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Energy and Nanotechnology: Strategy for the Future

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, and the future of the Middle East, home to 60 percent of the world's known oil resources, remains uncertain. Dependence on Persian Gulf oil is likely to grow over time given investment barriers around the world and the realities of the concentration of geologic resources in the Middle East. Indeed, the sudden loss of the Saudi oil network would paralyze the global economy in a manner that would be hard to counteract, given oil production capacity limitations in other countries.

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 or disrupt U.S. and global security in the 21st century. Energy is not just a critical national concern to the United States but also a global one. The rate of growth in energy demand worldwide runs the risk of outpacing affordable, clean supplies unless we can muster not only conservation and evolutionary improvements to existing technologies but also revolutionary new breakthroughs in the energy field.

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, the Environmental and Energy Systems Institute, and the Rice Alliance for Technology and Entrepreneurship, convened a major three-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 more than 50 scientists, policy experts, and industry leaders in the nanotechnology and energy fields, was aimed at investigating how scientific developments, including breakthroughs in the nanotechnology field, might contribute solutions to the global energy problem.

The Rice University energy and 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 also is geared toward broadening 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 is designed to help educate leading scientists and policy-makers about the great technical challenges facing the energy industry today. With its program "Energy and 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 resolution of national and international energy predicaments.

Understanding Our Energy Situation

The strategic and economic reality of U.S. dependence on Middle East oil is costing the United States dearly in terms of military operations and national security. Continued dependence on Middle East oil can potentially place costly constraints on the U.S. freedom to maneuver in international relations. Over time, the United States and other oil-importing nations run the risk of paying ever-higher prices for resources under the control of a small group of nations.

Maintaining plentiful oil and gas supplies needed to meet the 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 2025. As the U.S. faces depleting affordable world hydrocarbon supplies and greater reliance on Middle East resources by 2025 and beyond, it will be imperative to have prepared for new energy sources that do not derive principally from oil or natural gas.

The September 11 attack on the United States has changed the geopolitical landscape in major ways. 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 and natural gas supplies from the Middle East, said Edward Djerejian, director of the Baker Institute, in his opening remarks at the conference.

Among the most important technical challenges facing the world in the 21st century will be energy supply, according to Djerejian. 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. Despite great advances in oil and gas drilling techniques and progress in renewable fuels, more than one-quarter of the world's population has no access to electricity today, and two-fifths are forced to rely mainly on traditional biomass—firewood 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 more than 2 million women and children a year worldwide from respiratory infections, according to the World Health Organization. Energy specialists calculate that, without a major technological breakthrough, well over 1 billion people will still be without modern electricity in 2030.

"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. "The percentage could rise significantly in the future, depending on policies in consumer countries and on the pace of development of new resources and technologies." The U.S. Department of Energy (DOE), in one business-as-usual forecast, predicts that the need for OPEC oil could rise to 60 million barrels per day in 2020 from 28 million b/d in 1998, with the majority of supply having to come from the Middle East, especially Saudi Arabia.

The need for breakthrough energy solutions is all the more important because scientists have become increasingly convinced that the consequences of continuing to burn fossil fuels at current or expanded rates will have deleterious impacts on the global climate.

Martin Hoffert, professor of physics at New York University and author of the widely-quoted *Science* article "Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet," told the conference participants that stabilizing the carbon-dioxide-induced component of climate change is an energy problem. He noted that stabilization not only will require an effort to reduce end-use energy demand but also the development of primary energy sources that do not emit carbon dioxide into the atmosphere. Hoffert argued that a broad range of intensive research and development is urgently needed to produce energy technological options that can allow both climate stabilization and economic development.

Under a business-as-usual energy supply scenario, carbon concentrations in the atmosphere would rise to 750 ppm by the end of the century, a concentration level that would melt the west Antarctic ice sheets and erode coastlines around the globe, Hoffert told the conference. To hold atmospheric CO_2 concentrations to 350 ppm by midcentury—the level targeted by environmental scientists as preventing catastrophic changes—at least 30 terawatts would need to be derived from nonfossil sources, and 15 terawatts of nonfossil fuel energy will be needed to reduce CO_2 levels to modest targets of 550 ppm by 2050.

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 midcentury. According to Hoffert and other speakers, this program—on par with the Apollo space exploration 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.

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, according to Nobel laureate and Rice University Professor Richard Smalley.

Smalley, who also is the Gene and Norman Hackerman Professor of Chemistry and professor of physics, has identified energy as the number one problem facing humanity. In a list of humankind'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 societal problems, such as water, environment, and poverty. According to Smalley, there is no other item on the list able to generate answers to the other problems in the way that energy can. "Energy is unique not only in its ability to give us answers to most other problems," Smalley explained, "but it is uniquely something we can do something about."

Energy is a "quantitative business," noted Smalley. Total worldwide energy use is 13 to 14 terawatts per day, the equivalent of 200 to 210 million barrels of oil per day. Smalley projected 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 satisfy 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 of citizens in the developed world.

Nanotechnology is the art and science of building materials that act at the nanometer scale. It 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 in biotechnology. The "dry side" of nanotechnology, which relates to energy, includes electrical and thermal conduction and provides materials of great strength, toughness, and high-temperature resistance—properties not found in biotechnology. Nanotechnology as a whole, said Smalley, "holds the answer, to the extent that there are answers, to many of our most pressing material needs."

Smalley noted that to find an answer to the 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 separately to gain research dollars for uncoordinated pursuits that lack a clear road map to a better energy future.

What is needed is a vast effort capable of providing a new "nontraditional" source of energy that is at least twice the size of all worldwide energy consumed today and is available by the middle of the 21st century, according to Smalley. This source, he added, 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 so it can provide the basis for sustained economic prosperity for 10 billion people," Smalley pointed out.

Richard Russell, associate director for technology in the Office of Science and Technology Policy in the Executive Office of the President, agreed with Smalley that research and development must be one of the major vehicles that helps address many of the challenges facing the United States, including developing new energy sources and making energy available cheaply and abundantly.

U.S. research and development priorities include several specific nanotechnology and new energy initiatives, most notably the National Nanotechnology Initiative (NNI), the Freedom Car, the Hydrogen Fuel Initiative, and the International Thermonuclear Experimental Reactor project (ITER). According to Russell, President Bush has pledged $1.7 billion over the next five years for these programs.

But, Russell stressed, 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 midcentury before there is significant commercialization. He added that, regarding commercialization of fuel cell vehicles, the government envisions 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, says Russell. "The National Nanotechnology Initiative will set the research priorities in order to address many of these issues," he told conference attendees.

Of the 10 government agencies contributing to the NNI in fiscal year 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 of the $91.1 million spent by the DOE in 2002 to fund the NNI, $36 million was spent on university research; $10.5 million on work supported by Sandia, Los Alamos, and Lawrence Livermore National Laboratories; $34 million on fundamental research; $29 million on NNI grand challenges; $15 million on nanotechnology centers; $15 million on research infrastructure; and $18 million on DOE labs. Unfortunately, less than $10 million of the allocation went into nanoenergy and renewable energy research.

Although many conference participants agreed that the Bush administration's initiatives on energy technology were laudable, concerns remained about whether the level of financial commitment is large enough to achieve needed breakthroughs. Both Smalley and 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 United States. 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 will be required to provide an answer.

The conferees suggested 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 at a new electrical energy grid that can tie all these power sources together.

The International Energy Agency (IEA) projects that the total investment requirement for energy supply infrastructure will top $16 trillion between 2001 and 2030. Of that, the majority of investment will be in the electricity sector, which will require a massive investment of more than $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. Failure to modernize and innovate ahead of this major commitment to new construction threatens to leave the world stuck with the same energy dilemmas in 30 years despite massive investments in energy infrastructure.

A new energy research program—equivalent in size and scale to the Apollo Program—would catapult the United States to unquestionable world leadership not only in 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 also would 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 U.S. science and technology workforce in physical sciences is in serious decline. The energy initiative would create a new generation of scientists and engineers to make the pioneering breakthroughs that will be the basis of new industries, new prosperity, and continued military superiority.

The currently proposed U.S. energy bill is a step in the right direction, Smalley said, as is the Hydrogen Fuel Initiative, but he noted that neither is bold enough to solve the worldwide energy problem. Further, neither initiative is inspiring enough to gain the political high ground in the energy and environment debate or to motivate American youth the way the Apollo Program did in the 1960s. “To do that,” Smalley said, “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.”

Acknowledging the potential benefits for a major science initiative on energy, Thomas A. Kalil, special assistant to the chancellor for science and technology at the 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 told the gathering that government investment in applied energy technology research and development—including fission, fusion, fossil fuels, and renewables—has declined to about $1.3 billion from $6 billion in fiscal year 1997, 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 pitching a new initiative can be extremely important, Kalil told the conference. In seeking new funding, backers of an initiative have the burden of justifying why existing funds can’t simply be reprioritized if the new program is so important, according to Kalil.

Fifty leading scientists, with input from an audience of more than 400 specialists, policy-makers, concerned citizens, and industry officials, concluded at Rice’s energy and nanotechnology conference 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 scientists stressed that advancement of nanotechnology 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 for storage and delivery systems.

The Rice University-led meeting identified 13 energy nanotechnology grand challenges:

1. Photovoltaic solar energy: lower costs by tenfold
2. Achieve commercial photocatalytic reduction of CO_2 to methanol
3. Create a commercial process for direct photoconversion of light and water to produce hydrogen

4. Lower the costs of fuel cells by tenfold to a hundredfold and create new, sturdier materials
5. Improve the efficiency/storage capacity of batteries and supercapacitors by tenfold to a hundredfold for automotive and distributed generation applications
6. Create new, lightweight 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 reduce or eliminate 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 degrees C and at commercial costs
10. Create superstrong, lightweight materials that can be used to improve efficiency in cars, planes, and spacecraft; the latter use, if combined with nanoelectronics-based robotics, possibly enabling space solar structures on the moon or in space
11. Create 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 CO_2 mineralization methods, possibly basalt-based, that can work on a vast scale without waste streams

The Hydrogen Solution: Benefits and Challenges

The focus of new thinking on energy systems in the United States and abroad has fallen squarely on hydrogen. Hydrogen is not an energy source that, like coal, oil, wind, or sun, can be converted into energy. Rather, it is an energy carrier—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 also can be easily converted into electricity or fuel through the use of a fuel-cell or another conversion technology.

World hydrogen production is growing at about 6 percent per year. Its proponents point out that the industrial infrastructure for centralized hydrogen production already exists, including some infrastructure in place in the United States. U.S. hydrogen production is close to one-third of the world total, and approximately 95 percent comes from natural gas. About 47 percent of U.S. hydrogen production—and about the same for hydrogen production worldwide—is made onsite, mostly by steam reforming of oil or gas, and is used in refineries to make gasoline and diesel fuel.

It is possible to refit existing natural gas pipelines to transport hydrogen. In addition, liquid hydrogen also regularly is distributed by truck, and existing capacity could readily be developed to accommodate up to 5 percent of new vehicles. To take advantage of current infrastructure, onboard 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. Using hydrogen as a fuel yields water, which many environmentalists say is preferable from a climate perspective, but reforming hydrogen from hydrocarbons still releases some carbon.

Houston mayor Bill White, former president and chief executive officer of the Wedge Group, 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. 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."

Although the hydrogen business is not "an infant industry," given the existence of a U.S. hydrogen pipeline system, the available methods for extracting H_2 are 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 stressed that, given the current competitive advantage of the United States in the world economy, it is paramount for America to be a leader instead of a follower in any new global energy-based economy that may emerge. Just as American investment in space technology and avionics during the Cold War created American world leadership of the aerospace industry, the U.S. must rise again to be a leader in the energy business. "After all," he said, "this is what is going to assure greater freedom and greater economic security for our nation."

Confirming the energy challenges addressed by other speakers, Carl Michael Smith, assistant secretary for fossil energy in the U.S. Department of Energy, said that hydrogen fuel can be a pivotal part of America's solution to the energy problem. 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 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, noted that a transition to hydrogen is needed to avoid three big crises that are associated with the current oil age: global warming, Third World debt, and the ongoing conflict in the Middle East. He concurred with Carl Michael Smith that fossil fuels likely will remain the dominant energy supply through the middle of the 21st century and 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. "The problem," Rifkin said, "is that if 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 primary near-term fuel to launch the hydrogen transition, particularly in North America, and that hydrogen produced from renewable energy is still 30 to 50 years in the making.

This road map has led some critics to argue that a transition to hydrogen, if it must be derived from traditional fossil fuels, fails to meet one of the principal purposes of a shift in energy systems: to diversify the United States from dependence on imported energy. The U.S. already is facing sporadic shortages in the domestic natural gas market and is expected to become increasingly dependent on imported natural gas, mainly from the Middle East and other OPEC countries, beyond 2020.

The supply challenges that are likely to face the global natural gas market beyond 2020 call into question the wisdom of developing a hydrogen economy based on natural gas feedstock to be converted to hydrogen. Still, policy-makers note the limitations that currently exist to develop hydrogen from renewable sources, and 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. "Over the long term, we want to make our hydrogen from sustainable, renewable energy, and that is where the majority of our hydrogen production research and development is focused," conceded Assistant Secretary of Energy David Garman. The United States has set a target to reduce the cost of producing hydrogen fuel from renewable sources to $3.90 per gallon of gasoline equivalent by 2010 from $6.20 gge in 2003.

Once experts acquire sufficient operating experience, hydrogen could be produced from nuclear, solar, hydro, wind, wave, geothermal, wood, organic waste, and biomass sources, thus allowing a significant future CO_2 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, in the long term, a greater number of large-scale choices for making hydrogen could emerge.

Although hydrogen likely can be extracted from coal through gasification, there is not yet a commercially cost-effective way to sequester the CO_2 left behind in the process. Creating hydrogen by splitting water with electricity (electrolysis) also is rarely cheaper than reforming natural gas except on a very small scale. Thus, unless the process 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.

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 (E.U.). 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, and several major U.S. states, notably California, are proposing carbon emissions restrictions that will stimulate demand for more fuel efficient vehicles, such as hydrogen-fueled automobiles. But the E.U. and U.S. have policy differences over approach. 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 coal and nuclear energy. Japan also has made a strong drive toward 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.

But 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 James Wang, program manager of analytical materials science at Sandia National Laboratories. The DOE is pursuing a number of different hydrogen storage research and development program approaches, Wang told the conference. But he cautioned that none of these systems likely will be able to meet the DOE targets set for 2010 and 2015. The DOE's Hydrogen Fuel Cells and Infrastructure Technologies Program has set target goals that on-board hydrogen storage systems must demonstrate a 6 percent capacity by weight by 2010 and a 9 percent capacity by weight by 2015. 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 percent capacity by weight at ambient temperature and moderate pressure and currently are too expensive to produce.

Hydrogen programs also will depend on development of improved fuel cell technology. Kenneth Stroh, program manager of hydrogen, fuel cell, and transportation programs at the Los Alamos National Laboratory, told participants that fuel cells being developed for potential transportation uses are primarily polymer electrolyte membrane cells, which are considered simpler to put together and more rugged than liquid electrolytes. 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.

There are a number of technical challenges and barriers facing commercialization of fuel cell usage, Stroh stressed, including cost, durability, reliability, power system performance, and issues involving supporting technologies, including hydrogen production and storage, distribution, and dispensing.

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. Nanostructured ceramic membranes, derived from metal-oxane nanoparticles, could present an improvement in the efficiency of fuel cells. Work on using this material to develop ceramic membranes has been undertaken by a team that includes Rice University scientists Mark Wiesner and Andrew Barron, along with Eliza Tsui and Maria Fidalgo-Cortalezzi, and their research suggests 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 Energy

Among the fuels discussed were geothermal, which has world potential of more than 12 gigawatts. Yoram Shoham, former vice president of external technology relations for Shell International Exploration and Production, said nanotechnology can be used to increase the opportunities to develop geothermal resources by enhancing thermal conductivity, improving down-hole separation, and aiding in the development of noncorrosive materials that could be used for geothermal energy production.

Unconventional Natural Gas Technologies

Melanie Kenderdine, vice president of the Gas Technology Institute and former director of policy at the Department of Energy in the Clinton administration, said nanotechnology could be used to enhance the possibilities of developing unconventional and stranded gas resources. World gas consumption is 169 TCF of gas per year, but roughly 50 to 60 percent of the proven reserves consist of stranded resources that are far away from transportation infrastructure and markets. Reserves of coal-bed methane and methane hydrates also are ample but face technical challenges to exploitation and production. Coal-bed methane has grown to account for 7 to 8 percent of the U.S. natural gas output from virtually zero in the early 1980s. While a growing resource, coal-bed methane development faces technical environmental challenges related to the disposal of coal seam waters.

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. Midterm challenges include developing super pipelines; floating GTL platforms; production, regasification, and storage issues; and compressed natural gas transport. Long-term issues to be addressed are production of 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.

Nanotechnology can address the problems associated with accessing stranded natural gas resources by developing nanocatalysts and nanoscale membranes for GTL production and creating nanostructured materials for compressed natural gas transport or long distance electricity transmission.

Gas hydrates also represent a major potential source of untapped energy. 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. Currently, evaluating and extracting from these hydrates is extremely costly and complicated, according to Rice's Walter Chapman, professor in chemical and biomolecular engineering, and Gerald Dickens, associate professor of earth science. 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. Chapman suggested several possible methods for recovering hydrates, including thermal injection, chemical injection, and pressure depletion. Production challenges are compounded by the environmental complications and consequences of exploring and producing gas hydrates, including the accidental release of methane and hydrate impact on seafloor stability.

Coal and Carbon Sequestration

The Bush administration is hoping that hydrogen produced from coal can be used to start a hydrogen economy, and it is investing significant government funding to support research on clean coal technologies. Coal could remain the primary fuel for electricity generation in the United States through 2025, according to William Fernald, portfolio manager of the DOE's Office of Coal Fuels and Industrial Systems. The Clean Coal Technology Demonstration Program has spawned successful NOx control technologies and improvements to integrated gasification combined cycle (IGCC) technology, where coal is gasified before it is burned for power generation, allowing key contaminants such as sulfur dioxide, mercury, particulate matter, and carbon oxides to be removed. There are more than 1,500 mW of IGCC coal-fired plants in operation today, with another 2,200 mW of capacity in design. The long-term goal of the IGCC technology is to achieve near-zero emissions, including carbon emissions, by coupling the IGCC technology with carbon sequestration methods.

To facilitate the latter, the U.S. government is developing several projects, including the $1 billion, 10-year FutureGen Demonstration Project, which will use coal gasification technology to produce 275 mW equivalent of electricity while the closed-loop system also will sequester the CO_2 produced in the process in deep geological formations.

The single largest impediment to the implementation of carbon sequestration on the large scale that is demanded is the cost of capture. According to S. Julio Friedmann, co-author of the recent *Foreign Affairs* article "Out of the Energy Box" and head of the Carbon Storage Initiative at Lawrence Livermore National Laboratory, nanotechnology 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. There are a handful of sequestration modes (geological, soil/plant, and chemical) that are being explored by the geological and other scientific communities, though each has its own range of associated problems.

Soil/plant sequestration, which already is being done, is problematic in that saturation could be reached quickly, Friedmann explained. Chemical sequestration, which is in the advanced concepts stage, currently costs five to 20 times more than geological sequestration.

In order to tackle the scale of carbon sequestration, large-scale results are necessary, Friedmann stressed. He also pointed out that the cost of carbon/hydrogen capture must be dramatically reduced to about $20 a ton from the current $35 to $80 a ton.

Fission

Although the growth trajectory for nuclear fission is not necessarily dependent on 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 waste-related concerns blocking growth in the nuclear fission industry, MIT professor of physics Ernest Moniz told conference participants. "It's all about economics at the moment, and then about handling the waste," Moniz explained. He pointed out that the most interesting impact—in the near term—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. In terms of developing advanced reactors, a nano-structured fuel for gas reactors also could be a very important development.

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. For nuclear expansion to meet the terawatt challenge, "you've got to get the 7-cent cost down," Moniz noted.

There currently are 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 that are concerned about safety and environmental issues, like Germany, are moving to dismantle their nuclear power industries and phase in other energy-supply alternatives. In the United States, nuclear power already contributes about 20 percent of the nation's electricity needs via 103 reactors, but 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. U.S. energy legislation has been proposed that includes $10 billion in loan guarantees to encourage new plant construction in the United States, but so far, such legislative help remains stalled in Congress.

Fusion

The United States is renewing its commitment to develop fusion as a possible source of power generation, with the U.S. joining in the International Thermonuclear Experimental Reactor project. Fusion has the potential ability to produce electricity and hydrogen for the long term through deuterium-lithium fusion reactions, according to Robert Goldston, director of the Princeton Plasma Physics Laboratory. Deuterium and lithium supplies are ample and easily extracted from seawater. Fusion-based energy generation usually results in products with zero carbon emission and short-lived radioactivity. The process of fusion reactions consist of fusing tritium and deuterium atoms, resulting in the production of an alpha particle and a neutron. The alpha particle enters into a plasma self-heating cycle while the neutron is used in tritium replenishment to further support the fusion process. However, scientists cannot yet adequately initiate and control large fusion reactions.

Negotiations for the location of the International Thermonuclear Experimental Reactor (ITER) are continuing; possibilities include northern Japan, Spain, France, and Canada (near Toronto). Goldston stressed, however, that the key issue for resolution resides in determining ITER's potential site, its cost sharing, and its risk allocation, as well as in defining the management of this major international construction project. Three areas of technology are thought to be critical for the development of magnetic fusion energy: high-heat flux components, tritium-generating blankets, and normal or superconducting magnets. Multiscale nanoscience simulations of materials for fusion need to be performed, according to Goldston.

Earth Solar and Other Renewables

Use of renewable energy is an extremely promising option for both reducing greenhouse gas emissions and enhancing diversity of energy supplies. Unlike nuclear energy or coal-derived fuel, solar-derived energy has no massive-scale waste product requiring expensive and environmentally challenging disposal. Environmentally-driven carbon taxes that favor renewable energy might be one policy route that would propel the use of solar technologies. 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 percent renewable energy by 2010. The E.U. directive on renewable energy sources sets a target of 12 percent of energy and 22 percent of electricity from renewable sources, including hydroelectric power, by 2010.

In the United States, state governments are leading the way for the promotion of solar energy. More than 20 states have passed renewable portfolio standard laws, 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.

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, compared with $375 million for nuclear energy science and technology programs and even larger amounts for clean coal technologies.

Nathan Lewis, the George L. Argyros Chair and professor of chemistry at the California Institute of Technology, conceded, however, that solar-derived energy will not play a large role in primary power generation until tremendous technological and cost breakthroughs are achieved or unless unpriced externalities are introduced into the market price.

According to Lewis, the only resource capable of satisfying the carbon-free energy gap of 2050 is solar-derived energy, and the use of photovoltaic semiconductor/liquid junctions currently is considered to be the most economically viable and technically practical solution. Lewis noted that the key 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? “Without policy incentives to overcome socioeconomic

Renewable Resource	Approximate Price per kilowatt hour (1980)	Approximate Price per kilowatt hour (2003)	R&D Goal Approximate Price Target
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

inertia," Lewis noted, "development of needed technologies will likely not occur soon enough to allow capitalization on a 10 to 30 tW scale by 2050."

With a production cost of around 20 to 30 cents per kilowatt hour, solar, or PV, 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 regions with high levels of solar radiation. In dense urban areas with constrained underground transmission and distribution networks, such as San Diego, PV can be competitive if the retail pricing fairly reflects the full value of generation at peak. Solar energy also has made inroads in Germany and Japan, where overall retail electricity prices are higher than in the United States.

Numerous challenges must be overcome to propel renewable energy to replace fossil fuels. Solar energy can be generated through the use of plants, through photovoltaic semiconductor/liquid junctions, and through catalysis, in which water is split using sunlight and produces relatively cheap hydrogen to produce electricity. Researchers will need to offer disruptive solar technology with inexpensive conversion systems and effective storage systems. One option is to reduce the costs by improving the efficiency of photovoltaic cells. Another is to lower costs by enhancing systems to generate thermal solar energy on a larger, more cost-effective scale. Lewis believes that new catalysts and integrated systems need to be developed to help convert intermittent power into base-load power, including new materials to convert sunlight to hydrogen and oxygen. John Mankins, the chief technologist at NASA's Human Exploration and Development of Space Program, told the conference that today's researchers, building on the technology developed in the 1970s, are considering the possibility of designing space solar power systems equipped with self-assembly capabilities.

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

Global electricity demand has been expanding at an average rate of 3 percent per year since 1980, resulting in an overall increase of 88 percent to 13,934 bkWh, up from 7,417 bkWh. World electricity demand is expected to double by 2030, growing at an annual rate of about 2.4 percent, as economic activity is enhanced in developing nations such as China and India. U.S. electricity demand grew to 3,602 bkWh last year from 2,094 bkWh in 1980, or an average annual rate of 2.6 percent. U.S. electricity demand is projected to increase by 1.9 percent 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. This is close to three times higher in real terms that the investment made in the sector over the past three decades. More than $5 trillion 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.

The advantages of developing a new, improved, and more efficient grid system are tremendous. But there are clear technological and political hurdles that must be overcome to achieve this target. New materials and technical approaches will need to be developed and an elaborate plan must be drawn 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, and adaptive controls.

Roger Anderson, the Doherty Senior Scholar at the Lamont–Doherty Earth Observatory at Columbia University, explained that nanotechnology could be part of the solution to today's electricity problems by enhancing the overall efficiency of the electricity delivery system. 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.

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 Terry Michalske, director of the Center for Integrated Nanotechnologies at Sandia National Laboratories. According to Michalske, scientists are still attempting to move from lab-scale experiments to producing devices commercially that are efficient and cost-effective, and this effort is expected to take at least a decade.

A new national initiative is being pursued to produce solid-state lighting (light emitting diodes and lasers) that promises to be 10 times more efficient and two times brighter than incandescent and fluorescent lights. General lighting is responsible for 20 percent of the global energy consumption, and conventional light sources offer very low energy efficiencies of 5 percent for incandescent and 25 percent for fluorescent bulbs. DOE road mapping studies predict that by 2025, government investments in nano-layered solid-state lighting will result in a 50-percent decrease in the amount of U.S. electricity used for lighting and a 10-percent decrease in the total U.S. electricity consumption overall. This will translate into a 17 gigawatt reduction in U.S. demand for electrical generating capacity and the equivalent of more than 28 megatons per year reduction in U.S. carbon emissions.

Nanomaterial applications are expected to play a major economic role in increasing the efficiency of light sources, motors, electrodes, and efficient wear-resistant material. In addition, nanoclusters, able to increase the efficiency of catalytic processes, are thought to hold the answer to reducing the emission of nitrogen oxides.

Beyond applications in materials science and catalysis, there also is great potential for first-order interaction between nanoscience and energy. According to Timothy Fisher, associate professor of mechanical engineering at Purdue University, nanoscience could have profound implications for 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. Direct thermal-electrical conversion is particularly appealing from an engineering point of view because of its ability to eliminate moving parts. 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.

In another perspective on how nanotechnology might be applied to enhance the electricity transmission system, John Stringer, director of the materials and chemistry department at the Electric Power Research Institute (EPRI), said at the conference that the most conspicuous challenges related to creating an efficient grid system include improving transmission capacity, grid control, and stability; providing better power quality and reliability for precision electricity users; and creating the required infrastructure for a digital society.

According to Stringer, 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 that are widely separated and connected to a broad-based grid.
- Moderate-sized generation plants that are close to a user community and connected by a limited-area minigrid.
- Small generation plants that serve a single user.

The second and third of these are generally referred to as distributed energy resources. For the percentage of distributed energy to rise to 25 percent as expected by 2020, new technologies, including potential storage technologies, will be needed so that the electricity industry can respond more effectively to the real time nature of the electrical generation (i.e., electricity is generated at the same time that it is used). Residential solar energy systems are one example of distributed energy. In electricity generation today, power cannot be stored. One envisioned solution to the operation of the electricity system would be to create a means of storage, either by increasing the flexibility for distributed generation to be integrated into the grid system or by introducing other storage mechanisms, such as conversion to hydrogen.

Stringer also noted that the temperature constraints of the lines currently are playing an extremely critical role in restricting their transmission capacity. Thus, nanoscience should try to address the need to increase the strength of the current transmission lines and to reduce heat and related sagging that can lead to service disruptions.

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 increasingly competitive electricity market, there is no doubt that only the most financially viable option will win in the marketplace, according to Peter Hartley, chair of the Department of Economics at Rice University. Hartley suggested that a mass implementation of high voltage direct current (HVDC) transmission lines might be the most financially viable and most efficient technical solution currently available. However, to be able to take full advantage of the tremendous benefits that HVDC transmission can offer, Hartley stressed that new technological developments are needed, including technical approaches for designing converter stations capable of handling high voltages and new nanomaterials that lower transmission line losses and enhance optimum voltage, eliminating the need for superconductivity.

Conclusion

As we move toward the middle of the 21st century, revolutionary breakthroughs in energy science and technology will be vital. Stunning new discoveries in underlying core science and engineering are needed. Breakthroughs in nanotechnology open up the possibility of moving beyond the current alternatives for energy supply. A solution to the global energy problem will require revolutionary new technology as well as conservation and evolutionary improvements in existing technologies.

Transmission and storage of energy—particularly electrical power and hydrogen—are major societal needs. It is in these areas that the majority of scientists in the group believed nanoscience can bring the most immediate benefits, with carbon nanotubes and other nanomaterials creating new opportunities to enhance efficiency and 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 also would 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 across great distances without loss would radically change the economics of moving "energy" supply from distant natural gas sources, distant wind and solar farms, and coal sequestration sites. Howard Schmidt, executive director of Rice's Carbon Nanotechnology Laboratory, believes that development of such a wire is possible within five years with adequate research and development funding. The armchair quantum wire could conduct 100 million amps per square centimeter with a packing density of 10E14 per square centimeter. Expected features of the new materials would be one to 10 times the conductivity of copper, one-sixth the mass, strength superior to steel, and zero thermal expansion. The benefits of the wire, once developed at lower cost and to be polymer dispersible, would be reduced power loss, minimal to no 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.

One vision of the distributed storage-generation (store-gen) grid for 2050 is that of Smalley, who conceptualizes a vast electrical continental power grid with more than 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 and storage buying low and selling high to the grid network. Optimized local storage systems will be based on improved batteries, superconductors, hydrogen conversion systems, and flywheels, 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, and wave power) to the common grid via carbon nanotube, high-voltage wires that minimize loss. Excess hydrogen produced in the system can be used in the transportation sector, and excess residential electricity can be used to recharge plug-in hybrid electric vehicles.

It will take trillions of dollars of investment and several decades to implement this new energy technology on an adequate scale to meet rising energy needs and environmental challenges. 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 in hopes of meeting 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.

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