The World's Energy Problem and What We Can Do About It

Steven Chu
Introduction by Robert J. Birgeneau

This presentation was given at the 1920th Stated Meeting, held at the University of California, Berkeley, on November 20, 2007.

Meltwater stream flowing into a large moulin of the Greenland ice sheet. Photo courtesy of Roger J. Braithwaite, University of Manchester, UK.

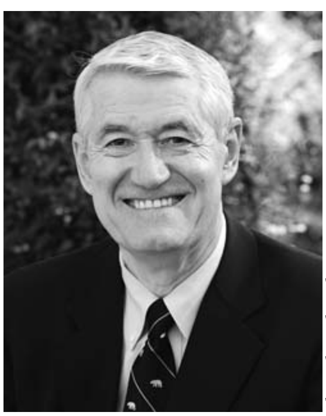

Photo by John Blaustein

Robert J. Birgeneau

Robert J. Birgeneau is Chancellor of the University of California, Berkeley. He has been a Fellow of the American Academy of Arts and Sciences since 1987.

Introduction

I am happy to welcome the American Academy back to the Berkeley campus and to greet so many of my fellow Academy members. The meetings that the Academy arranges on campus each year perform the valuable service of bringing together faculty from a wide range of disciplines who might otherwise not meet. I am proud to say that this university, with its broad array of excellent faculty in so many fields, is taking a role in multidisciplinary research leading toward practical solutions to some of the world's great challenges. All of us know that there will always be intellectual challenges that can only be solved by one brilliant mind. However, many of today's challenges can only be addressed with a multidisciplinary approach.

At Berkeley we recently initiated several new and exciting multidisciplinary initiatives. One seeks practical solutions to global poverty. Another initiative studies the challenges of multicultural societies. A third is searching for ways to mitigate life-threatening diseases through stem-cell research. A fourth is looking for alternative clean-energy solutions to reduce our energy demands.

This last multidisciplinary initiative is the largest of our new initiatives. With the success of the BP grant for the development of biofuels for transportation, which was formally signed this past week, and our many other approaches to alternative energy (from inventing solar energy devices to exploring energy conservation methods and studying the social impact of new technologies), Berkeley is strongly positioned to be a global leader in energy research.

Few people on this campus are better qualified to tell us about alternative energy research than our speaker this evening, Steven Chu. Steve is a graduate of Berkeley with a

Ph.D. in physics; in fact, his thesis advisor is here. He was also a postdoc at Berkeley. After many years, he has returned as Professor of Physics and of Molecular and Cell Biology and as Director of the Lawrence Berkeley National Laboratory. Steve happens to be an old friend of mine who arrived at Bell Labs not long after I left to go to MIT. At Bell, he invented optical tweezers, a laser trap that earned him the Nobel Prize in 1997. Although his Nobel Prize discoveries were in physics, they had applications not only in physics but also in both microbiology and nanoscience.

At Stanford, as the Theodore and Frances Geballe Professor of Physics and Applied Physics, Steve helped start Bio-X, a multidisciplinary initiative linking the physical and biological sciences with engineering and medicine. Steve has long been interested in the conversion of solar energy into a large-scale alternative to fossil fuels. He came back to Berkeley with an incredible passion for meaningful research on climate change and energy self-sufficiency, and played a central role in creating a new Energy Biosciences Institute for multidisciplinary research and institutional collaboration on biofuels, which will help take us from the laboratory to the fuel pump.

Most recently, Steve completed work on a major international report on energy sustainability to the InterAcademy Council. His civic contributions are numerous. A member of the Augustine committee that produced in 2006 the now-famous report, *Rising Above the Gathering Storm,* he has served on advisory committees to the Director of the National Institutes of Health and the National Nuclear Security Agency, and on the Executive Committee of the National Academy of Sciences's Board of Physics and Astronomy. Steve is also on the boards of foundations, universities, and corporations, including the Hewlett Foundation, the University of Rochester, and NVIDIA, and on the scientific boards of the Moore Foundation, Helicos, and Nabsys.

A Fellow of the American Academy, Steve is an active participant in its initiative on alternative models for the federal funding of science and on the potential to nurture the next generation of scientists. It is with great pleasure that I call my friend and colleague Steven Chu to the podium.

Steven Chu

Steven Chu is Director of the Lawrence Berkeley National Laboratory and Professor of Physics and Professor of Molecular and Cell Biology at the University of California, Berkeley. He has been a Fellow of the American Academy of Arts and Sciences since 1992.

I am delighted to be here to talk about something I care about deeply: our energy problem. Rather than focusing on just biofuels, though, I want to take a step back and look at the broader problem and options.

First, with our prodigious use of energy, we have created a number of serious environmental concerns, particularly climate change. The problem starts locally, but eventually affects everyone globally. I began to appreciate the extent of the problem when I worked on a study for the InterAcademy Council, a small group of people who represent over 150 academies of science, medicine, and engineering around the world. Second, about one-third of the people in the world have only primitive forms of energy: twigs, dung, lumps of coal. Some 1.6 billion people do not have electricity. This many people lacking access to modern forms of energy is an enormous issue. Third, competition is growing for increasingly rare energy resources, particularly oil and gas. Countries have gone to war for far less than this.

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Today I am going to focus on the first aspect of our energy problem: the environmental complications created by our use of energy. In Figure 1, we see how much the Earth has warmed up from 1860 to 2000 – keep in mind that 140 years is nothing on a geological timeline. Figure 2 illustrates the temperature today and looks back 420,000 years. Over that time, we have gone through an ice age, a rapid warming period, another ice age, and another rapid warming period. The temperatures depicted here were measured in oxygen samples taken from the ice sheets in Antarctica. Also plotted are concentrations of carbon dioxide and methane over time.

Looking at these figures, you might ask, "Well, what is the problem? We are in a warm period, but over the next 100,000

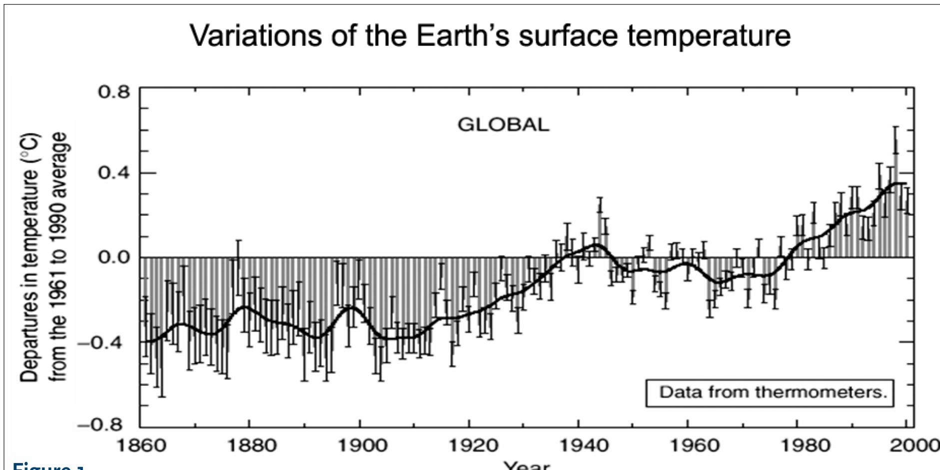

Figure 1

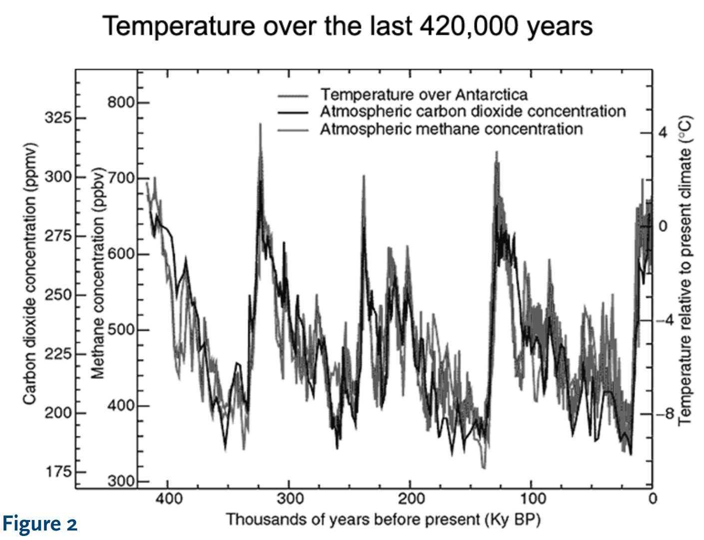

Figure 2

years, shouldn't we be more concerned about another ice age?" The reason scientists are concerned about global warming is because the current CO_2 level is at 380 parts per million (ppm), which is off the scale in Figure 2. In terms of total greenhouse gases (CO_2, methane, nitrogen oxide, etc.) we have an effect CO_2 concentration of 420 ppm. Moreover, most of this change occurred in roughly a hundred years, 1,000 times shorter than the time it took for the Earth to cool down from its warm periods.

What caused these shifts in the past? We now know that astronomical changes in the eccentricity of the Earth's orbit, a slight tip in the Earth, caused the initial rise. But that slight change in eccentricity does not account for the entire shift. One possibility is that positive feedback effects played a role; as the Earth warmed up, greenhouse gases trapped in the oceans and on land were released. The release of the greenhouse gases continued the warming process. The conjecture is that plants and other organisms that fix CO_2 prosper in a warmer climate that has more CO_2, and these organisms slowly sequester the carbon dioxide, causing a slow cooling.

If we followed a business as usual scenario, the Stern Review Report states that we have a greater than 50 percent probability of exceeding a 5°C global average temperature change. What will happen if this occurs? The good news is that life on Earth will go on. The bad news is that it will be a very different place. Twenty-five thousand years ago, the world was roughly 6 to 8°C colder. During this time, all of Canada and the United States down to Ohio and Pennsylvania were covered in a sheet of ice year round. A few degrees change in the *average* temperature has a profound effect on the Earth. Moreover, if this change occurs in less than a century, many species will face extinction. Life on Earth will almost certainly continue, since we know that 50 million years ago, the Earth had much higher levels of CO_2 and was more than 10°C warmer. In a much warmer world, however, it will not be as inviting a place for polar bears or people.

What is the evidence that humans are causing this warming? Figure 3 shows the concentration of greenhouse gases – carbon dioxide, methane, nitrous oxide – over the last thousand years. The lines are fairly flat until about 1750, when levels suddenly start to increase. It is at about that time that countries began to industrialize, and we began to burn coal in larger amounts.

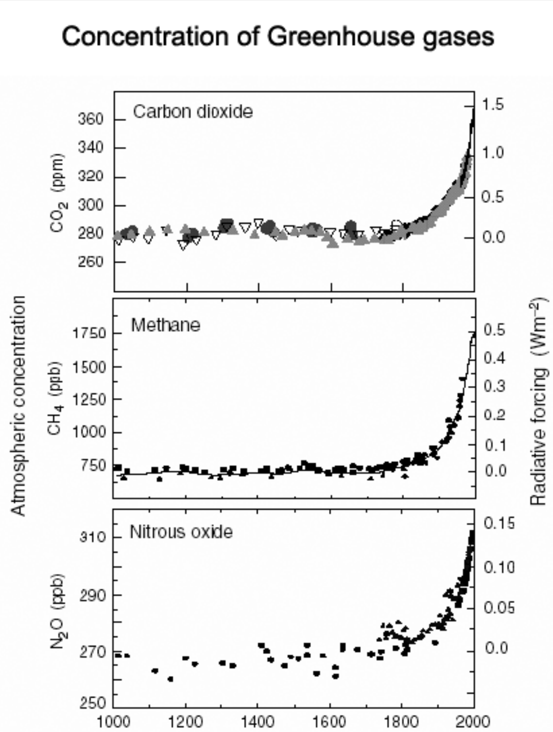

Figure 3

There is a growing preponderance of evidence that suggests that human activity was the major factor in the observed change in the average temperature of the Earth.

Yogi Berra, the great American philosopher of the twentieth century, was reputed to have said, "Predictions are hard to make, especially about the future." In order to get better about making predictions of the future, one can practice by trying to predict the past. I am going to take you through a prediction of what may have happened in the past. The dark line in Figure 4 is the observed average temperature increase over the world. The gray line represents a climate model of what the temperature change should have been due to natural causes, such as solar variations, volcanic activity, and so on. In the second graph, the gray line is a computer model that also includes the increase of greenhouse gases as shown in Figure 3. As we see, the climate model was able to predict the past, which gives us more confidence that it may be able to predict the future.

The bottom graph in Figure 4 suggests that humans might have caused climate change. Does it prove humans caused it? No. However, there is a growing preponderance of evidence that suggests that human activity was the major factor in the observed change in the average temperature of the Earth. This is why the Intergovernmental Panel on Climate Change Report in 1990 was not willing to say that any climate change we measure is due to humans, whereas in 2006 it was saying that there is a greater than 90 percent chance it was caused predominantly by humans.

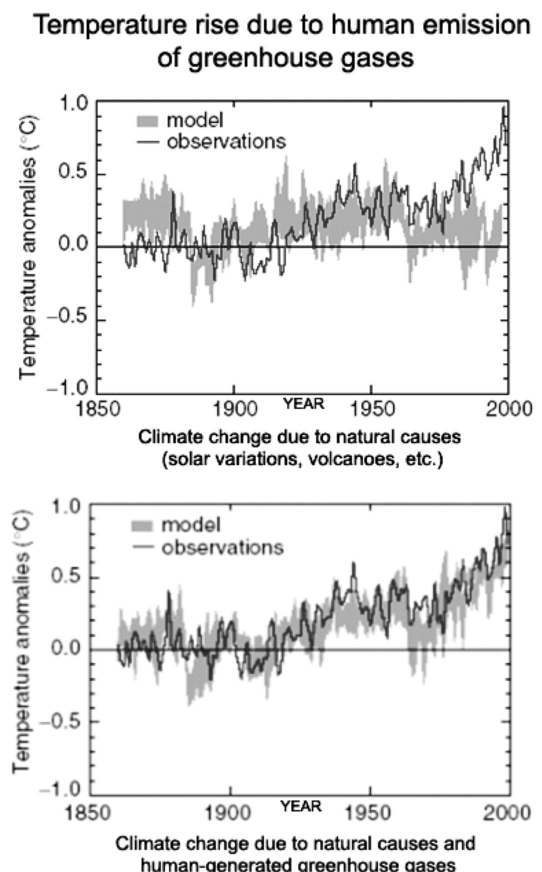

Figure 4

So again, with the caveat of Yogi Berra's wisdom about making predictions, let me discuss some predicted effects of climate change. People are forecasting many events, including a dramatic increase in species extinction, a rise in sea level, increased damage from floods, storms, and wildfires, and so on. There is mounting evidence that many of these predictions are beginning to happen, and in many cases, faster than what was predicted in the 1980s.

In Figure 5, we see images of the snow pack around the North Pole region, reconstructed from microwave radiometric and microwave imaging satellites. These images were made from data taken in September, when the Arctic melting is at a maximum. When the snow and ice melt to expose a darker ocean, there is a positive feedback mechanism that occurs. As more snow and ice melt, the area of the heat-absorbing dark ocean increases, allowing the Earth to absorb more heat, which leads to more melting of the reflective ice and snow.

As the ice pack melts, will it cause a rise in sea level? No, because this ice is in water, and because of our understanding of buoyancy: the combined combination of water and ice floating on top will not change sea level height when the ice melts. It is the decrease of snow and ice on land that will cause a rise in sea level.

The images in Figure 6 show the area of the Greenland ice sheet in 1992 and then in 2002 (the record melt of 2002 was exceeded in 2005). The bulk of the ice sheet in central Greenland is 2 to 3 kilometers thick, and the volume of ice, if it completely melts, will cause the sea level to rise by 7 meters. Here again there will be positive feedback effects. As the sheet melts to lower altitudes, the surface of the ice will be exposed to warmer conditions. Once the darker ground is exposed, more sunlight is absorbed.

I believe that it is possible to continue to consume large amounts of energy that have led to our prosperity while dramatically decreasing the production of CO_2.

It is vitally important that the developing countries learn to leapfrog past the mistakes of the developed world and grow into prosperity in a more environmentally friendly way.

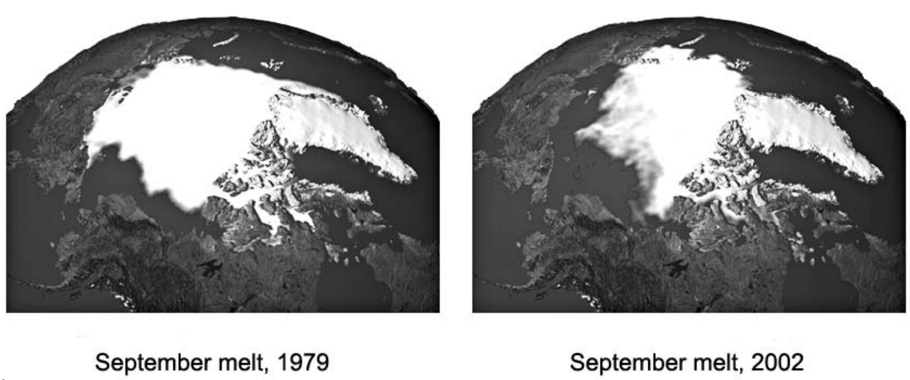

Figure 5

The melting is occurring faster than we predicted ten years ago due to two reasons. The snow is darker than we thought because there is more soot than originally estimated. We also did not fully appreciate the fact that in the summer months, when the ice melts, vertical shafts (moulins) permit water to flow to the base of the ice sheet. The water lubricates the interface between the ice pack and land, allowing the ice sheet to flow into the sea faster. Over the past decade, Jacobshaven, an extremely fast-moving glacier on the western side of Greenland, has doubled its rate of flow into the ocean, and is now moving at a speed of 40 meters per day. Global warming is giving a new meaning to the phrase "glacial speed."

Now let us shift our focus to energy consumption. The United States is the leader in both wealth and energy consumption per capita, but our energy consumption per unit of wealth (measured as the GDP per capita) is leveling off. There are several reasons: increased energy efficiency, and a shift from a heavy industry-based economy to a service-based economy.

The more relevant issue is not energy consumption *per se*, but the amount of greenhouse gases one emits while using the energy. I believe that it is possible to continue to consume large amounts of energy that have led

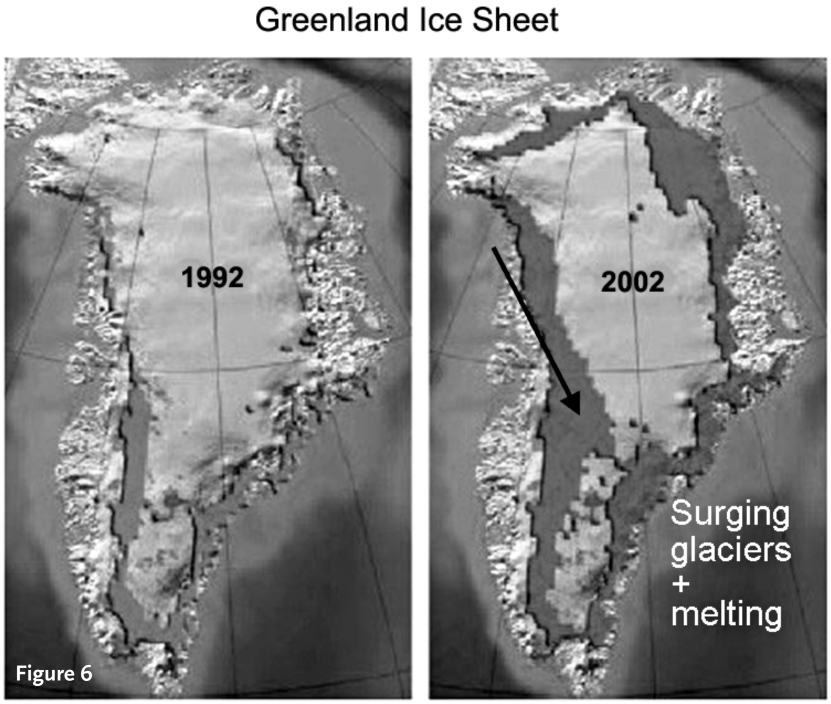

Figure 6

to prosperity while dramatically decreasing the production of CO_2. The governor of California, Arnold Schwarzenegger, has set a target of reducing the state's carbon emissions by a factor of five by mid-century. Others think that dropping by a factor of ten may be needed to stabilize the carbon in the atmosphere and allow the rest of the world's population, which will peak at approximately 9 to 10 billion people, to enjoy the same standard of living as the United States.

Are China and India going to follow in our footsteps in economic development and CO_2 emissions? Historically, as developing countries increased their wealth, they began to realize that their industrial development also generated considerable pollution of the air and water. The developed world made some terrible mistakes, and many people paid a heavy price for the initially unrestrained emission of many forms of pollutants. When the world was less populated (such as at the beginning of the industrial revolution), the consequences of the pollution were mostly localized to a particular region. In a world of 6.5 billion people, the emissions from burning coal (SO_2, nitrogen oxides, particulate matter, mercury, as well as CO_2) are becoming a worldwide problem. If China and India develop as the United States has, we will face an enormous challenge, and it is vitally important that the developing countries learn to leapfrog past the mistakes of the developed world and grow into prosperity in a more environmentally friendly way.

We need to maximize energy efficiency and decrease energy use.

The developed countries, and especially the United States, must dramatically reduce their carbon emissions. A dual strategy is needed: 1) We need to maximize energy efficiency and decrease energy use. Increasing the efficient use of energy will remain the lowest hanging fruit among the set of solutions for the next several decades. 2) We have to develop new sources of clean, carbon-neutral sources of energy.

Will the free market take care of the energy/climate change problem? The answer is resoundingly no. Free markets fail when there is a "commons problem": a problem that involves a shared resource. The term originated with the idea in medieval Europe of the common area of a town, where the local folk could graze their livestock, gather wood, etc. The town commons was a shared resource. Pollution is a "commons" problem. For example, if you are a city that is located on or near a river that is shared by many cities, it is much cheaper to dump raw sewage into the river than to treat it, especially if there are no cities upstream from you. However, to the cities downstream from the polluter, it is much more expensive to clean up the water than to suffer the health, economic, and social consequences of a polluted river. As a shared resource, the wisest and most economical use of the river is for all cities to treat their sewage. International fishing is also a commons problem that transcends national, and even continental, borders. If a fisherman (or nation) does not have total control over the asset, some people will want their fair share of the fish, and some maybe a bit more than their "share." Unfortunately, the result is that an estimated 24 percent of the world's fisheries have been either overexploited or depleted (FAO estimate). Climate change is the biggest commons problem we are facing today, and free markets will never respond to this problem. Ultimately, international agreements between governments have to intervene with a combination of regulations and fiscal incentives.

California has done a remarkable job since the mid-1970s of flattening electricity consumption per person, while the rest of the United States experienced a 60 percent increase. An important part of this energy savings was a provision that California wrote into its regulation of utility companies, separating the profits of a utility company from its sale of energy. They realized that it is not the total profit but the return on investment that investors really care about. If energy companies could make that return reasonable and stable, energy would still be a good investment. Furthermore, for any energy conservation measure that a utility company adopted, they could automatically pass that cost onto the ratepayer. Only three other states in the Union have adopted these measures, but we are trying to get the word out to the rest of the country and even to the rest of the world.

In my opinion, the biggest energy savings will occur in buildings. The United States spends nearly 40 percent of its energy in commercial and residential buildings. From talking to knowledgeable architects and design engineers, I learned that investments in energy

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efficiency in a new building that have a payback time of less than five or six years in many instances can reduce energy consumption by more than a factor of two. When a university plans to add a new building to its campus, and hopefully a building that will be useful for at least 50 years, most universities until very recently have been unwilling to invest the additional 5 percent to make the building more energy efficient. The reason these "better-than-free" energy investments are not currently being made is because the source of money that operates and maintains a building is not the same as the source that builds and/or purchases the building. With slight adjustments, I believe the ability to make better macroeconomic decisions will go a long way to improving the use of energy.

The Berkeley Lab helped design the new San Francisco Federal Building. It uses natural chimney-like ventilation instead of mechanical cooling or ventilation in the open-plan perimeter office space. The exposed structural concrete allows for thermal inertia to take advantage of the cool nights in San Francisco. It also incorporates as much natural lighting as possible. As a result of the success of the San Francisco Federal Building, the Lab has been asked to green the U.S. Capitol Building in Washington. Enthusiasm is growing for creating strong ties on campus with the School of Design, the School of Engineering, and the Lawrence Berkeley National Laboratory to work on projects such as these.

Let me turn now to potential supply-side solutions to the energy problem. Unfortunately, I do not think the world will turn its back on coal. It is too plentiful. Two-thirds of the world's known coal reserves are in the United States, Russia, China, and India, in that order. I am fairly certain that China and India will not turn their backs on coal. Nor will Russia because it wants to keep its coal for the domestic production of electricity and to sell its enormous oil and gas supplies on the international market for hard currency. China is building a coal-fired power plant every other week. As for the United States, the verdict is not yet in as to what we are doing, but there are now over 100 applications to the regulatory authorities to build coal plants. Coal plants are big investments; they cost anywhere from $300 million to $1 billion and have a 50-year lifetime. Once you make this kind of investment in a coal plant, there will be a huge incentive to use it for the life of the plant.

Coal plants vary widely in efficiency. Japan has the most efficient coal plants, at about 42 percent efficiency. Remarkably, U.S. plants are about 34 percent efficient. India's are 25 to 30 percent efficient. Going from 25 to 30 percent to 42 percent efficient is huge in terms of the amount of electricity per carbon unit. It is possible to increase the efficiency of electricity generation to better than 50 percent by using so-called "super critical" steam generation at higher temperatures. But in order to get to these much higher temperatures, we need more temperature-resistant, cost-effective metals or metal/ceramic composite materials. Thus, novel materials could decrease the amount of carbon emissions per unit of electricity generated by as much as 40 percent.

Biofuel production must be accomplished in an economically competitive and environmentally friendly way.

Electricity generation with natural gas or gasified coal has an even higher efficiency – roughly 60 percent – with today's technology. Why? Coal is dirty; burning it produces a lot of sulfur dioxide, nitrogen oxides, particulate matter, mercury, and radioactive uranium and thorium in the fly ash. These combustion products are also very corrosive. You cannot directly use the combustion gases in a conventional, pulverized coal plant to spin a turbine, but you can with natural gas or the syn-gas (a mixture of carbon monoxide and hydrogen) that results from gasifying coal. The exhaust of the turbine is so hot that you can put it in another heat exchanger and spin another turbine in a method called combined-cycle generation. Virtually all gas plants in the United States being built today are now combined-cycle plants. The burning of coal releases roughly twice as much carbon dioxide per unit of energy produced when compared to natural gas.

Increasing the geothermal generation of energy should also be considered. Geothermal energy is actually a very clean form of fission energy, since the heat deep inside the Earth is generated by naturally occurring radioactive decay. A good geothermal energy source has a combination of hot, porous rock and a supply of replenishable water. Anywhere around the world, if one goes down into the earth, you automatically get heat. Water is needed to extract the heat in surrounding rock and transport this energy to the surface where it can be used. We have a few geothermal sources in California, and geothermal energy is a major component of Iceland's energy supply. The trouble is that the combination of porous rock and water is not found everywhere. However, new methods of introducing lateral fractures in rock and pumping water into this rock can greatly enhance the potential of geothermal sources. A recent MIT study estimates that with existing technology, enhanced geothermal energy can supply up to 10 percent of the base-load electricity generation in the United States. At Lawrence Berkeley National Laboratory, we are also exploring the possibility of using carbon dioxide as a heat transfer fluid.

Wind is also a very good source of renewable energy. In terms of cost, it is within 20 percent of being competitive with fossil fuel. Currently, the biggest windmills have a generating capacity of 3 million watts per windmill, with the wingspan of a 747 airplane. Even larger, 5 MW windmills are on the drawing board, with wingspans of 126 meters. The bigger the windmills get, the more efficient they become, and because they stand higher off the ground, they can intercept more wind energy. I asked a senior engineer at GE how big he thought they could get. He answered, "5 MW is about as big as they can get. Any bigger, and we can't ship the blades. They cannot make turns on conventional railroad tracks and highways."

Where are the best wind sites in the United States? The good news is that many sites are where there aren't many people. But that is also the bad news, because now we must transmit this energy over larger distances.

Many of the best sites are in the upper Midwestern states, such as North and South Dakota, and in the mountainous regions of the United States.

For any variable supply of energy, such as wind or solar PV, or any capital-intensive form of carbon-neutral energy, such as nuclear, a long-distance transmission system that connects these sources to multiple local grids makes them much more valuable. We do not have a truly national, long-distance electricity transmission system in the United States. Our current interlocking grid is comprised of a collection of local transmission systems that connect to each other.

We already know that high-voltage DC transmission is less expensive and more efficient than AC transmission for distances greater than roughly 500 kilometers. It costs less money for many reasons. With DC, you need only two conductors instead of three or four. Also, the right-of-way costs can be considerably less. If you have ever wondered why high-voltage transmission lines are so high in the air, it is not because of the danger of electrocuting somebody; it is because as the voltage changes back and forth, the electric field polarizes the earth with alternating electric fields. This coupling causes charges to move in the medium and dissipates energy. To decrease the energy loss, the lines are moved higher in the air. For that same reason, you can't put in a high-power AC transmission line underwater because this so-called "capacitive coupling" would be enormous. With DC transmission lines, there is no energy loss due to capacitive coupling, and underground or undersea high voltage lines are possible. Already, there is an underwater HVDC line that goes between Sweden and Germany, and more undersea lines are being planned in Europe and the United States.

We can also convert the sun's energy into transportation fuel. This conversion is possible by using plants, algae, or some other microbe. It is also possible to convert solar energy to electricity, and then use the electricity to drive chemical reactions to store the energy in the form of chemical fuel that can either be converted back into electricity or used as transportation fuel.

If we consider using plants, we have to ask if we can grow enough food to feed a growing world population as well as grow energy. Unfortunately, much of the world is desert, and thus not well-suited for growing plants. Southern California is mostly desert, and it is the use of energy that allowed us to move massive amounts of water needed for agriculture, and to supply major cities such as Los Angeles and San Diego. Since much of the world is desert (and since arable land is much more valuable than desert land), the harnessing of solar energy without the use of water will likely supply a greater fraction of our energy needs compared to biofuels. At the present time, solar thermal and photovoltaic electricity generation needs substantial subsidies to compete with fossil fuel generation of electricity. If we reduce the cost by roughly a factor of three, many more people would install solar generators on the tops of warehouses and their homes without subsidy. If we reduce the cost by a factor of ten, power companies would begin to install large generating stations in desert areas. At LBNL, we are exploring the use of nanotechnology to create a new generation of very inexpensive solar cells that can be massively deployed on rooftops and deserts.

In the end, we need to seek transportation energy solutions that are not based on nature.

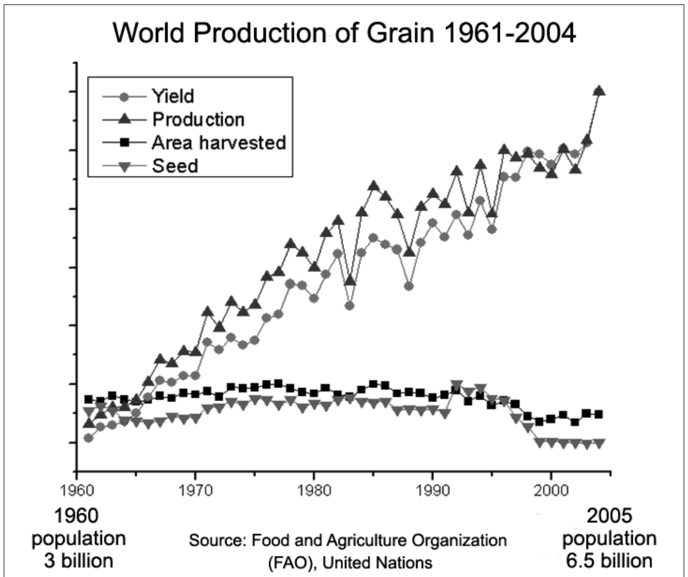

Figure 7

We are also looking at methods to greatly improve the conversion of sunlight to transportation fuel via biomass. Can we grow enough to feed the rising population of the world and still make transportation fuel? One of the greatest achievements of the twentieth century, at least as important as the invention of the transistor, the Internet, or the airplane, is the development of modern agriculture. Modern agriculture is heavily dependent on energy that goes beyond pumping water from wells or moving surface water in aqueduct systems. Our ability to make fertilizer from ammonia, which is synthesized from natural gas, transformed agriculture. At the beginning of the twentieth century, there was a huge problem with soil depletion, and Europe was contemplating importing soil or growing food abroad to feed its citizens. The ability to synthesize ammonia was considered so important that two *different* Nobel Prizes in chemistry were awarded for this work.

Even with the invention of fertilizer and irrigation, many scholars in the 1960s questioned whether we would ever be able to feed all the people in the world. The third vital advance in agriculture was the "Green Revolution": the creation of much higher yielding crops. Norman Borlaug, who was awarded the Nobel Peace Prize for breeding a dwarf wheat plant that produced 6 times as much wheat per acre as previous strains of wheat, prevented the imminent starvation of hundreds of millions of people. As a result of the Green Revolution, fertilizer, and irrigation, the amount of land devoted to the cultivation of grain actually decreased slightly while the production of grains increased fivefold, as shown in Figure 7. During this time, we went from a population of 3 billion in 1960 to 6.5 billion today, and fewer people are starving to death.

Returning to the growing of plants for biofuels, can we grow plants that are better than corn? The answer is definitely "yes." As an example, consider the grass *Miscanthus*. This plant is perennial, and hence no tillage is needed for 10 years or more. As a perennial, it can be harvested annually, and like a weed whose roots are left in the ground, *Miscanthus* will grow back with a vengeance the following year. This plant is expected to produce ten times the amount of ethanol per acre as compared to corn, and without the heavy energy and water inputs that corn demands. As Bob mentioned, a half-billion-dollar grant was awarded to the University of California, Berkeley, with its partners the Berkeley Lab and the University of Illinois, to develop this pathway to alternative fuels.

What do we want to do with this investment? We want to develop better plants and develop better methods of breaking down the woody ligno-cellulose material into material that can be converted into a biofuel. In the BP-funded project, we also want to look at the socioeconomic and environmental impacts of biofuels. The deployment of any new technology often is accompanied by unintended consequences, and it is important to try to anticipate and minimize (and ideally to avoid) harmful consequences. Biofuel production must be accomplished in an economically competitive and environmentally friendly way.

We are beginning to explore how to break down cellulose and convert it into biofuels with a new technology called synthetic biology. Jay Keasling, a professor of chemical engineering at Berkeley and also the Director of the Physical Biosciences Division at Lawrence Berkeley Lab, has incorporated at least a dozen genes into the genome of *E.coli* to make a precursor to a new anti-malarial drug, artemisinin. His research grabbed the attention of the Gates Foundation and his discoveries are being commercialized by a startup company. This anti-malarial drug is on schedule for worldwide delivery to begin in 2008–2009. It turns out that this drug is a very close relative of a biofuel. In order for the startup company, Amyris, to get support from the Gates Foundation, it had to provide the anti-malarial drug at no profit. The financial incentive for the company is that the technical knowledge gained in the creation of this drug can be applied to make money in other applications. Very recently, Amyris is applying its synthetic biology technology to produce a biofuel that would be superior to ethanol.

Figure 8: Earth Rise from Apollo 8 (December 24, 1968)

In the end, we need to seek transportation energy solutions that are not based on nature. Because of the limits on production of fuel using arable land, we need to develop an artificial photosynthetic system that will split water into oxygen and hydrogen, and to extract carbon dioxide out of the atmosphere and reduce it to carbon monoxide. These are the first three ingredients that are needed to construct hydrocarbon fuel.

To advance energy research further and faster, we also should change the way we do research. Most university research starts with a proposal. It takes at least a year for the peer-review process to approve of the research. Then, you get three years to produce enough results to obtain additional funding.

We would like to fund research a little bit differently. At Bell Labs, where I worked for nine years, funding decisions were made much more quickly by technically superb managers. Individual genius was nurtured, but people were encouraged to form teams quickly in order to exploit ideas rapidly. The scientific direction was guided by collective wisdom and "managed" by top scientists with intimate, expert knowledge. Part of the responsibility of the Bell Labs managers was to encourage bold approaches. Some failure was expected, but there was an emphasis on recognizing failure quickly, and moving on to other opportunities. Communication between groups was a high priority, and technical memos were flying all over the place. Part of our goal is to create in the various LBNL/UC Berkeley energy institutes that we are establishing the same kind of stimulating intellectual cauldron that the veterans of Bell Labs experienced.

At his Nobel banquet in 1950, William Faulkner said, "I believe that man will not merely endure: he will prevail. He is immortal, not because he alone among creatures has an inexhaustible voice, but because he has a soul, a spirit, capable of compassion and sacrifice and endurance." With these virtues, we can and will prevail over this great energy challenge.

Let me close by reminding you of the image, shown in Figure 8, of "Earth Rise" taken by the astronauts of Apollo 8. This picture shows the dramatic contrast between a beautiful planet and the stark landscape of the moon. We know that there is nothing else within our reach. The energy problem is about preserving our planet. ■

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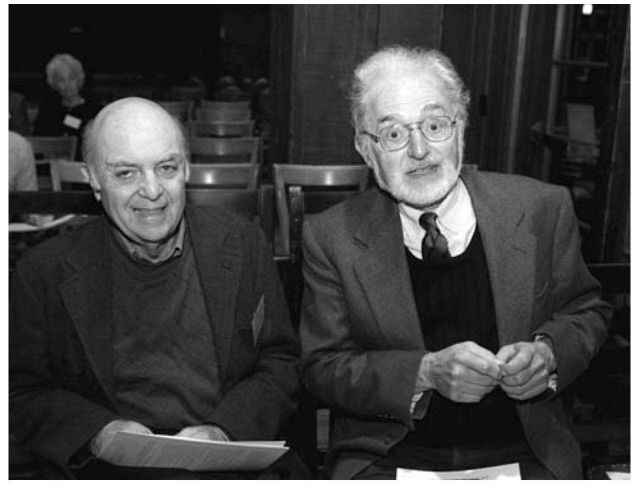

Marvin Cohen (University of California, Berkeley) and Eugene Commins (University of California, Berkeley)

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Karl Pister (University of California, Berkeley) and Christopher Edley (University of California, Berkeley)

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