions. This is exactly what the Kerry-Snowe Global Warming Pollution Reduction Act of 2007 calls for, and states goal of cutting greenhouse gas emissions by 65 % by 2050, starting in 2010.

I am pleased that Dr. Socolow was on the panel today as he and I are participants in Columbia University Earth Institute's Global Roundtable on Climate Change and both of us have signed on to GROCC's Joint Statement introduced just this past week in New York City. I do want to mention that I have sent the document defining actions for moving forward on global warming to all of my colleagues here in the Senate. My hope is that my colleagues will read the Joint Statement and consider signing on to the GROCC Joint Statement as well, and I would like to submit it for the Record to accompany my statement.

It was at the second GROCC meeting that Dr. Socolow presented his "Stabilization Wedges" concept, which I found both a fascinating and thought-provoking approach to CO2 emissions reductions. The Wedges game is a great teaching tool for students at Princeton - and for many levels of education - as to how to cut 25 billion ton "wedges" of carbon out of the predicted future emissions in the next 50 years to avoid a doubling of atmosphere carbon dioxide over pre-industrial levels. The concept is a simple tool for conveying the emissions cuts that can be made to avoid dramatic climate change and drives home the scale of the carbon mitigation challenge and the tradeoffs in planning climate policy.

Dr. Socolow should be commended for creating such an interesting approach to greater understanding as to how we can reduce CO2 emissions, and everyone at this hearing should take their turn at trying to solve the problem of preventing too much CO2 from entering the atmosphere in the next 50 years. It is an eye-opener! Unfortunately, we cannot put this "game" away like we can Monopoly at the end of the day. As the Wedges game stresses, we have a lot of hard policy decisions ahead of us that must be made for the health of the planet.

The new reality is that wasting energy is extremely expensive and very polluting. The Electric Power Research Institute, based in Palo Alto, has developed a report, released a report this month, which listed "Increased end-use energy efficiency in homes, buildings and industry" as the most important method to reduce carbon emissions and save energy. Also, Mr. Arivizu in his testimony, has stated that "Energy efficient solutions are often the most cost effective way to meet future demand and also provide additional non-energy benefits, such as improved productivity, increased durability and reduced air emissions."

I also believe that this committee should strongly consider extending the renewable energy Production Tax Credit (PTC) for a significant time period. The current PTC is due to expire on December 31st, 2008, and this does not allow renewable energy businesses to adequately prepare for the long-term. This problem was analyzed in a special report in the Economist, which stated that, "America's incentives for clean energy" are "relatively modest compared to Europe's."

Furthermore, the article illustrates that, "what one politician can mandate, another can terminate - and therein lies one of the biggest risks for clean energy. American politicians have periodically allowed a tax break for wind generation to expire, for example. This caused the industry to falter several times, before the credit was renewed again." We need to provide the renewable energy industry with consistency and long-term reliability and I look forward to working with my colleagues to make that a reality.

In my home state, energy prices are having a tremendous impact on the bottom-line of our businesses and the budgets of families. The United States must develop the technologies and energy efficiencies to maintain competitive and it is prudent to utilize the tax code to facilitate and accelerate this development. I look forward to working with the Chairman and Ranking Member as we begin this vital debate.

I thank the Chair.

GLOBAL ROUNDTABLE ON CLIMATE CHANGE

The Path to Climate Sustainability

A Joint Statement by the Global Roundtable on Climate Change

February 20, 2007

The Earth Institute
AT COLUMBIA UNIVERSITY

The Path to Climate Sustainability
A Joint Statement by the Global Roundtable on Climate Change

EXECUTIVE SUMMARY

Climate change is an urgent problem requiring global action to reduce emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs). Energy use is vital for a modern economy. Burning fossil fuels produces CO_2. Thus, confronting climate change depends, in many ways, on adopting new and sustainable energy strategies that can meet growing global energy needs while allowing for the stabilization of atmospheric CO_2 concentrations at safe levels.

Energy efficiency must play an important role in these strategies, but long-term success will require a concerted effort to de-carbonize the global energy system. This means significantly increasing the use of non-fossil-fuel energy sources, significantly raising the energy efficiency of fossil-fuel power plants through advanced technologies, and developing and deploying technologies that trap and store the CO_2 produced by the fossil fuels that will remain in use.

Cost-efficient technologies exist today, and others could be developed and deployed, to improve energy efficiency and to help reduce emissions of CO_2 and other GHGs in major sectors of the global economy. Research indicates that heading off the very dangerous risks associated with doubling pre-industrial atmospheric concentrations of CO_2, while an immense challenge, can be achieved at a reasonable cost. Failing to act now would lead to far higher economic and environmental costs and greater risk of irreversible impacts. To meet this challenge and take advantage of these opportunities:

- The world's governments should set scientifically informed targets, including an ambitious but achievable interim, mid-century target for global CO_2 concentrations, for "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system," in accordance with the stated objective of the Framework Convention on Climate Change (UNFCCC).
- All countries should be party to this accord, which should include specific near- and long-term commitments for action in pursuit of the agreed targets. Commitments for actions by individual countries should reflect differences in levels of economic development and GHG emission patterns and the principles of equity and common but differentiated responsibilities.
- Clear, efficient mechanisms should be established to place a market price on carbon emissions that is reasonably consistent worldwide and across sectors in order to reward efficiency and emission avoidance, encourage innovation, and maintain a level playing field among possible technological options.
- Government policy initiatives should address energy efficiency and de-carbonization in all sectors, allow businesses to choose among a range of options as they strive to minimize GHG emissions and costs, encourage the development and rapid deployment of low-emitting and zero-emitting energy and transportation technologies, and provide incentives to reduce emissions from deforestation and harmful land management practices.
- Governments, the private sector, trade unions, and other sectors of civil society should undertake efforts to prepare for and adapt to the impacts of climate change, since climate change will occur even in the context of highly effective mitigation efforts.
- Signatories to this statement will support scientific processes including the Intergovernmental Panel on Climate Change (IPCC); work to increase public awareness of climate change risks and solutions; report information on their GHG emissions; engage in GHG emissions mitigation, which can include emissions trading schemes; champion demonstration projects; and support public policy efforts to mitigate climate change and its impacts.

The Path to Climate Sustainability
A Joint Statement by the Global Roundtable on Climate Change

CLIMATE AND ENERGY

Climate change is an urgent problem that requires global action to reduce emissions of greenhouse gases in a time frame that minimizes the risk of serious human impact on the Earth's natural systems. While undeniably complex, confronting the issue of climate change depends, in many ways, on developing and deploying low-carbon energy technologies.

The modern age is powered largely by fossil fuels: coal, oil, and gas. The fossil-fuel era has been a period of unprecedented economic advance, with the world's average life expectancy roughly doubling and its per capita income rising roughly ten-fold since the start of the Industrial Revolution. Yet we now understand that fossil fuels—as they are currently used—increase the amount of carbon dioxide (CO_2) in the atmosphere which, along with the release of other greenhouse gases (GHGs), warms the planet and leads to other impacts of global climate change.[1]

Human-caused, or anthropogenic, climate change is now underway. If it continues on the current trajectory, it will become increasingly dangerous and costly for current and future generations through myriad impacts on the environment and human society and lead to the extinction of many species.[2] To avoid such risks, termed "dangerous anthropogenic interference with the climate system" in the 1992 UN Framework Convention on Climate Change (UNFCCC), which has been ratified by more than 180 countries, the world must adopt a new and sustainable energy strategy for the 21st century.[3]

Improving energy efficiency will be an important part of this strategy, especially initially because available and cost-effective strategies can be deployed quickly. Energy can be produced and used far more economically, contributing the same level of output with a lower input of energy.[4] Available options include increasing the efficiency of both power plants and the transmission of electricity to end users; expanding the use of combined heat and power generation technologies (co-generation); increasing the fuel-efficiency of cars, trucks, planes, and ships; and improving and expanding the use of more efficient buildings, furnaces, lights, and appliances. Energy efficiency presents win-win scenarios for the economy and the environment, helping to moderate both energy demand and GHG emissions and complementing other technologies needed to meet rising global energy demands.

Yet improving energy efficiency will not be enough. Because energy use is vital for a modern economy, the worldwide demand for energy is bound to increase as economic development continues around the world.[5] As a result, societies must not only use energy more efficiently, but also must emit much less CO_2 per unit of energy produced. The reduction of CO_2 emissions per unit of energy, an essential requirement of addressing climate change, is known as de-carbonization.

De-carbonization can be achieved in two ways. The first is to increase the use of non-fossil-fuel-based energy sources. Potential options here include wind, solar, geothermal, hydro, tidal, wave, nuclear, waste-to-energy, and/or biomass.[6] The choices among these technologies will depend on costs, safety, public acceptance, and other considerations. Effective and relatively cost-efficient technologies exist for some of these options today and others could be developed and deployed. Significantly increasing the use of such energy sources, both when building new infrastructure and when replacing fossil fuel facilities, is essential if we are to meet the climate change challenge while meeting global energy needs.

GLOBAL ROUNDTABLE ON CLIMATE CHANGE

The second is to adopt technologies that permit the use of fossil fuels while preventing the build-up of CO_2 in the atmosphere. One of the main options here is carbon capture and sequestration (CCS)—gathering and storing the CO_2 produced by burning or gasifying fossil fuels. CCS technologies that capture CO_2 emissions at the source (from a power plant, for example) and then sequester them beneath the Earth's surface have been proven technically but need to be demonstrated commercially and at the scale required to make a significant impact on efforts to de-carbonize the global energy system.[7]

Pursuing CCS should not be seen as an alternative to achieving significantly greater energy efficiency or greatly expanding the use of non-fossil-fuel-based energy sources but rather as an additional and important component to a comprehensive 21st century energy strategy. For example, realistic analysis suggests that, given the global distribution of immense coal reserves, coal is likely to remain an important fuel source for electricity production, and perhaps other energy needs, in many countries for an extended period.[8] CCS represents a potential method for significantly limiting the release of CO_2 from the use of these coal reserves, as well as the use of other fossil fuel reserves. Other currently available options that can reduce, although not eliminate, GHG emissions from coal-fired electric generation include distributed generation with co-generation and a variety of advanced coal technologies with improved energy efficiency and lower carbon emissions.

The impacts of climate change are already being observed, and each new power plant or factory constructed using standard fossil-fuel technology (especially without provision for CCS) locks in place a path of high CO_2 emissions during the life of the facility, which can be 50 years or more. Every year that passes without significant global efforts to reduce emissions means a higher concentration of atmospheric CO_2 and an increased risk that the world will surpass levels of atmospheric CO_2 that make "dangerous anthropogenic interference" unavoidable.[9]

The arithmetic behind the threat is compelling. The atmospheric concentration of CO_2 is now more than 380 parts per million (ppm), about 30 percent higher than it stood in 1900.[10] Nearly half of this increase has occurred since 1980. The world currently uses around 7 billion tons of carbon-based fuels per year, and emits roughly 2 billion tons of CO_2 from deforestation and land-use change, and CO_2 concentrations are now rising by around 2 ppm per year—a rate that is increasing.

As the CO_2 concentration rises, the impacts on the planet also mount. Some leading scientists put the threshold for "dangerous anthropogenic interference" as low as 450 ppm because of serious risks of major sea level rises, changes in weather patterns, and the extinction of many species.[11] Broad scientific consensus exists about the risks of reaching 560 ppm, which is sometimes called 2X CO_2 because 560 ppm is twice the pre-industrial concentration of 280 ppm.[12] However, even this higher threshold will be very hard to avoid unless strong actions are adopted in the near future. A "business-as-usual" path, meanwhile, could put the planet well above 750 ppm and perhaps at triple pre-industrial CO_2 levels (that is, 840 ppm) by the end of the century.[13]

The challenge is clear. Society must move reliably and swiftly toward a de-carbonized energy system and must do so in a manner that minimizes the transition costs, avoids economic dislocations, and does not jeopardize the economic development of poorer countries. Transition strategies should aim to reduce and/or compensate adjustment costs on workers affected by the move to de-carbonized energy systems.

There will be no single solution—many changes in energy efficiency and energy technology will play a role. Moreover, no single economic sector or group of countries can solve the problem alone. De-carbonization of the energy system will require global action in all key sectors of each economy. The changeover will require decades to complete, but the climate arithmetic dictates that we start now in order to avoid more dangerous risks in the coming decades.

GLOBAL ROUNDTABLE ON CLIMATE CHANGE

WHY WE CAN SUCCEED

The main source for optimism on heading off dangerous anthropogenic climate change is the potential to greatly reduce carbon emissions at reasonable adjustment costs to the economy. The world economy can achieve much lower carbon emissions per unit of output by achieving lower energy input per unit of economic output (energy efficiency) combined with much lower CO_2 emissions per unit of energy (de-carbonization):

Lower CO_2 / Output = Lower Energy / Output X Lower CO_2 / Energy
(efficiency) (de-carbonization)

The largest carbon-emitting sector is power generation, which the International Energy Agency identifies as responsible for more than 40 percent of global, energy-related CO_2 emissions, with that share likely to rise in the future. Industry accounts for more than 18 percent of energy-related CO_2 emissions. Transport (cars, trucks, and planes) contributes another 20 percent. The residential and services sector (which includes most commercial and residential buildings and agricultural energy inputs) accounts for nearly 13 percent,[14] although it can be considered to account for significantly more when electricity use is included.

Although completing the entire path to climate stability represents a very significant challenge, opportunities exist in each of these sectors for both increased energy efficiency (reduced energy per unit of output) and de-carbonization (lower CO_2 emissions per unit of energy). Here are some highlights:

Power Generation. Power plants can become more efficient in converting energy into available end-use electricity, as can the transmission of that electricity to the end-user.[15] Co-generation can be deployed more widely for use in district systems, industrial parks, and commercial malls at more than twice the energy efficiency as centralized power systems. The power sector can be gradually de-carbonized by shifting increasing proportions of electricity production to non-carbon fuels (this includes options such as wind, solar, hydropower, geothermal, tidal, nuclear, waste-to-energy, and/or biomass), utilizing lower carbon fuels where appropriate, developing and deploying advanced fossil-fuel technologies with high energy efficiency and low carbon emissions, and developing and deploying CCS technologies. Improvements in each of these technologies as well as a potential mix of new energy sources (e.g. solar thermal power, wave energy, and possibly nuclear fusion) will also play a role in further reductions. Increasing the use of low- and zero-CO_2-emitting distributed generation could also yield important ancillary benefits, particularly but not exclusively in developing countries.[16]

Industry. Important, large, energy-intensive, high-CO_2-emitting business sectors such as cement, steel, petrochemicals, and refining have a variety of options to improve energy efficiency and increasingly de-carbonize their operations. These include utilizing new production processes, installing highly efficient on-site generation technologies, converting to non-fossil-fuel energy sources, developing and deploying CCS technologies, and other options. Although global economic activity will likely increase energy demand in this sector, energy efficiency measures, co-generation, CCS, and GHG mitigation policies that favor low-carbon energy sources mean that the increased output can be combined with lower overall carbon emissions.

Transportation. All forms of transport (cars, buses, and trucks in particular, but also trains, planes, and ships), can become substantially more efficient (requiring less energy input per mile), in some cases through measures such as design and operational improvements, hybrid power systems, and lightweight design. Increasing levels of de-carbonization in the transport sector can be pursued by adopting biofuels, hydrogen, electricity produced by low- or zero-carbon emission technologies, and/or more efficient conversion technologies such as fuel cells. Mass-transit, traffic management, and commuting strategies can also help to decrease aggregate emissions from transport sector.

Residential and Services. Commercial and residential buildings account for a significant percentage of electricity consumption and CO_2 emissions.[17] Green building can play an important role in efforts to increase the efficient use of energy. Greater use of proven, scientifically based methods and standards for improved building design, sustainable site development, energy and water efficiency, enhanced insulation, materials selection, and indoor environmental quality would yield significant reductions in GHG emissions and produce other benefits.[18] De-carbonization can be pursued by converting heating and cooling systems reliant on fossil fuels to electricity and piped heat produced by low- or zero-carbon emission technologies.

In some cases, energy efficiency and de-carbonization will add little to the overall costs of energy to end users in these sectors. Significant, cost-efficient opportunities exist for efficiency gains using existing technology and proven practices. New technologies are on the horizon that might also save money and reduce GHGs at the same time. Pure win-win possibilities exist, but in some cases these technologies are impeded by government policies, lack of consumer information, or regulatory impediments. Such barriers to reduced GHG emissions should be removed as soon as possible.[19] Developing and deploying new technologies can also provide new business and employment opportunities for companies that take the initiative. In such efforts, "life-cycle thinking" on product and process design will be relevant.[20]

More often, however, the changeover to low-carbon and de-carbonized energy systems will require additional investments which will raise the costs to energy end-users. However, the costs of avoiding dangerous anthropogenic interference while achieving a more efficient and de-carbonized global energy system still appear reasonable, particularly compared to the costs of inaction and the consequential impacts of significant climate change. Again, while the precise figures are uncertain and we have not sought agreement on specific quantitative claims, it is reasonable to believe that heading off a doubling of CO_2 concentrations can be achieved at a cost of about 1 percent of global GDP and perhaps less as new technologies become established.[21]

Put in different terms, this equals an average cost of about 2 cents per kilowatt-hour and 25 cents per gallon of gasoline.[22] The cost-per-ton of avoided CO_2 emissions can probably be kept to an approximate average of $25 to $30.[23] The exact cost will of course vary by economic sector and region, as well as over time. Many of the least expensive and potentially profitable options will be available in the initial phase (e.g. in situations where energy efficiency savings cover investment costs or where locally cost-effective energy alternatives are available). Costs will likely increase as the need to develop and deploy new technologies and infrastructures increases. Costs will also vary to the extent that there is effective use of existing technologies (including timely government action to facilitate deployment of existing low- or zero-carbon-intensive technologies), timely government and private sector support for research, development, and demonstration of new technologies, and public acceptance of those technologies. Nevertheless, and most importantly, if we delay too long in beginning the changeover to increasingly de-carbonized energy systems the eventual costs will only rise and the impacts of climate change will only become more severe.

GLOBAL ROUNDTABLE ON CLIMATE CHANGE

HOW WE CAN SUCCEED: TOWARDS A GLOBAL PLAN

Participants in the Global Roundtable on Climate Change (GROCC) aim to support a greater global consensus on core aspects of a realistic policy on climate change; one that seeks the simultaneous objectives of effectively mitigating anthropogenic climate change while also creating the sustainable energy systems necessary to achieve long-term economic development and growth for all nations. In that spirit, we put forward the following as important principles for creating an effective climate policy.

- The world's governments should work expeditiously to agree on a target for stabilizing CO_2 levels in the atmosphere. The target should aim explicitly at "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" in accordance with the stated objective of the Framework Convention on Climate Change (UNFCCC).[24] Deliberations on this target should be informed by the best and most current scientific information available, in particular the comprehensive 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).[25] As part of this agreement, governments should agree on an ambitious but achievable interim, mid-century target for global CO_2 concentrations and on a series of specific measures to ensure that effective and meaningful action is undertaken immediately.[26] As with all effective policies, targets should be adaptable to new evidence in a reasonable and precautionary manner.
- All countries should be party to this accord and it should include specific national and international commitments for action in pursuit of the agreed-upon target. Commitments for actions by individual countries should reflect differences in levels of economic development and GHG emissions patterns, and the principles of equity and common but differentiated responsibilities. The need for all regions of the world, including developing countries, to participate reflects the basic arithmetic of carbon emissions. The developing countries, as a group, will soon be the largest emitters of GHGs, though on a per capita basis the developed regions will still be far larger emitters. There is no prospect for stabilization of GHGs unless all countries with major emissions are actively committed to that goal.[27]
- In accordance with the principles of equity and common but differentiated responsibilities, the global agreement should include specific mechanisms for industrialized countries to take leadership roles related to emission reductions, such as developing, demonstrating, and deploying low- and zero-carbon-emission energy technologies and CCS systems and/or providing appropriate assistance to developing countries to help them adopt low-carbon energy systems (for example, by creating a new sustainable energy fund to support the introduction of low- and zero-carbon-emitting energy technologies in low-income countries). Continued and effective support should also be provided to the Clean Development Mechanism (CDM) and related initiatives.[28] Deeper and wider mutual understanding among developed and developing countries should be promoted in order to realize these mechanisms. Developed countries should appreciate the special challenges faced by poorer countries in combining economic development with GHG mitigation, as well as the historical patterns of GHG emissions.[29]
- Clear and efficient mechanisms are needed to place an appropriate market price on carbon emissions at the national and international level.[30] The price on carbon emissions should be reasonably consistent across sectors and worldwide. Establishing such a market price (via tradable emission credits, permits, incentives, taxes, and/or other measures) is needed to reward efficiency and emission avoidance, encourage innovation, help induce energy producers and consumers to choose low- and zero-carbon emission technologies, create a level playing field across technology options, and, thereby, reduce the overall, system-wide cost of de-carbonization.[31] The most successful policies will give a clear price signal for many years into the future.
- Energy efficiency and timely de-carbonization should be pursued in all major economic sectors and include sector-appropriate mixtures of performance standards, market mechanisms, and incentives to discourage the creation of additional high-carbon emission energy production and encourage low- and zero-carbon emission energy technologies. Businesses should be allowed to choose among a wide range of options, locally and globally, as they strive to minimize both GHG emissions and costs. Subsidies and other policies that encourage the use of high-carbon emission technologies, especially

without provisions for CCS, or that discourage non-carbon, renewable energy sources, should be carefully reviewed and generally eliminated.

- Incentive schemes and policy mechanisms should not inadvertently work against early actions by companies, for example by inappropriately "raising the bar" on companies that have taken mitigation actions ahead of policy changes. Indeed, policy makers should make efforts to encourage rather than discourage such early actions.
- Carbon emissions from deforestation, which represent a significant portion of total global emissions, should be addressed. Incentives to protect forests should be included in relevant international and national policy mechanisms. These efforts should include providing appropriate financial incentives and emissions credits to developing countries that reduce CO_2 emissions by protecting tropical forests.[32]
- Land management patterns can have an important impact on net emissions of CO_2, methane, and nitrous oxide. Public policies should provide incentives to implement land management practices that reduce net greenhouse gas emissions or augment the carbon content of soils.
- Governments should support, through direct funding or incentives for the private sector, major increases in research, development, and deployment (RD&D) of advanced non-carbon-emitting energy technologies. Targets for increased RD&D could include (but are not limited to): solar photovoltaic, solar thermal power, geo-thermal, tidal, wave, and/or nuclear energy (including safety, waste storage, and proliferation issues); CCS; improved land management; and sustainable transportation (e.g. bio-fuels, hybrid technologies, fuel-cell technology, and/or lightweight design).[33] Special demonstration programs and other kinds of public policies (e.g. supportive regulations) should be adopted to enable promising new technologies and practices to reach the market expeditiously. Such programs will be of special importance in the rapidly industrializing developing countries.[34]
- Green building standards and incentives should be expanded and efforts to reduce energy use through green building initiatives should be supported at the public and private level. Efforts to reduce global emissions of methane from landfills should be expanded, including increased use of waste-to-energy facilities where appropriate and cost-effective. Policies that encourage or include provisions for GHG offsets (projects funded by industries, businesses, institutions, or individuals in order to compensate for their GHG emissions in other areas), should ensure that all GHG offsets are real, verifiable, additional, and quantifiable.
- Public-private councils should be formed in key sectors (for example, electricity production, cement, steel, petrochemicals, commercial building, and others) to assist the formulation, promotion, and adoption of standards for safety, efficiency, and consumer acceptability of key sustainable energy technologies. Such councils should include key stakeholders, such as policy makers, business leaders, trade unions, consumer groups, and civil society.[35]
- Efforts should be undertaken to prepare for and adapt to the impacts of climate change. Many of these impacts will fall most heavily on the poorest and most vulnerable communities and in developing countries with the least ability to adapt. Technical and financial assistance will be needed by particularly vulnerable, low-income, developing countries to meet their mounting adaptation needs. Mitigation and adaptation efforts need to be part of a coherent dual strategy. Effective climate adaptation will require stronger efforts within international climate agreements as well among development agencies, the private sector, and non-governmental organizations.

GLOBAL ROUNDTABLE ON CLIMATE CHANGE

OUR CLIMATE RESPONSIBILITY

Each company and institution, as well as each government, has the opportunity and responsibility to address climate change. This responsibility can be fulfilled in a variety of ways, which will differ depending on the nature of the business or organization. In this spirit, and in recognition of the importance and immediacy of this issue, we commit ourselves to pursuing the following measures and invite others to do likewise:

- Publicly supporting the global scientific processes that underpin international decision making with regard to climate change, including the IPCC.
- Advocating responsible climate and energy policies, including globally agreed-upon targets for stabilizing GHG levels in the atmosphere; policies designed to achieve these targets; increased research, development, and deployment of new technologies; and enactment of supportive market mechanisms and other policies.
- Helping to communicate information on climate change solutions, including energy efficiency, life-cycle thinking, and other options, to customers, suppliers, employees, and the public.
- Monitoring and reporting information on our annual emissions of greenhouse gases.
- Adopting clear goals and policies on our GHG emissions and engaging in appropriate GHG emissions mitigation efforts and programs, which could include participation in emissions trading schemes, offsets, CDM, or other mechanisms.
- Incorporating climate change and GHG emissions into relevant business management decision making, and communicating such actions to key stakeholders, such as investors, employees, suppliers, and customers.
- Examining the potential for advanced commercial and residential building designs and new energy technologies that result in lower GHG emissions when constructing new facilities or retrofitting existing facilities.
- Providing leadership in industry associations, trade unions, and other organizations appropriate to our company or institution to promote the adoption of climate change standards in each sector.
- Supporting demonstration projects and other activities that test, scale, or promote technologies, policies, or other programs that seek to mitigate climate change and its impacts.[36]

GLOBAL ROUNDTABLE ON CLIMATE CHANGE

AFFIRMATION

This statement seeks to help build consensus on the urgency and interconnected importance of adopting realistic government and corporate policies to address climate change and to build sustainable energy systems. It is neither a contract nor a formal policy proposal, but rather a brief, plain-language contribution to what we believe needs to be a serious global conversation and commitment for action. In this spirit, we endorse this statement and welcome others to join us.*

Companies and Institutions[37]

- ABB
- Air France
- Alcan
- Alcoa
- Allianz
- American Association of Blacks in Energy
- American Council for an Energy Efficient Economy
- American Electric Power
- Aristeia Capital
- BASF
- Bayer
- Calvert Group
- Canadian Electricity Association
- Center for Research on Environmental Decisions
- Center for the Study of Science and Religion
- Centrica
- Ceres
- China Renewable Energy Industry Association
- Citigroup
- Climate Group
- Climate Institute
- Climate Trust
- Community Research and Development Centre, Nigeria
- Covanta Holding Corporation
- Deutsche Telekom
- Doosan Babcock Energy Limited
- DuPont
- Earth Institute at Columbia University
- EcoSecurities
- Electricité de France, North America
- Electricity Generating Authority of Thailand
- Endesa
- Energetech Australia Pty Ltd
- Energy East Corporation
- Energy Holding Romania
- Eni
- Environmental Defense
- Environmental Development Action in the Third World (ENDA)
- Eskom
- ETG International
- Exelon Corporation
- F&C Asset Management
- FPL Group
- General Electric
- German Electricity Association (VDEW)
- Glitnir Bank
- Global Energy Network Institute
- Green Strategies, Inc.
- Iberdrola
- Iceland GeoSurvey (ISOR)
- ING Group
- Institute for Global Environmental Strategies
- Interface
- International Gas Union
- International Paper
- International Power
- Juelich Research Centre (FZJ)
- Lenfest Foundation

* Titles and affiliations for individuals are listed for identification purposes only. Affirmation is not considered legally binding to a particular policy position or course of action but an indication of support for the general consensus expressed in the document.

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- Marsh & McLennan Companies
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- Munich Re
- Nand & Jeet Khemka Foundation
- National Council of Churches USA
- National Grid
- National Power Company of Iceland
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- NiSource
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- NRG Energy
- Office of the Prime Minister of Papua New Guinea
- Old Harbor Outfitters
- Patagonia
- Pennsylvania Consortium for Interdisciplinary Environmental Policy
- Rainforest Alliance
- Reykjavík Energy
- Ricoh
- Rio Tinto Energy Services
- Rockefeller Brothers Fund
- Rolls-Royce
- Sea Breeze Power
- SGS (Société Générale de Surveillance) Group
- South East Asia and Pacific Secretariat of the Renewable Energy and Energy Efficiency Partnership
- Stora Enso North America
- Stratus Consulting
- Sun Management Institute
- Suntech Power
- Swiss Re
- UCG Partnership
- University of Akureyri
- University of Iceland
- U.S. Geothermal
- U.S. Green Building Council
- US Renewables Group
- Vattenfall
- Verde Venture Partners
- Volvo
- Women's Global Green Action Network
- World Council of Churches
- World Petroleum Council
- Wuppertal Institute for Climate, Environment and Energy

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Leaders from Business, Civil Society, Government, and Research Institutions

Daniel R. Abbasi
Director
MissionPoint Capital Partners

George Akerlof
Koshland Professor of Economics
University of California at Berkeley
2001 Nobel Laureate in Economics

Ernesto A. López Anadón
President
International Gas Union

Bjarni Ármannsson
Chief Executive Officer
Glitnir Bank

Roger S. Ballentine
President
Green Strategies, Inc.

Henry S. Bienen
President
Northwestern University

Ruth Greenspan Bell
Director, International Institutional Development and Environmental Assistance Program
Resources for the Future

Lennart Billfalk
Senior Vice President
Vattenfall AB

Sue Blacklock
The Lenfest Foundation

Paul Bledsoe
Director of Communications and Strategy
National Commission on Energy Policy

Eron Bloomgarden
Country Director, United States
EcoSecurities

Paul Brandt-Rauf
Chairman, Environmental Health Sciences
Columbia University

Wallace S. Broecker
Newberry Professor of Earth and Environmental Sciences
Columbia University

Donald A. Brown
Director, Pennsylvania Consortium for Interdisciplinary Environmental Policy

Mike Burnett
Executive Director
The Climate Trust

Mark A. Cane
G. Unger Vetlesen Professor of Earth and Environmental Science
Columbia University

Thomas R. Casten
Chair
Recycled Energy Development LLC

Wilton Cedeno
Chairman
American Association of Blacks in Energy

Kimball C. Chen
Chairman
ETG International, LLC.

Robert S. Chen
Director, Center for International Earth Science Information Network

Paul Clements-Hunt
Head of Secretariat
UNEP Finance Initiative

Steven Cohen
Director, MPA Program in Environmental Science and Policy
Columbia University

Daniel T. Colbert
Chief Technology Officer
NGEN mgt II, LLC

Rohan Courtney
Director
UCG Partnership

Phil Cox
Chief Executive Officer
International Power plc

David Crane
President and Chief Executive Officer
NRG Energy, Inc.

Fabrizio d'Adda
Chief Executive Officer
Dyna Network

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ON CLIMATE CHANGE

Tom Denniss
Founder and Executive Director
Energetech Australia Pty Ltd

Brynhildur Davidsdottir
Professor of Environment and Resources
University of Iceland

David L. Downie
Director
Global Roundtable on Climate Change

Rev. Bob Edgar
General Secretary
National Council of Churches USA

Paul R. Epstein
Associate Director, Center for Health and the
Global Environment
Harvard Medical School

S. Rick Fedrizzi
President, Chief Executive Officer, and Founding Chairman
U.S. Green Building Council

Ólafur G. Flóvenz
General Director
Iceland GeoSurvey (ISOR)

Ignacio S. Galán
Chairman and Chief Executive Officer
Iberdrola

John F. Gillen
President/Regional Manager
Stora Enso North America Corp.

Julie Fox Gorte
Vice President and Chief Social Investment Strategist
Calvert Group

Joseph H. Graziano
Professor of Environmental Health Sciences
Columbia University

Alain Grisay
Chief Executive Officer
F&C Asset Management plc

Thorsteinn Gunnarsson
President
University of Akureyri

David G. Hallman
Advisor, World Council of Churches Programme
on Climate Change

James E. Hansen
Director
NASA Goddard Institute for Space Studies

Paul G. Harris
Professor of International and Environmental Studies
Lingnan University

David G. Hawkins
Director, Climate Center
Natural Resource Defense Council

Geoffrey Heal
Paul Garrett Professor of Public Policy and
Corporate Responsibility
Columbia University

Daniel T. Hendrix
President and Chief Executive Officer
Interface, Inc.

Peter Hennicke
President
Wuppertal Institute for Climate, Environment and Energy

Thomas Heyd
Professor of Philosophy
University of Victoria

Robert L. Hill
President
American Association of Blacks in Energy

Daniel Hillel
Senior Research Scientist
NASA Goddard Institute for Space Studies

Joseph F. Huber
Managing Director
Credit Suisse

GLOBAL ROUNDTABLE ON CLIMATE CHANGE

Kristin Ingolfsdottir
President
University of Iceland

Giusepp Iorio
GHG Manager
Eni S.p.A.

Torsten Jeworrek
Member of the Board of Management
Munich Reinsurance Company

James W. Jones
Distinguished Professor, Department of Agricultural and Biological Engineering
University of Florida

Lars Josefsson
Chief Executive Officer
Vattenfall AB

Mary Rose Kaczorowski and **Tara DePorte**
Women's Global Green Action Network

Amy Kean
Regional Manager, South East Asia and Pacific
Renewable Energy and Energy Efficiency Partnership

Fred Kindle
President and Chief Executive Officer
ABB Ltd.

Thomas King
Managing Director
US Renewables Group

Chris Kirk
Chief Executive Officer
SGS (Société Générale de Surveillance) Group

Rev. Samuel Kobia
General Secretary
World Council of Churches

Christian Kornevall
Project Director, Energy Efficiency in Buildings
World Business Council for Sustainable Development

Daniel Kunz
President and Chief Executive Officer
U.S. Geothermal Inc.

Joseph M. Kwasnik
Vice President–Environment US
National Grid

Klaus S. Lackner
Ewing-Worzel Professor of Geophysics
Columbia University

Anthony Leiserowitz
Research Scientist
Decision Research

Gerry Lenfest
President
The Lenfest Group and The Lenfest Foundation

Joshua Lipton
Chief Executive Officer
Stratus Consulting Inc.

Gareth Llewellyn
Group Corporate Responsibility Director
National Grid

Mindy Luber
President
Ceres

Sasha Mackler
Associate Technical Director
National Commission on Energy Policy

Paul B. Manson
President and Chief Executive Officer
Sea Breeze Power Corp.

A. Roy Maybud
Senior Executive Vice President
Energy Holding Romania

Marco Mazzotti
Professor of Process Engineering
ETH Swiss Federal Institute of Technology

Michael McClain
Vice President-Finance,
Treasurer and Chief Integration Officer
Energy East Corporation

Eberhard Meller
Executive Director
German Electricity Association

Ivo Menzinger
Head, Sustainability & Emerging Risk Management
Swiss Reinsurance Company

Evan Mills
Staff Scientist
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory

Vijay Modi
Professor of Mechanical Engineering
Columbia University

Elizabeth A. Moler
Executive Vice President, Governmental and
Environmental Affairs and Public Policy
Exelon Corporation

Akio Morishima
Chair, Board of Directors
Institute for Global Environmental Strategies

Christian Nadal
President
Electricité de France, International North America

Susumu Nakamaru
Founder
Sun Management Institute

Shahid Naeem
Professor of Ecology, Evolution and Environmental Biology
Columbia University

David Nissen
Professor of Practice in International and Public Affairs
Columbia University

Michael Northrop
Program Director
Rockefeller Brothers Fund

Anthony Orlando
President and Chief Executive Officer
Covanta Holding Corporation

Gudrun Petursdottir
Director, Institute for Sustainable Development
University of Iceland

Robert Pollack
Professor of Biological Sciences
Director, Center for the Study of Science and Religion
Columbia University

Bill Prindle
Acting Executive Director
American Council for an Energy Efficient Economy

Mark Radka
Chief, Energy Branch
Division of Technology, Industry and Economics
United Nations Environment Program

Pierce Riemer
Director General
World Petroleum Council

Cynthia Rosenzweig
Senior Research Scientist
NASA Goddard Institute for Space Studies

Jeffrey D. Sachs
Director, The Earth Institute at Columbia University
Quetelet Professor of Sustainable Development
Columbia University

Masamitsu Sakurai
President and Chief Executive Officer
Ricoh Company, Ltd.

Peter Schlosser
Vinton Professor of Earth & Environmental Engineering
Professor of Earth and Environmental Science
Columbia University

Jonathan E. Schrag
Executive Director
Lenfest Center for Sustainable Energy

GLOBAL ROUNDTABLE ON CLIMATE CHANGE

Dayna Nadine Scott
Legal Research Fellow
Center for International Sustainable Development Law

Thorsteinn I. Sigfusson
Professor of Physics
University of Iceland

H. James Simpson
Professor of Earth and Environmental Sciences
Columbia University

Arthur E. Smith, Jr.
Senior Vice President & Environmental Counsel
NiSource Inc.

Joel B. Smith
Vice President
Stratus Consulting Inc.

Olympia J. Snowe
United States Senator
Maine

Robert Socolow
Professor of Mechanical and Aerospace Engineering
Princeton University

Friðrik Sophusson
Chief Executive Officer
National Power Company of Iceland

Glenn O. Steiger
General Manager
Massachusetts Municipal Wholesale Electric Company

Detlef Stolten
Director
Institute of Energy Research–Fuel Cells
Jülich Research Center

David B. Struhs
Vice President of Environmental Affairs
International Paper

Arnaud Cohen Stuart
Corporate Responsibility & Sustainable Development
ING Group

Steve Tempini
Chief Executive Officer
Old Harbor Outfitters

Nickolas J. Themelis
Chairman, U.S. Waste-to-Energy Research and Technology Council; Professor of Earth and Environmental Engineering, Columbia University

Michel Tilmant
Chief Executive Officer
ING Group

John Topping
President
The Climate Institute

Eli Turk
Vice President, Government Relations
Canadian Electricity Association

Bruce Usher
Chief Executive Officer
EcoSecurities

Etiosa Uyigue
Executive Director
Community Research and Development Centre, Nigeria

Patrick Van Grunderbeeck
Director
MEDIAS-France

José Luis del Valle
Chief Strategy and Development Officer
Iberdrola

Vilhjálmur Þ. Vilhjálmsson
Mayor
City of Reykjavik

Maria Eugenia Ibarrarán Viniegra
Professor, Department of Economics
University of the Americas, Puebla

Koko Warner
Coordinator, Munich Climate Insurance Initiative
United Nations University

GLOBAL ROUNDTABLE
ON CLIMATE CHANGE

Elke U. Weber
Jerome A. Chazen Professor of International Business
Columbia University

James D. Weinbauer
Senior Vice President–Director Environment
Stora Enso Oyj

Sara Weinheimer
Managing Partner
Verde Venture Partner

David Welsh
Director, Health, Safety & Environment
Rolls-Royce

Tensie Whelan
Executive Director
Rainforest Alliance

Marina v.N. Whitman
Professor of Business Administration and Public Policy,
University of Michigan
President's Council of Economic Advisers, 1972–1973

John F. Williams
Senior Vice President
National Director–Sustainable Development
HDR Engineering, Inc.

Mark Wolfe
Executive Director
Energy Programs Consortium

Robert C. Worrest
Senior Research Scientist
Center for International Earth Science Information Network

Holly Wu
Marketing Director
Suntech Power Holdings Co., Ltd.

Yukio Yanagisawa
Professor of Environmental Process Engineering
University of Tokyo

Zheng Yisheng
Research Fellow
Center for Environment and Development
Chinese Academy of Social Sciences

NOTES AND REFERENCES

Although not a technical document, we have chosen to provide references or additional details for particular statements contained in this document in order to demonstrate their mainstream status among experts in relevant fields.

1. Broad scientific consensus exists concerning the fact that human activities, particularly loading the atmosphere with carbon dioxide (CO_2) from the burning of fossil fuels and deforestation, as well as emissions of other greenhouse gases (GHGs), such as methane and nitrous oxide, are ultimately responsible for much of the increase in global temperatures observed over the last century as well as the associated and increasingly visible and troubling impacts of climate change. The 2007 Fourth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) provides the most authoritative review of this issue. See Alley, R. et al. IPCC. 2007. Climate Change 2007: The Physical Science Basis, Summary for Policymakers - Contribution of Working Group I to the Fourth Assessment Report of the IPCC. This report and the other IPCC documents referenced in this section are available through the IPCC website at www.ipcc.ch.

   Existing public expression of this consensus includes statements by the national science academies of Australia, Belgium, Brazil, Canada, China, France, Germany, India, Indonesia, Ireland, Italy, Japan, Malaysia, Netherlands, New Zealand, Russia, Sweden, Turkey, the United Kingdom, and the United States (U.S.), reports by the IPCC, the Arctic Climate Impact Assessment, the International Climate Change Taskforce (ICCT), as well as statements and findings by other international, national, and regional scientific and political bodies.

   For examples of the views of the national science academies see: National Science Academies of the G8 plus the National Science Academies of Brazil, China and India. 2005. Joint Science Academies' Statement: Global Response to Climate Change. Available at http://www.fco.gov.uk/Files/kfile/PostG8ClimChaAcademies.pdf; National Academy of Sciences (U.S.) Committee on the Science of Climate Change. 2001. Climate Change Science: An Analysis of Some Key Questions. p 1. (Washington, D.C.: National Academy Press) Also available at http://newton.nap.edu/html/climatechange/summary.html; Editorial, signed by 17 national science academies. 2001. "The science of climate change." *Science* 292 (5520): 1261.

   For reports by the IPCC, see: IPCC. 2007. Climate Change 2007: The Physical Science Basis, Summary for Policymakers; Watson, R.T. et al. IPCC. 2001. Climate Change 2001: Synthesis Report, Summary for Policymakers. p 5; IPCC. 1995. Second Assessment Report: Climate Change 1995. For the Arctic Climate Impact Assessment, which was sponsored by the governments of Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, and the U.S., see: 2004. Impacts of a Warming Arctic: Arctic Climate Impact Assessment. Executive Summary, p 8-9. The report and additional information is available at www.acia.uaf.edu. For the International Climate Change Taskforce, see: ICCT. 2005. Meeting the Climate Challenge. Available at http://snowe.senate.gov/icctreport.pdf.

   For statements by other prominent scientific bodies and government groups that review scientific reports, see: Development and Environment Ministers of OECD Member Countries. 4 April 2006. Declaration on Integrating Climate Change Adaptation into Development Cooperation. Preamble and paragraph 1. (Paris: OECD Headquarters); U.S. Climate Change Science Program, Synthesis and Assessment Product 1.1. 2006. Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences; United Kingdom, Parliamentary Office of Science and Technology. 2005. Rapid Climate Change. p 1-4; American Geophysical Union. 2003. "American Geophysical Union Position Statement on Human Impacts on Climate." Reprinted in *Eos* 84 (51): 574; Showstack, R. 2003. "Climate Change Statements Highlight Human Influence." *Eos* 84 (51): 574; American Meteorological Society. 2003. *Bulletin of the American Meteorological Society*. Vol. 84: 508. For a review of the scientific consensus on climate change as represented in the peer-reviewed science literature, see Oreskes, N. 2004. "The Scientific Consensus on Climate Change." *Science* 306: 1686.

   A number of business, civil society, and religious groups have also issued statements on the serious threat posed by climate change, and the need to take action. Representative examples include: Evangelical Climate Initiative. 2006. Climate Change: An Evangelical Call to Action. Available at http://christiansandclimate.org/pub/statement-booklet.pdf; World Council of Churches. 2005. Statement to the high-level segment of the UN Climate Change conference. See also: A statement from the World Council of Churches (WCC) to the High-Level Ministerial Segment of the UN Climate Conference in Nairobi. Statements available at http://www.oikoumene.org/en/home.html; United States Conference of Bishops. 2001. Global climate change: A plea for dialogue, prudence, and the common good. Available at www.usccb.org/sdwp/international/globalclimate.htm; Corporate Leaders Group on Climate Change. 2006 Letter to the Prime Minister. Available at http://www.cpi.cam.ac.uk/bep/clgcc/letter_2006.htm; Institutional Investors Group on Climate Change. 2006. Investor Statement on Climate Change. Available at www.iigcc.org; Pew Center on Global Climate Change. 2005. International Climate Efforts Beyond 2012: Report of the Climate Dialogue at Pocantico. (Washington, D.C.: Pew Center on Global Climate Change); Clinton Global Initiative. 2006. Clinton Global Initiative First Year Report. Available at http://www.clintonglobalinitiative.org/pdf/annual_report/CGIReportFeb-01-2006.pdf; World Business Council on Sustainable Development. 2004. Facts & trends to 2050: Energy and climate change. Available at www.wbcsd.org; and the ICCT. 2005. Meeting the Climate Challenge. Available at http://snowe.senate.gov/icctreport.pdf.

   Anthropogenic emissions of CO_2 – from fossil fuels use, cement production, land use change, and forestry – are the most important anthropogenic GHG due to the relative size of the emissions (nearly 75% of global GHG emissions) and the expected future growth of these emissions in the absence of effective action. Other notable GHGs include methane (CH4, about 4% from land-filling of municipal solid wastes and about 11% from other sources) nitrous oxide (N2O, about 9%) and a variety of fluorinated gases including perfluorocarbons (PFCs), chlorofluorocarbons (CFCs and their related replacement halocarbons, HCFCs), hydrofluorocarbons (HFCs), and sulphur hexafluoride (SF6). Methane and the other gases have far higher global warming potentials (GWPs) than does CO_2. GWP is a measure of how much a given mass of gas is estimated to contribute to global warming.

   It is well known that, historically, the vast majority of anthropogenic GHG emissions have come from the wealthier nations although rapidly industrializing developing countries now emit very substantial amounts as well and may surpass the emissions of developed countries by 2015. The United States emits the most CO_2 on an aggregate and per-capita basis. China is expected to pass the United States in national CO_2 emissions sometime this decade but, like developing nations in general, it is well behind in per-capita emissions.

   For detailed information on GHG emissions, compare data and sources in, for example: United States Environmental Protection Agency. 2000. Global Greenhouse Gas Data available at http://www.epa.gov/climatechange/emissions/globalghg.html; United Nations Framework Convention on Climate Change. Greenhouse Gas Inventory Data available at http://ghg.unfccc.int/index.html; World Resources Institute. Earth Trends: Climate and Atmosphere Searchable Database available at http://earthtrends.wri.org/searchable_db/index.php?theme=3; and for a directory to other Earth science data and services see: NASA Goddard Space Flight Center. Global Change Master Directory: Atmosphere available at http://gcmd.gsfc.nasa.gov/index.html.

2. In addition to the sources above, see also, as indicative examples: Schellnhumber et al. 2006. Avoiding Dangerous Climate Change. (Cambridge: Cambridge University Press); Epstein, P. and E. Mills. 2005. Climate Change Futures: Health, Ecological and Economic Dimensions. The Center for Health and the Global Environment at Harvard Medical School; Patz, J.A., et al. 2005. "Impact of regional climate change on human health." *Nature* 4387066: 310-317.

3. 1992 United Nations Framework Convention on Climate Change. Article 2. Objective. For the text of the Convention and a list of the 189 countries that have ratified it into international law, see the website of the Convention Secretariat at http://unfccc.int/.

4. This is widely acknowledged. For a recent analysis, see McKinsey Global Institute. 2006. Productivity of growing global energy demand: A microeconomic perspective. p 14-23. (San Francisco: McKinsey and Company)

5. For discussion of how energy production and demand, the key drivers of CO_2 emissions under current conditions, are expected to continue growing at significant rates, see International Energy Agency. 2006. World Energy Outlook 2006. (Paris: OECD/IEA) and Schmalensee, R., T.M. Stoker, and R.A. Judson. 1998. "World carbon dioxide emissions: 1950-2050." *The Review of Economics and Statistics*, 80(1), 15-27.

6. This is an indicative list of non-fossil-fuel-based energy sources, as are similar lists in this document. This statement endorses a significant increase in the use of non-fossil-fuel technologies but does not take a position on which technologies should or should not be used.

7. Although still in the early stages, ongoing work suggests that it might prove feasible to extract CO_2 directly from the air for sequestration. This would make CCS possible wherever conditions are most favorable, where the CCS facilities would not pose environmental risks, and where the permitting, construction, and operational costs would be relatively low. For a preliminary discussion, see Abanades, et al. IPCC. 2005. IPCC Special Report: Carbon Capture and Storage – Summary for Policymakers. p 12-13. (Cambridge: Cambridge University Press).

8. It is well known that coal is the most abundant fossil fuel, with known global reserves that could last for at least another two centuries at current rates of production. Coal reserves are also widely distributed, and vary significantly from those of oil and gas, with very significant reserves found in the United States, Russia, China, India, Australia, Germany, and South Africa. For a concise overview, see Energy Information Agency, United States Department of Energy. 2006. The International Energy Outlook 2006 (IEO2006). Available at http://www.eia.doe.gov/oiaf/ieo/index.html. See also International Energy Agency. 2006. World Energy Outlook 2006. Chapter 5, p 80. (Paris: OECD/IEA).

9. As noted, avoiding "dangerous anthropogenic interference" is a stated objective of the 1992 United Nations Framework Convention on Climate Change.

10. See, for example: Watson, R.T. et al. IPCC. 2001. Climate Change 2001: Synthesis Report, Summary for Policymakers. p 5; National Science Academies of the G8 plus the National Science Academies of Brazil, China and India. 2005. Joint Science Academies' Statement: Global Response to Climate Change. Available at http://www.fco.gov.uk/Files/kfile/PostG8ClimChaAcademies.pdf; Keeling, C.D. and T.P. Whorf. 2005. Atmospheric carbon dioxide records from sites in the SIO air sampling network. In: U.S. Department of Energy. Trends: A compendium of data on global change. (Oak Ridge: U.S. Department of Energy).

11. Representative examples include: Gregory, J.M., P. Huybrechts, and S. Raper. 2004. "Climatology: Threatened loss of the Greenland ice-sheet." *Nature* 428: 616; Hansen, J. 2004. "Defusing the global warming time bomb." *Scientific American* 290 (3): 68-77; O'Neill, B.C. and M. Oppenheimer. 2002. "Dangerous Climate Impacts and the Kyoto Protocol." *Science* 296: 1972; Parry, M., N. Arnell, et al. 2001. "Millions at risk: defining critical climate change threats and targets." *Global Environmental Change- Human and Policy Dimensions* 11 (3): 181-183; Azar, C. and H. Rodhe. 1997. "Targets for stabilization of atmospheric CO_2." *Science* 276: 1818-1819.

12. Many scientists now accept that 2X CO_2 will lead to about a 3°Celsius temperature increase as the best available working estimate. The 2007 IPCC Fourth Assessment Report discusses this point. Currently, many experts indicate that the potential for dangerous anthropogenic interference with the climate system increases rapidly as warming moves significantly above 2°Celsius from pre-industrial levels (see, for example, Watson, R.T. et al. IPCC. 2001. Climate Change 2001: Synthesis Report. Summary for Policymakers. p 9). Maintaining a low probability of the largest and most destabilizing disruptions would therefore indicate setting a prudent, science-based CO_2 stabilization target at levels below those associated with warming greater than 2°Celsius or well below 2X CO_2. For similar conclusions or supporting analysis, see: ICCT. 2005. Meeting the Climate Challenge. p 3. Stern, N. 2006. Stern Review: The Economics of Climate Change. Executive Summary. p xvii. Available at http://www.hm-treasury.gov.uk/media/8AC/F7/Executive_Summary.pdf; Den Elzen, M.G.J. and M. Meinshausen. 2005. Meeting the EU 2°C climate target: Global and regional emission implications. p 6. (Bilthoven, Netherlands: Netherlands Environmental Assessment Agency); Meinshausen, M. 2006. What does a 2°C target mean for greenhouse gas concentrations? In: Schellnhuber et al. 2006. Avoiding Dangerous Climate Change. (Cambridge: Cambridge University Press). For an accessible explanation of climate sensitivity, the relationship between atmospheric CO_2 concentrations and global average temperature, see: United Kingdom Met Office, Exeter. 2005. Stabilizing climate to avoid dangerous climate change: A summary of relevant research by the Hadley Center. p 14-15.

13. See, for example, Stern, N. 2006. Stern Review: The Economics of Climate Change. Executive Summary, p iv and xiv. For information on the full range of future emission scenarios see: Watson, R.T. et al. 2001. IPCC. Climate Change 2001: Synthesis Report. Summary for Policymakers. p 10-11. Houghton, J.T. et al. IPCC. 2001. Climate Change 2001: The Scientific Basis, Summary for Policymakers. p 14.

14. These global estimates and terms are those used by the International Energy Agency. See also International Energy Agency. 2006. World Energy Outlook 2006. p 80. For the United States, the U.S. Department of Energy estimates that in 2004, the electric power sector accounted for 39% of total U.S. energy-related CO_2 emissions, the transportation sector 33%, and the industrial sector 29%. U.S. Department of Energy. 2006. Emissions of Greenhouse Gases in the United States 2005. Available at http://www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html. For additional information on the availability of emission reductions in these sectors see International Energy Agency. 2006. Energy Technology Perspectives 2006. Available at http://www.iea.org/textbase/nppdf/stud/06/enertech2006.pdf.

15. For discussion, see: Davidson, O., B. Metz, et al. IPCC. 2001. Climate Change 2001: Mitigation- The Contribution of Working Group III to the Third Assessment Report of the IPCC. Chapter 3. Available at http://www.grida.no/climate/ipcc_tar/wg3/089.htm; G. Morgan, J. Apt, et al. Pew Center on Global Climate Change. 2005. The US Electric Power Sector and Climate Change Mitigation. (Washington D.C.: Pew Center on Global Climate Change).

16. Such benefits include increasing the market for renewable energy and other mitigation technologies and providing power in non-electrified or underserved rural areas to pump water, increase lighting, enhance schools, and power radios, phones, computers, and small businesses.

17. For example, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy estimates in its 2006 Buildings Energy Data Book that commercial and residential buildings account for 38% of CO_2 emissions, in the United States, when the impact from energy consumption is included. The U.S. Green Building Council (USGBC), estimates that in the United States, buildings account for: 36% of total energy use; 65% of electricity consumption; 30% of greenhouse gas emissions; 30% of raw materials use; 30% of waste output (approximately 136 million tons annually); and 12% of potable water consumption. This information and links to a large number of detailed research reports are available via the USGBC website at www.usgbc.org.

18. An increasing referenced example of such standards is the "Leadership in Energy & Environmental Design" (LEED) Green Building Rating System.

19. International Energy Agency. 2006. World Energy Outlook 2006. p 43 and 193-314.

20. The relevance of life-cycle thinking in this regard is increasingly recognized. Indicative examples from intergovernmental contexts include: Point 11 in the in the Malmö Ministerial Declaration agreed by governments during the First Global Ministerial Environment Forum in Malmö, Sweden, May 2000 (available at http://www.unep.org/malmo/malmo_ministerial.htm) and relevant elements of the 10-year program framework of programmes to promote sustainable consumption and production patterns agreed to at 2002 World Summit on Sustainable Development, see Report of the World Summit on Sustainable Development. Johannesburg, South Africa, 26 August-4 September 2002. Section III: Changing unsustainable patterns of consumption and production, point 15(a). Available at http://daccessdds.un.org/doc/UNDOC/GEN/N02/636/93/PDF/N0263693.pdf?OpenElement. Additional information on life cycle thinking can be found via the United Nations Environment Programme's Production and Consumption Branch: Sustainable Consumption website at http://www.uneptie.org/pc/sustain/lcinitiative/background.htm.

21. Examples of supporting analyses include: Davidson, O., B. Metz, et al. IPCC. 2001. Climate Change 2001: Mitigation- The Contribution of Working Group III to the Third Assessment Report of the IPCC. Chapter 8, p 1; Stern, N. 2006. Stern Review. The Economics of Climate Change. Executive Summary, p xii, xiii, and xiv; International Energy Agency. 2006. World Energy Outlook 2006. p 43 and 193-314.

GLOBAL ROUNDTABLE
ON CLIMATE CHANGE

22. As stated in the previous paragraph, please note that these figures, as well as those in the next sentence, are offered only as indicative examples of the probable reasonableness of costs of addressing climate change, particularly in comparison to the probable costs of inaction, not as firm conclusions or policy recommendations. For an influential early analysis of such figures, see: Rubin, E.S. et al. 1992. "Realistic Mitigation Options for Global Warming." *Science*. 257: 264.

23. For example, see: Stern, N. 2006. Stern Review: The Economics of Climate Change. Executive Summary, p xvii; Wiser, R. and M. Bolinger. 2004. An Overview of Alternative Fossil Fuel Price and Carbon Regulation Scenarios. Lawrence Berkeley National Laboratory. Available at http://eetd.lbl.gov/EA/EMP; Springer, U. 2003. "The Market for Tradable GHG Permits under the Kyoto Protocol: A Survey of Model Studies." *Energy Economics* 25: 527-551. As noted above, these figures are offered only as indicative examples not as firm conclusions or policy recommendations.

24. See Article 2, "Objective", of the 1992 United Nations Framework Convention on Climate Change.

25. The IPCC was established in part to provide authoritative information on climate change, independent of any one government, to inform policy makers devising individual and collective policy. Governments participating in negotiations under the Framework Convention on Climate Change agreed that their deliberations on targets and commitments beyond the time-frame of the Kyoto Protocol should be informed by the work of the IPCC and other scientific studies of the causes and impacts of climate change and potential mitigation and adaptation strategies, including economic and social factors.

26. Please note that signatories to this statement have not agreed, nor do we seek to propose, particular final or interim targets for atmospheric GHG concentrations. We do agree that such targets need to be set, that they should be based on the best scientific information available, that they should be linked to serious, ambitious national and international policies designed to achieve them, and that they should be adjusted in a precautionary manner as we learn more about both climate change and the costs and benefits of various mitigation strategies.

27. Article 3 of the UNFCCC delineates a series of principles, agreed to by more than 180 governments, that underlie the Convention and, by extension, any related policy protocol. These include the principles of equity and common but differentiated responsibilities, taking into account the respective capabilities of Parties, recognizing the specific needs and special circumstances of developing country Parties, noting that developed country Parties should take the lead in combating climate change, the right and responsibility of Parties to promote sustainable development, and other issues. Realistic political analysis suggests that these principles must be taken into account when considering global policy options or achieving climate stability. At the same time, GHG emissions in many rapidly-industrializing developing countries are increasing rapidly. The developing countries, as a group, will soon be the largest emitters of GHGs, though on a per capita basis the developed regions will still be far larger emitters and are responsible for the vast majority of historical emissions. Thus, realistic analysis of the climate change issue suggests that all major emitters of GHG must be part of a global climate policy or it will not succeed in stabilizing GHGs. This joint statement acknowledges both the reality of the carbon arithmetic and the principle of common but differentiated responsibilites and other principles agreed to under the UNFCCC.

28. CDM is a flexibility mechanism under the Kyoto Protocol which allows industrialized countries with binding greenhouse gas reduction commitments (often called Annex 1 countries) to invest in GHG emission reduction projects in developing countries. Verified reductions from such projects can help an Annex 1 country meet its reduction commitments under the Protocol. When successful, CDM and similar mechanisms can help lead to more total GHG emission reductions at less overall cost while helping to increase the availability of low- and zero-carbon emission energy systems to developing countries.

29. See Footnote 1 on the patterns of GHG emissions including historical emissions from today's developed countries.

30. For extensive discussion of this point see: Stern, N. 2006. Stern Review: The Economics of Climate Change. Executive Summary, p xvii, and Chapters 14-17.

31. Please note that the statement does not necessarily endorse using any particular mechanism. Those endorsing this statement agree on the importance of establishing a price but hold different views regarding which of these mechanisms should be used.

32. Reducing deforestation also yields important ancillary benefits, including but not limited to biodiversity protection.

33. This list is indicative. Inclusion on the list does not imply that all participants necessarily support RD&D for each technology or that a given technology is not used today or requires RD&D to become more widely used. Absence from the list does represent an opinion on the propriety of providing incentives for further improvement, or the potential for expanded deployment, of proven technologies such as wind, IGCC, co-generation, waste-to-energy, and green-building.

34. An international example of such an effort is the Asia-Pacific Partnership on Clean Development and Climate, whose founding partners, the governments of Australia, China, India, Japan, Republic of Korea, and the United States, have agreed to work together and with private sector partners to accelerate the development and deployment of clean energy technologies. Additional information is available at http://www.asiapacificpartnership.org/.

35. One example of analogous consultations involving trade unions and business experts is the OECD Labour/Management Programme, including the 1 March 2006 Joint Meeting of Management and Trade Union Experts on Implementing the OECD Environmental Strategy. Available via the OECD website at www.oecd.org.

36. Indicative examples of demonstration projects involving Roundtable participants and that enjoy the general endorsement of the Roundtable will be listed at www.earthinstitute.columbia.edu/grocc

37. Those endorsing this statement include participants in the Global Roundtable on Climate Change as well as other prominent members of the global community. For a list of Roundtable participants and other information on the Roundtable, see www.earthinstitute.columbia.edu/grocc. This list of endorsements is current as 15 February 2007. Additional endorsements are welcome and will be included in updated printings and on the Roundtable website. Endorsement of this Statement is not considered legally binding with regard to a particular policy position, characterizations of scientific opinion, specific levels of atmospheric concentrations that may result in impacts, the level of costs that may be reasonable for particular industries or communities to incur, or specific courses of action that could be pursued; but rather an indication of support for the general consensus expressed in this document. Participation in the Global Roundtable on Climate Change on its own does not imply support for this statement.

38. Titles and affiliations for individuals listed for identification purposes only. As noted above, endorsement of this statement is not considered legally binding but rather an indication of support for the general consensus expressed in this document. Participation in the Global Roundtable on Climate Change on its own does not imply support for this statement.

GLOBAL ROUNDTABLE ON CLIMATE CHANGE

ABOUT THE ROUNDTABLE

Recent scientific and technological advances provide the world with increasingly visible and troubling evidence that human activity is having a dangerous impact on the Earth's climate system. Consequently, there is an urgent need to better understand the threats posed by human-induced climate change and to build a consensus on proactive initiatives that can help society mitigate and adapt to its impacts.

The Global Roundtable on Climate Change assists this effort by bringing together officials and leading experts from business, civil society, international organizations, and research institutions for five years of meetings and related activities. The Roundtable has five overarching objectives:

- To assist development of a global consensus on core scientific, technological, economic, and policy issues related to climate change—one that simultaneously considers the need to mitigate the very significant risks posed by anthropogenic climate change and the need for economic growth and human development around the world.
- To identify technological and policy options for mitigating climate change while meeting global energy needs.
- To champion demonstration projects that test and scale sustainable energy technologies and other activities and policies that address climate change.
- To provide a unique forum for discussion, analysis and exchange of ideas among businesses, international institutions, non-governmental organizations, policy makers, and leading academic experts, from across economic sectors and all parts of the world.
- To catalyze new initiatives and interactions among Roundtable participants to address climate change.

Convened by The Earth Institute at Columbia University, the Roundtable is made possible by a generous grant from the Lenfest Foundation, which is dedicated to supporting programs primarily in the areas of education, the arts and the environment. Detailed information on the Roundtable can be found at http://www.earthinstitute.columbia.edu/grocc/.

The Roundtable meetings, as well as important intersession activities, have included discussions of the current scientific understanding of climate change; technological and policy options for mitigating climate change while meeting global energy needs; potential areas for demonstration projects; possible roles for the business community in discussing and addressing the climate issue; and potential principles that the Roundtable might agree upon as important for the development of more effective global action. These activities have provided the basis for this document, "The Path to Climate Sustainability: A Joint Statement by the Global Roundtable on Climate Change."

The Joint Statement has received endorsements from key economic stakeholders and independent experts: leading corporations from all economic sectors—with varied interests and operations in all regions of the world; smaller firms with very different perspectives and concerns; a diverse array of civil, religious, environmental, research and educational institutions; and a distinguished list of some of the world's leading experts in the fields of climate science, engineering, economics and policy studies. The ability of so many key stakeholders, with such diverse views, to agree upon the Joint Statement demonstrates the possibility of fostering a global consensus on a positive, proactive approach to meeting the challenge of global climate change.

The Earth Institute
AT COLUMBIA UNIVERSITY

The Earth Institute at Columbia University is the world's leading academic center for the integrated study of Earth, its environment and society. The Earth Institute builds upon excellence in the core disciplines—earth sciences, biological sciences, engineering sciences, social sciences and health sciences—and stresses cross-disciplinary approaches to complex problems. Through research, training and global partnerships, The Earth Institute mobilizes science and technology to advance sustainable development, while placing special emphasis on the needs of the world's poor.

www.earth.columbia.edu

COMMUNICATIONS

American Public Power Association
2301 M Street, N.W.
Washington, D.C. 20037
202-467-2900; fax: 202-467-2910
www.APPAnet.org

Statement of the American Public Power Association
For the Record of the Hearing Titled,
"America's Energy Future: Bold Ideas, Practical Solutions"
Senate Committee on Finance
February 27, 2007

The American Public Power Association (APPA) appreciates this opportunity to submit comments on the record in the above-referenced hearing. APPA is the national service organization representing the interests of the more than 2,000 state and locally owned electric utilities collectively serving over 44 million Americans. As not-for-profit units of state and local government, these public power utilities are authorized to issue tax-exempt and tax-credit bonds to construct and improve the infrastructure necessary to provide electricity and other essential services, such as advanced communication services. Electricity is the oxygen of the nation's economy; vital to its continued health. Continued access to, and flexibility in the use of, tax-exempt bonds and tax-credit bonds, is of critical importance in allowing public power utilities to continue to provide these services, and to do so in a cost-effective manner.

Our comments will primarily focus on the implementation of the Clean Renewable Energy Bond (CREB) program that was enacted as part of the Energy Policy Act of 2005 (P.L. 109-58). Specifically, our comments will focus on the completed allocation process under the CREB program last fall, and the pending allocation of additional CREB authority approved by Congress and the President last year as part of the Tax Relief and Health Care Act of 2006 (P.L. 109-432).

The public power sector of the electric utility industry is extremely interested in the CREB program. APPA and its members worked with Congress and the Administration for over five years during development of what became the Energy Policy Act of 2005 to establish a tax-based incentive for increased renewable energy production by not-for-profit electric utilities that is comparable to the Section 45 production tax credit available to investor-owned electric utilities. Congress ultimately enacted the CREB program precisely to provide such parity. We appreciate congressional acknowledgement of the need for such a mechanism, and the effort it took to achieve enactment. However, given that this is a new program, there are some problems that must be addressed.

While we also appreciate the effort and attention the Treasury Department and the Internal Revenue Service (IRS) have given this program, particularly in light of the increased administrative burden it has necessitated, we nonetheless have concerns about how the CREB program has been implemented. On November 20, 2006, the IRS announced a total of $800 million in allocations to authorize state and local governmental borrowers and electrical cooperative borrowers to issue tax-credit bonds to fund projects that generate clean renewable energy. The IRS announcement stated that $500 million of the total was allocated to state and local governmental borrowers, with the remaining $300 million allocated to cooperatives. Unfortunately, it is estimated from data received from APPA members that public power utilities have received only approximately $66 million in CREB allocations. Further, additional information provided by the IRS reveals that the program so far has not met our initial expectations or, in our view, those of the program's congressional advocates.

Without regulatory and legislative refinements and improvements to the CREB program, the public power sector will not be able to utilize the program as Congress intended. Due to the allocation methodology chosen by the IRS to fund projects in order of dollar amount, starting from the lowest amount and proceeding upward until the allocations are exhausted and the broad definition of governmental body in the statute, very few public power systems with obligations to serve retail customers received CREB allocations. This result is especially discouraging given that, as noted earlier in this statement, the legislative policy behind the CREBs program was to provide a comparable incentive to public power systems (along the lines of the Section 45 production tax credit) to invest in renewable energy facilities. We have also been concerned that the original CREB authorization treats certain elements of the program, such as the rate and term of the bonds, in a manner that hinders the intended benefits and the potential marketability of the bonds.

Public power systems – governmental entities that own and operate their own electric utilities - are distinct from other governmental issuers of CREBs in that public power systems have a *legal obligation* to serve their customers. This means they must plan for the resources necessary to meet that obligation, including investments in new facilities. In addition, a number of states now require electric utilities to provide a certain percentage of their electricity from renewable sources. In some of these states, public power systems are directly included in this requirement, and in others they are nevertheless expected to meet similar standards. Non-public power governmental entities are under no similar requirement.

Moreover, it appears that the great majority of the allocations were made to governmental entities applying to develop very small, dispersed solar projects. While solar technologies are quite deserving of support and clearly included in Congress' goals for the CREB program, the apparent hugely disproportionate allocations to solar projects raises significant concerns. First, the relatively very small output of each of these scores of solar installations, coupled with their geographic dispersion, creates substantial inefficiency, particularly when measured on a kilowatt hour-per-dollar-invested basis. Second, so many small dollar issuances of CREBs (e.g., bond issues with a par amount of $1 million or less) may threaten the ability to create a market that is attractive, particularly to institutional investors, and at the same time create a situation where the transaction costs of individual issuances cancel out the incentive provided by the CREB program in the first place.

Thus, from what we are able to discern, the results of the allocation process for governmental issuers clearly indicate to us the need for further modification of the allocation process to: 1) increase the amount and efficiency of renewable electricity generation resources; 2) better meet Congress' goal of comparability among sectors of the electric utility industry with regard to incentives for increased renewable energy production; and 3) create a stable, efficient and long-term program that is attractive to investors.

As mentioned earlier in this statement, the CREB program was extended through 2008 in the tax extenders bill passed in late 2006. In that bill, an additional $400 million was authorized for allocation, of which $250 million is to be allocated to governmental issuers. It is our view that this signals broad support for the long-term existence and success of the CREB program as part of our nation's goal of energy independence. We note also that the Technical Explanation of the legislation (H.R. 6408) prepared by the Joint Committee on Taxation states in part, "It is expected that the additional authority will be allocated through a new application process…". In addition, it is certain that some of the original $500 million of CREBs authority allocated to state and local governmental borrowers will not be utilized due to unforeseen circumstances and that some recipients will seek to return such amounts for reallocation to other eligible issuers. Thus, we suggest that these returned allocations be included in the application process for the new authorization. In either event, we strongly hope that our concerns regarding allocations as part of the new application process will be addressed either through regulatory or legislative means. We look forward to working with Congress and the IRS to refine and improve the program.

Green
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RICHARD W. GLADSTONE, II
Chief Executive Officer

3/8/07

STATEMENT FOR THE RECORD
UNITED STATES SENATE COMMITTEE ON FINANCE
2/27/07 HEARING:
"AMERICA'S ENERGY FUTURE: BOLD IDEAS, PRACTICAL SOLUTIONS"

SUMMARY:

Section 45 of the federal tax code should be amended to include a tax credit to facilitate high-Btu landfill renewable energy projects which convert landfill gas (50% methane and 50% mostly carbon dioxide) into pipeline quality natural gas. Currently, Section 45 provides a tax credit for landfill projects only if electricity is produced on the landfill from landfill gas.

More modern technology allows landfill gas to be processed into natural-gas-pipeline quality product gas ("High-Btu Projects"). Although these High-Btu Projects are more efficient and cleaner than the onsite electricity-generating projects, no tax credit is currently provided.

Thus, the current tax code disadvantages the more efficient, more environmentally friendly High-Btu Projects which are a significant source of clean, renewable energy. According to the EPA, just one High-Btu Project on a typical landfill (e.g., 5,000 cfm landfill gas flow) on an annual basis will: displace 65,233,741 gallons of gasoline; avoid the importation of 1,387,952 barrels of oil; or heat 37,543 homes.

Amending Section 45 to include High-Btu Projects on landfills would "level the playing field" for this important renewable energy source. This would allow the market to fairly determine the best renewable energy use for landfill gas, with a minimal net cost to the Treasury as discussed below.

LANDFILL GAS USES:

Most landfills are required to install landfill gas collection systems to burn ("flare") the landfill gas or to use the landfill gas for a renewable energy project. There are three types of landfill energy projects: (1) "direct

HEADQUARTERS
P.O. Box 485
226 Lumber Street
Yukon, Pa 15698
info@greengasenergy.com
Phone: 724.722.7069
Fax: 724.722.7068

PITTSBURGH OFFICE
5807 Walnut Street
Pittsburgh, PA 15232
rwgladstone@comcast.net
Phone: 412.365.0138
Cell: 412.980.3036

Green
Gas
Energy, LLC

RICHARD W. GLADSTONE, II
Chief Executive Officer

use", where the unprocessed landfill gas is piped into a nearby factory boiler; (2) "electric", where the unprocessed landfill gas is fed into a 12-cylinder internal combustion engine which drives a small generator producing electricity; and (3) "High-Btu Projects", where the landfill gas is processed to separate the methane which may be delivered into a nearby natural gas pipeline.

As of December 2005, there were 395 landfill energy projects in the US, over 80% of which are "electric" projects and most of the remaining are "direct use" projects, leaving only 9 "High-Btu Projects". See the EPA's website at www.epa.gov/lmop. The reason why "electric" projects dominate is that Section 45 (and its predecessor, Section 29) gives a tax credit (approximately $0.01/kWh) for only those landfill projects which produce electricity on the landfill.

HIGH-BTU LANDFILL PROJECTS versus ELECTRIC PROJECTS:

When Section 45 was passed, the technology for "electric" landfill projects was fully developed. However, the technology for "High-Btu Projects" was not perfected until after passage of Section 45.

The efficiency (Btu equivalent energy produced divided by Btus used) of "electric" landfill projects is about 16% due to the relatively small size engines/generators used; whereas, the efficiency of a typical "High-Btu Project" is over 85%.

Moreover, "electric" landfill projects produce SOX and NOX pollutants from the engines used; whereas, "High-Btu Projects" generate no emissions whatsoever.

Hence, Section 45, in providing tax credits only for landfill projects which produce electricity on-site, disadvantages the more efficient and cleaner "High-Btu Projects". Amending Section 45 to include a similar tax credit for "High-Btu Projects" would create a "level playing field" so that

HEADQUARTERS
P.O. Box 485
226 Lumber Street
Yukon, Pa 15698
info@greengasenergy.com
Phone: 724.722.7069
Fax: 724.722.7068

PITTSBURGH OFFICE
5807 Walnut Street
Pittsburgh, PA 15232
rwgladstone@comcast.net
Phone: 412.365.0138
Cell: 412.980.3036

Green
Gas
Energy, LLC

RICHARD W. GLADSTONE, II
Chief Executive Officer

the market could then fairly determine the best use of landfill gas for renewable energy projects.

PROPOSED LEGISLATION:

Section 45 should be amended to include a $2/million Btu tax credit which would be phased out to $0 when natural gas prices reach $8/million Btu (phased out proportionately as natural gas prices go above $6/million Btu to $8/million Btu, i.e., a $2 credit at $6 natural gas prices, a $1 credit at $7 natural gas prices and no credit when natural gas prices reach $8/million Btu or more). Senator Santorum introduced S. 3997 to so amend Section 45.

Such a credit is equivalent to the existing $0.01/kWh tax credit given to "electric" landfill projects under Section 45 (which, however, is not phased out as electricity prices rise).

Financing "High-Btu Projects" is made difficult by the volatility of natural gas prices (which determine the profitability of 'High-Btu Projects" which sell their product gas at natural gas prices). Because natural gas prices have fallen to $6/million Btu in the recent past, lenders and investors for "High-Btu Projects" will require conservative 15-year pro forma projections of natural gas prices at around $6 which makes financing difficult. Amending Section 45 to provide "High-Btu Projects" with a $2/million Btu tax credit (phased out at $8 natural gas prices) would then cause financing "High-Btu Projects" to assume an equivalent of $8 natural gas prices at which "High-Btu Projects" are then much more financially viable.

HIGH-BTU LANDFILL PROJECTS SHOULD BE ENCOURAGED:

One "High-Btu Project" on a typical landfill (5,000 cubic feet/minute landfill gas flow) on an annual basis (according to the EPA's website at www.epa.gov/lmop) will:

- Displace the use of 65,233,741 gallons of gasoline;

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P.O. Box 485
226 Lumber Street
Yukon, Pa 15698
info@greengasenergy.com
Phone: 724.722.7069
Fax: 724.722.7068

PITTSBURGH OFFICE
5807 Walnut Street
Pittsburgh, PA 15232
rwgladstone@comcast.net
Phone: 412.365.0138
Cell: 412.980.3036

Green
Gas
Energy, LLC

RICHARD W. GLADSTONE, II
Chief Executive Officer

- Avoid the importation of 1,387,952 barrels of oil; or
- Heat 37,543 homes.

There are 569 landfills on the EPA's above-referenced website listed as "candidate landfills" for landfill gas energy projects. "High-Btu Projects" on these landfills could provide a significant source of clean, renewable energy to combat our reliance on foreign oil. Our tax laws should not favor the less efficient and less clean use of landfill gas to produce electricity onsite. A "level playing field" should be provided by amending Section 45 to give equal treatment for "High-Btu Projects" on landfills.

NO NEW COST TO THE TREASURY:

Assuming the existing Section 45 tax credit for "electric" landfill projects is continued (which it should be), then there would be no new net cost to the Treasury from amending Section 45 to include "High-Btu Projects" on landfills.

Landfill gas rights are extremely competitive. Whenever landfill gas rights are available for an energy project, the landfill owner solicits proposals on the EPA's Landfill Methane Outreach Program website. At least 10 bids will be submitted, most for "electric" projects and a few "High-Btu Projects" will also be bid. The "electric" projects most always win in no small part due to the Section 45 tax credit being available only for the "electric" project bids.

If Section 45 were amended to include a similar tax credit for "High-Btu Projects", then for every landfill project awarded for a "High-Btu Project" there would be one less "electric" project receiving a similar tax credit. Thus, no new net cost to the Treasury from so amending Section 45.

HEADQUARTERS
P.O. Box 485
226 Lumber Street
Yukon, Pa 15698
info@greengasenergy.com
Phone: 724.722.7069
Fax: 724.722.7068

PITTSBURGH OFFICE
5807 Walnut Street
Pittsburgh, PA 15232
rwgladstone@comcast.net
Phone: 412.365.0138
Cell: 412.980.3036

Green
Gas
Energy, LLC

RICHARD W. GLADSTONE, II
Chief Executive Officer

BACKGROUND OF STATEMENT PROVIDER:

Richard W. Gladstone, II is a Lehigh University engineering graduate and CEO of Green Gas Energy, LLC which, with its affiliates ("GGE"), designs, builds and operates "High-Btu Projects" which convert landfill gas into pipeline quality natural gas. GGE is a Pennsylvania company employing 30 people and operating two "High-Btu Projects" in the Pittsburgh, Pennsylvania area.

Respectfully submitted,

Richard W. Gladstone, II
CEO, Green Gas Energy, LLC

HEADQUARTERS
P.O. Box 485
226 Lumber Street
Yukon, Pa 15698
info@greengasenergy.com
Phone: 724.722.7069
Fax: 724.722.7068

PITTSBURGH OFFICE
5807 Walnut Street
Pittsburgh, PA 15232
rwgladstone@comcast.net
Phone: 412.365.0138
Cell: 412.980.3036

STATEMENT OF NGVAMERICA

SUBMITTED TO THE SENATE FINANCE COMMITTEE

February 27, 2007 Hearing

America's Energy Future: Bold Ideas, Practical Solutions

Introduction

NGVAmerica appreciates the opportunity to provide the following statement concerning America's energy future. NGVAmerica is a national organization of over 100 member companies, including: vehicle manufacturers; natural gas vehicle (NGV) component manufacturers; natural gas distribution, transmission, and production companies; natural gas development organizations; environmental and non-profit advocacy organizations; state and local government agencies; and fleet operators. NGVAmerica is dedicated to developing markets for NGVs and building an NGV infrastructure, including the installation of fueling stations, the manufacture of NGVs, the development of industry standards, and the provision of training.

The Finance Committee has indicated it will hold a series of hearings to address the nation's energy future. This effort also will address the climate change implications of energy use. The first hearing on this issue was held February 27, 2007. NGVAmerica's comments respond to the committee's invitation for interested organizations to provide statements for the record. Our statement also addresses the Bush Administration's goal for 2017 of using 35 billion gallons of non-petroleum fuels.

NGVAmerica is pleased to provide the following statement to the committee as it considers these very important issues. NGVs can and will play an increasing role in replacing petroleum motor fuels and reducing emissions that contribute to climate change. Congress already has taken a number of steps to encourage greater use of natural gas and other alternative transportation fuels. These steps were enacted as part of the Energy Policy Act of 2005 and SAFETEA-LU. These incentives include tax credits for alternative fueled vehicles, alternative fuel infrastructure and alternative fuel use. Consumers and businesses alike are benefiting from the congressional action that was taken to encourage the increased use of alternative fuels. However, much more must be done if the U.S. is to begin the long process of transitioning away from the use of petroleum motor fuels – especially if America is to achieve the goal called for the President in his State-of-the-Union address of displacing 35 billion gallons of petroleum transportation fuels by 2017. This effort will require sustained and significant federal support since the risks associated with this effort are simply too great for private industry to undertake them alone in the timeframe needed. Moreover, this effort will require a mix of different transportation fuels to fill the void provided by petroleum since no one single fuel appears likely to supplant petroleum.

The comments provided below discuss the potential benefits of increasing the use of NGVs and ways in which the committee can assist in achieving them. Increasing the use of natural gas vehicles (NGVs) can: (1) reduce America's dependence on foreign oil, (2) improve air quality in urban areas,

(3) reduce emissions of greenhouse gases, and (4) pave the way for the more rapid introduction of hydrogen transportation technologies.

Summary of Recommendations

1. Extend and amend the tax incentives for purchasing natural gas vehicles, using natural gas in those vehicles and building natural gas fueling infrastructure.
2. Provide the same tax incentive for biogas converted to biomethane as currently exists for biogas used for electricity generation.
3. Provide tax incentives for natural gas use in off-road vehicles.

Rationale for Recommendations

Reducing Petroleum Reliance

There has been much discussion and controversy about the energy balance of various alternative fuels and their ability to reduce petroleum consumption. In the case of natural gas, each gasoline gallon equivalent of natural gas used for transportation displaces nearly 100 percent of the petroleum that would otherwise be used in the form of gasoline or diesel fuel. Furthermore, nearly 85 percent of the natural gas currently consumed in the U.S. is from domestic sources – produced right here in the continental U.S., the Gulf of Mexico, or Alaska. Most of the remainder is imported from Canada. The total U.S. natural gas resource base, including proved reserves, is more than 1,300 trillion cubic feet, over a 65-year supply of natural gas at current production levels.[1] Thus, U.S. supplies of natural gas are abundant and secure. With sufficient will, supplies of *conventional* natural gas will continue to grow as U.S. demand for this valuable fuel grows. And with the right incentives, non-conventional, renewable sources of natural gas also could increasingly be available to U.S. consumers. For example, an analysis previously conducted for DOE estimated that the U.S. could feasibly produce 1.25 quadrillion Btu *annually*. This is equivalent to 10 billion gasoline-gallon-equivalent of biomethane from landfills, animal waste processing facilities, and sewage.

Biomethane is pipeline-quality natural gas produced by cleaning up and purifying biogas. Biogas is a mixture of methane and other gases produced from the decomposition of organic materials such landfill waste. Thus, biomethane is a renewable source of natural gas. In the U.S., the production of biomethane has been overshadowed by the production of electricity from biogas. This is partly because the U.S. tax code encourages renewable electricity production but does not encourage biomethane production. In addition, many of the incentives recently adopted in the Energy Policy Act of 2005 (grants, loan guarantees, demonstration projects) favor bio-refineries that produce liquid fuels, or more specifically ethanol. If these incentives were expanded to be biofuels-neutral, the U.S. could more quickly realize the potential of this valuable fuel source. Other countries are moving forward with biomethane development even as they also move forward with increased ethanol use. In Sweden, twenty-five biomethane production facilities are in use and there are sixty-five fueling stations now dispensing biomethane for transit buses and other vehicles.[2] Some positive developments are occurring here in the U.S. California officials recently signed a memorandum of

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[1] See - American Gas Associations (U.S. Resource Base) - http://www.aga.org.

[2] See State of California Department of Resources Press Release June 29, 2006 - http://resources.ca.gov/press_documents/CaliforniaSwedenBioenergyMOURelease_06_29_06.pdf

understanding to work with officials from Sweden to advance the use of biomethane as part of California's bioenergy initiative.[3] And just this year, Prometheus Energy, a Washington State-based company, began producing biomethane at the Bowerman Landfill in Irvine, California.[4] This facility will be producing 5,000 gasoline-gallon-equivalent of biomethane per day. The biomethane will be used to fuel low-emission, transit buses operated in Orange County.

If fully utilized, biomethane could offset nearly all or most of the future demand for natural gas as a transportation fuel. As noted above, the potential exists to produce an estimated 10 billion gallons equivalent. This amount of fuel represents nearly a third of the President Bush's announced target for 2017 of achieving the production and use of 35 billion gallons of non-petroleum motor fuels.[5] Current demand for natural gas as a transportation fuel in the U.S. stands at about 200 million gallons per year. Thus, the increased use of natural gas for transportation could grow substantially in the coming years, offsetting a large amount of petroleum, and be supplied almost exclusively by renewable sources. Importantly, most of the fuel inputs that would be used to produce biomethane (e.g., sewage, landfill gas, animal waste) are currently underutilized or not used at all. Therefore, encouraging the production and use of biomethane would not harm other industries and would provide additional revenue stream for those industries that currently process and handle these feedstocks. Farmers and other operators of animal facilities can install anaerobic digester systems to convert their animal waste to usable biomethane -- with valuable, sanitary fertilizer as a byproduct. Longer term, cellulosic crops could be used to produce biomethane. Currently, the focus on cellulosic biofuels is on cellulosic ethanol. However, cellulosic crops also could be used to produce biomethane if the government were to provide biomethane refineries the same level of incentives as currently being given to ethanol biorefineries.

Climate Change Benefits

The use of conventional natural gas in motor vehicles reduces greenhouse gas emissions by 15 – 20 percent.[6] More recent emission testing programs indicate that greenhouse gas reductions from using natural gas in heavy-duty applications may be as much as 20 – 30 percent, based on improvements to natural gas engine technology and changes to petroleum fueled vehicles.[7] These emission benefits are in addition to the very large reductions in volatile organic compounds, nitrogen oxides and air toxics provided by using natural gas as a motor vehicle fuel.

The greenhouse gas benefits provided by natural gas vehicles are significantly greater if the natural gas is biomethane. This is because capturing and using biomethane offsets flaring or venting of methane emissions that would otherwise occur, and also offsets the emissions associated with

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[3] See Memorandum of Understanding Between State of California and Sweden; http://resources.ca.gov/press_documents/CaliforniaSwedenBiofuelsMOU.pdf

[4] See GreenCar Congress (January 25, 2007) - http://www.greencarcongress.com/2007/01/prometheus_prod.html; or Prometheus Energy - http://www.prometheus-energy.com/whatwedo/bowerman.php

[5] The President's Advanced Energy Initiative now includes a target of achieving 35 billion gallons of non-petroleum motor fuels. Few details have been released on this target but it is believed that it is based largely on increased use of ethanol. A gallon of ethanol, however, has far less energy than a gasoline gallon, about 35 percent less energy content. If the 35 billion gallon target is based on the energy content in ethanol, achieving 10 billion gasoline gallon equivalent of biomethane would actually represent about 43 – 44 percent of the President's target.

[6] See Argonne National Laboratory, GREET Model (2007); http://www.transportation.anl.gov/software/GREET/

[7] See National Renewable Energy Laboratory, WMATA Emission Testing Report, December 2005; http://www.cleanenergyfuels.com/pdf/NREL-WMATA_DieselvNG21606.pdf

producing, refining and burning gasoline and diesel fuel. Methane is a significant greenhouse gas -- estimated to be 21 times as intense a greenhouse gas as carbon dioxide. Capturing and "flaring" biogas reduces the methane to carbon dioxide. But, in doing so, its energy value is wasted. An energy-wise and greenhouse gas-wise alternative is to capture the biogas from these renewable waste sources, convert that biogas to biomethane, and use the biomethane to displace petroleum or other fossil fuels in transportation or other energy applications. If the potential biomethane resources in the U.S. were realized (i.e., 10 billion gallons per year), the estimated greenhouse gas reductions would be on the order of 500 million metric tons of CO_2 per year – or the equivalent of removing 90 million light-duty gasoline vehicles from the roads.

Paving the Way for Hydrogen

DOE's long-range plans to address energy independence and lessen the environmental impact of motor vehicles call for a transition to hydrogen fuel cell vehicles (FCVs). This goal includes producing hydrogen from renewable energy sources, such as solar, wind, or even landfills. In the near-term, however, hydrogen will most likely be produced by steam-reforming natural gas. Currently, natural gas steam-reforming represents nearly all U.S. hydrogen production (used mostly by refineries) and about half of world hydrogen supply. Natural gas is used because methane (the main constituent of natural gas) has the highest hydrogen-to-carbon ratio of any hydrocarbon fuel. Thus, natural gas provides a near-term, widely available feedstock with a proven technique for separating out hydrogen molecules. During the initial launch of hydrogen-fueled vehicles (both FCVs and internal combustion engine vehicles, or ICEVs), it is likely that demand for hydrogen fuel in the transportation sector will be met through the steam reforming of natural gas.

There is another equally important link between natural gas and hydrogen, however. That link is the infrastructure, technology, and experience currently being developed to use compressed natural gas and liquefied natural gas as transportations fuels. By advancing the market for CNG and LNG, it just might be possible to accelerate the transition to hydrogen. Attached is a list of some of the ways increased use of natural gas is making the hydrogen future more viable.

Tax Policies and Incentives Needed to Increase Natural Gas Use

In order to achieve the potential benefits of increased natural gas use, NGVAmerica urges the Finance Committee and Congress to consider the following measures.

1. Alternative Fuel Excise Tax Credit

The 2005 Transportation Law (SAFETEA-LU, § 11113, Pub. L. No. 109-59) provides tax incentives for natural gas and other alternative fuels when used as vehicle fuels. That alternative fuel credit expires on 9/30/2009. This short timeframe sends the wrong message to businesses and consumers about the government's support for using natural gas and other alternative fuels, and is inconsistent with the President's 2017 goal of replacing 35 billion gallons of petroleum with alternative fuels. Therefore, the incentive for alternative fuels should be extended until the end of 2016. Moreover, Congress should clarify that the tax credits provided for alternative fuels are not includable in income since such treatment would significantly discount the benefit (and, therefore, the impact) of this incentive. The IRS is currently looking at the treatment of the tax credits when taken by taxable entities, and has indicated that they may be includable income. Also, the tax credits for alternative fuels should be amended so that they are available on an accelerated basis just like the alternative fuel mixture credits; taxpayers filing for alternative fuel credits currently must wait until end of year to file certain claims (over and above excise tax offsets) while persons filing for alternative fuel mixture credits may file multiple claims during the year for payments from the government.

2. Alternative Fuel Vehicle Purchase Income Tax Credit

The 2005 Energy Law (EPAct 2005, § 1341, Pub. L. No. 109-58) provides tax credits for the purchase of dedicated alternative fuel vehicles, including NGVs. The alternative fuel vehicle credit expires on 12/31/2010. As with the fuel credit above, the short timeframe for this incentive sends the wrong message to businesses and consumers about the government's support for NGVs, and is inconsistent with the President's petroleum replacement goal. Therefore, the incentive should be extended until the end of 2016. The existing credit covers 80 percent of the incremental price for dedicated vehicles that meet the most stringent emission standards, and 50 percent for other dedicated vehicles. Since much of the emphasis on promoting alternative fuels has shifted to petroleum replacement and since dedicated NGVs displace 100 percent of the petroleum that would otherwise have been used, the credit for dedicated vehicles should be expanded to 90 percent of the incremental price. Congress also should provide a credit of 50 percent of incremental cost for the acquisition of bi-fuel NGVs since some businesses and consumers will continue to demand the flexibility of a multi-fuel vehicle until alternative fueling infrastructure is more widespread. In order to make these credits attractive to businesses, they should be exempt from tentative minimum tax provisions. Imposition of the minimum tax means that most large fleets are only able to use the tax credits as an incentive to acquire a very small number of new NGVs each year. Fleets represent the best opportunity to maximize the use of alternative fuels but this opportunity will not be realized if fleets receive an incentive that encourages no more than one or two NGV acquisitions each year.

3. Alternative Fueling Station Income Tax Credit

EPAct 2005 (§ 1342, Pub. L. No. 109-58) provides for an income tax credit of 30 percent up to a maximum of $30,000 for the installation of business NGV fueling stations and $1,000 for home refueling equipment. This incentive is inadequate to spur fueling station expansion. Large natural gas fueling facilities, capable of fast-filling frequent customers, cost up to $1 million. The cost of even the least expensive home refueler (with installation) can be upwards of $5,000. Therefore, the fueling station credit should be increased to 50 percent with a maximum of $300,000, and the home refueling credit to a maximum of $2,000. The tax credit for fueling infrastructure also should be exempt from the minimum tax provisions. Most fueling facilities are currently being developed by a small number of companies that build and operate stations for customers. If tax credits are subject to minimum tax, these businesses will only be encouraged to install a minimal number of new stations each year.

4. AFV and Fueling Infrastructure Tax Credit for Not-For-Profits

As mentioned above, EPAct 2005 (§§ 1341 -1342, Pub. L. No. 109-58) provides an income tax credit for part of the incremental price of new alternative fuel vehicles and alternative fuel stations. In an effort to ensure that public agencies also could benefit from this incentive, Congress provided that, when the purchaser is a public entity, the income tax credit can be passed back to the vehicle or equipment seller – with the expectation that the seller would pass some or all of the incentive to the buyer in the form of a lower purchase price. For a number of reasons, however, very few public agencies have benefited from this provision. Frequently, the sellers do not have sufficient tax liability. Transit bus manufacturers are a good example. In other cases, the alternative minimum tax eliminates the seller's ability to capture (and, therefore, pass on to the public agency) the tax credit. To provide public agencies with a clear and certain incentive to buy alternative fuel vehicles and install associated fueling stations, Congress should provide public agencies with the option of receiving the value of the credit as a federal grant or other direct federal payment.

5. Biomethane Production Credit

Biogas (i.e., methane-rich gas produced from animal waste, crop waste, crops, sewage and landfills) that is used to produce electricity is eligible for a Section 45 production tax credit.[8] However, if that same biogas is used directly (e.g., for on-site steam production) or is converted to pipeline quality methane and used for any other purpose, the biogas producer receives no credit. All use of renewable biogas should be encouraged. Therefore, the Section 45 biogas credit should be redefined to include all energy uses of biogas.

6. Tax Credits for Off-Road Vehicles

The vehicle, infrastructure and fuel use credits for alternative fuel vehicles included in the 2005 Energy and Transportation laws are generally limited mostly to on-road vehicles. However, about a quarter of the fuels used in transportation are used in off-road vehicles. Since these vehicles do not have to meet on-road vehicle emission standards, they tend to produce far more emissions than comparable on-road vehicles. To help reduce our dependence on foreign oil as well as air pollution, off-road vehicles should be provided financial incentives to move to non-petroleum fuels and technologies.

Conclusion

NGVAmerica appreciates the opportunity to provide these comments. We look forward to working with the committee as it crafts legislative proposals to address our nation's energy future in ways that will diversify the mix of fuels used in transportation, provide greater energy security, reduce reliance on petroleum fuels, and increase the use of fuels that address climate change.

[8] See 26 U.S.C. § 45.

Attachment
How NGVs and Helping to Paved the Way for a Hydrogen Transportation Future

Fuel Storage
Until major breakthroughs in hydrogen storage technologies are realized, hydrogen will most likely be stored on-board vehicles as a compressed gas or a cryogenic liquid. Today's prototype hydrogen vehicles are able to use existing tank technology for CNG or liquefied natural gas (LNG) vehicles as base technologies for hydrogen storage. However, to achieve commercialization objectives (e.g., sufficient driving range), FCVs and other types of hydrogen vehicles will require ongoing advancements in on-board hydrogen storage technology. Fuel storage capacity also must be safely increased, while reducing cost and weight. Because of similar material and manufacturing issues, several companies that make NGV tanks are also designing improved fuel-storage systems for hydrogen vehicles, applying their vast experience from years of developing onboard CNG and LNG tanks.

Fuel Management and Safety Systems
As with fuel storage technologies, commonality exists among companies working on fuel management systems for NGVs and FCVs. Generally, advancements made for natural gas systems also have application to hydrogen systems. Onboard safety technology designed for NGVs (e.g., gas detection and fire suppression) are also being applied to hydrogen vehicles.

Fueling Station Infrastructure & Dispensing Equipment
Fuel cell vehicles will deliver the greatest benefits (zero emissions, highest system efficiency) if they are designed to operate on direct hydrogen, rather than operating on hydrogen reformed onboard the vehicle. FCVs, therefore, require access to hydrogen fueling stations. It is unlikely that, early on, hydrogen for these stations will be produced at large methane-reforming plants, and transported to the stations via trucks or pipelines. A far more likely scenario is that the hydrogen will be reformed in relatively small volumes *at* the local station using pipeline natural gas. Pre-existence of the necessary natural gas pipeline infrastructure makes this feasible. The U.S. has more than 1.3 million miles of natural gas transmission and distribution lines. In addition, the U.S. has more than 1,000 fueling stations that currently supply natural gas for motor vehicle use. It only makes sense that some of these stations also would be modified to serve fleets using hydrogen fuel. In fact, some already are providing hydrogen. The existing natural gas infrastructure makes reforming of natural gas at existing gasoline stations a convenient, relatively cost-effective option for producing hydrogen. Today's natural gas dispensers are a bridge technology to pumps that will fuel tomorrow's vehicles using either compressed or liquefied hydrogen. Much commonality exists between systems that dispense and meter these two fuels, whether in gaseous or liquid form. Consequently, today's natural gas dispensers are paving the way for affordable, user-friendly hydrogen dispensers. NGVs also can be refueled overnight at home -- a major advantage compared to gasoline vehicles. Today's home refueling appliances (HRAs) that dispense CNG are also being designed for longer-term capability to refuel FCVs in the residential setting. In this way, home refueling of NGVs provides a clear pathway to the longer-term scenario of fueling FCVs at home.

Natural Gas/Hydrogen Blends

Compressed hydrogen can be blended with CNG to produce an exceptionally clean transportation fuel. With relatively minor vehicle modifications, this blend can be used in today's heavy-duty NGVs. For example, transit buses at SunLine Transit Agency in the Coachella Valley are operating in revenue service on a blend of CNG and hydrogen. This is helping SunLine to gradually transition its bus fleet to 100 percent operation on hydrogen. Similar efforts are underway in other areas, such as Las Vegas. Many members of the NGVAmerica are cooperating in efforts to develop and demonstrate vehicles that operate on this type of hydrogen-natural gas mixture.

Codes & Standards, and Safety Training

A host of other ongoing issues must be addressed for hydrogen to become a common transportation fuel. Many of these issues currently are being addressed by users of natural gas vehicles. As hydrogen transportation technologies gradually move from the demonstration phase into commercial deployment, a new structure of human support services will be needed. This includes specialists such as mechanics, inspectors, and fire marshals who are familiar with FCVs, hydrogen fuel, and fueling stations. The NGV industry is already helping to create such a support structure. To serve today's well- established markets for NGVs and natural gas fueling stations, thousands of people have been trained in related jobs. This support structure continues to grow, serving as a harbinger for training of America's future hydrogen workforce and the people who will be responsible for deploying hydrogen vehicles and fueling stations on a commercial scale.

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