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ENERGY AND NANOTECHNOLOGY: STRATEGY FOR THE FUTURE

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RICE UNIVERSITY INITIATIVE ON ENERGY POLICY AND NANOSCIENCE

IN LIGHT OF REPEATED OIL SUPPLY DISRUPTIONS AND EMERGING ENVIRONMENTAL PRESSURES, THE INTERNATIONAL ENERGY INDUSTRY AND SCIENTIFIC COMMUNITY ARE LOOKING TO NONCONVENTIONAL SOLUTIONS TO CONFRONT OUR ONGOING ENERGY SECURITY CONCERNS.

ENERGY IS NOT JUST A CRITICAL CONCERN TO THE UNITED STATES BUT ALSO A GLOBAL ONE. AMONG THE MOST IMPORTANT TECHNICAL CHALLENGES FACING THE WORLD IN THE 21ST CENTURY IS PROVIDING CLEAN, AFFORDABLE ENERGY, WHOSE SUPPLY IS SUSTAINABLE AND UNIVERSALLY AVAILABLE. A SOLUTION TO THE GLOBAL ENERGY PROBLEM WILL REQUIRE REVOLUTIONARY NEW TECHNOLOGY, AS WELL AS CONSERVATION AND EVOLUTIONARY IMPROVEMENTS TO EXISTING TECHNOLOGIES.

ADVANCEMENT OF NANOTECHNOLOGY SOLUTIONS CAN BE AN INTEGRAL COMPONENT TO SOLVING THE ENERGY PROBLEM. BREAKTHROUGHS IN NANOTECHNOLOGY OPEN UP THE POSSIBILITY OF MOVING BEYOND OUR CURRENT ALTERNATIVES FOR ENERGY SUPPLY BY INTRODUCING TECHNOLOGIES THAT ARE MORE EFFICIENT, INEXPENSIVE, AND ENVIRONMENTALLY SOUND. THE BENEFITS OF SUCH TECHNOLOGY WILL NOT BE CONFINED TO THE UNITED STATES OR THE DEVELOPED WORLD; INDEED, ITS IMPACT WILL BE GREATEST FOR THE 1.6 BILLION INDIVIDUALS AROUND THE GLOBE, MOST SPECIFICALLY THE POOR, WHO LACK ACCESS TO ELECTRICITY AND OTHER VITAL ENERGY SERVICES.

TO ADDRESS INCREASING INTEREST IN SCIENTIFIC SOLUTIONS TO OUR MONUMENTAL ENERGY CHALLENGES, THE JAMES A. BAKER III INSTITUTE OF RICE UNIVERSITY, TOGETHER WITH THE RICE UNIVERSITY CENTER FOR NANOSCALE SCIENCE AND TECHNOLOGY (CNST), THE RICE ALLIANCE FOR TECHNOLOGY AND ENTREPRENEURSHIP, AND THE RICE ENVIRONMENTAL AND ENERGY SYSTEMS INSTITUTE (EESI) CONVENED A CONCLAVE ON "ENERGY AND NANOTECHNOLOGY: STRATEGY FOR THE FUTURE." THE CONFERENCE WAS PART OF A BROADER CAMPAIGN TO REINVIGORATE PUBLIC INTEREST IN THE PHYSICAL SCIENCES. IT AIMED TO BRING TOGETHER POLICY-MAKERS, SCIENTISTS, OPINION-SHAPERS, AND BUSINESS LEADERS TO SHOWCASE POTENTIALLY REVOLUTIONARY BREAKTHROUGHS IN THE ENERGY TECHNOLOGY ARENA.

THE CONFERENCE PROVIDED THE OPPORTUNITY FOR SCIENTISTS TO CONFER NOT ONLY AMONG THEMSELVES, BUT ALSO WITH POLICY SPECIALISTS AND VARIOUS EXPERTS FROM OTHER DISCIPLINES TO EXAMINE ENERGY ISSUES FROM BOTH A POLICY AND TECHNOLOGICAL PERSPECTIVE. THE CONFERENCE EXAMINED CREATIVE ALTERNATIVES TO THE TRADITIONAL APPROACHES IN POLICY AND TECHNOLOGY.

A PRIMARY GOAL IN CONVENING THE CONFERENCE WAS TO HELP BROADEN PUBLIC UNDERSTANDING OF HOW SCIENTIFIC DISCIPLINES SUCH AS NANOSCIENCE, WHICH CAN APPEAR TO HAVE LITTLE BEARING ON PEOPLE'S LIVES, IN REALITY SPAWN TECHNOLOGIES THAT CAN HAVE A DIRECT IMPACT. THIS CONFERENCE ADDRESSED THE POTENTIAL FOR TECHNOLOGY TO HELP SOLVE THE CHALLENGE OF DEVELOPING CHEAPER, MORE EFFICIENT, AND ENVIRONMENTALLY SOUND ENERGY SUPPLIES.

THE CONFERENCE WAS ALSO DESIGNED TO EDUCATE LEADING NANOSCIENTISTS ABOUT THE GREAT TECHNICAL CHALLENGES FACING THE ENERGY INDUSTRY TODAY. RICE UNIVERSITY IS TAKING THE LEAD IN CREATING DIALOGUE BETWEEN NANOSCIENCE AND ENERGY TECHNOLOGY EXPERTS TO SHARE IDEAS ABOUT POTENTIAL APPLICATIONS FROM THEIR ARENA THAT COULD LEAD TO RESOLVING BOTH NATIONAL AND INTERNATIONAL ENERGY PREDICAMENTS.

ORGANIZING PARTNERS

JAMES A. BAKER III INSTITUTE FOR PUBLIC POLICY: THE MISSION OF THE BAKER INSTITUTE IS TO BRIDGE THE GAP BETWEEN THE THEORY AND PRACTICE OF PUBLIC POLICY BY DRAWING TOGETHER EXPERTS FROM ACADEMIA, GOVERNMENT, MEDIA, BUSINESS, AND NON-GOVERNMENTAL ORGANIZATIONS IN A JOINT EFFORT TO UNDERSTAND AND ADDRESS THE UNDERLYING FORCES SHAPING OUR WORLD. IN THE PROCESS, IT IS HOPED THAT THE PERSPECTIVES OF ALL OF THOSE INVOLVED IN THE FORMULATION AND CRITICISM OF PUBLIC POLICY WILL BE BROADENED AND ENHANCED, BRINGING A FRESH, INFORMED, AND INCISIVE VOICE TO OUR NATIONAL DEBATE.

THE BAKER INSTITUTE IS AN INTEGRAL PART OF RICE UNIVERSITY, ONE OF THE NATION'S MOST DISTINGUISHED INSTITUTIONS OF HIGHER EDUCATION. RICE UNIVERSITY'S LONG TRADITION OF PUBLIC SERVICE AND ACADEMIC EXCELLENCE MAKES IT AN IDEAL LOCATION FOR THE KIND OF INTELLECTUAL INNOVATION THAT IS REQUIRED IN A WORLD OF BREATHTAKING CHANGE. RICE'S FACULTY AND STUDENT BODY PLAY AN IMPORTANT ROLE IN ITS RESEARCH PROGRAMS AND PUBLIC EVENTS. THE HONORABLE JAMES A. BAKER, III, THE 61ST SECRETARY OF STATE AND 67TH SECRETARY OF TREASURY, SERVES AS THE INSTITUTE'S HONORARY CHAIR.

CENTER FOR NANOSCALE SCIENCE AND TECHNOLOGY: THE CENTER FOR NANOSCALE SCIENCE AND TECHNOLOGY AT RICE UNIVERSITY IS A UNIVERSITY-FUNDED ORGANIZATION DEVOTED TO SCIENCE AND TECHNOLOGY AT THE NANOMETER SCALE AND THE EDUCATION OF FUTURE SCIENTISTS AND ENGINEERS. THE CENTER'S MISSION IS TO PROVIDE A VENUE FOR RESEARCHERS FROM ALL DISCIPLINES OF SCIENCE AND ENGINEERING TO SHARE IDEAS AND DISCUSS VIEWS AND PROSPECTS IN NANOSCIENCE, NANOENGINEERING, AND NANOTECHNOLOGY.

CNST PROVIDES ADMINISTRATIVE SUPPORT FOR THE FACULTY AND JOINT PROJECTS AND PROGRAMS, SUPPORTS JOINT RESEARCH INITIATIVES, PERFORMS FUND-RAISING, SPONSORS SEMINARS AND CONFERENCES, ENCOURAGES ENTREPRENEURSHIP, AND ENCOURAGES COLLABORATIONS BOTH INTERNALLY AND EXTERNALLY. CNST SEEKS TO CONNECT WITH EXTERNAL ORGANIZATIONS INCLUDING THE TEXAS NANOTECHNOLOGY INITIATIVE (TNI) AND THE NANOTECHNOLOGY FOUNDATION OF TEXAS. THE CENTER ALSO SUPPORTS EDUCATIONAL INITIATIVES FROM "K TO INFINITY" (KINDERGARTEN TO LIFELONG LEARNING).



THE ENVIRONMENTAL AND ENERGY SYSTEMS INSTITUTE: EESI BRINGS TOGETHER FACULTY AND STUDENTS SPANNING ALL OF RICE'S ACADEMIC DIVISIONS IN PROGRAMS OF RESEARCH, EDUCATION, AND COMMUNITY SERVICE THAT PROMOTE THE GUARDIANSHIP OF ENVIRONMENTAL QUALITY AND NATURAL RESOURCES. THE INSTITUTE FOSTERS PARTNERSHIPS BETWEEN ACADEMIA, BUSINESS, GOVERNMENTS, NON-GOVERNMENT AGENCIES, AND COMMUNITY GROUPS TO HELP MEET SOCIETY'S NEEDS FOR SUSTAINABLE ENERGY, ENVIRONMENTAL PROTECTION, ECONOMIC DEVELOPMENT, AND PUBLIC HEALTH AND SAFETY. EESI ENCOMPASSES FACULTY AND STUDENTS IN THE RICE UNIVERSITY'S SCHOOLS OF SOCIAL SCIENCES, ENGINEERING, NATURAL SCIENCES, HUMANITIES, ARCHITECTURE, AND MANAGEMENT.

RICE ALLIANCE FOR TECHNOLOGY AND ENTREPRENEURSHIP: THE RICE ALLIANCE FOR TECHNOLOGY AND ENTREPRENEURSHIP IS A COLLABORATIVE EFFORT AMONG RICE UNIVERSITY'S SCHOOLS OF ENGINEERING, MANAGEMENT, AND NATURAL SCIENCES, WHICH ENHANCES THE BREADTH OF ITS TEACHING, RESEARCH, AND BUSINESS SUPPORT ACTIVITIES. THIS COLLABORATIVE DESIGN DIFFERENTIATES THE RICE ALLIANCE FROM ENTREPRENEURIAL CENTERS LOCATED IN OTHER UNIVERSITY BUSINESS OR ENGINEERING SCHOOLS. RICE'S RELATIVELY SMALL SIZE FACILITATES THE CULTIVATION OF SUCH A COLLABORATIVE PARTNERSHIP TO ASSIST START-UP BUSINESSES EMERGING FROM RESEARCH AND DEVELOPMENT ON THE CAMPUS.

THE ORGANIZATION'S MISSION IS TWO-FOLD: TO CREATE A FORUM FOR EXCHANGE AND COLLABORATION AMONG RICE MANAGEMENT, ENGINEERING, AND SCIENCE COMMUNITIES, AND TO BE A SOURCE OF EDUCATION, SUPPORT, AND ADVICE TO INVENTORS, INNOVATORS, AND ENTREPRENEURS IN THEIR PURSUIT OF NEW BUSINESS CONCEPTS. THE INTENDED CUMULATIVE RESULTS ARE NEW JOBS AND NEW SOURCES OF WEALTH FOR RICE, HOUSTON, AND THE U.S. ECONOMY.



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The international community, has in recent years, faced the most difficult energy market it has seen in two decades. Oil price volatility has experienced record swings; oil companies have lower surpluses of stored oil in their tanks than seen in the last 25 years; and the future of the Middle East, home to 60% of the world's known oil resources, remains with great uncertainties.

Energy resources will be vital to sustain worldwide economic growth, progress, peace and security. New policy approaches are needed to make sure that energy supply issues do not dampen economic growth nor disrupt U.S. and global security in the 21st century.

To stimulate a broader national dialogue on science and energy policy, the James A. Baker III Institute for Public Policy, together with Rice's Center for Nanoscale Science and Technology (CNST), the Environmental and Energy Systems Institute (EESI) and the Rice Alliance for Technology and Entrepreneurship convened a major two day conclave, *Energy and Nanotechnology: Strategy for the Future,*" on May 2-4, 2003 at the Baker Institute.

The conference, which involved public presentations and discussion among over 50 scientists, policy experts and industry leaders in the nanotechnology and energy fields, was aimed to investigate how scientific developments, including breakthroughs in the nanotechnology field, might contribute solutions to the global energy problem. It brought together over 400 policy makers, scientists, opinion-shapers, and business leaders to showcase potentially revolutionary breakthroughs in the energy technology area. The conference, sponsored by the Shell Oil Company Foundation, the Baker Institute Roundtable, the Baker Institute Energy Forum, Matthew R. Simmons, Simmons & Company International, and Dr. and Mrs. John F. Thrash, provided the opportunity for scientists to confer not only among themselves, but also with policy specialists and various experts from other disciplines to examine energy issues both from a policy and technological perspective. Among the topics covered were energy policy and societal impacts; national science initiatives; the challenge of conventional oil and gas; the transportation challenge; and energy choices: possibilities and barriers -- a one-day session that investigated the state of the art for over a dozen different energy systems and fuels. Among the energy systems

and fuels discussed were oil and natural gas, geothermal, methane hydrates, clean coal, carbon sequestration, solar and renewable energy, fission, fusion, electrical and thermal energy, electricity transmission and fuel cells.

The Energy & Nanotechnology project is part of a broader campaign to reinvigorate public interest in the physical sciences. Beyond the detailed discussion of energy issues, this project is also aimed to help broaden public understanding of how scientific disciplines such as nanoscience, which can appear to have little bearing on people's lives, in reality spawn technologies that can have a direct impact.

This conference report will specifically address the need for new technologies that can aid the development of cheaper, more efficient, and environmentally sound energy supplies. It is designed to help educate leading scientists and policy makers about the great technical challenges facing the energy industry today. With its program *Energy & Nanotechnology: Strategy for the Future*, Rice University is taking the lead to create a much-needed dialogue between nanoscience and energy technology experts, promoting the sharing of ideas about potential applications from emerging science that could lead to resolving both national and international energy predicaments.

Understanding Our Energy Situation

Energy is not just a critical national concern to the United States but also a global one. War in the Middle East, the recent political disturbances in Venezuela and Nigeria, emerging environmental pressures –all these events underscore the need for new, more secure sources of energy. The rate of growth in energy demand worldwide runs the risk of outpacing affordable, stable supplies unless we can muster not only conservation and evolutionary improvements to existing technologies, but also revolutionary new breakthroughs in the energy field.

Among the most important technical challenges facing the world in the 21st century is providing clean, affordable energy, whose supply is sustainable and universally available. Lack of access by the poor to modern energy services constitutes one of the most critical links in the poverty cycle in Africa, Asia and Latin America, Baker Institute director Edward Djerejian explained in opening remarks to the conference. Despite great advances in oil and gas drilling techniques and progress in renewable fuels, more than a quarter of the world's population has no access to electricity today, and two-fifths are forced to rely mainly on traditional biomass—fire wood and animal waste—for their basic cooking and heating needs. Indoor air pollution from this traditional energy source is responsible for the premature death of over 2 million women and children a year worldwide from respiratory infections, according to the World Health Organization. Without a major technological breakthrough, well over 1 billion people will still be without modern electricity in 2030, energy specialists predict.

The September 11 attack on the United States has changed the geopolitical landscape in major ways. U.S. response to the attacks has prompted it to forge new strategic relationships and undertake new military initiatives that have affected old alliances and linkages. This shifting landscape of international relations will have significant ramifications for the geopolitics of oil in the coming decades, Edward Djerejian told the conference.

Already, the terror attacks and the implementation of the subsequent U.S. "War on Terror" has thrown a spotlight on the inherent risks associated with heavy reliance on oil supplies from the Middle East, Djerejian and other speakers noted. In addition, as strategic policies are reviewed, many countries, such as the U.S. and other European, Asian, and Latin American powers, are re-evaluating their energy security policies.

The shift in geopolitical relationships that is developing as the U.S. responds to the attacks on its citizens is already influencing oil trade and supply relationships. Changing patterns can be expected in the years to come. Almost overnight, Russia announced its willingness to help the West diversify its oil sources to include a growing stream of Russian crude. Russian President

Vladimir Putin in a historic address at the Baker Institute declared that Russia could be a strategic alternative to the Organization of Petroleum Exporting Countries (OPEC).

The international and regional political relationships that have come to have bearing on Caspian oil exports appear to be shifting as well. The importance of other non-OPEC producers and non-conventional oil supplies like Canadian heavy crude and oil sands is expected to increase in the years to come.

Still, the International Energy Agency is warning that the geographical sources for new hydrocarbon supplies will be shifting in the next three decades, coming mainly from the developing world, Djerejian warned. This is in contrast to the past three decades when 40% of new production came from within the industrialized West.

“American science and technology policy will have a pivotal influence on whether the world will become increasingly dependent on Middle East oil in the coming decades,” Djerejian said. More than 60% of the world’s remaining conventional oil reserves are concentrated in the Middle East. A quarter of these reserves sit in Saudi Arabia alone. The Middle East is currently supplying over one third of world oil demand.

“This percentage could rise significantly in the future, depending on policies in consumer countries and on the pace of development of new resources and technologies,” Djerejian added. The U.S. Department of Energy, in one forecast, even predicts that the need for OPEC oil could rise from 28 million b/d in 1998 to 60 million b/d in 2020, with the majority of supply having to come from the Middle East, especially Saudi Arabia.

Iran, Iraq, Syria, Sudan and Libya produce around 8 million barrels a day at present or about 10% of world oil supply. Saudi Arabia alone is responsible for almost 10% of world supply and holds a unique position in oil markets. It maintains the largest share of spare idle production capacity of any other nation in the world. The kingdom has historically been the *only* oil

producer in the world that could replace single-handedly, within a short period of time, the total loss of exports for any other single oil producer on the globe. No other nation currently has enough spare capacity to claim this role. Saudi Arabia is also the world's largest exporter, in past years selling almost 100% more than its next largest export competitor, Russia.

“Saudi Arabia’s cushion of spare capacity has provided security and stability to world oil markets for two decades,” Djerejian noted. But policy makers and analysts have begun to question whether reliance on one ally, no matter how reliable and strong an ally it has been over the years, makes sense in today’s changing world.

“Political and economic reform in the Middle East faces formidable challenges, Djerejian explained to the conference. “There is a huge gap between the agenda of the “political Islamists” and the existing “liberalized autocracies”—one that is not easily bridged. Many countries in the Middle East have gravitated into liberalized autocracy for concrete reasons having to do with both historical experience and current societal, cultural and political realities. The region as a whole faces severe social and economic problems as governments have had difficulty finding the resources to provide adequate services for a growing and restive population.”

The delicate compromise that now represents the *status quo* ante among the middle class, reformists, Islamicists and ruling regimes in many countries in the Middle East, if upended, could usher in prolonged, bloody civil chaos long before it produces, if it ever does, political peace and stability, Djerejian warned. “Even the history of our own country demonstrates the potential volatility of change,” he said.

With the outlook in the Middle East so uncertain, the international energy industry and scientific community are looking to non-conventional solutions to confront the world’s ongoing energy concerns.

The need for this effort is all the more important because scientists have become increasingly convinced that the consequences of continuing to burn fossil fuels at current or expanding rates will have deleterious impacts on the global climate. “Climatologists have reconstructed the records of the earth’s surface temperatures and overlapped them with the instrumental history and it shows that over the last 100 years, there is clearly a spike in global temperatures that coincides with increases in CO² concentration of the earth’s atmosphere,” explained Martin Hoffert, professor of physics at New York University and author of the controversial Science article “Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet.”

In his article, Hoffert asserted: “Stabilizing the carbon dioxide-induced component of climate change is an energy problem. Establishment of a course toward such stabilization will require the development within the coming decades of primary energy sources that do not emit carbon dioxide to the atmosphere, in addition to efforts to reduce end-use energy demand. Mid-century primary power requirements that are free of carbon dioxide emissions could be several times what we now derive from fossil fuels (10 terrawatts), even with improvements in energy efficiency...Possible candidates for primary energy sources include terrestrial solar and wind energy, solar power satellites, biomass, nuclear fission, nuclear fusion, fission-fusion hybrids, and fossil fuels from which carbon has been sequestered. Non-primary power technologies that could contribute to climate stabilization include efficiency improvements, hydrogen production, storage and transport, superconducting global electric grids, and geoengineering. All of these approaches currently have severe deficiencies that limit their ability to stabilize global climate. We conclude that a broad range of intensive research and development is urgently needed to produce technological options that can allow both climate stabilization and economic development.”

In 1998, the World Meteorological Organization and the United Nations Environment Programme established the Intergovernmental Panel on Climate Change (IPCC-<http://www.ipcc.ch/>) to review and evaluate the latest technical and scientific information about

global warming. The primary task of the IPCC is to comprehensively, objectively and transparently assess scientific and technical information about climate change, resulting in the publication of policy relevant reports that review the current state of understanding.

The IPCC's Third Assessment Report, published in 2001, involved the participation of more than 2,500 scientists from 100 countries, and the analysis of over 20,000 articles. In this latest assessment of the scientific basis of climate change, the IPCC concluded that, "an increasing body of observations gives a collective picture of a warming world and other changes in the climate system." Examples of these observations include:

- The global average surface temperature has increased over the 20th century by about 0.6°C.
- Temperatures have risen during the past four decades in the lowest 8 kilometers of the atmosphere.
- Snow cover and ice extent have decreased.
- Global average sea level has risen and ocean heat content has increased.

The Third Assessment Report also concludes that "emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate." Arguing that future greenhouse gas emissions due to human activity appear to be growing, the IPCC noted that significant emission reductions would be necessary to stabilize the climate. The report argues that recent warming can largely be attributed to the "fingerprint" of human causation. "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."

According to Hoffert, a concentration of 450 ppm is enough to do irreparable damage to the world's coral reefs and a concentration of 550 ppm would melt the West Antarctic ice sheets, eroding coastlines all around the globe. Statistics such as these make it painfully obvious to Hoffert that "human kind has the ability to dramatically transform the planet." Hoffert noted that with at least 5,000 gigatons of carbon contained in the earth's reserve of remaining fossil fuel

resources and 700 gigatons in the atmosphere, that CO² concentration in the atmosphere, which has already increased from 270 ppm to 360 ppm, could rise to dangerous levels. “There is enough carbon to make it go up to 1,200 ppm, that is, if we burned all the coal and oil in the world.” He added that “we do think the earth at one time did have this high a concentration of CO² and that was 100 million years ago when the average temperature of the earth was 10 degrees celcius higher than today, the earth was completely deglaciaded and there were dinosaurs at the North Pole.”

Hoffert suggested that while we won't have to worry in this century about fossil fuel supply per se since coal can be converted to synthetic oil and gas, environmental concerns may take precedence over the convenience of fossil fuels as the basis for energy supply through the coming century. “What global warming has done is that it has caused an acceleration in the agenda, and we may have to go through a radical change in the energy system before the end of the century and that has enormous implications.” Under a business as usual scenario, Hoffert calculates that carbon concentrations would rise to 750 ppm by the end of the century. He argues, therefore, that it will be necessary to go through a fossil fuel revolution before century's end.

In order to hold atmospheric CO² concentrations to 350 ppm, where environmentalists indicate they should be, Hoffert estimates that at least 15 terawatts of non-fossil fuel energy will be needed to reduce CO² levels to modest targets of 550 ppm by 2050. Put in perspective, that would require a scale up by the factor of 20 what nuclear power represents globally. To reach the goal of 350 ppm, at least 30 terrwatts would need to be derived from non-fossil sources. Hoffert noted that the international community must look to physics, chemistry, engineering and nanoscience for a technical solution. Researchers and scientists must be committed to finding affordable, available, applicable non-fossil fuel sources.

Hoffert noted that possibilities for alternate energy sources include wind and solar power but the demands for infrastructure development are huge, making critical breakthroughs in science of vital importance. “Mass produced, widely distributed PV arrays and wind turbines may

eventually generate 10 to 30 terawatts, emission-free,” Hoffert said, but he noted that PV cells so far cover only 3 square kilometers, compared to the 220,000 square kilometers of land use that would be needed to generate the massive amount of emission-free energy that could be required. Some 5 to 10 gigatons of carbon would have to be sequestered for sequestration to be a viable alternative.

Enter Science: A Major Initiative?

“We need an aggressive Apollo style program to create options from which markets can select the winners,” Hoffert asserted. Given the lead times involved, delays will make it increasingly difficult to reach clean energy supply goals for mid-century.

This “Apollo-style” program should be international, but U.S. led, and must be focused across a broad spectrum of options, including research on mitigation technologies and identification of new strategic technologies. Hoffert believes that nanoscience could become the major player in producing a solution if cost barriers fall.

Breakthroughs in nano-technology open up the possibility of moving beyond our current alternatives for energy supply by introducing technologies that are more efficient, inexpensive, and environmentally sound, according to Nobel Laureate and Rice University Professor Richard Smalley. The benefits of such technology will not be confined to the United States or the developed world; indeed, its impact will be greatest for the world’s poor.

Smalley has identified energy as the number one problem facing humanity. In a list of humanity’s ten most pressing problems, Smalley notes that energy rises to the top because of its ability to provide solutions to many of the other problems on the list, including water, food, environment, poverty and terrorism and war. According to Smalley, there is no other item on the list that can generate answers to the other problems in the way that energy does. “Energy is unique not only in its ability to give us answers to most other problems, but it is uniquely

something we can do something about,” he explained. “The international community needs to be committed to providing clean, affordable energy, whose supply is sustainable and universally available. We are in search of vast amounts of energy and we need a “technical fix” to the world’s energy crisis.”

Just as materials science and engineering rely on the nanometer as the key unit of scale, energy too has a key unit: the terawatt, Smalley explained. Energy is a “quantitative business” and he noted that we need to be concerned with finding *many* terawatts. Worldwide, we currently use 13-14 terawatts per day, the equivalent of 200-210 million barrels of oil per day. Dr. Smalley projects that we will need at least twice as much energy in the next 50 years, but even doubling current resources and finding a way to sustain twice our current levels of consumption for the next half-century would not be enough to give each individual on the planet a life comparable to that in the developed world. Projections of energy use would rise to between 50 and 60 terawatts per day by 2050, the equivalent of 900 million barrels of oil per day.

“The earth is swimming in energy; there is plenty of energy there to be had. The only reason we have a problem is that we haven’t figured out a technical way to do it cheaply,” Smalley elaborated. This is precisely where nanoscience and nanotechnology come into play.

Nanotechnology is “the art and science of building materials that act at the nanometer scale.” The ultimate nanotechnology builds at the ultimate level of finesse, one atom at a time, “and it does it with molecular perfection,” explained Smalley. The “wet side” of nanotechnology includes all the nano-machinery of cellular life and viruses and manifests itself as biotechnology. The “dry side” of nanotechnology, which relates to energy, includes electrical and thermal conduction and provides great strength, toughness and high temperature resistance, among other things. Nanotechnology as a whole, “holds the answer, to the extent that there are answers, to most of our most pressing material needs.”

Smalley concluded his presentation with a list of enabling nanotechnology revolutions, which included, among others, photovoltaics, hydrogen storage, fuel cells, batteries & supercapacitors, photocatalytic reduction of CO_2 to produce a liquid fuel such as methanol, nanoelectronics to revolutionize computers, sensors and devices, thermochemical catalysts to generate H_2 from water that work efficiently at temperatures below 500°C , CO_2 mineralization schemes, nanoelectronics-based robotics, nanomaterial coatings that will reduce the cost of deep drilling and enable HDR (hot dry rock) geothermal mining and nanotech lighting to replace incandescent and fluorescent lights.

He noted that the energy industry is facing great technical challenges but nanoscience and energy technology have enormous potential for resolving both national and international energy predicaments. Indeed, a solution to the global energy problem will require revolutionary new technologies, as along with conservation and evolutionary improvements in existing technologies.

Richard Russell, Associate Director for Technology in the Office of Science and Technology Policy within the Executive Office of the President agreed with Dr. Smalley that research and development must be one of the major vehicles that helps address many of the challenges facing the U.S., including the challenges of developing new energy sources and making energy available cheaply and abundantly. Russell emphasized that science and technology are key factors in U.S. President George W. Bush's top priorities for the nation, namely: winning the war on terrorism; securing the Homeland; and strengthening the economy.

For those reasons, the U.S. is proposing to spend \$123 billion on research and development in fiscal year 2004, a 7% increase over 2003. "When you compare what the United States is doing in research and development funding to the rest of the G-8 countries, you'll notice that we are very much the leader; in fact, we are spending more in terms of research and development than the rest of the G-8 countries combined," Russell stated.

U.S. research and development priorities include several specific nanotechnology as well as specific new energy initiatives, most notably the National Nanotechnology Initiative (NNI), the FreedomCar, the Hydrogen Fuel Initiative and ITER (the International Thermonuclear Experimental Reactor project). According to Russell, the President has pledged \$1.7 billion over the next five years for these programs, making it a significant push towards hydrogen as a fuel for the future—covering not only with fuel cell technology but also hydrogen infrastructure. The President, he noted, is committed to rejoining ITER because “If we’re going to be looking for huge new sources of energy, then certainly fusion has to be part of the mix.”

But, Russell stressed that all of the emphasis on research and development funding for nanotechnology, hydrogen and fuel cell applications is not intended to be a short-term solution as it is likely to be mid-century before there is significant commercialization. He added that the government’s goals for the commercialization of fuel cell vehicles envision production decisions by 2015 and showroom models by 2020.

Nanotechnology could play a pivotal role in providing stronger, lighter materials to build lighter-weight vehicles and to provide safer, more cost-effective storage for hydrogen fuels, according to Russell. “The National Nanotechnology Initiative will set the research priorities in order to address many of these issues,” Russell told conference attendees. In addition to the potential for hydrogen-fueled vehicles, there are great possibilities for applications for stationary and smaller portable fuel cells, he stressed.

Russell laid out several key research areas that must be addressed, including safety codes and standards; hydrogen production; hydrogen transport, distribution and delivery; hydrogen storage; and fuel cell applications. In terms of fuel cells, the challenges that must be met involve lowering their cost, improving their durability, increasing their reliability and efficiency and addressing power density and safety. The NNI will examine technologies that will focus on fuel cell development, such as materials, electrochemistry, and components, including stacks (developing

thinner flow plates), membranes (developing higher temperature substrates), electrodes (decreasing platinum utilization) and catalysts (developing more effective platinum alloys).

By employing nanotechnology applications, materials can be manipulated at both the atomic and molecular levels, resulting in new properties. “We’re finding that not only are we achieving new properties such as strength, but we’re achieving all sorts of new interactions, both on the biological level, where we can build new biomaterials, but also on the electrical level, where charges can change just based on the manipulation of a single molecule,” Russell explained.

Currently, there are nine grand challenges or priorities set by the NNI. These include: energy conservation and storage; advanced chemical, biological and radiological explosive detection; manufacturing at the nanoscale; nanoscale instrumentation and meteorology; nanostructured materials by design; and health care therapeutics and diagnostics. “The notion that nanotechnology is already creating a revolution in materials that is going to dramatically change the way we can deliver health care has really caught on,” Russell noted.

He pointed out that because nanoscale research has such potential, the NNI has become one of the most important priorities of the current administration’s research and development funding, with funds earmarked for the NNI at nearly \$850 million with the increase in fiscal 2004 spending. “It’s rapidly approaching the magical \$1 billion level, which will make it a fully grown-up program,” Russell said.

There are several categories defined by the NNI funding, including fundamental research, grand challenges, research infrastructure, centers of excellence and societal impacts, with grand challenges and fundamental research accounting for more than half of the funding requirements. Russell noted that it’s vital to keep examining societal impacts of research and development, as new technologies that are being developed always have associated environmental and social implications.

Of the 10 government agencies contributing to the NNI in Fiscal 2004, the largest is the National Science Foundation at \$249 million, followed by the Department of Defense at \$222 million and the Department of Energy at \$197 million. However, it is pertinent to note that in 2002, of the \$91.1 million spent by the DOE to fund the NNI, \$36 million were spent on university research, \$10.5 million on work supported by Sandia, Los Alamos and Livermore National Labs, \$34 million on fundamental research, \$29 million on NNI grand challenges, \$15 million on nanotechnology centers, \$15 million on research infrastructure, \$18 million on DOE labs; strangely, less than \$10 million of that went into nanoenergy and renewables' research. Because the NNI has such broad implications, there is significant interest from a variety of agencies, including those perhaps not expected, such as the Department of Agriculture and the Department of Justice. Russell pointed out that as a new organization, the Department of Homeland Security is just starting to get involved with the NNI with a \$2 million contribution to funding, but he expects to see an increase in their involvement over time as the department ramps up.

To ensure that the NNI is on track, the National Research Council conducted a study on Nanotechnology in 2002 and issued a report with several specific recommendations. These included:

- The need for a clear, compelling, overarching strategy
- The importance of better interagency collaboration
- The benefits of enhanced use of external advice by the NNI
- The need for improvement in technology transfer and industrial participation

As for external advice, President Bush has tasked the President's Council of Advisors on Science and Technology (PCAST) to review the NNI and come up with its own recommendations, looking into critical points such as the grand challenges to ensure that the initiative is covering the correct issues. PCAST is made up of 24 members from government, industry and academic institutions. Corporate members include executives from Kleiner Perkins, Lockheed, Comcast, Dell, Dimension Data Microsoft, Morehouse, Intel, Sagemetrics, and Powershift. The group has no representative with an energy background.

Although many conference participants agreed that the Bush Administration's initiatives on energy and budget increases were laudable, concerns remained whether the level of financial commitment was large enough to achieve the breakthroughs that might be necessary as the century progresses. Both Dr. Smalley and Dr. Hoffert specifically mentioned that a commitment in the billions of dollars would be needed to promote the fundamental science work that is needed to solve the energy and environmental problems facing the US. Conference participants discussed the need for a vast effort, capable of providing a new "non-traditional" source of energy, which is at least twice the size of all worldwide energy consumed today. It was concluded that this source will have to be readily available by the middle of the 21st century. This source must not rely on oil and natural gas as the initial component (as current plans for using hydrogen as an energy carrier assume) but provide a clean, affordable answer that is possible to serve as the basis for sustained economic prosperity for 10 billion people. Dr. Smalley and other participants argued that current technology will not be able to meet the need for energy as the century progresses but that stunning new discoveries in underlying core science and engineering base will be required to enable an answer.

The conferees argued that the cost of new energy science discoveries could be extremely expensive, requiring funding at the level of \$10 billion per year for frontier, enabling research in the physical sciences and engineering, and perhaps ramping up to \$20 billion a year as progress is made. This research could be aimed at revolutionary advances in solar power, wind, clean coal, hydrogen, fusion, new generation fission reactors, fuel cells, batteries, hydrogen production, storage, and transport, and a new electrical energy grid, which can tie all these power sources together.

The International Energy Agency projects that the total investment requirement for energy supply infrastructure will top \$16 trillion between 2001- 2030. Of that, the majority of investment will be in the electricity sector which will require massive investment of over \$10 trillion over the period in question. Required oil and gas infrastructure investment is estimated to reach \$6 trillion between 2001 and 2030, according to the IEA.

A new energy research program -- equivalent in size and scale to the Apollo Program -- would catapult the U.S. to unquestionable world leadership in not only fundamental science capability, which is a priority for national defense but also in energy technology exports, which will keep the U.S. economy strong and prevent other countries from becoming overly dependent on oil producing states. The program would also have a corollary benefit of inspiring a new generation of young American men and women to enter careers in the physical sciences and engineering, much like they did in the Sputnik era of the 1960s. The US S&T workforce in physical sciences is in serious decline. The energy initiative would create a new Sputnik Generation of scientists and engineers to make the pioneering breakthroughs that will be the basis of new industries, new prosperity, and continued military superiority.

Dr. Smalley noted that the currently proposed U.S. energy bill is a step in the right direction, as is the Hydrogen Fuel Initiative, but he added that neither is bold enough to solve the worldwide energy problem. Neither initiative is inspiring enough to gain the political high ground in the energy and environment debate, or to motivate American youth, much the way the Apollo Program did in the 1960s. "To do that, we need to create a bold new vision, which leverages the American entrepreneurial spirit and ingenuity on a topic like energy and environment that the younger generation cares deeply about," said Dr. Smalley.

Acknowledging the potential benefits for a major science initiative on energy, Thomas A. Kalil, Special Assistant to the Chancellor for Science and Technology at University of California Berkeley and a former member of the National Economic Council under President Bill Clinton, noted in his address to the conference how difficult it is to turn an idea for a major initiative into a policy reality within decision-making circles inside the U.S. government.

Kalil said that industry experts and nanoscientists can find important lessons for a new initiative from the processes involved in putting together previous National Science and Technology (NST) initiatives—including the National Nanotechnology Initiative (NNI)—as models to follow.

A NST initiative may have wide advantages but it also has inherent risks associated with getting off the ground and ensuring that it runs effectively, Kalil noted.

Kalil, who worked on forming a number of NST initiatives under the Clinton Administration, explained to the Energy and Nanotechnology conference attendees that it's not enough to have a big idea for an initiative that captures people's minds, it is also important to have a variety of different kinds of experts involved in the process, including entrepreneurs, policy experts with strong organizational and political skills, and individuals with technical depth. The team needs to do their "homework" and understand the multiple audiences, actors and agencies that need to say "yes" for the initiative to become a reality. Understanding the forces to which each of these gatekeepers respond is also a critical element, according to Kalil.

The development of the NNI, for example, began several years before the announcement by President Clinton of the NNI formation during a speech at Cal Tech in January 2000. The NNI concept emerged from grassroots meetings from 1996 to 1998 that led to the creation of a National Science and Technology Council (NSTC) working group in September 1998 that brought together all of the disparate agencies.

Workshops to develop a research agenda occurred in early 1999—including a global technology assessment to look at where the United States stood vis-à-vis Europe and Asia on nanotechnology research and development. A draft of the NNI initiative was produced that August. Following Clinton's announcement of the NNI initiative, his administration sought a \$225 million increase in the government's investment in nanotechnology research in development to \$495 million in the 2001 fiscal year budget.

In the current Bush Administration, the NNI has enjoyed wide bipartisan support, and President George W. Bush sought to boost investment in the NNI to \$679 million in his 2002 fiscal budget. In his 2004 fiscal budget, the President requested the smallest boost in federal spending on nanotechnology to date, calling for a 9.5% increase to \$847 million. But, as Kalil noted in his

presentation to the Energy and Nanotechnology Conference, the current \$400 billion deficit is “clearly going to have an impact on getting funding for things on the civilian side that are not related to homeland security.”

Kalil told the gathering that government investment in applied energy technology research and development—including fission, fusion, fossil fuels, renewables -- has declined from \$6 billion in fiscal year 1997 to about \$1.3 billion, mainly because energy issues did not remain front and center in the public consciousness and political arena. However, recent interest from the current administration in new initiatives such as the Freedom Car and the transition to hydrogen may mean that energy science research has the potential to find a more sympathetic ear than in past years.

Timing for a pitch for a new initiative can be extremely important, Kalil told the conference. The timing for the NNI to be pursued under the Clinton Administration was fortuitous, he added, “It was a favorable environment for the NNI. We had budget surpluses; a growing concern about the balance between biomedical research and the physical sciences and engineering; a high level of interest by the then president and vice president in science and technology; and the clear connection between technology and economic growth in 1999 and 2000,” he said. To push through the NNI, “We needed to convince the various governmental agencies to request nanodollars in the fiscal year 2001 budget; we needed to get early involvement of the Office of Management and Budget (OMB); we needed to get senior White House staff educated and excited about nanotechnology, and we needed to comply with some of the agency-specific issues,” Kalil stated.

One of the common mistakes that is made in the U.S. science and engineering community in pursuing new initiatives is that a push for more research dollars gets framed as simply an increase from the previous year. This can be a “loser argument,” Kalil argued. “By the time budget decisions get to the White House, people are weighing the allocation of scarce resources between concrete outcomes; this typical approach of the science and engineering community of

demanding more money than the previous year has not been particularly effective in terms of increasing the government's investment in research and development," he said. The OMB is particularly cautious, looking for concrete reasons why funding should have to be increased.

The advantage of seeking a NST initiative, as opposed to incremental increases in funding, is that an initiative focuses on a problem or outcome in an inter-disciplinary way as opposed to a particular academic discipline. Such a strategy can be used to generate more public understanding of the outcomes and pay-offs, Kalil pointed out, and this can help build support. But, he also stressed that there are definite risks associated with the multi-disciplinary approach to the initiative process. Such an effort involves more agencies and overhead, including much time and energy spent on developing and coordinating multi-agency consensus, implementation, and oversight. Broader initiatives can also face the "disease of the week" phenomenon, in which politicians respond to what is deemed "hot and trendy" at that moment but then lose interest as a new topic moves into play.

"Clearly there is always the risk that, in the absence of more money for science and engineering generally, initiatives could crowd out core research budgets. Certainly not all science and engineering research topics are going to support an initiative," Kalil noted, making it difficult to get the science community to join forces to get an initiative off the ground. In addition, "Even after you've developed one of these initiatives, it's not clear that the congressional process will always reward this, because remember that appropriations decisions are made by 13 different appropriations subcommittees," he said. For this reason, one could have sculpted an elaborate initiative that clearly defines roles and responsibilities for a number of different agencies, and it could meet total indifference from congressmen who are focused entirely on the budget for their particular agency. "You always run into the tension between creating a national plan and agency autonomy and its mission, because they [bureaucrats] will say, 'At the end of the day, I'm accountable to my appropriations and unless I can be shown how it's going to relate to my mission, I'm not going to get funding for this,'" Kalil told the conference.

The first stage in formulating an initiative is to answer the question of why this should be a priority—why should the government invest taxpayers’ dollars in this particular area? According to Kalil, there are a broad number of rationales used in research and development initiatives, including: economic growth and job creation; health, environment and sustainable development; national security, and more recently, Homeland Defense; expanding the science and technology workforce; allowing us to make better decisions in a particular area; and new knowledge as an end in itself. He advocated the need to continue supporting curiosity-driven research that may not have a concrete societal outcome but could lead to important developments.

Another step in putting together an initiative is to answer the question of why a government role in the process is appropriate. Kalil said that one concrete justification of government involvement could be that the research related to a project might be mission-oriented and thereby focused mainly on a particular government agency, for example, defense. Another reason often cited is that the social rate of return is likely higher than the private sector rate of return, because the research may be too long-term or too risky or impossible for the private sector to capture some or all of the benefits.

In seeking new funding, an initiative has the burden of justifying why existing funds can’t simply be re-prioritized for this new initiative if it is so important. This is a favorite query of OMB, he noted, and the agency will want concrete answers as to what the position of the United States to the rest of the world is in this area of research and development. Rationale for why the research must be done now, as opposed to some indefinite time in the future, is also needed. The OMB is also likely to want to know what the return on investment was for past government expenditure in the particular area.

In terms of the goals of the initiative, the proponents of the proposal must be able to succinctly identify what the ultimate pay-offs will be to society if the goals are reached and if it is possible to quantify the goals. As for the research agenda, the research topics viewed as most important and promising by the research community must be clearly identified. On budgetary concerns, the

initiative must address how much the government is currently spending in this area and whether the research community will be able to truly absorb an increase in investment. Kalil cited the example of education research, pointing out that there isn't a lot of research currently being conducted in this area and what does exist isn't very good, so "It doesn't inspire a lot of confidence with policy makers to expand funding in this area."

Proponents of an initiative must also think through what the mechanisms of support need to be, according to Kalil. Is it something that's going to be done through private initiatives, small groups or centers? Is there a need for support of research infrastructure or an IT component that might look at computational science or laboratories?

There also arises the overall concern of how the initiative is going to be managed and coordinated. Understanding the clear breakdown of the division of labor between the agencies is imperative, according to Kalil, and can hopefully be based on the agencies' different missions and their recognized competencies. Washington policy makers also want to know possible linkages of the initiative to non-research and development policies and the different types of partnerships envisaged with industry and with state organizations, as well as the potential for international collaboration.

Considering new legislation such as the government's Performance and Results Act, in which Congress and the OMB are looking at metrics for relevance and quality of importance in research, an initiative must have a concrete idea of the type of mechanism that will be put into place for evaluation and input.

Kalil said that the politicians who allocate the important research and development resources came to appreciate the importance of the NNI because they were able to see clearly the pay-offs for the initiative, pay-offs explained succinctly and effectively by the architects of the initiative. The proponents of the NNI argued that a major nanoscience initiative would create the ability to store the Library of Congress in a device the size of a sugar cube; the ability to detect tumors

when they are a few cells in size; the ability to make materials that are stronger than steel and at a fraction of the weight; and the ability to sequence the human genome in hours, not months.

The challenges facing any new NST initiative like hydrogen research and development are many, including the reality that Washington well remembers the less than successful experience of creating new technologies such as synfuels and the Clinch River Breeder reactor, Kalil noted. In addition, fluctuating energy prices suggest no real sense of urgency to change the *status quo*. Long timetables associated with developing new energy options pale next to an assumed short duration of an energy crisis.

In addition, internal warfare among advocates of different energy solutions and competition between energy research and development and water projects could detract from establishing a new NST initiative. Proponents of a new energy scheme will also have to confront the inherent skepticism of many economists who might argue that market-oriented mechanisms, like emissions fees and caps, can bring about a solution from the private sector.

But, despite the hurdles involved and the basic risks associated with proposing new energy research and development, Kalil said that the science and engineering communities should not give up. “I do think there are reasons for optimism; it’s an important area,” he told the conference audience. He cited several reasons for optimism: that providing cleaner sources of energy is a big “man on the moon” class goal; that nearly 80% of Americans believe global warming is a problem, with 50% contending that it is a “very serious” issue; and a growing number of businesses acknowledge that climate change is “one of our most serious challenges.” These businesses also are realizing that the more energy efficient they become, the more productive they are.

Moreover, Kalil stressed that research and development is a relatively non-controversial component of energy policy, making it more socially and economically acceptable. Finally, he

pointed out that there is a huge export and growth potential associated with these new energy technologies, and the United States should take the lead in this arena.

The Hydrogen Solution: Benefits and Challenges

The focus of new thinking on energy systems in the U.S. and abroad has fallen squarely on hydrogen as an energy carrier. Hydrogen is plentiful in the known universe, comprising 75% of all matter. But it is not an energy source like coal, oil, wind or sun that can be converted into energy. Rather, it is an energy carrier: that is, a way of transporting energy from an energy source to the user, much the way gasoline or electricity operates. Hydrogen (unlike electricity) can be stored in relatively large amounts –albeit with current technology at a much higher cost than petroleum or petroleum products. It can be derived from many conventional energy sources such as fossil fuels and can also be easily converted into electricity or fuel through the use of a fuel cell or other conversion technology.

To gain pure hydrogen, it typically must be separated from chemical compounds of which it is a component. Hydrogen can be collected by using heat and catalysts to remove it from hydrocarbons (separating it from carbon and other atoms) or carbohydrates; by splitting water molecules with electricity (electrolysis); or by more complicated laboratory processes which utilize sunlight, plasma discharge or micro-organisms. At present, only separating hydrogen from hydrocarbons is considered commercially viable for the near to intermediate term.

Nearly half of current U.S. hydrogen production is used in the nation's refineries to produce gasoline and fuel oil. The U.S. Department of Energy (DOE) reports that approximately 48% of global hydrogen production is reformed from natural gas, 30% from oil and 18% from coal. At present, about 50 million metric tons of hydrogen is made for worldwide industrial use each year. World hydrogen production is growing at about 6% per year, equating to a doubling every 11 years.

Hydrogen proponents point out that the industrial infrastructure for centralized hydrogen production already exists, with most hydrogen made at large plants and either consumed there or nearby. It is also possible to refit existing natural gas pipelines to transport hydrogen. By adding polymer-composite liners, plus a hydrogen-blocking metallized coating and converting the compressors, existing gas transmission pipelines could generally be converted to hydrogen service. Several newer gas pipelines may already have hydrogen-ready valves, alloys and seals, and in fact, Japan is making plans for its Siberia-China-Japan gas pipeline and a 200-mile crude-oil pipeline has already been converted to hydrogen service. There are no unique safety issues in converting natural gas lines for hydrogen service. In addition, liquid hydrogen is also regularly distributed by truck and existing capacity could be readily developed to accommodate up to 5% of new vehicles. To take advantage of current infrastructure, on-board reforming technologies could be investigated in parallel to the development of other viable hydrogen storage and refueling technologies.

Burning hydrocarbons directly results in the release of carbon to the atmosphere, primarily as carbon dioxide—along with minor amounts of CO, SO_x, NO_x and soot. Using hydrogen as a fuel yields just water and some nitrogen oxides, which many environmentalists say is preferable from a climate perspective. However, reforming hydrogen from hydrocarbons still releases carbon, and a few scientists have also warned of other deleterious effects from water vapors or molecular hydrogen releases into the atmosphere.

Moreover, there is some concern that a large-scale hydrogen economy would alter Earth's climate, upset the water balance or change atmospheric chemistry. In fact, water vapor does strengthen the warming effect of CO₂ by about 70% and many of its climatic effects remain unknown. Concerns that using hydrogen would release or consume too much water, consume too much oxygen, or dry out the Earth by leaking hydrogen to outer space have been considered. But experts believe that a sensibly designed hydrogen transition does not appear to pose an environmental threat if appropriate attention is given to carbon releases.

Scientist and author Amory Lovins has suggested that a well-designed hydrogen system could resolve most of the existing environmental problems of the current fossil fuel system without creating new ones while enhancing energy security. He argues that a well-designed hydrogen transition could exist using the same or less natural gas than is currently being consumed. By saving more gas in displaced power plants, furnaces and boilers, and in refineries to make gasoline that is made into hydrogen to displace gasoline, integrated hydrogen transition of the sort recommended by the Rocky Mountain Institute (RMI) and assumed by General Motors (GM), could simultaneously decrease net U.S. consumption of oil and natural gas. But such a strategy faces some practical obstacles.

William White, former president and CEO of the Wedge Group and current Mayor of Houston, noted at the conference that “at present, hydrogen is extremely expensive to produce” and in order to implement it as an energy source, a large new infrastructure for producing and distributing hydrogen will need to be installed. Furthermore, tremendous technological breakthroughs in storage will need to be achieved before the use of hydrogen can become widespread. According to a recent study published by the RMI, this vital step is expected to cost hundreds of billions of dollars for the US alone. Although the hydrogen business is not “an infant industry,” given the existence of a U.S. hydrogen pipeline system, the available methods for extracting H₂ is still not economically-viable for the kind of large-scale production that would be required to implement a hydrogen-based automobile transportation system. In order for the large-scale production of hydrogen to be feasible, researchers must find a new approach for producing hydrogen.

White pointed out that although hydrogen is abundant in nature, it is typically mixed or combined with other elements, making it challenging to harvest cheaply. Since hydrogen is one of the smallest particles available in nature, extracting H₂ molecules is analogous to “trying to strain the smallest particles in a spaghetti pot,” he said. Under one method where the hydrogen is derived from methane, chemists have to apply relatively large amounts of heat and pressure to combust the methane molecules in order to extract H₂. The extracted hydrogen can then be

compressed and put into storage units for use as a transportation fuel. However, with the tremendous technological challenges facing the development of efficient fuel cells and with the relatively high cost of extracting hydrogen, White stressed that “having a hydrogen car (or economy) instead of an oil/natural gas car (or economy) is hardly ever justified on an economic basis at this point.”

While the transition to a hydrogen-based economy is not currently considered to be an economically-viable option, it is undeniable that the need to reduce the American dependence on foreign oil is a task that will need to be accomplished in the near future. According to White, “with the access to hydrocarbons being highly dependent on a (fierce) race over time between technology and depletion and with this primary source of energy being mainly available in regions of high political instability (Iraq, Saudi Arabia, Venezuela, and Nigeria), finding alternative sources of energy should be at the (very) top of the government’s priority list.” White also stressed that disruptions in current energy supplies can present major threats to both economic and national security. “Having access to energy is not only vitally important to maintaining the quality of life but also imperative to defining many aspects of every American’s freedom,” he explained. White noted that diversification of energy sources was critical to U.S. national security. “Diversifying the energy supply gives people the ability to substitute (other forms of) energies,” he said, thereby reducing the country’s vulnerability to any one source of oil and natural gas. But White noted that “any new energy technologies or advancements that reduce energy consumption, while they should be encouraged, will also require major investments.”

Given the U.S. current competitive advantage in the world’s economy, White stressed that it is paramount for America to be a leader instead of a follower in any new global energy-based economy that will emerge. Just as the American investment in space technology and avionics during the Cold War created an American world leadership of the aerospace industry, the US must rise again to be a leader in the energy business. “After all, this is what is going to assure greater freedom and greater economic security for our nation,” he said.

Most importantly, he stressed that reaching a position of world leadership will unquestionably need an American collective will. Institutions of higher learning in science and engineering will need to prepare their students to succeed in the competitive, global economy, and policy makers and educators need to work together to find a way to stop the declining number of American students in science and engineering graduate schools. The government will need to make a serious commitment of funding to trigger the interest of young kids in science and engineering. “This is the only way to retain the political advantage that served us so well during the last century and an investment that can yield the highest financial return ever,” White concluded. Only by having enough scientists and engineers doing research can the US find an approach that will allow the cheap harvesting of hydrogen.

Confirming the energy challenges addressed by other speakers, Carl Michael Smith, Assistant Secretary for Fossil Energy in the U.S. Department of Energy, emphasized that “while most Americans take for granted the availability of cheap and abundant energy, many obstacles are projected as we transition toward other energy-based economies.”

According to Smith, the U.S. consumption of natural gas reached 22 trillion cubic feet (Tcf) in 2002 and will rise to 30 Tcf need by 2010. Smith noted that the administration of President George W. Bush has initiated over eighty recommendations of the National Energy Policy drafted by the Energy task force led by Vice President Richard Cheney. That program, which contained nearly one hundred recommended elements, called for promotion of greater energy efficiency, an increase in domestic energy supplies, and a modernized energy infrastructure.

Smith said that hydrogen fuel can be a pivotal part of America’s solution to the energy problem but that technical obstacles and challenges remain. “During the 1960s, President Kennedy challenged Americans to put a man on the moon and we were able to do it. Similarly, this year, President Bush, in his state of the union address, challenged us to have an automobile powered by hydrogen by 2020 and the DOE will unquestionably strive to meet the deadline,” Smith said.

According to Smith, transitioning to a hydrogen based economy cannot be done in a few years. It is a major step that is expected to take decades and that will require heavy reliance on hydrocarbons in the first phases of development.

Jeremy Rifkin, author of *The Hydrogen Economy* and President of The Foundation of Economic Trends, concurred with Carl Smith that fossil fuels will likely remain the dominant energy supply through to the middle of the 21st Century. He concurred that use of natural gas will be the immediate choice to produce hydrogen, eventually transitioning to the use of renewable energy technologies to produce hydrogen. Rifkin noted that a transition to hydrogen is needed to avoid three big crises that are associated with the current oil age, namely: global warming, Third World debt and the ongoing conflict in the Middle East.

“Global warming may be the most powerful accomplishment of the human race; It is a negative one but we’ve affected the chemistry of a planet in the solar system in less than 100 years,” Rifkin stated. He noted that the summary report, *Hydrogen Energy and Fuel Cells*, composed by the High Level Group for Hydrogen and Fuel Cells released by the European Commission, found that greenhouse gas savings of approximately 140 million metric tons of carbon dioxide (MtCO₂) per annum could be achieved if 17% of electricity demand that is presently supplied from primarily coal-based centralized power stations is replaced by more efficient decentralized power stations that incorporate stationary high temperature fuel-cell systems fuelled by natural gas. In addition, CO₂ sequestration could make further greenhouse gas savings possible.

Rifkin added that a new energy system was needed because a second oil-related crisis has continued over the past thirty years -- high oil costs and Third world debt. Rifkin noted that the developing world, rather than the West, has suffered dramatically from the massive increase in oil prices that began in 1973. For the past 30 years, developing countries have been borrowing money from the IMF and the World Bank and other lending institutions to pay for oil they cannot afford,” Rifkin argued. He added that 83 cents of every dollar today borrowed in the Third World is actually being used to pay off their old debt.

Adding to these oil-related problem is a third source of potential crisis, according to Rifkin. This risk surrounds the unstable condition of the Middle East, a key oil supply region. “If we think the Persian Gulf is a hot spot today, what’s it going to be like in five, eight, nine, 10 or 14 years from now, when India’s and China’s energy needs will be equal to the G-7?” Rifkin asked.

Rifkin concurred with Mayor White that downside risk to a shift to a hydrogen economy is that hydrogen is not free-floating and must be extracted. He noted that most of the hydrogen extracted today comes from natural gas. “The problem,” Rifkin said, “is that if world natural gas peaks a few years after oil, we’ll have created an entire infrastructure for extracting hydrogen from fossil fuels that will be irrelevant.” Yet, most hydrogen advocates believe that natural gas is logically the main near-term fuel to launch the hydrogen transition particularly in North America and that hydrogen produced from renewable energy is still thirty to fifty years in the making.

This roadmap has led some critics to argue that a transition to hydrogen, if it must be derived from traditional fossil fuels, fails to meet the one of the main purposes of a shift in energy systems, that is, to diversify the U.S. from dependence on imported energy. The U.S. is already facing sporadic shortages in the domestic natural gas market and is expected to become increasingly dependent on imported natural gas.

Matt Simmons, chairman of Simmons & Co., suggested that in 2003, the “depletion fog” started to lift, making it clear that field declines in mature basins in the United States and Canada will limit the continuation of supply increases. In the U.S., conventional domestic gas production has been flat for a decade, despite miracles in technology being performed and a drilling boom.

When these additions are stripped out, a quite startling picture emerges, Simmons said. “Conventional natural gas in the United States, as we know it today, would have appeared to have peaked in the early to mid-1990s,” he commented. The decline in conventional sources for natural gas has been offset by a significant growth in less conventional resources such as coal bed methane, associated deepwater gas, and deep formation multiple-zone giant gas wells.

Forecasts project that natural gas demand in the U.S. will rise between 1.5 to 2.0% per year over the next two decades. This is likely to mean that the United States will have to import up to 20-25% of its natural gas by 2025, much of it from the same countries in the Middle East and Africa that currently supply oil. The United States will also have to compete for these international gas supplies with other large energy consuming countries, such as Mexico, China, Japan, and Europe. Over the next two decades, gas use is projected to rise at more than three times the rate for oil use, according to the U.S. Department of Energy. Overall world gas consumption is expected to increase by 5% per annum under a business as usual case projection as natural gas demand rises substantially in the electricity sector, as well as for cooking and home heating in developing Asia.

The supply challenges that are likely to face the global natural gas market in the 2010s and 2020s call into question the wisdom of developing a hydrogen economy based on natural gas feedstock to be converted to hydrogen. In twenty years, much of the natural gas feedstock will have to be imported to the U.S. from the same countries that are now major oil exporters, reducing the value of a shift in energy security terms. Still, policy makers note the limitations that currently exist to develop hydrogen from renewable sources. “Over the long term, we want to make our hydrogen from sustainable, renewable energy, and that is where the majority of our hydrogen production R&D is focused. But if environmental advocates persist in the notion that all hydrogen must come solely from renewable energy in the near term, they will only ensure our continued and growing dependence on foreign oil,” argues Assistant Secretary of Energy David Garman. According to the EU/US conference on the Pathways to the Hydrogen Economy, natural gas reformation is the least expensive means to produce hydrogen and the only technique that is currently economically-viable. The Bush administration is also hoping breakthroughs in clean coal technologies and carbon sequestration will enhance the opportunities to make hydrogen from coal, but this effort remains uncertain given the relatively low percentage of hydrogen that can be extracted from coal compared to other sources as well as the commercial and technical hurdles that still need to be addressed in sequestering carbon.

Still, scientists hope that by 2030, technological advancements will significantly contribute to producing low cost hydrogen in a manner other than extracting it from fossil fuels. Once experts acquire a sufficient operating experience, hydrogen could be produced from nuclear, solar, hydro, wind, wave, geothermal, wood, organic waste and biomass sources, allowing thus a significant future CO₂ reduction in the longer term

Electricity from today's cheapest renewable energy sources or nuclear electrolysis is rarely competitive with natural gas for producing hydrogen. But, longer-term, a greater number of large-scale choices for making hydrogen could emerge.

Reformers can use a wide range of biomass feedstocks, which, if sustainably grown, won't harm the climate. With biomass, waste and fossil fuel feedstocks, reformers can also be coupled with carbon sequestration. Some experimental methods of sequestration—particularly those that capture the carbon in blocks of artificial rock—may be modified to serve decentralized reformers. Carbon sequestration, however, remains a questionable technology. At present, a Norwegian firm is developing a plasma-arc process that separates hydrocarbons into hydrogen, steam and carbon black which can be used or stored. Since no CO₂ is released, this process could potentially be a backstop technology that will serve as an alternative to more traditional carbon sequestration techniques.

Although hydrogen can likely be extracted from coal through gasification, there is not yet a commercially cost-effective way to sequester the CO₂ left behind in the process. Creating hydrogen by splitting water with electricity (electrolysis) is also rarely cheaper than reforming natural gas except on a very small scale. Thus, unless the electricity is heavily subsidized, neither coal gasification nor electrolysis is a commercially competitive way to derive hydrogen at present, according to Rifkin and other conference presenters. However, small-scale electrolyzers can avoid the cost of distribution from remote central plants and may someday be able to compete with decentralized gas reformers.

Rifkin suggested that in the future, perhaps with the help of nanotechnology, there may be new discoveries that allow the extraction of hydrogen from renewable energy and electrolysis of water at a lower cost. With such breakthrough technology, it would be possible to use renewable sources—solar, wind, geothermal, hydro and biomass—to generate electricity immediately, and then use the surplus electricity to produce hydrogen from water. The hydrogen could then be stored for later use. Rifkin noted that hydrogen storage could be the key to a successful renewable energy society because of the nature of many renewable sources, such as wind, solar and hydro, the availability of which can be affected by changes in the natural environment. Recent drought in Brazil and California demonstrated the need for a means to store the electricity from renewable sources as the electricity markets of both were dramatically disrupted by unexpected and prolonged droughts that interrupted hydroelectric supplies.

The U.S. government program has set a target to reduce the cost of producing hydrogen fuel from renewable resources:

	Approximate price per gallon of gasoline equivalent (gge) (2003)	Approximate price per gallon of gasoline equivalent (2010 R&D Goal)
Hydrogen produced from renewables	\$6.20	\$3.90

Source: U.S. Department of Energy

Rifkin noted that certain companies and industries are already leading the way in developing hydrogen fuel cells for particular applications. NASA, for one, is opening the door to a new period in history, he contended, through their research on eliminating CO₂ from civil aircraft by converting propulsion systems to hydrogen, both as a fuel for jet engines and aviation gas turbines but also as fuel for the possible development of advanced, ultra-light weight fuel cells as aviation power plants for, initially at least, 5-6 passenger planes.

The auto industry has invested more than \$2 billion to develop hydrogen-powered vehicles. Ford Motor and Toyota both unveiled hydrogen-powered prototype vehicles alongside the earlier-introduced GM's Hy-Wire and Daimler-Chrysler's F-Cell models at a Detroit auto show in February 2003. Ford claimed that its Model U was the first ever vehicle with a supercharged hydrogen internal combustion engine. The Model U's concept incorporates a 2.3 liter four-cylinder supercharged intercooled motor running on compressed hydrogen gas, a derivative of a standard Ford engine used in the Ford Ranger, the European Mondeo, and several Mazda vehicles. Toyota's Fine-S fuel cell prototype was based on cell technology, and modeled on the Highlander five-passenger sport utility vehicle, fuel cell versions of which were launched in late 2002 in Tokyo and California.

General Motors and other leading auto manufacturers have sued the state of California to water down requirements that a certain percentage of vehicles be zero-emitting. California's low emission vehicle program currently requires zero emission vehicles to make up 16% of new vehicles sales by 2018, up from 10% in 2005. More recently, the California Air Resources Board approved new regulations specifically to reduce greenhouse gas emissions that in the near term (2009-2012) will result in about a 22 percent reduction as compared to the 2002 fleet, and the mid-term (2013-2016) will result in about a 30 percent reduction.

California represents over 10% of the U.S. automobile market, ensuring that some manufacturers will comply to preserve market share. The program will force hybrid and hydrogen fuel cell vehicles into the market place in California as the state emissions goals will not be able to be met fully without significant improvements in operating efficiencies for individual passenger cars. To meet the regulations, automakers say they will have to make cars with an average fuel economy that is 22 to 30% higher than at present. The California standards, if they stand, are likely to be introduced in other like-minded states such as New York, New Jersey and Connecticut. If that happens, auto analysts say the car companies will change over their national production standards as these several states together will represent a critical mass of the American market,

making it more commercial to adjust manufacturing across the country rather than for just a target market.

There are a host of organizations within the energy industry that are looking at the best way to carry out a transition to a hydrogen era. One, the RMI, suggests starting the process with decentralized natural-gas reformers in buildings, followed by establishing a fleet of hydrogen fuel cell cars that return to a depot for nightly refueling at or near the buildings where fuel cells have been implemented. RMI's proposal reflects the realities that the infrastructure costs for a newly implemented, centralized hydrogen production and distribution system are currently prohibitive and that only an interlinking system that gains efficiencies and taps existing infrastructure can work to reduce the expense of the shift to hydrogen as a carrier.

Some hydrogen infrastructure already exists in the United States. U.S. hydrogen production is close to one-third of the world total and comes approximately 95% from natural gas. About 47% of U.S. hydrogen production (and about the same for world hydrogen production) is made on-site, mostly by steam reforming of oil or gas, and used in refineries to make gasoline and diesel fuel.

In one version, the U.S. Senate Energy Bill calls for development of a plan to support the production and deployment of 100,000 hydrogen-fueled vehicles in the U.S. by 2010 and 2.5 million hydrogen-fueled vehicles by 2020. The Senate Energy Bill calls for \$3 billion for hydrogen and fuel cell-related programs, almost twice the \$1.7 billion proposed by President Bush to develop hydrogen fuel cells, hydrogen infrastructure and advanced automotive technologies over the next five years. The private sector has already committed billions of dollars to the process but transition costs to a hydrogen transport system will be in the hundreds of billions.

In recent years, there has been some progress made on furthering the growth of the hydrogen and fuel cell industries in the United States and the European Union. On June 17, 2003, the United

States and the European Union (E.U.) agreed to collaborate on research efforts into hydrogen fuel cell research. Under the agreement, joint U.S.-E.U. projects will include the demonstration of fuel-cell vehicles and fueling networks, development of fuel cells as auxiliary power units, writing of codes and standards, and fueling infrastructure. Engineers and scientists also will work together on assessing the economic and social effects of exploiting “critical materials” required for low-temperature fuel cells and rare-earth materials to build special high-temperature cells.

But, even that agreement belies the stark differences between the goals of the two partners—the E.U. sees hydrogen-powered fuel cells as a means to harness renewable energy sources like wind and solar power, while the U.S. is focusing on methods to extract hydrogen from fossil fuels and nuclear energy. Japan has also made a strong drive towards research and demonstration of hydrogen and fuel cells, announcing initial commercialization targets of 50,000 fuel cell vehicles and installed stationary fuel cell capacity of 2,100 megawatts by 2010.

In October 2002, the European Commission initiated the High Level Group for Hydrogen and Fuel Cells to formulate a collective vision on the contribution that hydrogen and fuel cells could potentially make to the realization of future sustainable energy systems. The group’s June 2003 Summary Report highlights the potential of hydrogen-based energy in the context of a broader global energy and environment strategy. The level of public (financial?) support in Europe is, however, far below that in the United States—the proposed U.S. support is almost six times the level of public support anticipated for hydrogen and fuel cells in the European Sixth Framework Programme for Research. A substantial increase in support and well-coordinated research, development and deployment is needed for Europe to compete with the United States and Japan.

While the advantages of developing a hydrogen-driven economy are tremendous, there are clear hurdles that must be overcome, particularly in transitioning to hydrogen-fueled vehicles. In looking at the transportation side, one of the biggest challenges to tackle is on-board hydrogen storage, according to Dr. James Wong, program manager of Analytical Materials Science at Sandia National Laboratories. Speaking to the Energy and Nanotechnology Conference, Wong

suggested several areas of concern that must be addressed to see hydrogen-fueled transportation become a reality.

For one, the low volumetric density of gaseous fuels requires a storage method that densifies the fuel. For another, a 300-mile driving range in a combustion engine vehicle equates to 45 kgs of hydrogen, but storing enough hydrogen on the vehicles to achieve a greater than 300-mile driving range is difficult. “The storage system adds an additional weight and volume above that of the fuel,” Wong explained.

The DOE is pursuing a number of different hydrogen storage R&D program approaches. Wong cautioned, however, that none of these systems will likely be able to meet the DOE targets set for 2010 and 2015. The DOE’s Hydrogen, Fuel Cells & Infrastructure Technologies Program has set target goals that on-board hydrogen storage systems must demonstrate a 6% capacity by weight by 2010 and a 9% capacity by weight by 2015.

The most mature hydrogen storage R&D program, Wong said, is the development of compressed liquid tanks. The upside is that these tanks are very lightweight. Although 5,000-psi Type IV all-composite tanks are currently available and 10,000-psi compressed liquid tanks are being developed, tank materials and insulation remain a challenge to be solved. Liquefying hydrogen requires substantial energy and without proper insulation and pressurization, boil-off of the liquid inside the tank will result.

The second most mature hydrogen research and development program examines the use of metal complexes, like sodium aluminum hydrides, to store hydrogen. So far, this program has only resulted in the storage of 5% of hydrogen at moderate pressure at room temperature. “Even though 5% is attractive, it is not meeting the DOE’s requirements,” Wong pointed out. The drawbacks to the reversible metal hydride system are both low hydrogen capacity and slow kinetics. Regeneration costs in the current state of reversible chemical hydrides systems are the major barrier to commercial development. For example, Wong noted that compared to the cost of gasoline at \$1.50-\$2.00 a gallon, the equivalent cost of this system is \$50 a gallon.

Single-wall carbon nanotubes are a very attractive option being examined and funded by the DOE as a new material to be used in hydrogen storage, but they currently attain only 4% capacity by weight at ambient temperature and moderate pressure. Higher reported storage capacities of 8-10% capacity by weight have been difficult to reproduce. Moreover, low-cost, high-volume fabrication processes for carbon nanotubes have yet to be developed. And, according to Wong, “I think there is maybe more controversy [regarding carbon nanotubes] about contamination or other metals providing a catalyst for absorbing more hydrogen than carbon.”

Wong expressed some skepticism about advanced concepts that have yet to be explored but have been discussed at a DOE Hydrogen Storage Workshop in August 2002. One example of a technology he thought is less promising is employing hydrogenated amorphous carbon, something familiar to scientists in the fusion business. While scientists know how hydrogen diffuses into the first layer of carbon, the ratio of carbon to hydrogen will be hard to manipulate. “The maximum they ever get is a ratio of 1 carbon to 1 hydrogen; it would be next to impossible to get the hydrogen out, and at a 1:1 ratio, it’s like a 6% capacity by weight, maximum,” Wong said.

Wong’s opinion is that hydrides might be the most promising of all of the storage R&D approaches. “We know that some hydrides can become reversible with catalysts, so maybe there are other undiscovered hydrides that can do the same,” Wong said. Noting that many hydrides have high percentage weights, he pointed out that the most efficient storer of hydrogen is methane at 25% capacity by weight, but added, “We just can’t get it [hydrogen] out.” Still, he suggested that nanotechnology might provide the solution in terms of developing catalysts that will work to retrieve hydrogen.

In summary, Wong highlighted the challenges ahead for transitioning to a hydrogen-fueled economy in the U.S. “We know that for transportation, if you can’t store enough energy on-board, you might as well forget about it,” he warned. Although hydrogen storage is one of the

highest technical priorities of the DOE's Office of Hydrogen, Fuel Cells & Infrastructure Technologies, today's hydrogen storage technologies don't meet vehicle requirements. Wong argues that new materials and/or new technical approaches are required to meet hydrogen storage targets for vehicular fuel cell systems and that nanotechnology might play a key role in new storage materials development.

Timing in effectively meeting required hydrogen storage targets is crucial to the success of fuel cell vehicles and the hydrogen-fueled economy. "In talking to General Motors, they say that if you can't make storage work in the next few years, forget about reaching the DOE's targets for 2010," Wong noted.

Fuel cells that are being developed for potential transportation uses are primarily polymer electrolyte membrane (PEM) cells, which are considered simpler to put together and more rugged than liquid electrolytes. In addition, according to Dr. Kenneth Stroh, the PEM fuel cells operate at relatively low temperatures—80 Centigrade—which is ideal for systems that may fluctuate frequently.

Stroh, program manager of Hydrogen, Fuel Cell and Transportation Programs at the Los Alamos National Laboratory, told participants at the Energy and Nanotechnology Conference that using PEM cells in transportation devices is more appropriate than high temperature fuel cells that employ fossil fuels in stationary applications. High temperature fuel cells require more careful temperature management.

Stroh noted that a fuel cell operates like a battery, but instead of having chemical energy stored inside a case, fuel will be fed to the cell from outside. As long as the fuel is fed, the cell will provide full output as required. "In this case, we're talking about fuel cells that run on hydrogen and oxygen extracted from air," he said.

Typically, a single cell would have a voltage across it of six-tenths or seven-tenths of a volt, so in order to get a useable voltage for the application, cells are stacked together in series and the

voltage adds up. According to Stroh, “At a particular operating condition, the fuel cell will have a characteristic current density in the order of about 600-700 milliamps per centimeter square; a fuel cell like that in an automobile may run at about 200-300 amps.” Operating at 500 Volts, such a fuel cell could deliver 120KW of electrical power, a key goal for electric and hybrid vehicles.

Modular in design, fuel cells can be used in many different applications from battery replacement in portable electronic devices to stationary generation. However, Stroh pointed out that most of the federally-funded cell work at the Los Alamos National Laboratory is oriented towards transportation applications. “In a lot of ways, that’s like doing the hardest problem first,” he claimed. This is because transportation fuel cells, to be successful, have to be inexpensive, light, small and rugged; They have to have a turndown of maybe 50 to 1 and a fast, dynamic response. “That’s why when people talk about fuel cell vehicles, they’re not talking about right now,” Stroh said. One clear advantage over batteries is that in fuel cells, power conversion is separated from the energy storage, so if more energy is needed, a bigger tank of fuel can be added.

Stroh discussed the various requirements for different fuel cell applications. Portable electronics would be run at a range of sub watts to about 100 watts of power. For example, a cell phone not transmitting may require a couple tenths of a watt, while some battery applications like motorized wheelchairs would demand a few hundred watts.

In terms of residential applications, the designs are currently focusing on between 1 kW-10 kW of power, with 1 kW the norm and 7 kW the peak. This way, if a user wanted to sell back to the utility unused power, he would target the higher end, while a user who wanted to simply take care of the base load would welcome the lower end.

As for automotive applications, “We used to think it would be around 50 kW, but everybody now wants a higher performance, so we’re talking about around 120 kW,” Stroh said. Industrial

applications may require between 200 kW and 3 MW of power, but he noted that at the higher end of this spectrum, the logical move would be away from PEM fuel cells to using solid oxide fuel cells with fossil fuels. But Stroh warned that these processes are still in the developmental and pre-commercialization stages and not to equate press releases with technological advances.

In developing a fuel cell for transportation applications, there is a long laundry list of needed breakthroughs. This includes: a low-cost fuel cell; either hydrogen storage or a way to make hydrogen gas on demand; batteries; a traction motor; and the power electronics to get everything going. As Stroh stressed, fuel cells work best when they are pressurized, so most of the systems need to have an air compressor, though some specialists are working on ambient pressure systems. So far, the approach has been to develop liquid hydrogen tanks to handle the requisite amount of hydrogen for vehicular use, but this is not proving to be commercially viable. If nothing else, Stroh said, “You’d have to use a third of the energy content of the hydrogen liquefied.”

There have been some interesting steps made in the conversion to fuel cell automobiles. Almost 100 years after the first coast-to-coast automobile trip by an internal combustion vehicle, the first fuel cell vehicle crossed the U.S. from San Francisco to Washington from May 20th-June 4th, 2002. This vehicle had a methanol reformer in it, which as Stroh pointed out, was effective, as methanol is a strong hydrogen carrier.

He also noted that there are some fuel cell applications that only make sense as a transition, such as the gasoline reformer fuel cell. It makes no sense to change the entire energy convergence system and fuel distribution and maintenance just to derive the benefits from the gas reformer fuel cell. It only makes sense to pursue this application as a transition to get to a different place, in Stroh’s opinion.

Stroh stressed that there are a number of technical challenges and barriers facing commercialization of fuel cell usage, including: cost; durability; reliability; power system

performance; and issues involving supporting technologies, including hydrogen storage, hydrogen production and hydrogen distribution and dispensing. Although he claimed that targets for fuel cell efficiency are being met quite well, he stated that the primary problem is still cold start-up, with the cells responding too slowly.

In all of the systems being explored, the cost of the fuel cell stack is roughly half of the cost or more of the entire system. According to Stroh, about 70-80% of the stack cost derives from the membrane electrode assemblies, which means that it is a few pieces of plastic that costs the most. “If you look at the membrane electrode assembly—at 500,000 units a year -- roughly 70% of the cost is in the catalyst and another quarter is in the membrane ... We’ve managed to reduce the cost of platinum by a factor of 40 or 50, but it’s still not enough and we need another factor of 10 to reduce the cost,” he pointed out.

The electrodes themselves are about a micron thick in size. Despite being called film electrodes, they are actually composites of metal, carbon and polymer. Inside the electrode are supported catalysts, consisting of a fairly large carbon particle with a very finely divided platinum catalyst on a surface. The typical catalyst particle sizes being used are roughly 3 nanometers; as received, they have a surface area of about 100 square meters per gram. By the time the composite structure is made, that surface area is reduced to about 40 square meters per gram. And, as the electrode is run for some time, catalyst sintering and stack delamination lead to loss of performance and eventually cell failure.

But, Stroh suggested that nanotechnology could play a pivotal role in helping design these structures to work more effectively. As he pointed out, at present, fuel cells fail early and for different reasons, with durability a big issue. “You try to make them thin, because thickness is resistance; everyone’s trying to make them thin, but then the materials creep,” Stroh noted.

Nanotechnology can play a key role in the development of sturdier fuel cells and improved membrane technology by providing new, light materials that can withstand the large changes in

temperatures required in automotive operations. At present, polymer electrolyte membranes are the most common membranes commercially available. But scientists are working to develop ceramic electrolyte membranes that will be more durable under extreme conditions. Several problems arise in using the most commonly used polymer electrolyte membrane, Nafion, a perfluorosulfonate membrane, in fuel cell applications. Operations are limited to temperatures below 80 degrees celcius, and the membranes are expensive. In addition, when used in hydrogen fuel cells, problems emerge with back diffusion of water.

Nanostructured ceramic membranes, derived from metal-oxane nanoparticles, could present an improvement in the efficiency of fuel cells. Ferroxane is a new derived material based on iron oxide nanoparticles with surface carboxylate groups. Particle size, 5 to 100 nanometers, is controlled by the identity of the carboxylate substituent. Work on utilizing this material to develop ceramic membranes has been undertaken by a team including Rice University scientists Mark Wiesner and Andrew Barron, along with Eliza Tsui and Maria Fidalgo-Cortalezzi. When utilized to make iron-based ferroxane-derived proton exchange ceramic membranes, these scientists found that the new membranes were tolerant to temperatures in excess of 300 degrees celcius and exhibited similar conductivities to those of Nafion mebranes. Moreover, proton conductivity was found to be virtually independent of relative humidity at values greater than 50%. These results suggest that a promising breakthrough in less expensive, more durable materials may be on the horizon.

Beyond a New Hydrogen-based Energy System:

Other Energy Sources and Nanotechnology

There are many other potential clean energy sources that could be enhanced through the use of nanotechnology. On the second day of the energy and nanotechnology conference, speakers investigated other sources of energy that might be able to make a major contribution to the world energy supply chain.

Geothermal

Dr. Yoram Shoham, Vice President of External Technology Relations for Shell International Exploration and Production provided participants a glimpse of the potential for geothermal energy to supplement world energy supply. Dr. Shoham's presentation, "The Heat of the Earth: An Undervalued Opportunity for Secure, Sustainable Energy" discussed various facets of geothermal energy.

Wind, hydroelectric, and tide energy are all important alternative sources but, they cannot produce the enormous amounts of energy that the global community will demand in the future, according to Shoham. Photovoltaics, biomass, safe nuclear and geothermal, on the other hand, could potentially deliver the terawatts needed to avoid an international energy crisis. "Philosophically, we may even say that basically all the energy in the world is coming from nuclear reactions," Dr. Shoham explained. "The sun is a nuclear reactor and in a way, over long periods of geologic time, hydrocarbons have converted energy that came from the sun into energy that we can use today. But there is another nuclear reactor and we are walking right above it—on a very thin crust." Earth's diameter is over 6,300 kilometers but its crust is very thin—0 to 80 kilometers thick. The reason the Earth does not simply implode is that there is a very large amount of heat induced pressure coming from inside the Earth, Dr. Shoham explained. At about 400 kilometers, the temperature inside the Earth is approximately 4,000 degrees Celcius. "Generally, talking about geothermal is talking about mining the heat generated by the nuclear reactor under our feet."

Geothermal energy falls under four categories: hydrothermal, direct use, hot rocks and magma. Producing energy by drilling directly into magma chambers is not a viable option at the moment and is not likely to become so anytime in the near future. Hydrothermal, direct use and hot rocks, on the other hand, are viable options and are currently being used in many areas around the world. As Dr. Shoham explained, the heat of the earth is readily accessible in areas along the West coast of the United States, throughout South America and in the Pacific. Earth's crust is a

series of tectonic plates floating on hot magma. These hot areas coincide with those plate boundaries and are typically home to various thermal phenomena including volcanoes and hot springs.

Hydrothermal energy is produced naturally when rainwater comes into contact with hot rocks, producing steam. Unfortunately, this contact is not likely to happen enough in nature; the coincidence of abundant fresh water and extremely hot rock is low. The situation can, however, be produced artificially in a hydrothermal power plant. At present, approximately 40 countries produce hydrothermal energy, including the United States, Phillipines, Italy, Mexico, Indonesia, Japan, New Zealand, El Salvador and Costa Rica. The world potential for hydrothermal production is about 12 gigawatts, and collectively, these nations produce almost 8.5 gigawatts from hydrothermal power plants.

Another 12 gigawatts could potentially be produced from direct use—geothermal energy from geysers and hot springs. Hydrothermal and direct-use produce a fraction of all gaseous emissions; the only by-product is steam. Although clearly a viable energy source and wonderfully non-polluting, hydrothermal and direct use are limited in the volume of energy that can be produced.

The future of geothermal energy lies in hot rocks. The cooling of one cubic kilometer of granite by one degree Celsius produces the energy equivalent of 0.4 million barrels of oil. “If we can find 250 degrees Celsius shallower than three kilometers—overcoming some technical issues—we could bring the energy to the surface and produce electricity,” Shoham believes. He noted that it is possible to find 250 degrees Celsius as shallow as one kilometer, meaning that essentially the entire Western part of the United States has potential.

Dr. Shoham argued that the heat of the earth must be mined in the very same way that oil is mined. By going to the hot rock, creating a reservoir and injecting water, a continuous cycle of steam production can be established. The steam can, in turn, be used by a power plant to

generate electricity. The technical challenges to creating this ideal cycle involve exploration, well technology and subsurface heat exchange. Pumping too much water into the reservoir will cool the rocks; the idea is to pump just enough water to derive the maximum output without cooling the reservoir. Experts must build upon existing knowledge from the oil and gas industry to solve the tough challenges of geothermal, including reservoir thermal conductivity, creating a closed system and drilling.

As Dr. Shoham explained, rocks are thermally not very conductive. Technology must be developed to “convince the rocks to give up their heat.” In addition, a closed system must be created to prevent loss of water. Knowledge from the oil and gas industry can be used to develop ways of drilling that are optimized for geothermal fields. A very high intensity, very high temperature laser could possibly be used to melt into the rocks to create as perfect a hole as possible.

Geothermal wells must be “smart” wells that behave like the roots of a tree. The well will have to be an “organic creature” sensing its environment, perhaps with nano-sensors, and adapting to changes in temperature and water availability. The end of the optimization cycle is, Dr. Shoham argued, not simply the well itself, but rather the entire robust, controlled system that controls the well and its evolution, together with the surface facility and down the line to the consumer.

Geothermal energy addresses a variety of sustainable development issues because it leaves a relatively small environmental footprint. Moreover, geothermal energy reduces hydrocarbon imports and is suitable for small scale development as well as large scale. One geothermal success story is Iceland, which has gone further than any other country in exploiting its abundant sources of renewable energy. Nearly all of its electricity and heating comes from hydroelectric power and the geothermal water reserves tapped from the hot rock layers lying just beneath the surface of the island. Reykjavik, the largest city in Iceland now produces 95 percent of its energy via thermal.

Geothermal energy has enormous potential and the nanotechnology implications are numerous. Nanoscience can be used to enhance thermal conductivity. By fracturing large volumes of hot rock and developing reservoirs through the injection of conductive, porous cement the maximum amount of heat can be produced. Furthermore, nanotechnology can improve down-hole separation and aid in the development of non-corrosive materials.

Natural Gas Technologies

Natural gas is a clean burning fuel in abundant supply in many parts of the world. There are four technology challenges facing the growth of the natural gas industry that can be tackled with the help of nanotechnology, according to Melanie Kenderdine, vice president of the Gas Technology Institute and former director of policy at the Department of Energy (DOE) in the Clinton Administration. Kenderdine, who addressed the Energy and Nanotechnology Conference, cited the challenges as the following: development of conventional/unconventional gas resources; accessing stranded gas resources; extending the resource base by developing alternatives to natural gas; and increased efficiency of natural gas use and environmental mitigation.

Kenderdine stressed that the premise of her presentation to the conference attendees was that gas demand is primarily driven by the abundance of the resource. Other drivers included: overall growth in energy demand globally; the geopolitics of oil; inexpensive power generation; and environmental benefits. There are four geographic blocks that are generating the growth in gas demand from the period 1999 through 2020, she said. Western Europe will see an impressive increase of 87% in gas consumption during this period, while Eastern European gas consumption will jump 62% during the same timeframe. Developing Asia will see a giant boost in consumption over the period of about 256%, while U.S. gas use will rise 56%, according to Kenderdine.

She pointed out that the Middle East and the former Soviet Union each contain a high percentage of the world's gas reserves. Recent data from the Energy Information Administration (EIA)

suggested that there are about 5,500 trillion cubic feet (TCF) of proven reserves of natural gas worldwide. Although the world is currently consuming 169 TCF of gas per year, roughly 50-60% of the proven reserves consist of stranded gas.

Kenderdine noted that gas use for electricity globally is anticipated to increase 4% a year from 1999-2020, compared to coal at -1% a year. On the other hand, carbon emissions are expected to jump 61% globally during the same period. “Everyone knows the value of natural gas in this regard,” said Kenderdine, adding that natural gas generates less than half the CO₂ that coal does, on a megawatt-hour basis. In terms of end-use equipment of equal efficiency, oil has 1.4 times more potential for creating greenhouse gases than natural gas, while coal has 1.5 times more potential than natural gas.

Kenderdine said she sees a number of technology challenges for developing the world’s conventional and unconventional gas resources. In the near term, there is a lot of discussion about enhanced drilling, enhanced seismic techniques, reservoir management and unconventional gas production. Mid-term challenges include: ultra deepwater (over 10,000 feet) production; unconventional gas production from multiple sources; deep drilling; and advanced coal bed methane. For the long-term, the technology challenges include methane hydrates and new architecture for ultra deepwater production and transport.

The EIA has stated that in 2020, the largest incremental increase in U.S. gas supply will come from unconventional gas resources, totaling about 5.8 TCF. One source of unconventional gas is coal bed methane. Since 1985, when there was no coal bed methane production whatsoever, it has grown to now account for roughly 7-8% of the U.S. natural gas output. “This has inspired a lot of coal bed methane programs around the world,” stated Kenderdine.

As for ultra deepwater gas production, there have been a number of noteworthy discoveries and emerging frontiers, she said. As part of the Technology Roadmap of Ultra Deepwater directed by MIT Physics Professor Ernest Moniz within the DOE in 2000, the conclusions suggested that

there is significant gas and oil in the ultra deepwater, that the costs of producing from ultra deepwater needed to be reduced by 30-50%, and that the best way to do this for developing those gas resources was to take the platform from the ocean's surface and put it on the ocean floor.

There are a number of technical challenges that must be addressed in accessing stranded natural gas resources. Near term challenges focus on liquefied natural gas (LNG) infrastructure and efficiency, LNG quality, and developing gas to liquids (GTL) technology. Mid-term challenges include: developing super pipelines; floating GTL platforms; production, regassification/storage issues; and compressed natural gas transport. Long-term issues to be addressed are methane hydrates and gas by wire (that is, producing electricity at the location of the gas source and carrying the electricity by wire to market rather than the gas to market by pipeline).

The R&D needs for developing LNG as a gas resource involve lowering the costs and increasing its flexibility. Expanding LNG use will require floating LNG liquefaction/regassification/storage facilities, subsea cryogenic pipelines for offloading product to onshore storage facilities, the use of salt caverns for LNG storage and creating micro-LNG facilities.

GTL technology enables stranded gas to be brought to markets by converting gas into high quality liquid fuels that can be transported in existing petroleum infrastructure. The advantage of GTL technology is that it produces no sulfur or aromatics and a much higher cetane number than conventional diesel fuel. Kenderdine pointed out that while the capital costs of GTL have been reduced by 60% over the last decade, they are still quite high. She said that research is being conducted to help address these costs, including on direct conversion from methane to desirable liquid hydrocarbons via catalytic oxidation, on catalysis improvements for indirect conversion and plasma technology for conversion of natural gas into syngas before catalytic reaction.

The environmental emissions benefits of coal/biomass gasification rival those of natural gas, Kenderdine claimed. These technologies can produce hydrogen, ammonia or synthetic natural gas, and generate high-efficiency electricity with no release of carbon dioxide into the

atmosphere. One of the R&D challenges for commercial coal or coal/biomass gasification is lowering the cost from \$1,200 per megawatt hour compared to \$900 per megawatt hour for conventional coal-fired plants. Other technological challenges faced in coal/biomass gasification are the need to develop membranes to separate oxygen from air during the gasification process and hydrogen and CO₂ from coal gas, improved gasifier designs, advanced cleaning technologies, the recycling of solid wastes and carbon sequestration.

As for the technological concerns of Kenderdine's fourth challenge—the more efficient use of natural gas and the environmental mitigation associated with its increased use—the near term focus is on power generation, including the end-use efficiencies of exploring improved gas turbines and distributed generation. The mid-term challenges focus on advanced gas turbines, large-scale distributed generation, fuel cells, GTL technology and gasification, while the long-term challenges should address carbon sequestration and super batteries.

Kenderdine said that she was bullish on GTL applications because, with the world's major automobile manufacturers moving to meet low sulfur diesel engine regulations, "GTL provides a 'no sulfur' alternative to diesel," she told conference attendees, adding that it can be a good substitute for diesel if the investments can be made to reduce its costs. "I think GTL is one of the early targeted areas we should work on with nanotechnologies," Kenderdine asserted. The other environmental benefits from GTL include: 43% less hydrocarbons emissions in gas-derived diesel than petroleum-derived diesel; 45% less carbon monoxides in gas-derived diesel than petroleum-derived diesel; 9% less nitrogen oxides in gas-derived diesel than petroleum-derived diesel; and 30% less particulates in gas-derived diesel than in petroleum-derived diesel.

There are a number of possible nanotechnology applications that can be employed to resolve Kenderdine's first challenge, developing conventional and unconventional natural gas resources. She suggested the development of advanced fluids mixed with nanosized particles to improve drill speed, nanosensors created for reservoir characterization, the removal of gas impurities via nanoseparation, and producing nanocrystalline substances for drilling materials.

Nanotechnology can address the problems associated with accessing stranded natural gas resources by performing nanocatalysis for GTL production, developing nanoscale membranes for GTL production and creating nanostructured materials for compressed natural gas transport. As for meeting the challenges of extending the energy resource base by developing alternatives to natural gas, the following nanotechnology applications should be pursued, Kenderdine said: developing nanotubes for fuel cell cars; performing nanocatalysis for coal liquefaction; creating nanocomposites for reservoir characterization; and designing filters for more efficient ethanol processing.

The potential nanotechnology applications for resolving the challenges of providing more efficient uses of natural gas and mitigating its environmental impacts include developing nanocrystals or photo catalysts to speed up the breakdown of toxic wastes and nanoscale coatings for more efficient catalytic conversion. In addition, Kenderdine recommended the creation of nanostructured catalysts to remove pollutants and impurities from natural gas and the design of nanocrystalline materials for water treatment. One final possible nanotechnology application is the development of polymeric nanoparticles to remove pollution from the catalytic conversion process.

Methane Hydrates

Around the world, huge reserves of methane have been discovered trapped in ice-like crystals beneath the ocean floor and the Arctic tundra. These “crystals” are called hydrates and it is estimated that more energy resides in gas hydrates than in all of the energy available in existing oil, gas and coal reserves. Rice Professors, Walter Chapman (Chemical Engineering) and Gerald Dickens (Earth Science) provided participants of the Energy and Nanotechnology Conference with a brief introduction to the incredibly complicated world of gas hydrates, explaining the energy potential, the production challenges and the environmental concerns associated with this vast energy source.

Gas hydrates are crystalline solids, naturally occurring compounds trapped inside a rigid lattice of water molecules. These compounds are stable at conditions of relatively low temperature and relatively high pressure. Gas hydrates of primarily methane (the main component of natural gas) occur naturally in Arctic permafrost at depths greater than 200 meters, and they also form at ocean depths of 500 meters or more, where temperatures hover near freezing and the weight of the water produces high pressures. In these systems of high pressure and low temperature, a methane molecule becomes trapped in a cage of six water molecules, giving rise to a clathrate solid. The resulting gas hydrate looks like normal ice, but burns if touched by a flame.

Gas hydrates represent a major source of untapped energy. Potentially gas trapped within or below the hydrate structure can be extracted and utilized just as conventional natural gas resources are today. The world is facing an increased demand for methane as a result of the desire for fuel with reduced CO₂ emissions and the need for more efficient power production than from oil or coal fired plants. It is estimated that twice as much methane-carbon lies in gas hydrates than in all other known fossil fuel deposits, and if even a fraction of this could be recovered, methane from gas hydrates would be a viable energy source.

Gas hydrates as an energy source are of particular interest to countries presently lacking energy security, including Japan and India. Following recent international drilling efforts targeting natural gas hydrates in several ocean and permafrost locations, the scientific community has documented the fundamental characteristics of these systems. The current challenge is to take these observations and build predictive models for how natural gas systems operate. Greater understanding is needed of the science and technology of hydrates resource development as well as its environmental implications. The key questions focus on developing environmentally safe and economically viable procedures by which to locate and extract gas accumulations associated with gas hydrates and incorporating gas hydrates into models of the global carbon cycle so that past and future increases in deep ocean temperature include the effects of seafloor methane release.

Though discussion of hydrates has increasingly emerged in scientific literature, little is essentially known about the way gas hydrates behave and how they affect the global carbon cycle. The physical knowledge scientists have of hydrates comes from the three sites where drilling has actually been conducted. The Blake Ridge off the coast of Georgia, an area roughly the size of the state of Rhode Island, is estimated to contain 35 gigatons of methane. Scientific drilling at Hydrate Ridge, off the coast of Oregon, indicates that it may be the archetypical reservoir for commercial use, and exploration and drilling of the Messoyakha Field in Siberia suggests that the reservoir could produce five billion cubic meters of methane gas, 36% of its production, from gas hydrates.

As Dickens explained, evaluating as well as extracting these hydrates is extremely costly and complicated. Gas hydrates cannot simply be plucked from ocean floor sediment because as they exit a system of high pressure and low temperature, the hydrate begins to dissociate, and the gas is lost. Researchers most commonly use a Bottom Simulating Reflector (BSR) to measure the amount of gas hydrate in reservoirs. A BSR is an acoustic interface that sends sound waves through sediment and measures the speed of the waves as it travels through the various layers. The velocity of sound increases when traveling through a clathrate structure (gas hydrate) in the pore space because it is solid but when the waves encounter free gas, the speed of sound drops. Scientists have also developed ways to drill under high pressure to prevent dissociation of the gas hydrate. By drilling bore holes and using pressure cores, researchers measure the amount of gas present and try to raise the gas hydrate without allowing it to change its phase.

Research at Blake Ridge, Hydrate Ridge and the Messoyakha Field has helped scientists begin to understand the nature of hydrate systems. More research, exploration and drilling will be required to discover where areas of high hydrate exist and whether or not the formation is permeable enough for production.

Dr. Chapman suggested several possible methods for recovering hydrates, including thermal injection, chemical injection and pressure depletion. Thermal injection is likely to be the most

economical and realistic method for “harvesting” gas hydrates. It involves thermal dissociation of the hydrate through electrical or electromagnetic heating, in-situ combustion or circulation of hot formation brine in the pore space.

Chemical injection requires inserting CO₂ into the formation to chemically dissociate the hydrate. When the CO₂ comes into contact with the hydrate, the CO₂ will displace the methane with no melting and less heat effect. This method of chemical dissociation highlights the potential for storing and sequestering CO₂ in hydrates. However, since hydrate systems are dynamic, wherein hydrates are forming and dissociating constantly, it remains unclear whether a hydrate structure can permanently and stably store CO₂.

Another method of chemical injection involves using a hydrate inhibitor, such as methanol, to prevent dissociation. At present, methanol is too costly to have this method be commercially viable. Chemical injection involving CO₂ could become the primary method for extracting energy from these gas hydrate reservoirs. One idea is to build a power plant offshore, inject CO₂ into the formation, producing methane and, in turn, produce electricity, which then could be sent onshore for use in urban areas.

Pressure depletion, however, is almost certainly the best opportunity for recovering gas from hydrates. Pressure depletion, simply stated, is free gas production. One third of the gas at The Blake Ridge is free gas, but the free gas is located in impermeable clay soil. The objective is to find permeable conditions where free gas can be produced, leaving the gas hydrate to dissociate and recharge the reservoir.

Worldwide, research on gas hydrates is being conducted. U.S. investigation of the energy potential of gas hydrates accelerated in 1998. Prior hydrates research had been primarily focused upon inhibiting hydrate formation, which can plug pipelines transporting oil and gas. Gas hydrates can plug flow lines in offshore energy production creating an economic and safety problem. Oil and gas companies presently spend more than half a billion dollars annually on

chemical inhibitors to prevent gas hydrate plugging. Formation of gas hydrate plugs also plague further refining of natural gas products. Research is needed to understand the mechanism and kinetics of hydrate formation and decomposition and the effects of chemical inhibitors.

Several nations, most notably Canada, Japan, India and the United States, are engaged in active gas hydrates research and evaluation programs. A study released in September 2002 by researchers at the University of Victoria found that a huge portion of Canada's energy reserve potential lies in onshore and offshore gas hydrates. Resource-poor Japan has become a global leader in gas hydrates exploration and in March 2002, Japan National Oil Corporation (JNOC) announced that JNOC, along with its international partners, succeeded in production of gas hydrate—the first time that gas hydrate was recovered through its underground dissociation into methane gas.

The DOE and U.S. Geological Survey (USGS) partnered with the Geological Survey of Canada, JNOC, BP-Chevron-Burlington Joint Venture Group and others to drill appraisal and production test wells in the Mackenzie Delta of the Canadian Arctic in 2002. The DOE has also partnered with Anadarko Petroleum Corporation, Noble Engineering and Development and Maurer Technology to conduct a test program near Deadhorse, Alaska.

The energy potential of gas hydrates is becoming increasingly obvious; however, numerous production challenges must be resolved before commercial production is possible. A reservoir must contain a high concentration of gas hydrates in order to produce, and permeable areas of high hydrate content must be identified. Production strategy depends on the accumulation process, which requires knowledge of the distribution of the hydrate in the reservoir. Additional research in the area of modeling is necessary to understand how the hydrate develops into the form it takes in the reservoir. Reservoir modeling is important in understanding reservoir heterogeneity and permeability. If free gas exists but it is in an impermeable formation, it cannot be produced. Further modeling research will provide scientists with a better understanding of brine flux, heat effects and thermal conductivity, and the mechanism and role of dissociation.

These production challenges are compounded by the environmental complications and consequences of exploring and producing gas hydrates. Current scientific literature has emphasized that gas hydrates probably played a major role in the global carbon cycle and climate change in the world's geologic history. The large amount of carbon stored in gas hydrates is likely 10 to 20 times the mass of carbon in the atmosphere so that a relatively small release of methane from gas hydrate systems could have significant impact. Current carbon cycle models, however, neglect gas hydrates and possible methane releases and it is not well understood why, how, where, and when gas hydrates should be incorporated into the global carbon cycle.

As Dickens explained, the carbon cycle has traditionally been understood as ocean, atmosphere and biomass, but if the numbers about gas hydrates are correct, scientists are dealing with a much bigger box. "There is a huge, dynamic part of the carbon cycle that is missing from our models of how the world works," Dickens noted. In order to develop this concept and account for seafloor methane release (from natural disturbances such as rising ocean temperature or from production), a cross-disciplinary approach is needed that includes the inputs and outputs of methane to and from the ocean and atmosphere and how these fluxes can be perturbed.

Massive amounts of methane -- a potent greenhouse gas with twenty-two times the effect of carbon dioxide -- might also escape from the seafloor during the warming of oceans. Studies of geologic record indicate several past intervals of deep ocean warming, such as the Paleocene/Eocene thermal maximum 55 million years ago, when immense quantities of carbon suddenly entered the ocean and atmosphere, presumably through disruption of gas hydrate systems. Dickens and other Rice researchers have conducted significant initial research into the topic of gas hydrates and climate change. According to their model of the first basic global carbon cycle that includes gas hydrates, significant amounts of methane have been released from gas hydrates during several past intervals of abrupt (< 100kyr) environmental change when ocean bottom water warms.

The stability of the seafloor can also be affected by gas hydrates in underlying sediment and whether or not hydrates are produced. In addition to the methane release from changing environmental conditions, the safety of offshore drilling platforms is a major concern in the commercial production of energy from gas hydrates. The impact drilling for gas hydrates has on seafloor stability is currently unknown, and further research is needed to assess the safety of gas hydrate production.

Greater understanding is needed of the science of hydrates resource development as well as its environmental implications. The scientific community has documented the fundamental characteristics of gas hydrates systems, but to gain the knowledge needed to tap this energy source in a commercially viable and environmentally sound manner and to understand the global carbon cycles, these observations must be elaborated, including the creation of predictive models that indicate more accurately and clearly how gas hydrate systems accumulate, dissociate and operate.

Gas hydrates are dynamic systems with enormous energy supply potential and serious environmental implications. Applications range from storage and transportation of natural gas, to gas separations and materials handling to templates for novel nano-materials. Further research will produce reservoir and environmental modeling that improves present knowledge of reservoir lithology and permeability and transforms our understanding of the potential release of greenhouse gases and global carbon cycle.

With commercial production only ten to twenty years away, today's research and development must be multi-disciplinary and cross-sectoral to adequately address the range of issues surrounding gas hydrates.

Coal and Carbon Sequestration

Despite expectations for renewable energy sources to make big inroads into power generation in the coming decades, coal could remain the primary fuel for electricity generation in the U.S. through 2025, according to William Fernald. Fernald, portfolio manager of the DOE's Office of Coal Fuels & Industrial Systems, told Energy and Nanotechnology Conference attendees, "We're not saying that renewables will never have a role. But, we're proposing producing hydrogen from coal to get a hydrogen economy started and get its infrastructure started; we think that coal is the most practical and cost-effective way to do that."

Fernald pointed out that coal in the U.S. accounts for about one-quarter of primary energy consumption, but that the coal share of electricity generation is expected by the International Energy Agency (IEA) to fall from 52% in 2001 to 47% in 2025 with the rise in natural gas used to produce electricity.

He also stressed that there are a number of serious challenges facing the coal industry, including: its capability to meet changing environmental performance requirements; its ability to achieve required operational and economic performance goals; its ability to meet increased competition from alternative fuel sources; and public acceptance of coal as a clean source of energy. Environmental emissions, in particular, are the main threat to the continued use of coal in the U.S. economy. For that reason, the role of clean coal technologies is to address and eliminate the existing concerns and to open the door to the continued and increased demand for coal.

There are three major U.S. government/industry R&D programs in place to meet the major challenges facing coal. The Clean Coal Technology Demonstration Program (CCT) was established in 1985 as a government/industry co-funded effort to demonstrate a new generation of innovative coal utilization processes that would be responsive to the energy and environmental needs of the 21st Century. The program called on the industry participants to share at least 50% of the program's cost and in return, they would retain equipment, real estate and

intellectual property while also being responsible for technical management. The government holds the oversight role and can recoup its investment if the technology proves commercially successful.

Goals of the CCT program include: developing or improving the effectiveness of pollution control technology for use in existing plants and dramatically reducing its cost; developing higher efficiency new plants that are inherently clean and lower in cost than current designs; and establishing the engineering and scientific foundation for the next generation of clean coal technologies with near zero emissions and generation efficiencies that are double those of the existing fleet. Of a total of 60 projects that were selected in the CCT program from 1986 through 1993, the program currently has 38 projects, 30 of which have completed operation.

There are a number of successes that have resulted from the CCT and Coal R&D programs. One area of success has been in NO_x controls. Through new technologies developed in the programs, some 75% of existing coal power plants are now equipped with low NO_x burners. In addition, the cost of selective catalytic reduction technology (SCR) for the control of NO_x emissions has been roughly halved since the 1980s and that technology is being used in approximately 30% of U.S. coal power plants. The end result of these accomplishments is that there is an anticipated 25 million ton reduction in NO_x through 2005 and a cost reduction of approximately \$25 billion in the same time period.

As for SO₂ controls, flue gas desulfurization (FGD) scrubber technology now costs one-third of what it did in the 1970s and more than 400 commercial systems have been deployed. This has produced an estimated seven million ton reduction in SO₂ through 2005 and an overall \$50 billion savings from lower FGD costs and improvements to the environment.

An exciting outcome of the CCT and Coal R&D programs is the Integrated Gasification Combined Cycle (IGCC) technology, said Fernald. It is a revolutionary new, clean and highly efficient technology that is just reaching its technical and economic potential. Under IGCC

technology, coal can be used as an electricity fuel with substantially less pollution than conventional coal plants. In an IGCC plant, the coal is first gasified by subjecting it to heat and pressure in the presence of steam. Key contaminants including sulfur dioxide, mercury, particulate matter, and carbon oxides are then removed from the gas before the cleaned syngas (primarily hydrogen) is burned in a gas turbine. The hot exhaust gases from the turbine are then used to produce steam, which is also run through a steam powered turbine to produce additional electricity before the steam is passed back to the gasifier. Nitrogen oxides are removed from the exhaust gases before they are vented to the atmosphere. There are more than 1,500 Mw of IGCC coal-fired plants operational today, with another 2,200 Mw of capacity in design. The economic/environmental benefits of this new technology are estimated at more than \$12 billion through 2020. The long-term goals of the IGCC technology are to achieve near zero emissions (including carbon emissions when coupled with sequestration) and efficiencies of 60% from today's fleet average of 32% under the proposed FutureGen Initiative.

Under the DOE's Power Plant Improvement Initiative, the six projects involved are primarily focusing on cultivating technologies that will enable coal-fired power plants to meet increasingly stringent environmental regulations at the lowest possible cost. As for the Clean Coal Power Initiative, the DOE announced in January 2003 that the department had chosen the first eight projects in a series of competitions to implement President Bush's 10-year, \$2 billion commitment to clean coal technology.

Of the eight projects, three are dedicated to finding ways to comply with dramatic reductions in air pollutants from power plants over the next 16 years and another three are expected to contribute to the Climate Change Initiative to reduce greenhouse gases. The remaining two projects are aimed to reduce air pollution through advanced gasification and combustion systems designed to extract the energy potential from waste coal piles.

With an eye to anticipating future concerns involving the coal industry, the U.S. government is developing two projects. The first, the FutureGen Demonstration Project, is a \$1 billion, 10-year

project to create the world's first coal-based zero emissions power plant. The goal, according to Fernald, is for an industry consortium to determine the technical and economic feasibility of producing electricity and hydrogen from coal while capturing and sequestering the CO₂ generated in the process. The FutureGen plant is aimed at utilizing coal gasification technology to produce 275 MW equivalent of electricity while the closed loop system will also sequester the CO₂ produced in the process in deep geological formations.

To promote FutureGen and other projects like it, the Bush Administration has created an international partnership in carbon sequestration called the Carbon Sequestration Leadership Forum. The Forum, created last year, includes the European Union and 15 other nations from five continents. The Forum's goals include research on transport and long term safe storage of carbon emissions and a means to make such new technologies broadly available in the international community. The administration hopes that its clean coal power technology program can help reduce emissions from new coal plants considerably.

The Vision 21 Plant project, announced in 1999, envisions a new class of fossil fuel plants would produce electricity, chemicals, fuels or perhaps a combination of products in ways tailored to meet specific market needs. The new generation of coal-based plants would focus on the capture, sequestration and disposal of CO₂, noted Fernald. They would incorporate atmospheric or pressurized fluidized combustors and integrated gasification combined cycles. The success of these advanced clean coal concepts would result in low-cost production of electricity, process heat and high-value fuels and chemicals, the ability to use multiple feedstocks, and produce virtually no pollution emissions and with efficiencies greater than 60%.

The issue of carbon sequestration must be tackled successfully if the world is to move towards a hydrogen-based economy, particularly when utilizing abundant fossil fuels. What's more, the single largest impediment to the implementation of carbon sequestration on the large scale that is demanded is the cost of capture. According to Julio Friedmann, assistant research scientist in the department of geology at University of Maryland, the world has a wealth of fossil fuels --

conventional and unconventional -- to draw from over the next couple of hundred years, but carbon dioxide and greenhouse gas (GHG) emissions are the major challenges that must be tackled.

Nanotechnological applications may play a critical role in the development of effective sequestration methods, including in advanced concepts like chemical sequestration, and in resolving high leak rates, according to Friedmann.

Friedmann told participants of the Nanotechnology & Energy Conference, “As long as you have increased population and increased GDP, you’re going to have increased CO₂ emissions ... We are already higher in CO₂ emissions than we’ve been in the last 1,000 years.” For that reason, carbon sequestration will have to be deployed very rapidly and on an enormous scale for safe greenhouse gas (GHG) stabilization in the atmosphere, he stressed.

Yet, despite the awareness of the need for carbon sequestration, Friedmann argued that, “If we’re serious about carbon sequestration, our funding base right now is off by a factor of about 100, even though the funding is doubling every year ... Part of the funding mix must be dedicated to large-scale projects, and we must do the geoscience work at the same time we’re doing the engineering and economic work.”

There are a handful of sequestration modes that are being explored by the geological and scientific community, though each has its own range of associated problems. Ocean sequestration is risky, uncertain and pricey, and according to Friedmann, is “off the docket” for environmental and scientific reasons. Geological sequestration is point source limited, and for that reason, pricey. Soil/plant sequestration, which is already being done, is problematic in that saturation could be reached quickly in just a few short years, Friedmann explained. Chemical sequestration, which is in the advanced concepts stage, currently costs five to 20 times more than geological sequestration.

“If geological sequestration in the U.S. is going to be successful, then plant siting is the order of the day,” said Friedmann. He noted that geological sequestration is constrained by the need for “near sources” (power plants, refineries and coal fields) and nearby infrastructure like pipelines that are close to the reservoirs where carbon storage will be implemented. In addition, the geological sequestration must be verifiable, avoiding populated areas and involve prevention of release of CO₂ during the transportation and storage process. “You need to be able to put the CO₂ away in the same place you generate it,” Friedmann noted.

One logical place for geological sequestration to be pursued is in the U.S. Ohio River Valley because of its quantity of coal reserves and power plants. Refineries, IGCC plants and gas processing facilities are likely to offer the least expensive options for CO₂ capture for geological sequestration. “You need a lot of gasified coal plants to do this; the good news is that gasification is growing and will continue to grow,” Friedmann commented. And, what is also critical to carrying out geological sequestration is that a high purity CO₂ stream exists.

Several possible storage options in this mode are for enhanced oil recovery (EOR) and in saline reservoirs and coal beds. However, in the EOR process, some of the carbon used is re-released to the atmosphere. The coal bed option is attractive because CO₂ adheres to mineral surfaces, sticking to nanopores, and in the case of coal, frees up a small amount of methane. In this advanced coal bed methane recovery, for every two CO₂ particles injected, one methane particle comes out. Friedmann pointed to a large active project being conducted in northern New Mexico in the Alison Field, whereby CO₂ and N₂ are being injected for coal bed methane recovery.

Two “dark horse” options, he said, are oil shales (total organic carbon mudstones) and plateau basalts. Although low- or moderate-grade organic-rich mudstones have some petrologic similarities to coal such as gas adsorption, there is little known about these rocks as potential reservoirs. Plateau basalts may react with carbon-rich fluids to form iron and magnesium carbonates, but slow reaction rates and uncertain hydrology make these targets problematic.

The most popular geological reservoir platform is EOR, which Friedmann noted is a well-demonstrated technology. By injecting CO₂ into the subsurface, the volume of oil in the subsurface is expanded while the *in situ* viscosity is decreased, improving recovery of oil in place. However, some CO₂ is co-produced in this process. At an initial phase injection, most CO₂ remains in subsurface oil while some is co-produced. The latter volume can be re-requested and re-injected with less leakage, but EOR does not currently provide a fully closed loop system.

In order to tackle the problem with carbon sequestration, large scale-results are necessary, Friedmann stressed to conference attendees. He also pointed out that the cost of carbon/hydrogen capture must be dramatically reduced from the current \$35-\$80 a ton to about \$20 a ton. Although Friedmann suggested that this was a steep task, it was also doable, by employing amine scrubbing, ceramic membranes and oxygenated scrubbing. “Significant reductions of cost or even comparative costs will enable rapid deployment of carbon storage,” he said.

Friedmann also discussed advanced storage concepts that have the goal of producing solid-state disposition of carbon as new materials, including genetic engineering of carbonate-forming materials, distributed capture devices (such as venetian blind technology) and pulverized serpentine wind tunnels. In spite of the fact these approaches rely on untested technology with large costs or uncertainties Friedmann, believes they should be a critical component of a research portfolio.

Asked a question about the problem of storage leak rates, Friedmann admitted that the estimates are grim, but that he saw nanotechnology applications as perhaps resolving the problem. He suggested a concept of clogging nanopores for potential leak sites, noting that leak points are usually on the scale of nanometers and a big permeable conduit is the equivalent of just a few microns across.

Earth Solar and Other Renewables

With an ever increasing need to cope with global warming and other environmental problems caused by current energy resources, there is growing interest in the adoption of renewables (solar, hydroelectric, wind and biomass) as a source of energy. Use of renewable energy is an extremely promising option for reducing greenhouse gas emissions by replacing carbon emitting fuels with these cleaner energy alternatives. However, according to Dr. Nathan Lewis, the George L. Argyros Chair and professor of chemistry at the California Institute of Technology, “as long as we have an abundant, relatively inexpensive global energy resource of fossil fuel, renewables are not going to play a significant role in today’s energy market.”

Based on a study of global energy consumption in 1998, Lewis pointed out that, of the 12.8 TW energy consumed during that year, 10.2 TW were supplied by oil, gas, and coal, while only 0.286 TW were supplied by renewables. Among the renewables used, he cited biomass supplying 0.1 TW, hydroelectricity supplying 0.3 TW, and solar (thermal and photovoltaic) supplying only 0.00015 TW. In fact, with a production cost of around 20 to 30 cents per KWh for solar energy, solar energy is not yet positioned to be a major competitor to fossil fuels whose electricity generation costs are as low as 2 to 3 cents per KWh. However, distributed customer sited PV, where transmission and most distribution costs are avoided, is currently competitive as a peaking technology with small subsidies in areas with high levels of solar radiation. In dense urban areas with constrained underground transmission and distribution networks, such as San Diego, CA, PV can be competitive if the retail pricing fairly reflects the full value of generation at peak.

Renewable Resource	Approximate Price per Kilowatt hour (1980)	Approximate Price per kilowatt hour (2003)	R &D Goal Approximate PriceTarget
Wind	\$0.80	\$0.05	\$0.03 (2012)
Solar (PV)	\$2.00	\$0.20 -\$0.30	\$0.06 (2020)
Biomass	\$0.20	\$0.10	\$0.06 (2020)
Geothermal	\$0.15	\$0.05 -0.08	\$0.04 (2010)

Source: U.S. Department of Energy

Lewis believes that renewables will not play a large role in primary power generation until tremendous technological and cost breakthroughs are achieved or unless unpriced externalities are introduced. Environmentally-driven carbon taxes that favored renewable energy might be one policy route that would propel its use. But so far, many countries have favored direct subsidies to investors in renewable energy and imposition of renewable energy target standards. China, with the highest energy use growth rate in the world, has set a target of 10% renewable energy by 2010. The EU directive on Renewable Energy sources sets a target of 12% of energy and 22% of electricity from renewable sources by 2010. (The EU Directive includes hydro.)

In the U.S., Renewable Portfolio Standard laws are being implemented at the state, not federal, level. Eighteen states have now passed Renewable Portfolio Standards while 14 states have set up Renewable Energy Funds to subsidize or promote development of new renewable technologies such as solar and wind power. Clean Edge, a research firm in Oakland, California, predicts that spending in renewable energy will jump to \$89 billion by 2012, from \$10 billion today.

Seventeen U.S. states have established renewable energy funds that are propelling exciting entrepreneurial energy companies such as solar energy firms, including Arizona (\$25 million a year), Massachusetts (\$20 million a year); and California (\$135 million through 2012).

U.S. States with Renewable Portfolio Standards

States with RPS	Percentage	Effective Date
California	20%	2017
Nevada	15%	2013
Arizona	1.1%, 60% solar	2007-2012
New Mexico	10%	2011
Texas	2880 MW, 880 MW can be from existing generation	2009
Minnesota	10% (non-mandated) Xcel- 425 MW wind and 125 MW biomass must add 400 MW wind	2015 2006
Iowa	105 MW to investor-owned utilities	
Wisconsin	2.2%	2011
Illinois	15%	2020
New York	25%	End of 2013
Maine	30% of retail sales	
Massachusetts	4% and 1% increase per year then after	By 2009
Rhode Island	3% 16%	2007 max: 2019
Connecticut	Class I: 7% Class II: 3%	2010 2004
Pennsylvania	PECO- 0.5% annually others vary	
New Jersey	Total of 6.5%	2008
Maryland	Class I: 7.5% Class II: 2.5%	2019 2018
Hawaii	20%	2020

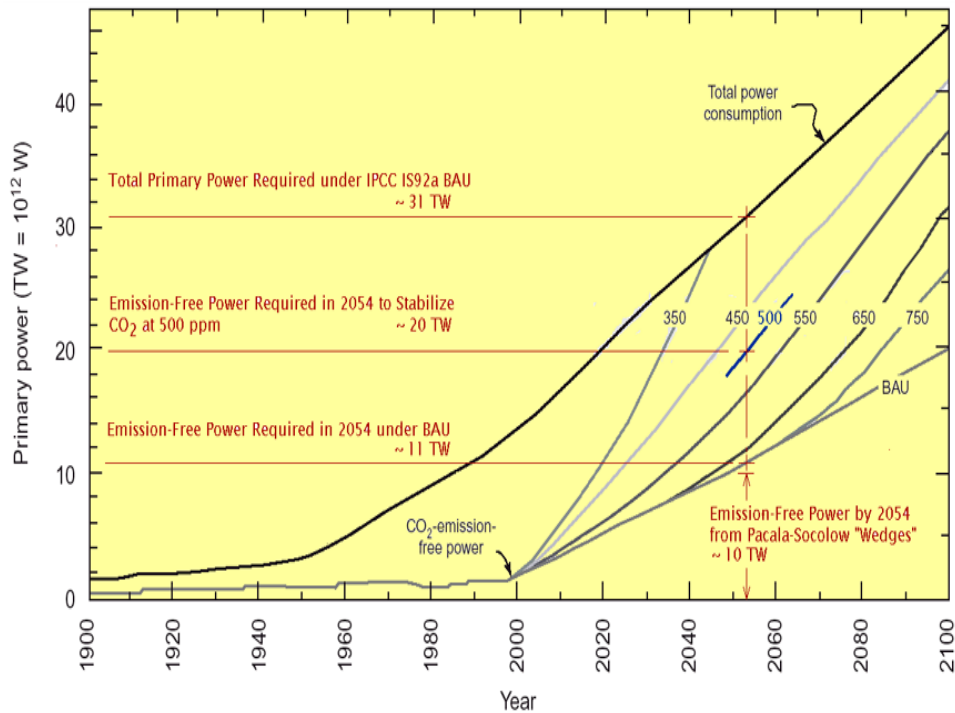
Source: EPRI

U.S. States with Renewable Energy Funds

States/Renewable Energy Funds	Dollars
Arizona	\$25 million/year
California	\$135 million/year through 2012
Oregon	\$10 million/year Energy Trust
Montana	\$14.9 million/year total \$1.8 million/year for renewable
Minnesota	\$16 million/year
Wisconsin	\$3 million/year
Illinois	\$5 million/year and \$250 million Clean Energy Community Trust
Ohio	\$15 million/year 2001-2011
Pennsylvania	\$12.1 million through 2004 GPU \$20.5 million through 2004 PPL \$11.4 million through 2005 West Pennsylvania
Maine	\$70000
Massachusetts	\$20 million/year
New York	\$14 million/year 1998-2006 Energy Smart Program
Connecticut	\$23.6 million/year average
Rhode Island	\$2.5 million/year
New Jersey	\$76 million in 2004
Delaware	\$1.5 million/year
Washington D.C.	\$2.1 million/year

Source: EPRI

With population growing to 10–11 billion people expected by 2050 and a primary power consumption increase to 28 TW, 10–30 TW of carbon free power is going to be needed if the world wants to stabilize increasing CO₂ concentrations. The main question remains: how will experts manage the risk of having adequate technology that will enable them to deploy renewables on such a large scale by 2050 if the current market is not allowing any renewables' development?



Source: Hoffert, Martin. “A Renewable Energy Rationale.” Presentation available at: http://cohesion.rice.edu/centersandinst/cnst/conference_energy.cfm?doc_id=5168

“Without policy incentives to overcome socioeconomic inertia, development of needed technologies will likely not occur soon enough to allow capitalization on a 10–30 TW scale by 2050,” Lewis noted. “Researching, developing, and commercializing carbon-free primary power technologies capable of 10–30 TW by the mid-21st century could require efforts, perhaps international, pursued with the urgency of the Manhattan Project or the Apollo Space Program.” With current pricing not being the driver for year 2050 primary energy supply, Lewis stressed that experts will need to examine the energy potentials, technologies, and costs of the various renewables and attempt to determine their impact on secondary power infrastructure and energy utilization.

U.S. federal spending on renewable energy research and development is small in comparison to spending on nuclear energy and hydrogen despite the important role that renewable energy could play in providing an alternative energy future. Annual spending on solar energy, for example,

averages just above \$80 million as compared with \$375 million for nuclear energy, science and technology programs.

Renewable Resource	Annual Spending on R,D&D (FY 2004 Appropriated Levels)
Wind	\$ 41,310,000
Solar	83,393,000
Biomass	93,977,000
Geothermal	25,508,000

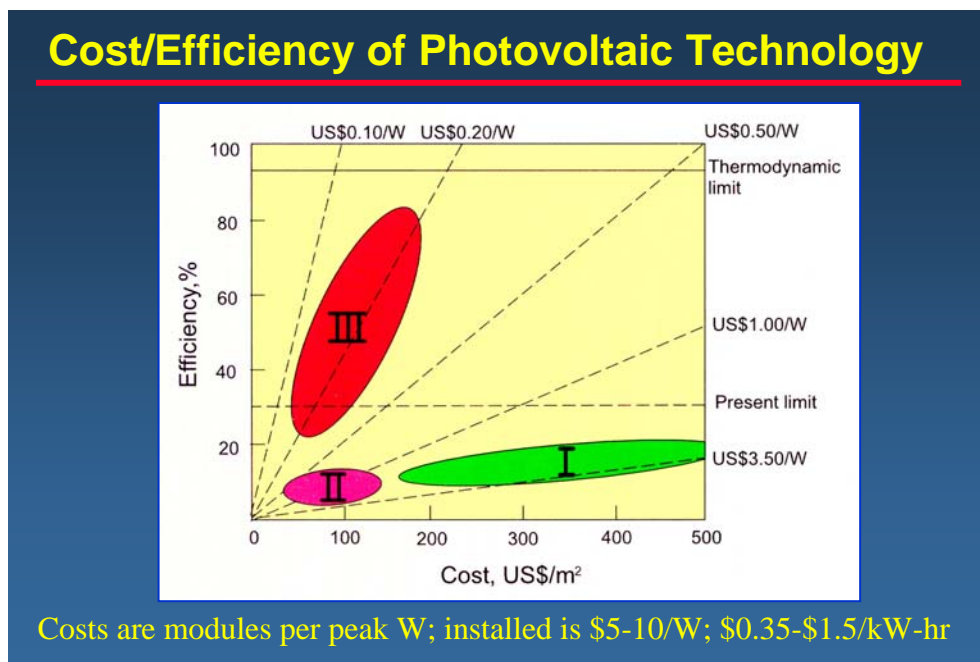
Source: U.S. Department of Energy

“At present,” Lewis explained, “experts are currently considering three potential ways to meet the 2050 carbon-free energy needs: wide-scale carbon sequestration, the wider use of nuclear power, or the deployment of renewables.” However, one half to two thirds of the fossil fuel energy produced will need to be sequestered if the carbon sequestration option is adopted or 10,000 nuclear power plants will have to be built in order to meet those needs. Therefore, Lewis concludes that renewables could be the preferable solution. The key issue remains to determine which of the renewables can provide a source able to furnish the largest amount of terawatts of energy by 2050.

Among the various renewables, hydroelectricity is currently the cheapest renewable resource available and the most environmentally benign. However, due to its low cost, hydroelectric power has already been implemented in many areas where its use has proved to be economically-viable. With 0.3 TW currently being produced from hydro power, Lewis stressed that there is not a lot of room left for hydro to supply more energy. Wind, on the other hand, if deployed in all areas where wind is class 3 or above (that is the areas where the wind has a wind power density range between at least 150 W/m² and 200 W/m²) with 4% utilization, can provide a source of 2–3 TW. However, to achieve this amount of energy, offshore turbines will need to be deployed and new techniques need to be created in order to pipe the energy produced offshore to land for distribution. “While wind should be definitely a player in the renewables’ energy portfolio, it is evident that it is not a resource that can provide the 10 TW needed by 2050,” he asserted.

According to Lewis, it is evident that the only resource capable of satisfying the carbon-free energy gap of 2050 is solar-derived energy. With a potential power of 120,000 TW and a practical harvestable output of 600 TW, solar energy could be a favorable renewable solution with less downside. While there is no doubt that the implementation of solar power as a primary source of energy is going to be a massive project, the main challenge remains to design low-cost means for converting solar energy to fuel and electricity.

In order to achieve this low cost conversion, three energy conversion strategies are being pursued nationwide: the use of plants (which have a very low efficiency of about 0.01%), the use of photovoltaic semiconductor/liquid junctions (which are extremely efficient, but relatively expensive and not scalable), and the use of catalysis (in which water is split using sunlight and produces relatively cheap hydrogen to produce electricity). According to Lewis, the second strategy is currently considered to be the most economically viable and technically practical solution.



Source: Lewis, Nathan. “Global Energy Perspective.” Presentation available at: http://cohesion.rice.edu/centersandinst/cnst/conference_energy.cfm?doc_id=5168.

Consequently, five approaches are currently being pursued to further develop photovoltaics. Researchers are testing the implementation of crystalline Silicon (Si), amorphous Si, nano TiO₂, CIS/CIGS (a semiconductor that acts like an electrical insulator until it is induced by various means to conduct electricity like a metal), and CdTe in the production of photovoltaic cells, with only crystalline Si displaying 25% efficiency so far. However, all five strategies impose the same installation cost of \$5 to \$10 per watt and a cost of \$0.35 to \$1.5 per kilowatt-hour. This is still extremely expensive compared to the \$0.05/KWh for electricity produced by fossil fuel.

According to Lewis, one set of approaches to reduce the cost of solar power resides in improving the efficiency of photovoltaic cells. At present, PV cells are able to absorb light only when they are designed to have a particular thickness. They absorb light either through large grain single crystals or small grain polycrystalline solids implanted in the material. As the grain size is being reduced, the efficiency of the PV cell decreases. Similarly, using a different fundamental base for the organic material, Lewis explained that the use of ordered crystalline solids can yield high efficiency with a higher cost while the use of disordered organic films results in a lower cost but lower efficiency.

With the average installed system cost of photovoltaic cells being \$200/m² and current technologies not allowing the implementation of solar energy on a large scale, there is no doubt that major technological breakthroughs are needed. Lewis offered that chemists should attempt to develop disruptive solar technology consisting of a solar paint in which they can achieve grain boundary passivation that will allow them to fool the particles on the surface into being a part of a crystalline structure. “Using solar power should be made as easy as spraying paint on your house,” he asserted. Furthermore, chemists should also attempt to develop the proposed solar paint which consists of designing interpenetrating networks while minimizing recombination losses. This will lead to a relaxation of the constraints that carriers were limited in, allowing them to reduce the perturbation they cause in the material before they are separated. According to Lewis, this can significantly enhance the performance of sheet materials.

While many technological advances are needed, Lewis stressed that trying to improve the current techniques for solar energy harvesting is not practical. He believes that new catalysts and new integrated systems need to be developed to help convert intermittent power into base-load power. At present, new materials are being designed to convert sunlight to hydrogen and oxygen. However, since these devices are only capable of operating on the moon under ultraviolet (UV) radiation, Lewis stressed that researchers need to develop an analogous system that can achieve the same effects on the earth at a great reduction in cost.

It is undeniable that having the ability to convert sunlight to hydrogen and oxygen is going to constitute a major pathway toward a hydrogen-based economy. Since H_2 is an inferior transportation fuel relative to liquid hydrocarbons, Lewis believes that there is no compelling need for hydrogen in the present and that hybrid gasoline and electric transportation should be used to satisfy the world's transportation needs until new technologies for producing hydrogen emerge. Lewis noted that a majority of the benefits derived from the improved air quality of H_2 use can be obtained from clean diesel without a gross change in distribution and end-use infrastructure.

Numerous challenges must be overcome to propel renewable energy to replace fossil fuels. Particularly, researchers will need to be able to offer disruptive solar technology with inexpensive conversion systems and effective storage systems. According to Lewis, "They should provide the new chemistry to support an evolving mix in fuels for primary and secondary energy, and this can only be achieved through improvements in multi-electron transfer reactions such as methane-to-methanol, direct methanol fuel cells and improved O_2 fuel cell cathodes."

Lower costs for solar power can be achieved from thermal solar energy. However, thermal solar energy harvesting is only effective in relatively small areas on earth and in very small scales and consequently will not be economically-viable or effective to produce large scale TW energy solutions, according to Lewis.

Space Solar: A Promise for a Bright Future

For decades, scientists have been attempting to demonstrate the feasibility of long-distance wireless power transmission from space. Some of the earliest attempts in this field were credited to Nikola Tesla who, in 1881, wrote: "Throughout space there is energy. If static, then our hopes are in vain; if kinetic—and this we know it is for certain—then it is a mere question of time when men will succeed in attaching their machinery to the very wheel work of nature." Although Tesla's thoughts seemed revolutionary at that time, it wasn't until the late 1970s that the idea of beaming energy from space was given scientific consideration.

According to Dr. John Mankins, the chief technologist at the Human Exploration & Development of Space program at NASA, "the notion of energy from space, in its current incarnation, was first introduced in 1968 by Dr. Peter Glaser, a technologist at Arthur D. Little in Cambridge, Massachusetts." First studies, conducted by private American industries, revealed the existence of numerous challenges. However, in the late 1970s, the Department of Energy (DOE) and NASA embarked on a federal study, investing 55 million dollars over four years. Using the technologies of the time and the system concepts that emerged from those studies, researchers were able to design a structure that promised the realization of the space energy dream.

The proposed model consisted of two massive aluminum or carbon-composite stick-built structures (with dimensions in the order of 5x15 km), holding conventional photovoltaic cells in between. These structures would be equipped with a 14 GW power management and distribution system designed to harvest energy from the cells and supply the earth with power in the order of 10 GW, through photon transmission to the earth receivers. However, with these monolithic stick-built components requiring huge space factories and huge space shuttles for manufacturing and launching and with the technological limitations of the time, the project was considered unrealistic and never brought to fruition.

Yet, “the fact that the engineering capabilities of the 1970s didn’t lend themselves to the realization of this project, doesn’t imply that the physics involved was erroneous,” emphasized Mankins. Recent technological advances, especially in materials and computing, opened the door for new opportunities in this field. In the late 1990s, a new strategy was pursued at NASA resulting in the proposition of a revolutionized model for a “power satellite.” The new satellite would be designed to either employ large thin-film structures or mirrors to redirect incoming photons to the PV and transmitting arrays. According to Mankins, this would allow the energy conversion to be done locally within a meter of the transmitting radio frequency (RF) elements, thus eliminating the necessity to transmit many gigawatts of power over kilometers of distance. In addition, the tremendous advancements that are currently being achieved in the robotics field are promising major improvements to the proposed “power satellite” model. Researchers are considering the possibility of designing Space Solar Power (SSP) systems equipped with self-assembly capabilities. By the end of the first round of development, “the SSP systems should be able to assemble themselves with the help of a robotics mechanism or through the implementation of a biomimetic approach where the system can autonomously assemble its individual components the same way living systems do,” he explained.

The new strategy, significantly enabled by numerous advances in materials and by Moore’s law (an empirical observation made by Gordon Moore, stating that at our rate of technological development and advances in the semiconductor industry, the complexity of integrated circuits doubles every 18 months), is projected to eliminate the requirement for large earth-to-orbit transportation systems. Without the need for infrastructure and large manufacturing facilities, the costs are thought to be extremely reduced and the task of generating space-based power increasingly facilitated. According to Mankins, this new approach is promising tremendous benefits. “If researchers can employ new technologies to reduce the mass and cost of the system, there is no doubt that it is becoming possible to contemplate a stepwise progression toward a time where the implementation of these devices might be tangible,” he explained.

However, reaching that stage will require the resolution of many complex problems. With the existence of numerous parameters that need be satisfied—from the point of generating electricity to the point of satisfying the market demands—the process is not expected to be facile. At present, researchers are looking at steadily increasing trend lines for space applications of power. The most potent application currently under consideration is the deployment of huge space-based radars to satisfy national security and air traffic control needs.

With the variety of other potential applications that are also requiring tremendous amounts of space power, new innovations are needed to respond to the world's exploration and commercial development needs. According to Mankins, developing commercial systems can only be achieved through future advancements in wireless power transmission, space platforms, space transportation, instruments, labs, and automation. Such advancements could lead to tremendous benefits, among which Mankins cited the example of designing highly-efficient solar powered propulsion vehicles for transportation within the earth neighborhood and also for implementation in interplanetary transportation within the solar system. SSP techniques, currently in application in the international space station with a power capacity of 100 KW, could also be significantly expanded by implementing higher capacity systems.

It is undeniable that wide areas of similarities exist between designing an SSP system for terrestrial markets, and other power space applications. According to Mankins, this is increasingly leading to the belief that a roadmap might be framed to allow for a steady progress in many of the systems and component technology areas for space purposes, while collecting information on which the decision of using SSP for terrestrial markets would be based. A series of roadmaps were recently proposed, and researchers are considering increasing the space power generation steadily by one order of magnitude every five years.

To evaluate the effectiveness of these roadmaps, the Aeronautics and Space Engineering Board (ASEB) of the National Research Council (NRC) assessed the technology investment strategy of

the SSP program to determine its technical soundness. Their review contributed to the roadmap by providing many recommendations, including the following which Mankins cited:

- Critiquing the overall technology investment strategy in terms of the plan's likely effectiveness in meeting the program's technical and economic objectives
- Identifying areas of the highest technology investment necessary to create a competitive space-based electric power system
- Identifying opportunities for increased synergy with other research and technology efforts
- Providing an independent assessment of the adequacy of available resources for achieving the plan's technology milestones
- Recommending changes in the technology investment strategy

According to Mankins, "The Space Electric Rocket Test (SERT) program has provided a credible plan for making progress toward the goal of providing space solar power for commercially competitive terrestrial electric power despite rather large technical and economic challenges." But, the ultimate success of the terrestrial power application is thought to critically depend on dramatic reductions in the cost of transportation from Earth to GEO (Geostationary Earth Orbit, on which Geosynchronous satellites have a period of rotation that is equal to the Earth's period of rotation). Still, demonstration is likely to be an extremely slow process, with many challenges still ahead.

Significant advancements in solar power generation, wireless power transmission, space power management and distribution, assembly, maintenance, and in-space transportation would be needed to enable SSP to attain a reasonable competitive market price. According to Mankins, the current goal is to drive the research and technology capabilities to furnish a cost of five cents per kilowatt-hour (kWh) for power generated by SSP. However, at this point, the program is still significantly distant from reaching realistic economic viability.

At present, SSP systems are being designed to receive the photons coming from the sun and then transmit them to earth via laser or microwave beams. Once the energy reaches the earth's receiving stations, the energy will be converted to electricity and transmitted to power grids for use in terrestrial markets. According to Mankins, the main economic obstacle facing the commercialization of these products resides in the tremendous costs associated with beaming the energy from the SSP systems to earth.

In the case of radio frequency transmission—the most practical and economic transmission technique currently available—many improvements are still needed. Particularly, phased arrays need to be redesigned to have very low mass per square meter. Converters should not be installed and all thermal and Power Management and Distribution (PMAD) components should be local to prevent the need for transmitting many gigawatts over long distances. Furthermore, the transmitter's diameter will need to be designed to be extremely large (in the order of one to several kilometers) to reduce the spot size on the ground. In addition, sub-arrays should be manufactured to be less than one wavelength in size and able to provide adequate electronic beaming to supply multiple relatively-small ground sites.

Mankins also emphasized that advancement in mechanical engineering, materials science, and nanotechnology are expected to play a pivotal role in the development of such systems. “As systems become modular, more interconnections are needed for their self-assembly. The system becomes massive and a new challenge of reducing its mass arises,” he explained. To reduce the system's mass, a wide variety of advances in devices are needed. Experts need to attempt to design systems able to self-assemble with a relatively low number of interconnections, while still able to handle high temperature and maintain good efficiency.

Scientists will need to continue their efforts designing higher strength-to-weight materials and higher temperature solid state devices applicable in the space environment. According to Mankins, the need for such devices is paramount to improve the structures of deployable and rigid-structure self-assembled thin films as well as enhance the performance of PV cells, FET

amplifiers, and phase shifters. In addition, advancements in laser wireless electric and solar-pumped power transmission, high-voltage and/or HTc (High Critical Temperature Superconductor) PMAD, and achieving very low costs for space transportation are still highly needed to make SSP more commercially viable.

Mankins also emphasized that the realization of this target is associated with a wide variety of ambitious goals that must be achieved. Particularly, to reach the goal of two to five dollars per installed watt and a 500 W/m^2 of RF output, experts will need to achieve a 50% photovoltaic (PV) energy conversion efficiency. In addition, RF transmitters with 500 W/m^2 of output should be designed to be five kilometers in diameter and able to furnish a total power output of 10 GW, while ground rectennas with less than 2 km of diameter each should be able to receive the energy and distribute it at a cost of less than two dollars per watt.

Two major challenges face an SSP energy system. To begin, the cost of space transportation is a major barrier as is its lack of tested technical reliability. Mankins also admitted that ensuring the safety of power beaming is another major obstacle facing the adoption of an SSP system. According to Mankins, “there is a continuing concern regarding the health and safety issues associated with electromagnetic radiation.” With the power densities varying greatly across an incoming beam, this subject must undergo extensive safety testing. For instance, a 2.45 GHz, 5 GW incoming beam would have densities of 230 W/m^2 at the beam center, 10 W/m^2 at the rectenna edge and 1 W/m^2 at the fence edge. With the US standard limit for microwave exposure being less than 100 W/m^2 over six minutes, recent studies showed no discernable effect on fauna or flora outside the fence. Mankins emphasized that further research is still required to ensure that any possible health factors associated with SSP/WPT (Space Solar Power/Wireless Power Transmission) (people and animals) are within acceptable limits.

With the tremendous technological challenges facing the implementation of SSP and especially its long development timetable that is expected to last for decades, it is undeniable that another revolutionary alternative is still needed to overcome the clear limits of the conventional options.

According to Dr. David Criswell, director of the Institute for Space Systems Operations at the University of Houston, the solution resides in the implementation of a Lunar Solar Power (LSP) system.

With the sun sending 13,000 TW of reliable solar power to lunar surfaces, Criswell pointed out that a clear benefit could be derived if part of this energy could be beamed to the earth. One plan proposes that microwave beams with an intensity equivalent to 20% that of sunlight would either deliver power to rectennas on earth (when the Moon is 33 degrees above the horizon) or to satellites orbiting around the earth before being redirected to the rectennas. Rectennas would then convert the beams to electricity with 85% efficiency (according to a study conducted in the 1970s by NASA) and deliver the electricity to the power grid locally and regionally. According to a rectenna's demonstration in the 1970s, Criswell emphasized that this technique has proved to be extremely reliable through all weather condition and its output is not expected to fluctuate with clouds, rain, or smoke.

According to Criswell, the cost of implementing a lunar system is projected to be equivalent to 1.6 trillion dollars: 8 billion dollars for building 100,000 Km² of reflective rectennas on earth and 0.8 trillion dollars for the lunar and space cost. The latter covers transporting 62,915 tons of construction materials to the Moon as well as the cost required for performing human maintenance on the Moon, the lunar orbit and the Earth orbit.

Fission

Although the growth trajectory for nuclear fission is not necessarily dependent upon major technology breakthroughs, improvements in political acceptance and waste removal will be important if nuclear power is to make headway in the coming years. Nanotechnology applications may well solve some of the existing concerns involving nuclear fission and transform the industry, MIT Professor of Physics Ernest Moniz told Energy and Nanotechnology Conference participants.

“The issue of materials is, of course, ubiquitous when we talk about nanotechnology—high temperature materials, for example, gas reactors, particularly materials that are radiation resistant,” Moniz explained. In terms of developing advanced reactors, a nanostructured fuel for gas reactors could be a very important development. “If you could have the fuel have a temperature resistance even greater than what is currently talked about, you could imagine moving towards a lack of containment requirement—which would have a big economic impact—if the fuel itself were really assured of maintaining efficient products under any conditions in effect,” he added.

Nanoscale modeling of materials could be equally important, such as understanding cracking by linking nano to macro scales. And, Moniz pointed out that the most interesting as far as the near term impact is the potential for nano-engineered barriers for a waste repository, perhaps with nanoparticles in clay, producing a barrier that would be extremely effective in holding up the migration of any nuclides of concern.

But, he stressed as the bottom line, “It’s all about economics at the moment and then about handling the waste.” Moniz dismissed the argument by many in the nuclear industry that there will be a major global expansion of nuclear power in the coming decades. “The fact is, when you look at it, that is not a credible scenario ... This is one scenario for terawatt of electricity, and what you see is frankly, there is no way the world is going to reach those terawatts if the U.S. isn’t going to be driving the train,” he said.

One of the key issues in the development of nuclear power is the economics. According to Moniz, the cost of running a nuclear plant is about 7 cents a kilowatt hour, compared with pulverized coal at 4.2 cents a kilowatt hour and gas at 3.8 cents a kilowatt hour over the lifetime of the plant. Gas, as opposed to nuclear, is driven by the fuel cost and that may not be something one wants to count on for a 40-year investment in the plant, he noted.

For nuclear expansion to meet the terawatt challenge, “you’ve got to get the 7 cent cost down,” Moniz advised, suggesting that the most effective means to do so is in operations and maintenance reduction. If the cost of capital for nuclear power were the same as for coal or gas, the operational costs for nuclear could be reduced to around 4.4 cents a kilowatt-hour, he said.

As for technological improvements, he explained that there is much discussion among nuclear professionals regarding advanced fuel cycles, but he pointed to economics again as being a spoiler for this factor to be part of a nuclear growth scenario. For one, “advanced fuel cycles cost a lot of money,” Moniz warned. One application that does look promising, however, is the development of evolutionary thermoreactors, specifically the gas reactor.

The gas reactor may well be the best waste minimizing option because it is much more efficient in thermoconversion. In addition to passively safe features, it has some fuel form advantages that are attractive for safety and non-proliferation concerns, including small micropellets with a carbon composite coating. The gas reactor would appear to be economically beneficial because the production favors modular formats at reasonable costs.

But, Moniz also cautioned that proponents of advanced fuel cycles are overestimating the advantages they see in waste management. “Waste is a huge issue, obviously ... another possible showstopper,” he said. The waste volume reduction benefit is questionable, he suggested, because other than the uranium that you have taken out of the equation—which was not a problem—“you have all of the fission products per kilowatt hour you had before.”

And, while advanced fuel cycles can theoretically remove the actinide load and possibly resolve the long-term waste storage problem, Moniz questioned whether “geological isolation” properly executed might not already be an adequate solution. He contended that other geological solutions, such as deep bore holes in appropriate locations, may offer a far greater advance in waste isolation than other approaches do and provide greater confidence in waste handling.

There are currently 447 nuclear reactors producing electricity in 31 countries across the globe. Another 37 reactors are under construction in 12 countries, including South Korea, China and India. But, some nations, like Germany—concerned about safety and environmental issues—are moving to dismantle their nuclear power industries and phase in other energy supply alternatives. In the U.S., nuclear power already contributes about 20% of the nation’s electricity needs through 103 reactors. The American nuclear industry has come under greater scrutiny in the past two years as reactors continue to be a perceived potential target of terrorism. In May of 2003, the FBI warned operators of U.S. nuclear power plants to remain vigilant about suspicious activity that could signal a possible terrorist attack.

Ongoing concerns about nuclear plant safety were heightened by reports of the operational failures of FirstEnergy Corp., the nation’s fourth-largest investor-owned utility, which may well have contributed to the August 14th blackout that affected some 50 million people from Detroit to New York in 2003. A top investigator had said the failure of three transmission lines in northern Ohio likely started the blackout that swept into eight U.S. states and Ontario. FirstEnergy, which reportedly owns four of the first five lines that failed, said a system that is supposed to flash a red warning on computer monitors at the company's control center was not operational when the lines began failing on the afternoon of August 14th.

The Akron-based utility, which has 16 power plants with a service area stretching from Ohio to New Jersey, has been under investigation since early 2002, after it closed its Davis-Besse nuclear point near Toledo for maintenance and it was discovered that a leak had allowed boric acid to eat nearly all of the way through the steel cap on the plant’s reactor vessel. In addition, reports that a cyber worm disabled a safety monitoring network at the Davis-Besse plant in January of this year not only adds to FirstEnergy’s public relations dilemma but also raises the real fear of the nation’s nuclear plants becoming targets of cyber-terrorists.

After encouraging signals from the Bush Administration and Congress as well as news that three utilities would begin seeking licenses to build new nuclear plants, the U.S. nuclear industry was

dealt a serious blow by Congress in August of 2003, when the Senate dropped a Republican energy bill with \$10 billion in loan guarantees to encourage new plant construction for the next generation of nuclear facilities. No nuclear power plants have been built in the United States since the partial meltdown of the reactor core of the Three Mile Island plant in Pennsylvania in 1979.

The U.S. Energy Information Administration has projected that even if the next generation nuclear plants can be built more cheaply, their construction costs will still likely be two to four times higher than natural gas, coal or wind plants. Both the Congressional Budget Office and investment rating firm Standard and Poor's stated in early 2003 that investing in loans to build large nuclear power plants in the U.S. is high risk.

Fusion

Despite the hurdles involved and the basic risks associated with the adoption of nuclear fusion as a primary source of energy, the United States is renewing its commitment to develop fusion as a possible resource of power generation. "With President Bush requesting that we join the International Thermonuclear Experimental Reactor (ITER) project, it seems that the US is starting to retake great interest in this field," according to Dr. Robert Goldston, director of the Princeton Plasma Physics Laboratory.

If developed, fusion can provide a potential energy multiplication of 450:1 and thus has the ability to potentially produce electricity and hydrogen for the long-term through deuterium-lithium fusion reactions. The process of these reactions consist of fusing tritium and deuterium atoms, resulting in the production of an alpha particle and a neutron. The alpha particle is then placed in a plasma self-heating cycle while the neutron is used in tritium replenishment to further support the fusion process.

Although not practical at this time due to the lack of technical resources able to adequately initiate and control large fusion reactions, fusion could possibly hold the key for an extremely

attractive domestic energy source. Goldston noted that future advancements in this field would mean an extremely abundant fuel source available to all nations. With deuterium and lithium being easily extractable from seawater, fusion's fuel supply is sufficient in quantity for thousands, if not millions, of years.

In addition to its fuel's abundance, fusion can also offer tremendous environmental and security-related benefits. Fusion-based energy generation usually results in products with zero carbon emission and limited waste material after heat. According to Goldston, its mechanism is fully resistant to terrorist attacks since only five minutes of fuel are available in the chamber at any given time. Fusion also displays a very low risk of nuclear material proliferation (with no fissile or fertile material required) and offers the benefits of modest land use compared to solar, wind, and biomass power generation.

If fusion systems could be developed, they might provide off-peak operation with very low marginal cost, resulting from the fuel cost of deuterium and tritium. In addition, off-peak H₂ production from fusion could be implemented, providing tremendous profits if H₂ was produced locally at power plants and then piped to refueling stations.

Furthermore, if developed, fusion could help reduce the CO₂ emission rates over the next 100 to 200 years. According to Lawrence Lindsey, assistant to the president for economic policy, "When confronting long-run challenges—and the environment is certainly one of these—investments in the research and development of new technologies, with actual applications decades in the future, are far more cost-effective than trying to act with existing technologies." "This is one of the reasons why the US is currently regaining great interest in developing fusion," Goldston told conference participants.

Goldstone stressed that increased efforts in nanotechnology might allow scientists to reach the 2050 goals of producing about 16 TW from fusion. At present, finding means for providing concentrated power generation is the main area of concern. According to Goldston, the main technique to achieve this goal is through advancements in plasma confinement, a highly-efficient way for concentrated power generation. Elaborating on the subject, he explained that there are

three major techniques to achieve plasma confinement: first, gravitational confinement, the process by which gravity holds hot gases together (for example, the sun, which is the biggest fusion power plant available); second, inertial confinement by which intense energy beams are used to compress and heat fuel pellets to make them to fuse before they can expand; and finally, magnetic confinement where magnetic fields are used to cause hot gas plasmas that were ionized to spiral around the field. According to Goldston, the latter method is considered to be the most effective and practical technique for holding hot gases together. “It is the only method allowing gases to travel for hundreds of kilometers (km) spiraling around the field before they move by one centimeter,” he explained.

While plasma science has impacts far beyond fusion energy (such as in astrophysics, computer chip processing, and space propulsion), the use of plasma in magnetic fusion is thought to have the greatest potential in the energy industry. Innovations in this field are expected to lead to a magnetic fusion power system able to supply a considerable amount of energy. According to Goldston, such a system would use fusion plasma to make neutrons which are absorbed in lithium to produce tritium. With the magnetic field and the high temperatures available, the addition of deuterium to the system would lead to its fusion with the produced tritium resulting in the production of energy. This energy can then be forwarded to heat exchangers for use in turbines, generators, or hydrolysis systems for H₂ production.

Although researchers did not reach the stage of producing magnetic fusion power systems, progress in fusion energy has outpaced computer speed. “While fusion energy outputs have increased by twelve orders of magnitude from a few milli joules (mJ) in 1970 to 10 MW in 2000, computer speed only increased by six orders of magnitude,” he explained.

Having for its goal: “to demonstrate the scientific and technological feasibility of fusion energy by producing industrial levels of fusion power,” ITER is providing researchers with an opportunity to recreate the conditions on the sun here on earth. Particularly, ITER could extend fusion science by providing opportunities for building larger burning (self-heated) plasmas where alpha particles from the fusion reaction can hold the plasma at temperature. It is also

opening the door for creating new fusion-relevant technologies (magnets and blankets) as well as operating on high duty factors (ratio of the duration of time when a system is actually operating to the total time for a complete cycle of the system) as high as 95%.

The US has reached a stage where researchers are able to produce 500–700 MW thermal fusion power with a pulse length of 400 seconds at a gain of ten, and a pulse length of an hour at a gain of five. While these results are still not sufficient to produce a fusion power plant, innovations in physics and particularly in the design of superconducting magnets and plasma physics may permit construction of a fully-functional fusion power plant able to supply 16 terawatts of power by 2050.

Negotiations for the location of ITER are continuing. Four possible sites include northern Japan, Spain, France, and Canada (near Toronto). Europe is talking about contributing 53% of the project and Japan 17%. Canada, the US, and South Korea are still working on their bids. However, Goldston stressed that the key issue for resolution resides in determining ITER's potential site, its cost sharing, and its risk allocation as well as defining the management of this major international construction project.

From a technological perspective, Goldston believes that there is a lot of work to be done in parallel to ITER to make fusion practical. With plasma's ability to play a major role in the development of fusion energy, major advancements are needed in plasma configuration. ITER is currently using the advanced Tokamak configuration (a large toroidal to create and maintain the conditions for controlled fusion reactions) to provide active instability control and driven steady-state. However, with this configuration requiring relatively large plasmas to ensure that high energy multiplication can be reached, a range of alternative toroidal magnetic configurations are being pursued worldwide in an attempt to reduce ITER's size. Particularly, two other configurations have been proposed to off-set these problems. The first is a spherical torus with reversed field pinch configuration able to produce high fusion power at a low magnetic field. The second is a compact stellarator configuration able to provide passive stability and steady-state operation.

While the design and implementation of new technologies is thought to be vital, Goldston stressed that only by combining domestic innovation with ITER's science and technology, would the world be able to achieve the goal of producing practical fusion energy. In addition, three areas of technology are thought to be highly-critical for the development of magnetic fusion energy: high-heat flux components, tritium generating blankets, and normal or superconducting magnets. High-heat flux components currently produced with tungsten mesh need to be redesigned with a carbon based material to reduce radioactivity and to be able to handle up to 25 MW/m² of heat flux as well as up to 5 MW per year/m² of neutron flux. Tritium generating blankets need be improved to handle up to 15 MW per year/m², provide about 1000 °C lithium coolant, and offer up to 100% of tritium regeneration. Superconducting magnets also need to be redesigned to provide super strong support structures able to handle high magnetic fields at high current densities of about 1000 amperes(A)/mm² at 20 tesla (T). According to Goldston, magnets need to be enhanced to provide low dissipation and to handle high stress. In addition, improvements in normal magnets are also needed. Particularly, designing magnets having conductivity greater than that of copper, having a low activation, and able to withstand 20 dpa (displacement per atom) caused by fast neutrons, is expected to revolutionize the fusion science.

Recent advancements were made in the field of fusion-developed steels. Goldston explained that researchers in the Fusion Energy Science (FES) were able to produce steels that have superior tensile strength, irradiated fracture toughness, and thermal conductivity, based on low activation variants of ferritic steels that were developed for breeder reactors. The 2003 FES studies have shown that nanocomposite ferritic steels can offer a highly-improved performance compared to other oxide dispersion strengthened (ODS) steels especially at high temperature and under high stresses.

Goldston also compared the products of fusion and fission Generation IV. Generation IV is a project actively developing fourth generation nuclear fission energy systems that offer advantages in the areas of economics, safety and reliability, sustainability, and commercialization (with an expected deployment by 2030). With these advantages, Generation IV reactors will constitute one of the major competitors for fusion-based energy and thus it is

pertinent to compare their outputs. While the maximum dose for core internal structures is about the same for both processes, Goldston pointed out the significant difference between the maximum transmutation of helium. In particular, the maximum transmutation of helium in fusion can reach up to 1500 atomic parts per million (appm) compared to a maximum of 10 appm for fission. In addition, Goldstone pointed out the existence of a common theme for fusion and Generation IV fission, which resides in the need to develop higher temperature materials with adequate radiation resistance.

Presently, a main area of concern is determining the effect of the tremendous amounts of helium being produced during fusion. Most importantly, multi-scale nanoscience simulations of materials for fusion need to be performed. According to Goldston, researchers will need to be able to understand the accurate energetics of point defects and defect clusters, as well as the molecular dynamics of the initial defect distribution and the migration after cascade.

Goldston concluded by stressing that Japan and Europe are currently investing much more in fusion energy than the US and that the US must enhance support to this field. Although developments in fusion have been severely limited by budget constraints over the past decade, “We are on the schedule (of reaching the 2050 goal of producing 16 TW of fusion based energy) versus the dollars,” said Goldston.

However, the main challenge remains to develop new technologies able to sustain the achieved advancements. Particularly, innovations are required to improve the fundamental understanding of the fusion process, to achieve configuration optimizations, and to design burning plasmas as well as new materials. All these innovations, in addition to designing improved materials and improved magnet systems, are thought to be associated with potential advancements in nanotechnology.

Electrical Grids and Efficiency: Creating the Infrastructure for a Digital Society

During the past century, the continuous growth in electrical consumption has been significantly non-linear, primarily due to three major events, according to Dr. Roger Anderson, the Doherty

Senior Scholar at the Lamont-Doherty Earth Observatory at Columbia University Anderson. The introduction of light and motors to the market in 1900, the implementation of air conditioning in 1947, and the widespread use of computers and internet in the 1980s have all resulted in great leaps in electrical consumption.

Global electricity demand has been expanding at a rate of 3.0% per year since 1980, resulting in an overall increase of 88% to 13,934 bKwh (billion Kwh), up from 7,417 bKwh. World electricity demand is expected to double by 2030, growing at an annual rate of about 2.4%, as economic activity is enhanced in developing nations such as China and India. U.S. electricity demand grew from 2,094 bKwh to 3,602 bKwh, or an average annual rate of 2.6%. U.S. electricity demand is projected to increase by 1.9% per annum by 2020.

Still, much of the world's population will remain without modern energy services unless new, aggressive policies and emerging technologies are launched in the coming years. The global electricity sector will require as much as \$10 trillion in new investments over the next three decades, according to the International Energy Agency (IEA). This is close to three times higher in real terms than the investment made in the sector over the past three decades. More than \$5 trillion of investment will go into transmission and distribution networks. In the developing world alone, \$5 trillion in spending in new electricity infrastructure will be needed to meet projected targets for economic growth and social development. Fuel costs will be of the same order of magnitude as investment in infrastructure, increasing the scale of the challenge to be overcome. The IEA projects that if no new dramatic global energy strategies are adopted, about 1.4 billion people will still have no access to electricity in 2030, relatively unchanged from today. It will take revolutionary breakthroughs in energy science and technology to alter this reality.

The advantages of developing a new, improved, and more efficient grid system are tremendous, there are clear technological and political hurdles that must be overcome to achieve this target: new materials and new technical approaches will need to be developed and an elaborate plan must be sculpted to map a smooth transition into an electrically digital society. Nanotechnology

holds great promise for the electricity sector through its ability to enhance the new grid by introducing post-silicon power electronics and complex, iterative, adaptive controls.

Dr. Anderson explained that nanotechnology could be part of the solution to today's electricity problems by enhancing the overall efficiency of the electricity delivery system, according to Anderson. He theorizes that if experts combine Larry Smarr's pyramid of digital convergence (a pyramid created by Smarr, professor of Computer Science and Engineering at UCSD, that denotes the various steps for digitalizing a system) with the characteristics and abilities of the human nervous system, they would be able to reach, electrical "innervation," a key application of nanotechnology to the electrical business. By supplying electrical systems with nano-sensors and nano-sources as well as nano-chips able to apply concepts of distributed business, adaptive learning, simulation, micro-real options, and workflows while performing peer-to-peer assessment, major changes can occur in terms of energy efficiency and energy supply. "In short, we will reach an ultimate scenario where we will be able to sense every aspect of the mechanism no matter how small it is," he explained.

Electrical "innervation" will not only offer greater efficiency but will also allow "placing entire business and engineering disciplines on silicon chips to assist humans on the field," Anderson explained. Nano silicon chips could be used to embed adaptive stochastic control at every enterprise level, Anderson speculated, allowing the automatic and mathematical identification of real options on real things.

At present, innovations on the micro-scale could allow every device to know its real options through embedded micro options. Everything is geo-located and equipped with peer-to-peer wireless to and from each component. For instance, Anderson cited the example of the smart dust concept that was developed by the CIA. This dust, when scattered in a room, would have the ability to identify every footstep and determine those that did not belong to the room at any particular time. Other examples include designing self-healing, aware networks, systems having a dream phase that use simulations to learn how to optimize the system and how to compute micro options, and intelligent devices using genetic algorithms as a discovery mechanism.

According to Anderson, real options can be easily implemented on a nano or micro computer scale. “Nature minimizes action while quantum physics is governed by the Uncertainty Principle that induces an uncertainty manifold for the principle of least action. Mathematically, this manifold can be viewed as the same type of problem as real options,” he explained. Thus, when stochastic adaptive control can use dynamic programming as an optimization method, quantum computers can be considered as a potential tool for real options valuation, according to Anderson.

Although attempts in this field are still at an early stage, Anderson stressed that once experts fully develop nano and micro “innervation,” aligning this “innervation” with overall business improvement is expected to have a pivotal influence on the market. Anderson explained that targeting business capabilities most in need of fixing, estimating the costs, benefits and risks and monitoring business improvements with tracking metrics, might lead to dramatic results. “If we can identify what the real options are, we might be able to accomplish dramatic improvements through direct investment in operational business drivers (technology, processes, and people) and consequently to orders of magnitude increase in electrical efficiency, leading to a partial solution to the many terawatt problem,” he asserted.

One example of an innervation operation is Capital One credit cards. Anderson explained that by adopting a plan of customization for the masses and by using dynamic programming to identify action plans and optimal decision paths, Capital One was able to demonstrate quantitative business improvement over their competitors by reducing payment delinquencies to less than 2%. Although their competitors reacted by asserting that the process is too complicated, too expensive, and that the data available is not good enough, Anderson stressed that Capital One was able to achieve an improved operation by using the intelligence of computer models.

Elaborating on the major benefits of innervating the global grid system, Anderson concluded by stressing the effectiveness of the new grid in resisting terrorism and protecting homeland security. Through a simulation that lasted for ninety seconds (the needed response time in the case of a terrorist attack), Anderson demonstrated how the innervated decision support threat

simulator (DSTS) successfully responds to multiple cascading threats. If the entire grid was innervated, once terrorists strike, DSTS leads to remedial actions using distant early warning (DEW) systems and if the problem spreads to the entire system, DSTS recognizes regional problems and coordinates remediation, leading thus to the full recovery of the grid without any human intervention.

While increasing electrical efficiency and reducing its costs are expected to play a major role in the success and commercialization of new nano-inventions, there are clear technological hurdles that must be overcome to reach that stage, according to Dr. Terry Michalske, director of the Center for Integrated Nanotechnologies at Sandia National Laboratories. “At this point, nanotechnology doesn’t offer any direct solutions to the problem of efficiency and conservation, Michalske cautioned. “Instead, there are tremendous challenges, especially technological ones that are accompanying this pathway.”

Nanotechnology is attracting an increasing number of scientists and engineers from different disciplines. With the new properties and new behavior that emerge on this small scale, nanotechnology is thought to bring new approaches to tackling many of the world’s unsolved problems. For instance, this field offers scientists the capability of transforming silicon (which is not a light emitter at large scales) into extremely efficient light-emitting nanoscale particles. Structuring of gold at the nanometer scale results in material hardness equivalent to the resistance of ceramic coating; and as particles were scaled from fifteen down to two or three nanometers, catalytic activity is increased by three orders of magnitude. It has been argued that these behaviors are a result of the change of the surface-to-volume ratio. Dr. Michalske indicated that plots scaled to surface area confirm these dramatic property changes.

As new behavior emerges on this small scale, the exploration and understanding of the observed properties remain the main area of interest. Indeed, only when scientists achieve that target, will engineers be able to easily overlay nanosciences on technological problems. According to Michalske, “when we reach that stage, integrated nanotechnology is expected to have a great impact on the Department of Energy (DOE) mission including energy, national security, and

environment.” Particularly, innovations in nanotechnology will provide engineers with means to create nano-layered materials capable of increasing the efficiency of light sources, producing nano-structured self-assembly membranes for chemical sensing and detection, and developing catalysts and new chemical routes that are environmentally-friendly.

However, Michalske believes that coupling nanoscale properties with large scale materials (where these properties are important) is the biggest challenge facing the nanoscience community. Scientists have to consider an approach that will allow them to produce nanomaterials in high volume and with high reliability in order to be able to impact real-world problems.

“At this time, experts are able to produce nanomaterials in one dimension, particularly as thin layers resembling pancake stacks of 5 to 10 nm in thickness,” he explained. These strained-layered super-lattice materials are providing researchers with the opportunity of building one-dimensional crystal structures that do not exist in nature in an effort to use their new properties to control the optical and electronic behavior of materials. On the other hand, the production of 3-D nanomaterials such as nanocrystals or self-assembled nano-membranes is at an extremely premature stage. According to Michalske, scientists are still attempting to move from lab-scale experiments to producing devices that are efficient and cost-effective, and this effort is expected to take at least a decade.

Taking the example of Light Emitting Diode’s (LED), Michalske asserted that over the past decade, LEDs have increased in efficiency by a factor of thirty and decreased in cost by a factor of ten. Innovations in the development of LEDs are reaching the stage where they can compete with traditional light sources of incandescent and fluorescent lighting. LEDs are increasingly becoming commercially available, mostly in specialized applications. One application is in stop lights which produce 10 times greater efficiency (than red-filtered incandescent) and a longer lifetime (100,000 hours). This longer life span is extremely useful with the great hurdles associated with changing conventional bulbs.

However, it is important to note that new technological innovations in this field are not going to replace the current devices in use but mainly open new opportunities. “For instance, until we find a new technology that will allow us to mimic the incandescent soft lighting character with more efficient light bulbs, incandescent lighting is still going to be widely in application,” Michalske explained.

In an effort to develop improved and more efficient bulbs, a new national initiative is being pursued to produce solid-state lighting (LEDs and lasers) that promises to be ten times more efficient and two times brighter than incandescent and fluorescent lights respectively. The Solid-State Lighting Initiative (SSLI), currently pursued at Sandia National Lab and Lawrence Berkley National Lab, is promising enormous global energy benefits even if it doesn’t hold terawatt-scale solutions.

General lighting is responsible for 20% of the global energy consumption, and conventional light sources offer very low energy efficiencies of 5% for incandescent and 25% for fluorescent bulbs. DOE road mapping studies predict that by 2025, government investments in nano-layered SSL will result in a 50% decrease in the amount of US electricity used for lighting and a 10% decrease in the total US electricity consumption overall. This will translate into a 17 GW reduction in the US demand for electrical generating capacity and at least 28 Megatons equivalent per year reduction in the US carbon emission. In addition, a seven billion dollars savings in construction costs is projected, according to Michalske.

While nano-layered systems are mainly thought to increase the SSL efficiency, their applications are starting to prove increasingly useful for other kinds of energy savings. For instance, at Argonne National Lab, researchers are currently using nanolayers to build exchange-spring magnets for use in highly-efficient electrical motors. The development of these strong magnets with controllable thickness is significantly improving the performance of motors with tailored magnetic properties. According to Dr. Michalske, “With the performance of the motors being

very sensitive to the thickness of the layers used, great improvements were achieved as the thickness was scaled from 20 to 1.2 nm.”

Improvements were also achieved in increasing the efficiency of the wear-resistance of certain materials. Through the use of nano composite structures, researchers at Sandia National Lab were able to transform aluminum (highly-inefficient wear-resistant material) into a material that has the wear-resistance of a bearing steel. “The nano-tailoring of aluminum through superimposing its hard-thin layers resulted in superior strength, which greatly reduced wear and friction,” he commented. He also added that nano-scaled texturing of surfaces, currently researched at the University of Florida, is also thought to have a major impact by improving the efficiency of electrodes, capacitors, and fuel-cells. Template-prepared nanostructured battery electrodes designed with an ensemble of monodisperse nanoparticles of the electrode materials (with diameters of tens to hundreds nano meters), provided highly-improved electrical performance at the electrode conductive interface.

While nanomaterial applications are expected to play a major economic role in increasing the efficiency of light sources, motors, electrodes, and efficient wear-resistant material, their application in catalysis is anticipated to have a pivotal environmental influence. In particular, nanoclusters, able to increase the efficiency of catalytic processes, are thought to hold the answer for reducing the emission of nitrogen oxides. By lowering the temperature at which the catalytic combustion and oxidation of hydrocarbons occur, Michalske suggested that such agents might be able to remove nitrogen reactions, leading to tremendous environmental savings. This effect might be achievable through the use of gold nanoclusters, currently developed at Texas A&M University, with their highly-efficient catalytic properties that emerge when their thickness is reduced to two atomic layers.

With all the benefits and savings that nanomaterials are offering, the main challenge remains to move from lab-scale experiments to commercial nano-production. Once that stage is reached, nanomaterials will start to have broad energy implications. According to Michalske, nano-layers

and composites are expected to lead to efficient lighting, low friction/wear resistant surfaces, permanent magnets for more efficient motors and photovoltaic energy generation. Nano-clusters and tubes are expected to help in the development of catalysis for chemical processing, hydrogen storage, artificial photosynthesis, and more efficient electrodes for batteries and fuel cells; while nanoporous membranes are expected to contribute to chemical separations and purifications, development of fuel cells, batteries, sensors, and detectors. But it still remains unclear how these nanomaterials will progress to systems that deliver energy performance.

According to Michalske, the solution resides in integrating different length-scales together. “Very few solutions are going to be nano alone,” he explained, “but nanomaterials are unquestionably going to be involved in some complicated engineering systems associated with processing energy and/or information.” Taking the example of the μ Chem Lab (a hand-held analysis system deployed in subways and airports around the country for security purposes), Michalske asserted that this device, which is the size of a name badge, contains micro-scaled pre-concentrators, Gas Chromatography (GC) columns, detectors, and two full gas chromatographs able to detect certain gases by analyzing their parts per billion concentration in the air. What delivers the performance of this integrated device is the self-assembly of a nano-scaled membrane attached to the pre-concentrator, where the individual molecular interactions drive the end structure. This structure has the ability to manipulate itself to the extent that all the pores can achieve a particular size allowing them to detect specific chemicals depending on the size of their pores.

While the sensitivity available at the nanometer scale constitutes the main driver behind the application of such devices, Michalske stressed that their usefulness only arises with the integration of different length scales together. According to Michalske, “everything in nature has its roots in some nano-scaled machinery and the function of the living systems is achieved via the integration of the different capabilities available over multiple length scales.” For instance, living nanomolecules assemble to form cell components, that come together to form cells, which in turn accumulate into larger organs that are functional. Only through an integrated architecture

that spans multiple length-scales is our body able to perform its micro- and macro- functions. Thus, understanding this architecture and knowing how to connect the different length scales is unquestionably going to play a major role in determining how nanotechnology will operate.

Michalske concluded his presentation by stressing the importance of achieving advancements in nano research. The DOE is developing nationwide nano centers able to provide researchers with open access to tools and capabilities, enhancing the possibility that nanoscience applications can be facilitated. However, Michalske cautioned that the impact of nanotechnology might be greatly minimized if experts do not focus their work. “We have to really understand where the real priorities are concentrated and where the real differences can be made,” he concluded.

Beyond applications in materials science and catalysis, there is also great potential for first order interaction between nanoscience and energy. According to Dr. Timothy Fisher, associate professor of mechanical engineering at Purdue University, this subject is considered to have profound implications on energy conversions and efficiency. “When materials are being spatially confined, the energy states of the energy carriers change,” he explained. This change in behavior can be particularly useful in direct energy conversion technologies and energy transport in electron emission processes.

The advantages associated with the creation of more efficient, direct energy conversions by tapping nanotechnology are significant. Direct thermal-electrical conversion is particularly appealing from an engineering point-of-view due its ability to eliminate moving parts. In the short-term, it offers enhanced reliability and the ability to generate solar-thermal power and radioisotope power while providing means for electronics cooling. For the long-term, scientists are projecting the development of supplementary cycles for fossil-fuel plants or for fuel cells and exhaust systems, which might be of great interest to the military, NASA, and space exploration missions.

To reach the phase where nano energy conversion devices could be produced, Fisher stressed that advancements in the field of nanoscale thermoelectrics are needed. According to research conducted at the Research Triangle Institute, the use of nanoscale structures is thought to significantly improve thermoelectric performance. By using layers of traditional semiconductors with 1 nm to 5 nm thickness, great enhancements in ZT values (a dimensionless figure of merit that indicates thermoelectric efficiency) were achieved, and a new value of 2.4 was reached compared to the typical bulk values of 1.

While the new results are encouraging, Fisher explained that a ZT of 2.4 is still not sufficient to produce room-temperature vapor-compression refrigerators. Materials with such ZT values are not very useful and do not have wide application (with the exception of coolers, where they are used to achieve room-temperature refrigeration). Making the semiconductor layers thinner is unlikely to produce the needed ZT values, Fisher explained, since nanoscale thermoelectric material operates on the principle of allowing significant electron transport while interfering with phonon transport. Thus, the particle's size is not expected to make a difference beyond a certain magnitude. The only solution, he believes, resides in significant material developments and the testing of different elements. According to some early attempts that were made in this field, extrapolation of nanowire models, developed by Hicks and Dresselhaus in 1993, projected achieving a ZT value of 4.

Fisher explained that there are two distinguishable methods by which electrons are excited and emitted. The first, thermionic emission, is where electrons are emitted over potential barriers as the material is heated sufficiently. The second, field emission, is where electrons tunnel through potential barriers as an electric field is applied. In the latter case, the tunneling probability of the emitted electrons was found to be a strong function of the field's strength and the barriers' width; and as the barriers' width is modified, scientists might be able to filter the electron's energy.

One method of changing the barrier's width resides in using small-tip emitters. For instance, a Spindt-type field emitter (an emitter equipped with a micron-sized metallic tip to enhance field

emission) with a tip radius of 10 nm can result in a drastic increase in electron emission as predicted by electrostatic theory. The electrons achieve an increased ability to tunnel out due to the tip's capability of concentrating the field near the source of the electrons instead of having a linear potential profile between the cathode and the anode. According to Fisher, studies have shown that as the emitter radius is reduced from 100 nm to 5 nm, the potential profile changes dramatically for the same current density. However, he noted that experts should not undervalue the different energetic distributions that arise as different materials are used to produce a particular current density.

The average emitted electron energy distributions from moments of emission integrals can be higher or lower than replacement electrons depending on the field strength and curvature. When subjected to a high electric field, the average energy level of an emitted electron is usually below the Fermi level (the collection of electron energy levels at absolute zero temperature where no electrons will have enough energy to rise above the surface of the "Fermi sea" of electron energy states) and thus its replacement tends to have a higher energy. However, when a material is subjected to a low electric field, electrons with an energy level above the Fermi level are emitted, and their replacements tend to have lower energy, specifically at the Fermi level.

This emission process, which corresponds to cooling the emitter with the higher energy electrons replacing the lower energy electrons, typically results in tremendous energy fluxes from the cooling rates.

Taking the example of a diamond-carbon material, Fisher explained that with a low work function equivalent to 1.7 electron volt (eV) (about four times lower than typical metal work functions), high energy fluxes can be obtained at different nanoscale emitter characteristic radii. For instance, an electric field of 1 V/micron resulted in an 80 W/cm^2 energy flux when an emitter radius of 10 nm was used on a material with a 1.7 eV work function; while the use of the same electric field and the same radius produced a $2,000,000 \text{ W/cm}^2$ flux on a material with a 1.0 eV

work function. These results are of high interest to industry because of their implications for high-efficiency solid-state cooling systems.

Fisher also discussed the process of thermionic emission. First observed by Thomas Edison in the 1880s and quantified by Owen Richardson in 1912, thermionic emission operates on the principle of thermal-to-electrical power generation. During the thermionic device operation, low energy replacement electrons are excited by heat sources to higher energy states causing the electrons above the chemical potential μ to be emitted. As the energy level of the electrons exceeds the work function, they escape the surface of the cathode toward the anode through a vacuum or vapor space used to minimize the space charge effects as well as to lower the work functions. The anode in turn dissipates the energy across a load or through an electrical circuit.

Although highly-efficient, once backward radiation and heat/line conduction losses are reduced, thermionic emission devices have not seen widespread use because high work functions and high temperatures in the order of 2000 K are associated with their operation. To remedy this problem, researchers are currently considering the effects of spatially confining the energy states of the emitter. If the emitter's energy dissipation can be reduced from 3-D (where they display a parabolic energy distribution) to 1-D where the lateral dimensions are confined, scientists project that a drastic improvement in the performance of thermionic emission can be achieved.

According to Dr. Fisher, studies have shown that the electron supply function, which measures the number of electrons striking the emitting surface (per unit of time, energy, and area) was dramatically increased as emitter surfaces were spatially confined in quantum wires. At large energy scales, the use of a 1 nm quantum wire radically promoted the current production and energy dissipation in the desired emission direction. However, Fisher noted that the quantum wires' radii have a pivotal influence on the energy dissipation. Even 2 nm and 4 nm quantum wires did not display any significant improvement but fully mimicked the behavior of bulk materials.

With the electron supply function achieving greater values for 1 nm quantum wires than for 3-D materials, innovations in nanotechnology and particularly in the production of nanowires are expected to have a pivotal influence on the commercialization and use of thermionic emission. For instance, in a recent study conducted at Purdue University, researchers modeled an array of closely packed nanowires congregated on a base, which faced a bulk emitter. With both systems being at the same temperature, the second law of thermodynamics predicts the existence of zero efficiency. However, due to the high electron supply (associated with the use of such dense and closely-packed nanowires), Fisher noted that a net current is likely to be produced. If the generated voltage and the chemical potential are changed, a power generation would occur giving rise to a possible 45% thermal efficiency and consequently, a violation to the second law of thermodynamics, similar to that of “Maxwell’s demon”. Maxwell speculated that an imaginary lossless shutter (the demon) should be able to spatially separate high energy molecules from low energy molecules giving rise to some thermal efficiency-without any obvious violation of the second law of thermodynamics.

Questions remain whether nanomaterials will come to serve as such separators. Fisher believes that this highly depends on understanding the nature of interfacial transport from 3-D to 1-D, the nature of interactions among the quantum wires and the internal loss and scattering mechanisms. Understanding all these processes will unquestionably allow scientists to approach the limits of the second law of thermodynamics differently if not challenge it. Recent evidence pointing to the existence of shoulders in some finely resolved emitted electron’s energy distributions is expected to hold some answers to this complex problem.

With the drastic change in properties that is occurring on small scales, prospects for energy conversion seem to be promising. The current development of direct energy conversion in niche markets is offering grand opportunities for greater efficiencies. However, Fisher stressed that there are enormous challenges ahead for creating an efficient direct energy conversion system suitable for large-scale production. Development in nanomaterials, surface science, combinatorial material, and controlled synthesis are needed in order to achieve lower work

functions. Furthermore, a greater understanding of the mechanism of transport at interfaces between bulk and confined material as well as the ability to scale up from nano to macro material will need to be achieved. “This after all is what promises exceptional performance and high power density,” he concluded.

In another perspective on how nanotechnology might be applied to the current problems of the electricity transmission system, Dr. John Stringer, director of the Materials and Chemistry Department at the Electric Power Research Institute (EPRI), suggested an innovative plan to electrify the world by providing the conference participants with a new perspective on revolutionizing the current grid system. He proposed the adoption of an “Electricity Technology Roadmap” that projects five destinations: to resolve the power delivery vulnerability, to foster a revolution in energy services, to accelerate competitiveness, to resolve energy/environmental conflicts, and finally to manage global sustainability.

Dr. Stringer noted that developing a roadmap will not only reflect advances in science and technology but will also allow experts to identify the “difficult challenges” which must be met to reach the destinations. This will further open the door for defining integrated technology development efforts necessary to address the obstacles that are projected. According to Stringer, the most conspicuous challenges related to creating an efficient grid system include: improving transmission capacity, grid control and stability, providing better power quality and better reliability for precision electricity users, and creating the required infrastructure for a digital society.

The most important challenge, creating a digital society, is to improve transmission capacity, grid control and stability. To remedy such problems, Stringer proposes that the adoption of a smart, electronically controlled network might hold the answer by providing the ability to increase throughput while decreasing vulnerability. However, to create such a network, it would be necessary first to develop several regional and national plans for grid expansion. To accomplish this, according to Stringer, first a wide-area measurement/monitoring system must be

deployed. Furthermore, Flexible Alternating Current Transmission Systems (FACTS), as well as hierarchical controls and fully automated Transmission and Distribution (T&D) systems will need to be implemented. These technologies will be particularly useful for allowing greater amounts of energy to flow on existing power lines. They offer highly-effective voltage stability and help improve the system's capacity and reliability while making the grid more resilient to electrical disturbances and system swings.

Wide-area measurement and monitoring systems are expected to play a major role in the development of new grids by allowing grid-wide monitoring and control of the power flows, identifying transmission limitations, and optimizing power plant operation. FACTS can enhance the security, capacity and flexibility of power transmission systems; while fully-automated T&D systems can significantly improve the capacity and reliability of the existing system, without adding a lot of visible transmission facilities, according to Stringer.

Stringer also emphasized the need to enhance the capability of transmission, distribution, and end-use systems in an effort to reduce the number and severity of power disturbances. He stressed the need for standards and integration guidelines for distributed resources. Interconnection standards play a major role in ensuring the reliable, environmentally-sound, and economic operation of an interconnected electric system. It further provides help in preventing the standards problem that previously arose and hindered wind power generation.

According to Stinger, instead of having larger generating stations, experts should look at the possibility of having smaller distributed units of power generation equipped with backup generation and storage systems that would be able to provide power for a short-duration if needed by the system. The current electricity delivery system is made up of three distinguishable methods by which electricity is generated and delivered to the user:

- Large generation plants which are widely separated and connected to a broad-based grid

- Moderate-sized generation plants which are close to a user community and connected by a limited area minigrid
- Small generation plants which serve a single user.

The second and third of these are generally referred to as distributed energy resources (DER). Stringer explained that whether there is communication between the National Grid and the DER is “a matter having significant implications.” According to Stringer, increasing DER holds the key to improving the efficiency of the grid system by minimizing the losses associated with large generation plants that are widely separated. Other areas where an integrated distributed energy and national grid might gain from technical solutions would be the introduction of better consumption metering controls and greater introduction of direct current DC microgrids that could increase the efficiency and the power quality of a distributed resources system.

“Distributed generators play an important part in optimizing the whole system;” he stated, “and in order to be able to create the infrastructure of a digital society, the integration of DC microgrids into the overall grid architecture is paramount. This can be done by very responsive control technologies and by more intelligent overall systems than we are currently used to.” However, he admitted that the development of such a system depends on the ability to overcome several projected challenges, including the difficulty of integrating a transmission grid with automated distribution and the commercialization of high-temperature superconducting technology. If technologies could be developed to control electromagnetic interference and achieve the hardening of end-use devices, undergrounding and the integration of electricity, communications, gas, and water corridors could have a pivotal influence on the market.

In the near term, PV technologies deployed in a distributed manner to provide direct DC services could be economic today without subsidy for some applications. PV’s value as a DER option, whether DC or with additional inverter costs, is currently recognized. Comparing PV costs per kwh against central station technologies is only appropriate where PV systems are concentrated at a single location, such as a PV farm. PV distributed at end use locations provides much higher

value net of transmission and most distribution costs versus central station power priced at the busbar.

The installed capacity of the United States power generation was 754 gigawatts (GW) in the year 2000, of which only seven percent was used for distributed generation. With 156 thousand miles of transmission lines, an intensity of 4.84 megawatts (MW) per mile and 99.99% (four nines) of transmission reliability, the energy consumption in the US reached 3800 billion kilowatt-hours (kWh) with delivered intensity of 0.41 kWh/\$GDP (Gross Domestic Product), and only 8–10% of which required digital quality power. However, by 2020, Stringer projects significant changes in those numbers. Most importantly, he noted that the percentage of distributed generation is expected to rise to 25%, the transmission density is expected to increase to 5.6 MW/mile and the percentage load requiring digital quality power is expected to reach 50%.

Stringer noted that new technologies could help the electricity industry respond better to the ‘real time’ nature of the electrical generation (that is the fact that electricity used is generated at the same time that it is used).

“In most industries, there are built-in storages of some kind to smooth out fluctuations in demand from the point of view of the supplier like the natural gas line which performs this function itself,” he explained. But in electricity generation, the option of storing power is nonexistent and one of the envisioned solutions that might help the short-term storage problem is thought to lie in either increasing the distributed generation integrated into the grid system or introducing hydrogen in fuel cell generators at low temperatures which will provide a medium containing capacity inside the pipeline system.

Stringer also noted that the temperature constraints of the lines are currently playing an extremely critical role in restricting their transmission capacity. “As the line gets warmer, it sags and it may contact trees or the ground causing deleterious effects,” he explained. Thus, the need to increase the strength of the current transmission lines and to reduce their sagging is important.

Nanotechnology researchers are currently considering the use of conductors with higher strength-to-weight ratios for a given current-carrying capacity in an effort to increase the overall capacity of the right-of-way.

Dr. Stringer told the conference about a radically new approach for creating a more efficient electrical grid that was presented in a paper to the November 2001 Winter Meeting of the American Nuclear Society by EPRI's founder, Chauncey Starr. The paper outlined the idea to launch a Supergrid that will consist of DC superconducting lines using liquid hydrogen as the coolant. Electricity would be supplied to the lines by power plants situated along the Supergrid, and the Supergrid lines would feed the conventional grid through DC to AC converters at appropriate locations. Under the scheme, hydrogen would leave the grid to be replenished. This, in turn, would provide a continental hydrogen pipeline grid with the ability to store tremendous amounts of energy when operating between the two different transmission systems.

Dr. Stringer stressed that enormous challenges remain for creating any kind of improved grid of the future: "The major technical challenge will be to find ways of controlling transmission systems in milliseconds rather than in the multiple seconds needed for control operations today." He added that "millions of commercial transactions should be able to take place on an open-access transmission system and we should have the capability to ensure that the power follows the contract path."

Stringer argued that in order to achieve the goal of creating a more efficient grid, there is a long list of enabling technologies that need to be developed first. His list included the need for sensors for real-time monitoring, complex network control and electronic power flow control, real-time dispatch of distributed resources, interference-free power line communications, DC microgrids for premium power services, and digital devices with greater tolerance to power disturbances.

Stringer concluded his presentation by stressing the need for nanotechnology to develop an intelligent, massive machine to comprise a new grid system. “This after all is what is needed to get the world into the next part of the century,” he asserted.

While the subject of creating a more efficient and improved electrical grid remains the major area of concern, it is undeniable that cost and economics will have a pivotal influence in deciding which approach will be adopted. In today’s competitive electricity market, there is no doubt that only the most financially-viable option will win in the marketplace.

Taking into consideration the increased competitiveness of the current electricity market, Dr. Peter Hartley, chair of the Department of Economics at Rice University, presented the conference attendees with a new cost-effective approach to solving the world’s electrical problem. He suggested that a mass implementation of High Voltage Direct Current (HVDC) transmission lines would be the most financially-viable and most efficient technical solution currently available.

Over the past decade, the use of HVDC for long-distance electricity trade has dramatically increased globally. Technological innovations played an important role in promoting the expansion of their implementation by enhancing the economically-viability of HVDC as an alternative to traditional AC systems. The development of semi-conductor thyristors able to handle high currents (4,000 ampere) and block high voltages (up to 10 kV) improved the efficiency of DC to AC conversions, paving the way for a drastic change in the market’s economic environment.

“As we move toward deregulated electricity markets, an increased opportunity of delivering power to other distributors’ areas will be developing,” Hartley explained. “This will increase the competition in the new wholesale electricity market and allow power companies to benefit from arbitrage price differences, which will increasingly promote the expansion of HVDC.”

HVDC systems are characterized by extremely high efficiency. The lower costs for having bi-directional power transfers and technology breakthroughs that allow more stable networks through contractual provisions are propelling HVDC systems into play. HVDC systems have some clear advantages because they require smaller transmission towers than an optimized AC link of equal capacity. The right-of-way for an AC Line designed to carry 2,000 MW is more than 70% wider than the right-of-way for a DC line of equivalent capacity. HVDC also provides less final conducting losses and requires much less insulation *ceteris paribus* than an equivalent AC link, paving the way for transmission of larger amounts of electricity more cost-effectively over great distances. Even though there are extra losses in DC/AC conversion relative to AC voltage transformation, the operation and maintenance costs are much lower for an optimized HVDC than for an equal capacity optimized AC system.

Meanwhile, there are other benefits of implementing HVDC transmission. According to Hartley, “HVDC links can stabilize AC system frequencies and voltages, and help with unplanned outages. These systems are specifically designed to carry a maximum load and cannot be overloaded by outage of parallel AC lines.”

HVDC links, however, entail an additional cost for building conversion stations designed to supply the consumer with alternating current. A trade-off exists between the economization that the construction of long DC lines offers and the capital costs of building the conversion units. Only at long distance and at relatively low-capacity transmission, the cost of building DC conversion stations becomes insignificant and HVDC transmission turns into a profitable business. Specifically, according to Hartley’s model, “the breakeven distance is approximately 300 km and as you transport more power, the breakeven distance becomes larger.”

Due to the high cost associated with building conversion stations, HVDC is currently only suited to certain kinds of specialized applications. It is mainly reserved for use in undersea transmission where losses from AC current are large and where back-to-back converters are needed to connect two AC systems with different frequencies—as in Japan—or two regions where AC is not

synchronized—as in the US. Taking the example of the US where there exists four major independent asynchronous networks (Quebec, Texas, the Eastern Interconnected Network and the Western Interconnected Network), Hartley explained that the only way of transferring energy between the four regions resides in using DC interconnections.

The earliest applications of HVDC transmission involved the 1954 Gotland 1 submarine cables in Sweden where the cost advantage of DC links was greatest, with HVDC being particularly suited to undersea transmission, where the losses from AC are large. Later application were associated with high voltage transmission of hydroelectric and solar energy over long distances and the installation of the Pacific DC intertie in 1970 where system stabilization was a major concern. In the Pacific system intertie, the DC system's controls were programmed to automatically remedy problems caused by line faults or other disturbances. At present, HVDC links are mainly used to lower transmission losses and to increase the stability and controllability of an electrical system. In the Rihand-Delhi project in India, an HVDC link cut the right-of-way needs in half, while taking power 814 km from a 3000 MW coal-based thermal power station to Delhi at ± 500 kV. In Itaipu, Brazil, two bipolar DC lines were implemented to bring power generated at 50 Hz in the 12,600 MW Itaipu hydroelectric plants to the 60Hz network in São Paulo. Also, in the Leyte-Luzon project in the Philippines, 430 km of overhead links and 21 km of submarine DC lines were used to take geothermal energy from Leyte to the main island while assisting with the stabilization of the AC network.

With the tremendous benefits DC offers, the implementation of HDVC links for long-distance transmission is expected to drastically increase over the next decade. The adoption of the proposed Neptune project for transmitting natural gas energy from Nova Scotia to Boston, New York City, and New Jersey is expected to have a major impact by avoiding a NIMBY (Not in My Backyard) problem and by retiring an old oil-fired plant in New York. With 1,000 km of submarine cable transmitting 1200 MW, this project will help improve network stability and reliability, as well as allow savings from electricity trade via the adoption of a bi-directional link. According to Dr. Hartley, “This link will increase electricity savings by allowing the shipment of

cheap power to the region with peak demand, particularly to the southern end in the summer and to the northern end in the winter.”

HVDC is particularly suited to many renewable energy sources and stranded natural gas supplies, which are often distant from demand centers. It could also have strong applicability for a successful geologic carbon sequestration program that might also be distant from demand centers. With the variable cost of its overhead link being 1.2 to 1.9 times less expensive than pipeline gas for the transmission of 1,000–5,000 MW over 5,000 km, Dr. Hartley argued that, according to a recent study conducted at the Baker Institute comparing the usage of HVDC versus a natural gas pipeline in Japan, the DC electricity option appeared to be quite competitive, not to mention the other benefits that DC can provide. He also noted that this competitiveness will allow the adoption of DC in large hydroelectric projects which supply multiple transmission systems as well as in wind turbines operating at variable speeds. “Wind turbines operating at variable speed generate power at different frequencies, requiring conversions to and from DC,” he explained.

HVDC also appears to be particularly relevant for developing large scale solar electrical power. With major sources tending to be remote from major demand centers and with photovoltaic cells producing electricity directly as DC, HVDC is expected to be an extremely favored option. It eliminates the need to convert at source as well as minimizes costs through transferring power over long distances from the desert or high altitudes, where the land is cheap and where the solar radiation is greatest. Hartley cited the example of the US: “According to the National Renewable Energy Laboratory, the average annual solar radiation is greatest in the southwestern part of the country and in northern Mexico. 6 kWh/m² of light a day is expected to yield about 280 kWh/m² of electricity a year for panels at 13% efficiency.” He claimed that with expected HVDC transmission losses of about 25% for a distance of 5000 km, the 3,800 billion kWh of electricity produced in the US in 2000 could have been easily produced by about 20 panels, each 30km×30km, over a total area of 18,000km².

According to Hartley, this region of the US is regarded to be extremely prospective for solar production. The available sunlight does not vary greatly by season and the ratio of summer to winter production is extremely close to one. He explained that with the adoption of a PV (photovoltaic) plant equipped with a HVDC linking system and with the lack of seasonal fluctuations, the US, by producing power in the Southwest, will not only have the ability to significantly reduce costs by the adoption of a bi-directional link (sending power west in morning hours, east in the afternoons) but will also be able to strengthen the connection between the four continental independent networks reducing thus some states' supply constraints.

The adoption of grid connected PV plants has increasingly come to be regarded as a highly effective and financially-viable solution in various parts of the world. The earliest plants were installed in Saijo, Japan and in Hesperia, CA in the early 1980s. At present, there exists more than 25 PV plants world-wide with peak output ranging from 300 kW to more than 3 MW. These plants have proved to be easy to monitor and control and have achieved a 25% annual capacity factor even with modest downtime.

However, one of the major challenges associated with PV plants resides in controlling the daily fluctuations of the solar output. Extra capacity is needed to meet unexpected decreases in output or demand surges. With at least two peak demands expected to occur during the day, Hartley suggested positioning the panels on different longitudinal lines in a system that allows them to track the sun. But, this technique, which significantly reduces the effect of the solar output's daily fluctuations, considerably raises costs, making this solution unfavorable. He also proposed the use of pumped hydroelectric power as a possible solution. "When the solar power is cheap during the day, some of its energy can be invested to pump water uphill. Then, when the demand is peaking, hydroelectric power could be used as a source for the extra-capacity needed," he explained.

The adoption of PV plants equipped with HVDC does not only offer more efficient solutions but also provides power suppliers with the ability to take advantage of spatial and temporal arbitrage.

According to Dr. Hartley, “High capacity HVDC bi-directional links between time zones, or different climates, can flatten peaks in solar output and in demand. Only excess demands are traded as geographical differences in prices are eliminated through arbitrage.” For example, the large coal and gas reserves of Siberia could produce 450–600 billion kW of hydroelectricity annually, 45% of Japan’s output in 1995. A 1,800 km 11,000 MW HVDC link would enable electricity to be exported from Siberia to Japan or even link Siberia to Alaska. Zaire could produce 250–500 billion kW of hydroelectricity annually to send to Europe (5-6,000 km) on a 30-60,000 MW link.

Canada, China, and Brazil could also benefit from hydroelectric projects on a large scale. Dr. Hartley pointed out that hydroelectric capacity, pumped storage, and hydrogen produced through electrolysis could play an important role in allowing electricity prices to be arbitrated over time by providing a much-needed cost-effective way to store electricity.

However, to be able to take full advantage of the tremendous benefits that HVDC transmission can offer, Dr. Hartley stressed that new technological developments are needed to enable the creation of the grid of the future. Particularly, new technical approaches are required for designing converter stations capable of handling high voltages; and new nanomaterials will need to be developed in an effort to produce lines with lower losses and lower optimum voltage eliminating the need for superconductivity.

Conclusion

As we move toward the middle of the 21st century, it is critical that we find **revolutionary breakthroughs in energy science and technology**. Our national security and global interests are at stake. Close to one-third of the world’s population lives today without modern energy services, perpetuating poverty and human suffering that leads to desperation and regional instability and conflict.

Maintaining plentiful oil and gas supplies needed to meet rising world energy demand will become more challenging as time goes on, given the natural peak expected in fossil fuels in this century, especially in the industrialized West. Natural gas will provide a bridge, but North American sources are very limited, meaning America will become highly dependent on Middle Eastern natural gas imports as well as oil imports by 2020. As the world faces greater reliance on Middle East resources by 2030 and beyond, it will be imperative to have prepared for new energy sources that do not derive principally from oil or natural gas.

Environmental problems predicted for the middle of the century also dictate that we develop new, cleaner sources of energy. Scientists have become increasingly convinced that the consequences of continuing to burn fossil fuels at current or expanding rates will have serious, deleterious impacts on the global climate. Under a business as usual scenario, carbon concentrations in the atmosphere would rise to 750 ppm by the end of the century. In order to hold atmospheric CO² concentrations to 350 ppm by mid-century –the level targeted by environmental scientists as preventing catastrophic changes-- at least 15 terawatts of non-fossil fuel energy will be needed to reduce CO² levels to modest targets of 550 ppm by 2050. Put in perspective, that would require a scale up by the power of 20 what nuclear power represents globally today. To reach the goal of 350 ppm, at least 30 terrwatts would need to be derived from non-fossil sources.

To find a timely answer to this energy supply dilemma, we must prepare well in advance. At present, scientific inquiry in the energy arena is scattered and unfocused, with various groups working apart to gain research dollars for uncoordinated pursuits that lack a clear roadmap to a better energy future.

What is needed is a vast effort, capable of providing a new “non-traditional” source of energy, which is at least twice the size of all worldwide energy consumed today **and have it readily available by the middle of the 21st century.** This source must not rely on oil and natural gas as the initial component (as current plans for using hydrogen as an energy carrier assume). It must

be clean, and, most importantly, it must be cheap. It must provide the basis for sustained economic prosperity for 10 billion people.

Current technology simply cannot do this. We need stunning new discoveries in underlying core science and engineering base to enable an answer.

Breakthroughs in nano-technology open up the possibility of moving beyond our current alternatives for energy supply by introducing technologies that are more efficient, inexpensive, and environmentally sound. A solution to the global energy problem will require revolutionary new technology, as well as conservation and evolutionary improvements in existing technologies.

Advancement of nano-technology solutions can be an integral component to solving the energy problem. Funding committed to nanoscience and energy has great distributive benefits as it is a *cross-cutting* research area. Incremental discoveries, as well as disruptive discoveries, could have implications for many fuels and energy sources as well as storage and delivery systems.

Fifty leading scientists gathered at Rice University for the Energy and Nanotechnology conference concluded that key contributions can be made in energy security and supply through fundamental research on nanoscience solutions to energy technologies. The group agreed that a major nanoscience and energy research program should be aimed at long term breakthrough possibilities in cleaner sources of energy, particularly solar energy, while providing vital science backup to current technologies in the short term, including improving technologies used in finding and recovering fossil fuels and technologies for storing and transmitting electricity.

The Rice University-led meeting identified 14 energy nanotechnology grand challenges:

1. Photovoltaic solar energy: Lower costs by 10 fold
2. Achieve commercial photocatalytic reduction of CO₂ to methanol
3. Create a commercial process for direct photoconversion of light and water to produce hydrogen
4. Lower the costs of fuel cell by 10 to 100 fold and create new, sturdier materials
5. Improve the efficiency/storage capacity of batteries and supercapacitors by 10 to 100 fold for automotive and distributed generation applications
6. Create new light weight materials for hydrogen storage for pressure tanks, LH₂ vessels and an easily reversible hydrogen chemisorption system
7. Develop power cables, superconductors or quantum conductors made of new nanomaterials to rewire the electricity grid and enable long-distance, continental and even international electrical energy transport, and reducing or eliminating thermal sag failures, eddy current losses and resistive losses by replacing copper and aluminum wires.
8. Enable nanoelectronics to revolutionize computers, sensors and devices for the electricity grid and other applications
9. Develop thermochemical processes with catalysts to generate hydrogen from water at temperatures lower than 900 C and at commercial costs
10. Create super strong, light weight materials that can be used to improve efficiency in cars, planes and in space travel, the latter, if combined with nanoelectronics-based robotics possibly enabling space solar structures on the moon or in space
11. Create nanotech efficient lighting to replace incandescent and fluorescent lights
12. Develop Nanomaterials and coatings that will enable deep drilling at lower costs to tap energy resources, including geothermal heat, in deep strata
13. Create CO₂ mineralization methods that can work on a vast scale without waste streams (possibly basalt based)

Transmission and storage of energy (particularly electrical power and hydrogen) is a major societal need. It is in this area that the majority of scientists in the group believed nanoscience can bring the most immediate benefits, with nanotubing and other nanomaterials creating new opportunities to lower the costs of transporting electricity over long distances. One key issue for scientific investigation involves improved technologies for temperature control during the energy transmission process. Improved technology in this area could allow greater storage of energy, “stretching” the capacity of the electrical supply chain to deliver enhanced energy supply and making the entire system more efficient. In addition, any gains made in the area of energy storage, particularly electrical energy storage, would have dramatic impact on the energy problem by removing key barriers (variability and cost) to the wide dissemination of renewable energy.

The participating scientists agreed that nanotechnology could revolutionize lighting and electricity grid technology. A breakthrough in electricity transmission technology would facilitate not only distributed electricity but also render commercial the transmission of electricity from distant sources of energy such as solar collector farms located in desert geography or closed-loop clean coal FutureGen sequestration power plants built near geologic formations. Improvements in electricity transmission would also permit the transportation of electricity by wire from power stations built near stranded natural gas reserves in remote regions.

Scientists theorize that transmission lines built from carbon nanotubes that could conduct electricity efficiently across great distances without loss could radically change the economics of moving “energy” supply from distant natural gas sources, distant wind and solar farms, and coal sequestration sites. Rice University’s executive director of the Carbon Nanotechnology Laboratory Dr. Howard Schmidt believes that development of quantum wire prototypes is possible within five years with adequate research and development funding. Expected features of the new materials would be one to ten times the conductivity of copper, six times less mass, strength superior to steel, and near-zero thermal expansion. The benefits of the wire, once

developed at reasonable cost, would be reduced power loss, minimal sag, reduced mass and higher power density.

Advanced storage technologies that allow for easy conversion and storage of hydrogen would mean that excess electricity produced anywhere on the grid could be converted to hydrogen and stored, to be used to eliminate the risks from intermittent production of renewable energy.

These new technologies could be used to enhance the potential of distributed generation which is increasingly viewed as a key to meeting the world's future energy needs in a manner that is more universal and sustainable. As journalist and commentator Vijay Vaitheeswaran notes in his popular book "Power to the People," The happy collision of markets, environmentalism, and innovation explains the most powerful trend in all in energy today; micropower, which puts small, clean power plants close to homes and factories. That may sound unremarkable, or even like commonsense, to the reader –but in the energy business it is near heresy. It is in fact a dramatic reversal of the age-old utility practice of building giant power plants far from the end-user. The most surprising aspect of the micropower revolution is that tomorrow's energy world will be based as much on silicon chips, software, and superconductors as on soot and sulfur...Today's antiquated power grid, designed when power flowed from big plants to distant consumers, is being upgraded to handle tomorrow's complex, multi-directional flows (the result of micropower plants selling power into the grid as well as buying from it). It is this breakthrough that will finally make possible the intelligent homes and the Energy Internet of the squeaky-clean, not-too-distant future."

One vision of the distributed store-gen grid for 2050 is that of Dr. Richard Smalley who conceptualizes a vast electrical continental power grid with over 100 million asynchronous local storage units and generation sites including private households and businesses. This system will be continually innovated by free enterprise, with local generation buying low and selling high to the grid network. Optimized local storage systems will be based on improved batteries, hydrogen conversion systems and fly wheels, while mass primary power input to the grid can come from

remote locations with large scale access to cleaner energy resources (solar farms, stranded natural gas, closed-system clean coal plants, wave power) to the common grid via nanotube, high voltage wires that minimize loss. Excess hydrogen produced in the system can be used in the transportation sector.

Current technology simply cannot provide the energy that will be needed by mid-century. Major new discoveries in underlying core science and engineering base are needed to provide clean, affordable, sustainable alternatives to fuel the globe. A vast and coordinated effort is needed—a focused program radically different than today’s haphazard energy research and development agenda.

Even once this enabling core work is done, it will take trillions of dollars of investment, and several decades to implement these new energy technologies on an adequate scale. We must get started now, before our S&T workforce of American citizens declines much further. While the costs sound high, these same trillions of dollars of investment in traditional energy sources would be needed over the same time period to refurbish aging infrastructure and to meet new demand.

It should be the overriding mission of a new energy science program to map out the path to development of new sources for a better energy future for the 21st century, sources that can serve as a catalyst for sustained worldwide economic growth without harming the planet.

CONFERENCE AGENDA

2 MAY 2003

OPENING SESSION

SHELL OIL COMPANY FOUNDATION AUDITORIUM
JESSE H. JONES GRADUATE SCHOOL OF MANAGEMENT, RICE UNIVERSITY

5:00 P.M. **WELCOME ADDRESS**
THE HONORABLE KAY BAILEY HUTCHISON
UNITED STATES SENATOR, TEXAS

6:00 P.M. **OPENING RECEPTION**
DORÉ COMMONS, BAKER HALL, RICE UNIVERSITY
HOSTED BY THE BAKER INSTITUTE ROUNDTABLE

3 MAY 2003

ENERGY POLICY AND SOCIETAL IMPACT

DORÉ COMMONS, BAKER HALL, RICE UNIVERSITY

7:30 A.M. **REGISTRATION AND COFFEE**

8:00 A.M. **WELCOMING REMARKS**
THE HONORABLE EDWARD P. DJEREJIAN
DIRECTOR, JAMES A. BAKER III INSTITUTE FOR PUBLIC POLICY

8:15 A.M. **OUTLINING THE POSSIBILITIES: NANO-ENERGY INITIATIVE**
DR. RICHARD SMALLEY
NOBEL LAUREATE (CHEMISTRY, 1996); DIRECTOR, CARBON NANOTECHNOLOGY
LABORATORY, UNIVERSITY PROFESSOR, GENE & NORMAN HACKERMAN
PROFESSOR OF CHEMISTRY, AND PROFESSOR OF PHYSICS, RICE UNIVERSITY

8:45 A.M. **NATIONAL SCIENCE INITIATIVES**
RICHARD RUSSELL
ASSOCIATE DIRECTOR FOR TECHNOLOGY, OFFICE OF SCIENCE AND TECHNOLOGY
POLICY, EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES

9:30 A.M. **STRATEGIC ENERGY POLICY**
WILLIAM WHITE
President and CEO, The Wedge Group

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- 10:00 A.M. **STATE OF THE NATION'S ENERGY POLICIES**
CARL MICHAEL SMITH
ASSISTANT SECRETARY FOR FOSSIL ENERGY
U.S. DEPARTMENT OF ENERGY
- 10:45 A.M. **THE ROOTS AND IMPORTANCE OF THE NATIONAL NANOSCIENCE
INITIATIVE: POLICY AND THE CHALLENGES OF IMPLEMENTATION**
THOMAS A. KALIL
SPECIAL ASSISTANT TO THE CHANCELLOR FOR SCIENCE AND TECHNOLOGY,
UNIVERSITY OF CALIFORNIA AT BERKELEY
- 11:30 A.M. **LUNCH**
MUSICAL ENTERTAINMENT BY KIRK FARRIS
GRAND HALL, RICE MEMORIAL CENTER
HOSTED BY EESI

AMERICA'S ENERGY FUTURE

DORÉ COMMONS, BAKER HALL, RICE UNIVERSITY
SHELL LECTURE SERIES EVENT

- 1:00 P.M. **TECHNOLOGY AND ECONOMIC DEVELOPMENT**
DR. STEVEN CURRALL
WILLIAM & STEPHANIE SICK PROFESSOR OF ENTREPRENEURSHIP AND
ASSOCIATE PROFESSOR OF MANAGEMENT, PSYCHOLOGY, AND STATISTICS,
RICE UNIVERSITY
FOUNDING DIRECTOR, RICE ALLIANCE FOR TECHNOLOGY & ENTREPRENEURSHIP
- 1:15 P.M. **THE CHALLENGE OF CONVENTIONAL OIL AND GAS RESOURCES**
MATTHEW R. SIMMONS
CHAIRMAN, SIMMONS & CO. INTERNATIONAL
- 2:00 P.M. **THE GEOPOLITICS OF OIL**
FAREED MOHAMEDI
CHIEF ECONOMIST, PFC ENERGY
- 2:45 P.M. **THE TRANSPORTATION CHALLENGE**
JEREMY RIFKIN
PRESIDENT, THE FOUNDATION ON ECONOMIC TRENDS
AUTHOR, *THE HYDROGEN ECONOMY*
- 3:30 P.M. **AFTERNOON BREAK**

4:00 P.M. **GLOBAL WARMING AND FUEL CHOICES**
DR. MARTIN HOFFERT
PROFESSOR OF PHYSICS, NEW YORK UNIVERSITY

4 MAY 2003

ENERGY CHOICES: POSSIBILITIES AND BARRIERS
DORÉ COMMONS, BAKER HALL, RICE UNIVERSITY

7:30 A.M. **REGISTRATION AND COFFEE**

FOSSIL FUELS

8:00 A.M. **NATIONAL NANOTECHNOLOGY INITIATIVE ON ENERGY: OUR MISSION**
DR. WADE ADAMS
DIRECTOR, CENTER FOR NANOSCALE SCIENCE AND TECHNOLOGY,
RICE UNIVERSITY

OIL AND NATURAL GAS PANEL DISCUSSION

DR. WOLFGANG SHOLLNBERGER
TECHNOLOGY VICE PRESIDENT, BP

DR. ROGER ANDERSON
DOHERTY SENIOR SCHOLAR, LAMONT-DOHERTY EARTH OBSERVATORY
COLUMBIA UNIVERSITY

DR. LEE ESTEP
SENIOR SCIENTIST
LOCKHEED MARTIN SPACE OPERATIONS-STENNIS PROGRAMS

9:00 A.M. **MORNING BREAK**

9:15 A.M. **NATURAL GAS TECHNOLOGIES**
MELANIE KENDERDINE
VICE PRESIDENT, WASHINGTON OPERATIONS
GAS TECHNOLOGY INSTITUTE

9:40 A.M. **GEOHERMAL**
DR. YORAM SHOHAM
VICE PRESIDENT EXTERNAL TECHNOLOGY RELATIONS,
SHELL INTERNATIONAL EXPLORATION AND PRODUCTION, INC.

10:05 A.M. **METHANE HYDRATES**
DR. WALTER CHAPMAN
PROFESSOR OF CHEMICAL ENGINEERING, RICE UNIVERSITY

DR. GERALD R. DICKENS
ASSOCIATE PROFESSOR, EARTH SCIENCE
RICE UNIVERSITY

10:30 A.M. **COAL**
WILLIAM E. FERNALD
PORTFOLIO MANAGER, OFFICE OF COAL FUELS & INDUSTRIAL SYSTEMS
U.S. DEPARTMENT OF ENERGY

10:55 A.M. **CARBON SEQUESTRATION**
DR. JULIO FRIEDMAN
ASSISTANT RESEARCH SCIENTIST, DEPARTMENT OF GEOLOGY
UNIVERSITY OF MARYLAND

11:20 A.M. **LUNCH**
GRAND HALL, RICE MEMORIAL CENTER
HOSTED BY EESI

ENERGY CHOICES: POSSIBILITIES AND BARRIERS
DORÉ COMMONS, BAKER HALL, RICE UNIVERSITY

RENEWABLES, FUSION, AND FISSION

1:00 P.M. **EARTH SOLAR AND OTHER RENEWABLES**
DR. NATHAN S. LEWIS
GEORGE L. ARGYROS CHAIR AND PROFESSOR OF CHEMISTRY,
CALIFORNIA INSTITUTE OF TECHNOLOGY

1:25 P.M. **SPACE SOLAR**
DR. JOHN MANKINS
MANAGER, ADVANCED SPACE CONCEPTS, NASA

1:50 P.M. **DR. DAVID CRISWELL**
DIRECTOR, INSTITUTE FOR SPACE SYSTEMS OPERATIONS,
UNIVERSITY OF HOUSTON

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- 2:15 P.M. **FISSION**
DR. ERNIE MONIZ
PROFESSOR OF PHYSICS, MIT
- 2:40 P.M. **FUSION**
DR. ROBERT GOLDSTON
DIRECTOR, PRINCETON PLASMA PHYSICS LABORATORY
- 3:05 P.M. **AFTERNOON BREAK**
- EFFICIENCY*
- 3:20 P.M. **ELECTRICAL SYSTEMS**
DR. TERRY MICHALSKE
DIRECTOR, THE CENTER FOR INTEGRATED NANOTECHNOLOGIES
SANDIA NATIONAL LABORATORIES
- 3:45 P.M. DR. TIMOTHY S. FISHER
ASSOCIATE PROFESSOR, SCHOOL OF MECHANICAL ENGINEERING
PURDUE UNIVERSITY
- 4:10 P.M. **ELECTRICAL GRIDS**
DR. JOHN STRINGER
DIRECTOR, MATERIALS AND CHEMISTRY DEPARTMENT, EPRI
- 4:35 P.M. DR. PETER HARTLEY
CHAIRMAN, DEPARTMENT OF ECONOMICS, RICE UNIVERSITY
- TRANSPORTATION*
- 5:10 P.M. **FUEL CELLS**
DR. KENNETH R. STROH
PROGRAM MANAGER, HYDROGEN, FUEL CELL AND TRANSPORTATION PROGRAMS
LOS ALAMOS NATIONAL LABORATORY
- 5:35 P.M. **HYDROGEN STORAGE**
JAMES C. F. WANG
MANAGER, ANALYTICAL MATERIALS SCIENCE DEPARTMENT
SANDIA NATIONAL LABORATORIES

6:00 P.M. **CLOSING PLENARY ADDRESS**
SHELL DISTINGUISHED LECTURE SERIES EVENT

INTRODUCTION

DR. NEAL LANE

**SENIOR FELLOW, JAMES A. BAKER III INSTITUTE FOR PUBLIC POLICY
UNIVERSITY PROFESSOR, RICE UNIVERSITY**

THINKING OUT OF THE BOX ON ENERGY SOLUTIONS

DEAN KAMEN

CHAIRMAN, SEGWAY LLC

PRESIDENT, DEKA RESEARCH AND DEVELOPMENT