ENERGY CHALLENGES

Presented to the 145th Annual Meeting
of the National Academy of Sciences
Ralph J. Cicerone, President
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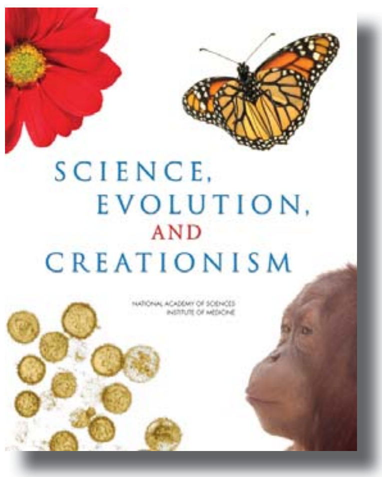
As I stand before the members of the NAS, I feel as each of you would in my place --- that it is a great honor and a rare opportunity to address you here in our historic NAS building. As you know, we are planning a major restoration of the building which will be discussed further in tomorrow's business meeting.

I want to recognize NAS Presidents-Emeritus Frank Press and Bruce Alberts who are here with us today. Each of them led the Academy with distinction and continues to represent us well.

The past year has been a very busy one, reflecting the importance of science and technology in contemporary society. One project, the revision and updating of our 1984 and 1999 booklets on science and creationism, was completed when the new booklet, *Science, Evolution and Creationism* was released in January. This project was initiated and supported by the NAS Council. For this third edition, we invited the Institute of Medicine to join the NAS.



The authoring committee is shown here. I ask each of the authors who is here today to stand.

AUTHORING COMMITTEE

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Bruce Alberts, University of California, San Francisco
May R. Berenbaum, University of Illinois, Urbana-Champaign
Betty Carvellas, Essex High Scool (Vermont)
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Holly Wichman, University of Idaho

Today I want to use the opportunity to draw your attention to a major issue of today, human demand for and usage of energy, a topic that has become progressively more serious, one that will take years to address and which requires scientific efforts of many kinds.

In the past fifty or sixty years there have been other transforming issues that have dominated national and international attention and which required science and technology for any successful outcome, but these earlier cases have not been numerous. One can recall the nuclear arms race, the polio outbreaks of the 1950's, and the very rapid increases of human populations of the 1950's and 1960's.   Science made possible the cessation of nuclear weapons testing through demonstrated capability to detect the detonation of even relatively small weapons, while computational methods enabled stockpile stewardship. Similarly, through medical immunology, scientists came to understand the cause of polio and created preventive vaccines; and the Green Revolution made it possible to feed many more people. Two other major issues in which public attention was focused on science and technology were the launching of early Earth-orbiting satellites (and placing a man on the Moon), and the capabilities that emerged in the early 1970's from molecular biology for safe laboratory DNA-transfer experiments.

Now in 2008, we see that human demand and usage of energy is a pervasive issue. The issue has multiple dimensions and constraints. It is both national and worldwide. Enormous in scale, it will remain serious for the foreseeable future, and science and engineering are essential for progress.

Main Points

My main points today are:

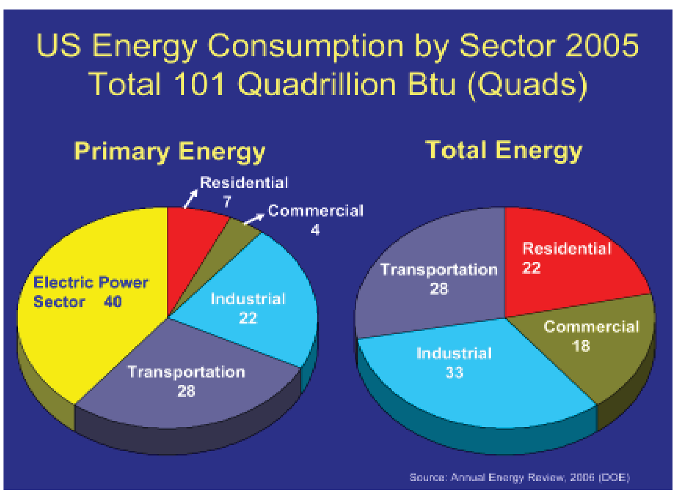
Our energy-intensive way of life, population growth and worldwide economic progress combine to create large and growing demand for energy.

Our options to meet this large demand with types of energy now available to us are seriously constrained. We must assure access to energy and geopolitical security, overcome the financial impact of high costs, deal with climate change, other environmental impacts, nuclear safety and wastes. There is no simple single solution and some attractive options are mutually incompatible.

Science and technology and scientists are essential to meeting this pervasive challenge.

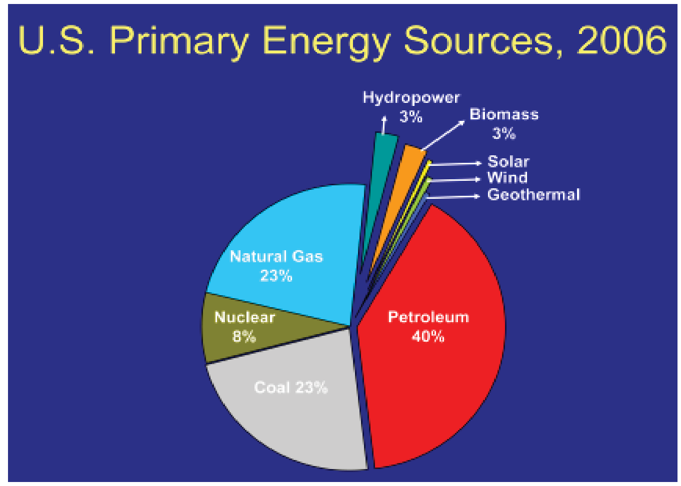
Energy Usage and Demand

The scale of human energy usage today is large and projections of future demands are even larger. Let me begin by outlining current energy usage in the United States.

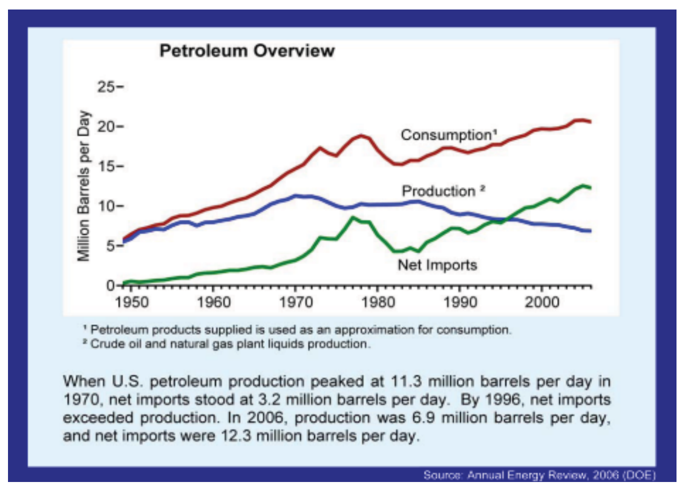


We consume 100 Quadrillion BTU (one Quad is 10^{15} BTU) per year as a nation, or 3.3×10^8 BTU per person annually.(1) There are many ways to disaggregate these figures. For example. we can examine end usage by economic sector or by function. One such cut reveals that 28% of U.S. energy usage is for transportation (burning gasoline, diesel and jet fuel) and 39% is used in buildings for lighting, heating, cooling, appliances and office equipment.

What are the sources of our primary energy? For the U.S., 85% comes from the burning of fossil fuels: 23% from natural gas, 23% from coal and 40% from petroleum (using rounded numbers). Eight % is derived from nuclear power and six % from renewable sources like hydropower (3%), biomass (3%), geothermal sources, wind, and solar.



Two key factors are liquid fuels for transportation and coal burning to generate electricity. Slide 5 shows growth in U. S. imports and consumption of petroleum.

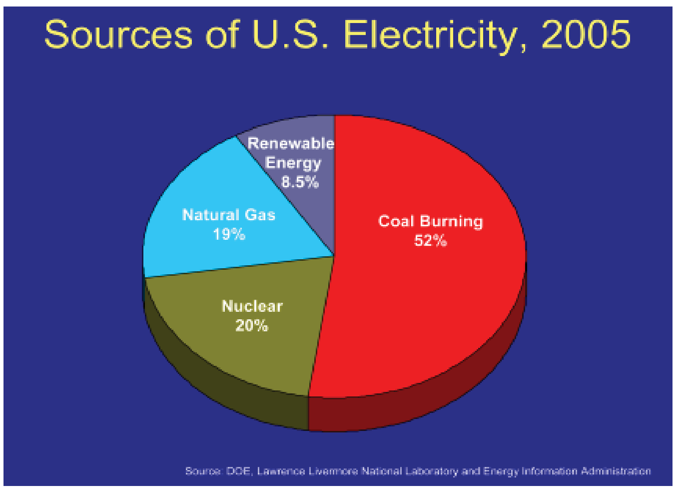


Net imports grew from 3 million barrels per day in 1970 and surpassed domestic "production" in 1996. Today, we import approximately twelve million barrels of oil daily, most of it for transportation, and we consume about six million barrels of oil more each day for running our automobiles and trucks than is produced (extracted, to be more precise) domestically.

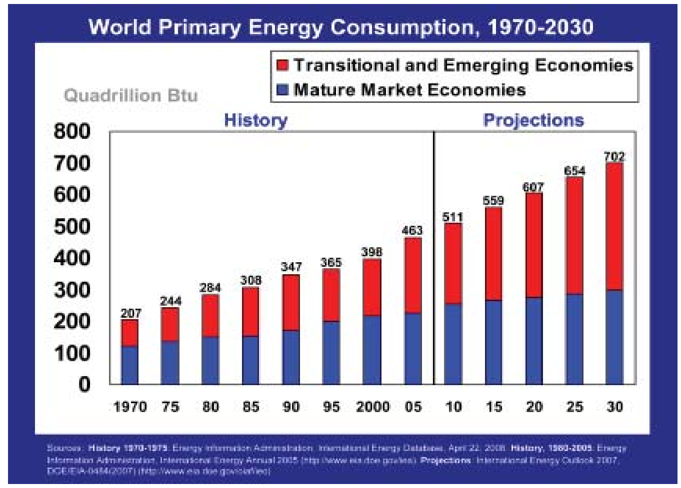
A related figure is the fraction 41% of primary energy consumption that goes into producing electricity.

Annually, the U.S. consumes about 3800 billion kWh of electricity, with an average instantaneous consumption rate of 440 million kW, or 1.47 kW per person. Because of considerable inefficiency in the conversion of primary energy into electricity during generation and losses in its distribution, the electrical energy received by the end user is only about one-third of the primary energy invested in generating it.

Our electricity is generated in several ways but the major pathways are from coal burning (52%), nuclear power (20%), natural gas (19%) and renewable energy including hydropower (8.5%). While still small, electricity generated from wind power grew by over 25% compounded annually from 2001-2005.



Slide 7 shows world energy consumption 1970-2005 and projected usage to 2030, developed & developing countries. Worldwide energy consumption was about 447 quadrillion BTU in 2004. This figure grew from approximately 207 quadrillion BTU in 1970; it doubled in 30-32 years. World average energy consumption is approximately 6.2x10^7 BTU/person, or only one-fifth as much as for Americans. The fraction of total world energy usage from fossil-fuel sources was about 87% in 2004, slightly higher than the corresponding U.S. figure. The fraction of world electricity from nuclear power was only six % as opposed to eight % in the U.S. although it is well known that France's electricity is generated primarily (70%) from nuclear power, and of course, there are other nations that employ no nuclear power at all. Recently, Germany has emerged as a world leader in capturing wind energy and in the manufacturing of photovoltaic cells for the direct conversion of sunlight to electricity, as is Japan.



World energy consumption is projected to grow to approximately 700 quadrillion BTU in 2030, another doubling from its early 1990's value. Much of this projected growth is likely to occur in developing, or emerging market countries, where there is great demand for energy usage *per capita* to grow, while slower growth is projected for mature market countries like those of advanced developed countries. One projection is for non-OECD countries (including China and India) to increase energy usage by over three % annually, more than doubling between 2004 and 2030 while U.S. energy growth is projected to be one % annually. This differential growth will continue trends observed from 1999-2005 when China and India increased their energy usage by 80% and 25%, respectively.

The dynamics and impacts of this differential growth are extremely important to analyze. For example, we must understand what is driving this increased demand (electrification, pumping water for irrigation and for manufacturing and consumer uses, population growth…). We must also anticipate impacts on world prices and availability and on world geopolitics, environment and climate. A recent report from the InterAcademy Council is a rich source of data on growing demand and strategies for satisfying it worldwide.[(2)]

Impacts of Energy Usage and Constraints

For many years there have been concerns over the stability of energy supplies or the cost of energy or the consequences of too much dependence on overseas sources or over various environmental impacts. Now all of these concerns are operative at once and they are seen as long term as opposed to temporary.

Constraints from Energy Extraction and Consumption

- Security
- Financial Costs
- Environment
- Climate
- Nuclear Operations and Wastes
- Nuclear Weapons Proliferation

For example, as U. S. consumption of petroleum, mostly for transportation, has grown, and costs have risen to over $100 per barrel, the net flow of dollars to oil-exporting countries has ballooned to between $450 to $500 billion annually, as noted recently by former CIA Director James Woolsey.[3] Let me note that even at the now past price of $65 per barrel, 300 million Americans send $1000 each overseas for oil annually. At our NAS/NAE energy symposium on March 14, former Secretary of Energy and Secretary of Defense James Schlesinger said that our dependence on foreign oil is allowing some hostile oil-exporting countries to accumulate dollars, resulting in diminished U.S. influence not only toward them but also with our allies. He stated that "we cannot ensure energy security, only mitigate energy insecurity".

Predicting future energy costs is perilous and certainly not a talent of mine. Personally, I did not predict that gasoline would cost $3.5 to $4 per gallon as it is now. However, there is general consensus that the era of low cost energy is over, largely due to increasing demand from developing countries. Thus, one can expect U.S. purchases of oil to continue and world prices to remain high enough to cause difficulties for poorer countries. Worldwide fleets of car and trucks demand oil as does the growing commercial airline sector. High costs of energy are being felt by individuals, families, businesses, universities, governments, and hospitals, for example. High energy costs are now beginning to be blamed for rising grain costs and food shortages in some countries.

The imperative for access to secure energy supplies prompts some regions and countries to turn to coal or to nuclear power. For example, the U. S., China, South Africa and India have substantial domestic coal supplies. Environmental and climatic impacts must be dealt with. Inadvertent emissions of soot, sulfur, nitrogen oxides and mercury, historical challenges which have been met in some selected regions, remain major problems elsewhere and due to the scale of coal usage, they are increasingly serious problems, as are deleterious effects of coal mining on land surfaces and ground water. In each of the last several years, a large number of coal-fired power plants have been built in China; total generating capacity from these plants has increased annually by approximately 95 Gwatts (adding approximately the entire capacity of France or Germany).

In recent years it has become clearer that the global climate is changing in response to increased atmospheric concentrations of carbon dioxide from fossil-fuel burning.[4] Current atmospheric concentration of CO_2 is over 380 ppm, compared to a pre-industrial level of 280 ppm. Climate change is being observed in elevated air and sea temperatures, losses of ice, rising sea level and several other variables, and it is judged mostly due to greenhouse gases, including carbon dioxide, from human activities.[4] While some climate change can be accommodated, there is increasing evidence and concern that dangerous changes can also occur. "Dangerous" here is defined as irreversible changes such as sea-level rise and loss of biodiversity, and generally other physical variables whose rates of change exceed the rates at which we can adapt to them. Large or prolonged changes in regional water supplies can destabilize entire nations.

While it might be intuitive to guess that we could stabilize worldwide atmospheric carbon dioxide amounts by holding worldwide emissions constant, the natural uptake of atmospheric CO_2 by the global carbon cycle is only about 40% of current emissions; this figure has been derived by decades of research, much of it by NAS members. Current annual emissions are nearly seven billion tons of C as CO_2. The eventual steady-state atmospheric concentration of CO_2 from current emissions would be over 650 ppm. Thus, a specified carbon constraint such as preventing atmospheric CO_2 from rising above say

450 parts per million, is difficult to satisfy: it would require reducing emissions by more than four billion tons (C) from current levels. Several examples show how difficult it will be. Reducing emissions by just one billion tons C per year would require a fleet of two billion cars to achieve 60 mpg instead of 30 mpg, or replacing 700 one GW coal-burning power plants with nuclear plants, or replacing coal-burning plants with one million 2 MWe (peak) wind turbines or 2,000 1-GWe(peak) photovoltaic power plants.[5]

Instead, if worldwide energy usage continues to grow as projected and fossil fuels continue to supply over 80% of that energy, worldwide CO_2 emissions would grow to over ten B tons C annually by 2030, just 22 years from now. At such a rate of fossil-fuel burning, humans would inject as much CO_2 into the air from fossil-fuel burning between 2000 and 2030 as they did between 1850 and 2000.

In addition to climatic change from carbon dioxide, we expect the world's oceans to become acidified by the CO_2 added from the atmosphere. Research on the biological effects of this acidification is in its early stages and there are many questions surrounding the ability of calcifying marine organisms to make shells, for example. [6]

The view that emerges is of a carbon-constrained world. Taking into account the fact that coal is relatively plentiful and that its supplies are secure within several large countries, and recognizing the carbon constraint gives rise to the need for research on carbon capture and storage (CCS) and to other means to tap into coal's energy without releasing CO_2 to the atmosphere and oceans.

Even if coal, for example with effective CCS, could be used even more intensively to generate electricity, one must realize that to use today's fleets of cars and trucks and airplanes, one requires liquid fuels, presumably from oil. While coal yields less energy per unit of CO_2 released, carbon constraints apply to oil and natural gas as well as to coal.

The constraints of energy supply, dependence on foreign sources and atmospheric carbon dioxide cause us to consider wider usage of nuclear power. Nuclear power plants, currently based on nuclear fission processes, offer several advantages in that their operation does not emit carbon dioxide nor are supplies of nuclear fuel thought to be seriously limited physically or immediately.[7] Widespread utilization of nuclear power is limited instead by concerns over safety of operation and over waste handling, storage and disposal. Strongly related is the need to prevent the misappropriation of nuclear wastes to produce nuclear weapons or conventional bombs spiked with radioactivity (dirty bombs). In addition, costs of electrical power from current nuclear plants exceed those for coal and from natural gas; capital costs of nuclear plants are much higher. These concerns have virtually stopped the building of new and replacement nuclear power plants in many countries since approximately 1980.

For nuclear power to satisfy large parts of current and future world demand for electrical energy would require the siting, construction and operation of large numbers of new and replacement nuclear power plants such as a tripling or quadrupling of the number of such plants now in service.[7] Local limitations on volumes and temperatures of cooling water will tighten as tensions grow over water supplies and heat waves intensify. Even if successful, we would not have satisfied much of world demand for energy to drive transportation, now supplied by petroleum, with today's fleet of automobiles and trucks.

Agenda for Scientists, the National Academy of Sciences and the National Research Council

The constraints placed on energy choices for the United States and for the world today can appear to be intractable. For example, large U.S. domestic coal reserves, much of our existing infrastructure and the goal of energy security all argue for more dependence on coal. However, we are pushed in the opposite direction by the pressing need to reduce CO_2 emissions to the atmosphere so as to limit climate change, and by several other environmental impacts including ocean acidification. In a democracy there are many different voices representing people with differing values and interests, such as protecting or advancing locally based industries, and also with differing weighting factors for addressing the various constraints.

All of these challenges place scientists and engineers in an essential position --- we can:

- Perform research relevant to energy supplies and usage,
- Formulate and analyze options for decisionmakers,
- Inform the public about research and policy options,
- Advise and help government officials and business leaders,
- Develop scientific and engineering human resources.

We must address each of these needed roles with complementary skills. Along with creating specialized processes and strategies, we need big-picture synthesis. For example, achieving increased energy efficiency can relax all of these constraints but implementing this goal requires great attention to detail.

The NAS and the NAE, working through the NRC, are conducting a study, America's Energy Future, and it will be published in less than a year from now. This report will present objective, quantitative data and estimates of contributions to our energy supply from various energy technologies, including energy-efficiency technologies, along with their costs. Many NAS and NAE members and other experts are involved on this project. It is led by economist Harold Shapiro, President-emeritus of Princeton University (and an IOM member). This report will lay a foundation for much more work to follow on energy research, energy-policy options and worldwide cases. It is intended to provide what Benjamin Franklin aptly described as "useful knowledge" to individuals and groups in business and government and the general public as they consider how to transition to the energy trajectories that are needed.

We are also beginning a new suite of studies on climate change, focusing on how to benefit from and extend the scientific understanding of climate change and also how to mitigate it and adapt to it.

Scientific research, as always, offers possibilities for improvements in how we extract, convert, store, distribute and consume energy. Indeed, research can lead to major changes which could revolutionize our current systems and which could dodge some of the constraints that now bind us. Opportunities for this research to create new technologies with worldwide business potential are enormous.

There are numerous fascinating research topics in physical and biological sciences which could dramatically transform the energy landscape or which could at least improve our options.[8] Photovoltaic devices based on new materials to convert sunlight into electricity and chemical means to convert sunlight into chemical fuels offer great opportunities. Photosynthesis-based designs are beginning to receive some attention. Energy-storage devices with high energy and power densities could enable much wider use of solar, wind and nuclear energy, for example, in electric-drive vehicles.

Alternative energy sources for transportation must match or overcome a large advantage of liquid hydrocarbons; the oxidizer for their combustion does not have to be carried along with the fuel. A major goal is to derive petroleum substitutes from plant matter other than food crops which would be approximately carbon-neutral. Microbiological processes enhanced by molecular biology comprise many potential advanced pathways toward creating liquid biofuels such as alcohols. In such advanced processes, efficient use of normally recalcitrant material like plant cellulose and lignins must be made. Progress from this laboratory-based biological research is needed to obtain higher biofuel yields which justify inputs of energy, fertilizer, water and land. These input/output ratios themselves and corresponding tradeoffs require research to clarify the value of this option.

Wider usage of nuclear power to generate much larger amounts of electricity could displace some fossil-fuel usage but it requires safe and efficient handling of wastes which in turn require secure geological and geochemical storage. Similarly, economical and safe waste-to-fuel reprocessing represent research and engineering challenges and opportunities, and some materials problems with reactors remain.

As has been the case for too many years, nuclear fusion remains a distant but tantalizing pathway toward plentiful energy, with almost no radioactive waste, but very difficult problems in confining high-temperature plasmas have impeded progress.

A host of other research frontiers must be explored, for example, can carbon dioxide be effectively captured and stored in geological reservoirs in amounts measured in tens of billions of tons and for centuries? Can transmission lines be vastly improved through superconductivity or by using direct current transmission instead of AC, with better system analysis and control? If so, solar and wind energy can be distributed in ways to match generation and demand time functions better

Scientific research on climate change is essential to enable us to predict how climate will change in smaller geographical areas and shorter time intervals than is now possible so as to guide our efforts in mitigating the changes and in adapting to changes that do transpire. Economic science and social phenomena must be incorporated in this endeavor, and as is the case in all of the topics mentioned here, computational science has become essential.

In deciding how to deal with the constraints placed on us by U.S. and global energy usage, governments, businesses, NGO's and individuals want to know what options they have. An important role for us as individuals and through National Research Council committees is to help to formulate and analyze options that can illuminate the consequences of various proposed actions. This work can consist of focused analyses of specific energy sources or pathways and respective technologies, or on comparisons of many alternatives. Variables include physical, chemical and biological principles, costs, readiness for deployment, social acceptance and time frames. In many cases, those who will make decisions amongst the options will be political or business leaders who have little or no scientific background, so scientists' communications skills will be tested. In these interactions centered on formulation and analysis of options, scientists must be prepared to interact with such decisionmakers in iterative ways. It is likely that some overall pathways to a more secure, safe and robust energy strategy will involve short-term options in preparation for transitions to a longer term.

More broadly, scientists can inform the public about research prospects and goals and about policy options. The pervasive nature of our challenges with energy requires wide public awareness and consensus, and arriving at consensus will be challenging. Whether deciding how to locate solar collector arrays, nuclear power plants or wind farms or how to gauge the benefits of various biofuels or automobile fuel efficiency, and how to invest their own resources or public funds, people must appreciate the constraints and the goals to choose the best options and to avoid costly mistakes and ineffective actions. Scientists who are effective communicators should present public talks and/or help other scientists and journalists who are even more effective. In our NAS communications with the general public, we plan to emphasize energy topics in several ways.

We depend on many structures and institutions to govern us. Agencies of the U.S. Government which support science research, set standards, monitor and regulate trade, products and pollutants need qualified people to serve in them and they need external counsel through advisory committees, for example. Each of us should serve when invited, and we should prepare thoroughly for each assignment. Important roles in advising the government are carried out by the National Research Council. State and local governments have many significant energy issues in front of them so the need for scientific advice is even larger. Scientists can also help each other when one is called to advise.

Education of the current and future generations of students is a high priority. All of the needs listed above require an educated public to recognize our options, to understand their consequences, and to exploit opportunities. Students who will go on into business and government will have big roles just as future scientists will. We must develop human resources, both broadly and in specific scientific endeavors, from microbiology and molecular biology to nuclear science and engineering. Our university curricula for science and for *non-science* students must create awareness of challenges and opportunities surrounding energy usage, efficiency and related research. As always, research opportunities for students are especially important.

Conclusion

We must change the trajectories of our energy usage and energy sources. World peace, economic development for much of the world, continuing prosperity for the developed countries and a stable climate require us to do so. To create and analyze options, and to educate and inform people about the work ahead, scientists and engineers are critical.

There is no single action or individual technology that will take us to this goal. (The glass(es) are partly filled and partly empty. The baseball is just for fun!)

Rather we must explore all sources and pathways and discover, invent and optimize in each case. While it might disappoint some people that there is no single pathway to success, a world in which many energy sources and solutions are integral to the whole will be more stable and less susceptible to disruption. Our enthusiasm and efforts must be broad as we seek to discover and disseminate useful knowledge.

A great deal of innovative and determined work is needed by scientists and engineers in the years ahead. It is our privilege and our responsibility to rise to these energy challenges. Let's get going; there is a lot of useful knowledge to be gained.

REFERENCES

(1) One BTU = 1.05×10^3 Joules. Sources of data are the Energy Information Administration Web site, eia.doe.gov, the International Energy Agency Web site, http://data.iea.org, the Lawrence Berkeley Laboratory, the Lawrence Livermore National Laboratory. I also used reports from the National Petroleum Council (2007) and the McKinsey & Co. Global Institute (2006, 2007).

(2) *Lighting the Way: Toward a Sustainable Energy Future*, the InterAcademy Council, Amsterdam, 2007, 174 pp.

(3) Washington Post, March 19, 2008, page A5.

(4) IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

(5) R. Socolow and S. Pacala, *Scientific American* September, 2006.

(6) *The Ocean in a High-CO_2 World*, American Geophysical Union, a series of 17 reprints from *Journal of Geophysical Research* vol. 110, 2005. See also, *Ocean acidification due to increasing atmospheric carbon dioxide*, The Royal Society, London, policy document 12/05, 2005, 57 pp.

(7) *The Future of Nuclear Power: An Interdisciplinary M.I.T. Study*, Massachusetts Institute of Technology, 2003, 170 pp.

(8) See presentations by Steven Chu "Lighting the Way Toward a Sustainable Energy Future " and by Raymond Orbach "Basic Science for America's Energy Future" at the March 14-15, 2008 *National Academies Summit on America's Energy Future*, http://www7.nationalacademies.org/energysummit/energy_summit_agenda.html.

See also *Directing Matter and Energy: Five Challenges for Science and the Imagination,* U. S. Department of Energy Basic Energy Sciences Advisory Committee, chair, J. Hemminger, report authored by Graham Fleming and Mark Ratner et al. December 20, 2007. The presentation by Steven Chu "Energy research at the intersection of the physical and life sciences" at an NAS Symposium on Future directions in Research at the intersection of the Physical and Life Sciences, December 19, 2007 describes a great variety of research opportunities.