Future Global Energy Prosperity: The Terawatt Challenge

Richard E. Smalley

The following article is an edited transcript based on the Symposium X—Frontiers of Materials Research presentation given by Richard E. Smalley of Rice University on December 2, 2004, at the Materials Research Society Fall Meeting in Boston.

Recently, I watched a humorous news segment on CNN about the U.S. election, specifically about the Blue States and Red States. In this piece, CNN correspondent Jeanne Moos was touring New York City, interviewing people in downtown Manhattan. Many of them felt rather disenfranchised from the rest of the country, while some actually felt much more affinity for Canada than for what the United States seems to have become for them. After the interviews, up popped this map of the North American continent, with all the Blue States in blue, all the Red States in red, and all of Canada in blue. Written across the top of Canada was "The United States of Canada" and written across the red section of the United States, it said, "Jesusland." It was funny, of course, but it also had a serious side. I have just finished reading a book called *The Faith of George W. Bush* by Stephen Mansfield (Strang Communications/Penguin Group, New York, 2003). I found it to be an excellent book, and I recommend it for those who want to gain some insight into why the folks in Jesusland voted for this man, and to learn about what motivates him.

"A Charge to Keep"

Relative to that, about a year ago I was in the Oval Office, along with a number of other people, when President Bush signed the nanotechnology bill. Most of us expected the event to be something like a five-minute photo-op—sign the bill, shake hands, and leave. Instead, the door closed and for about half an hour the president chatted with us. So here was my great opportunity to talk to the president, and I could not think of a thing to say! But something else noteworthy happened. As Mr. Bush walked around the Oval Office, pointing out items of interest, he focused on a painting by W.H.D. Koerner, titled *A Charge to Keep*, and remarked that he had a personal connection to this painting. The subject of the work is a lone horseman riding western saddle up over a difficult hill, probably someplace out in Texas. The horseman is actually a Methodist circuit rider, and the whole notion is that this rider is on a mission to go out and do good work, specifically, to spread religion and belief in God across the early Western frontier.

The more I think about that experience and the significance of that painting, the more I believe that the concept of "mission" is at the core of what really does motivate our president. Now that we are embarking on four more years of the Bush administration, I have also been pondering just what implications that mission might have for us. With a Republican majority in both the House and the Senate, and four years to move his agenda forward, President Bush has an excellent opportunity to make his mark on history.

> *"At some point, almost certainly within this decade, we will peak in the amount of oil that is produced worldwide."*

Of course, I have my own concept of what the president's mission should be—my own list of "charges to keep" for this administration. There are three core problems that I think the president ought to address, all of which are connected with and impinge on the major issue of energy prosperity: inspiring the next generation of U.S. scientists and engineers, developing replacements for the dwindling fossil fuel resources that have provided a majority of our energy in the past, and finding a solution to global warming. I believe that taking on these challenges would be a deeply moral and wise course of action.

Problem 1: Creating a "Sputnik" Effect

The top charge to keep on my list for President Bush should be to inspire the next generation of U.S. scientists and engineers. Currently, despite all we have done in the past decade, we are not spurring young Americans to go into the physical sciences and engineering. This problem is getting worse as the years go by. Today, the number of U.S. citizens getting degrees in physical science and engineering alone is low—it is at best static, and dropping off. My latest data is for the year 2002 (see Figure 1); the 2003 and 2004 numbers will be a bit lower. The number of Americans getting degrees in all fields of sciences and engineering, excluding psychology and social sciences (the increase coming mostly from the life sciences), is about a factor of two higher but is still static and tapering off.

Another bleak indicator is the waning influence of the United States on the scientific education of students from other countries. For a number of decades, the United States, particularly after World War II, was the premier place for the advancement of physical science and engineering. Now, that is no longer true. In fact, in today's world, Europe and Asia, having recovered from their wars, have dramatically enhanced their education experience and are strongly pushing the physical sciences and engineering, along with the life sciences. This trend has been remarkable. Back in the early 1980s, some of the first Asian students I had in my group—very bright students from China—were among the first who came over during the Carter administration. In the decades that followed, many young Asians who received their degrees here stayed here in the United States. Now, however, a great majority of bright, young, highly motivated Asian scientists are returning to their own countries. More and more, new students are not coming over here at all for their education because it is not necessarily true anymore that to be on the frontier of science and engineering, to be in the cutting-edge research groups, one has to come to the United States. Asian citizens now dominate new PhD production in the sciences and engineering worldwide. They are bright, creative, and extremely hard-working. As current trends continue, they are the future.

So the handwriting is on the wall. We are entering a world where the vast majority of young Americans no longer go into the physical sciences and engineering. This is a major concern. In October 1957, the launch of the Russian Sputnik satellite was a wake-up call for

https://doi.org/10.1557/mrs2005.124 Published online by Cambridge University Press

the United States, pointing to a critical gap in its space technology and sparking a dramatic enhancement in technical and science education programs.

My hope is that President Bush will take up the charge of promoting careers in science—particularly in the physical sciences and engineering. Somehow, if he can find a way, our president should try to do today for science and engineering what John Kennedy so effectively did in the early 1960s with the Apollo space program. We need a new "Sputnik Generation" of scientists and engineers.

Problem 2: Peaks in Oil Production

Another charge to keep that should be at the top of the president's list is the assurance of abundant, low-cost energy for us and our posterity. We are used to living in a world where energy is cheap, and most of that energy was produced right here in the United States. The majority of our oil came from Texas, which was once the premier oil producer in the world and is still the center of the world's oil and gas businesses. Yet, as far back as 1970, we peaked in the amount of oil we could produce in this country. Even though we still think of Texas as the land of people getting crazy-rich discovering oil in their back yard, in fact Texas has been a net importer of energy for over a decade now, with billions of energy dollars a year going out of the state. Saudi Arabia and the Middle East are now the dominant oil sources. Even their oil production, however, will eventually decline. At some point, almost certainly within this decade, we will peak in the amount of oil that is produced worldwide. Even though there will be massive amounts of oil produced for the rest of this century, the volume produced each year will never again reach the amount produced at its peak. This year, 2005, might very well end up being the historic date of that global peak.

Oil, along with gas, is tremendously important. The history of oil is basically the history of modern civilization as we have known it for the past 100 years. As our principal transportation fuel, oil has been the basis of our country's power and prosperity. What will we do when there is no longer enough oil and gas? We do not yet have an answer.

Problem 3: Dealing with Atmospheric CO_2

The third charge to keep is care of the environment for the century to come. Confounding the energy challenge just described is the problem of global warming. For decades now, the average surface temperature of the earth has been going up. During this same time, the CO_2 level in the atmosphere has also been increasing (see Figure 2). The sharp upswing in temperature and CO_2 levels during th e 20th century corresponds with the rise of fossil fuels as the world's primary energy source and the vast increase in global population.

It might turn out that there is no causal connection between CO_2 and the warming of the earth—that if we wait long enough we will see this warming trend go back down, even though CO_2 levels keep going up. On the other hand, most likely there is a causal connection. Even if you were a conservative businessperson, you would probably agree that if a vice president of your corporation told you that there is no need to worry about CO_2 in the atmosphere, you would consider that too risky a belief on which to base the future of your company—let alone the future of the world.

Whatever one's viewpoint, we need to find an answer to this problem. What better time to take on these issues than now, with the great resources available in President Bush's second term. What better time to challenge American young people—and for that matter, the rest of the world—to find ways to solve this global conundrum?

Energy Heads "Top Ten" Global Concerns

Energy is not just "any old issue." Most people, in fact, understand its importance very well. When I have given talks on this subject before, I have often asked people in the audience to name the most critical problems we will have to confront as we go through this century. In every case, after a bit of discussion, the audiences have agreed that energy is the single most important issue we face.

Why is energy always preeminent? When we look at a prioritized list of the

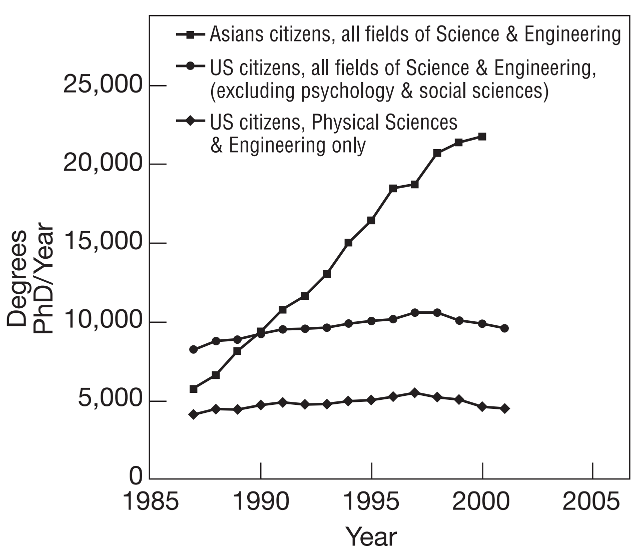

Figure 1. Earned doctoral degrees in science and engineering. Extracted from Science and Engineering Indicators 2, *National Science Board (NSB 04-01), 2004, www.nsf.gov/nsb/documents/reports.htm (accessed April 2005).*

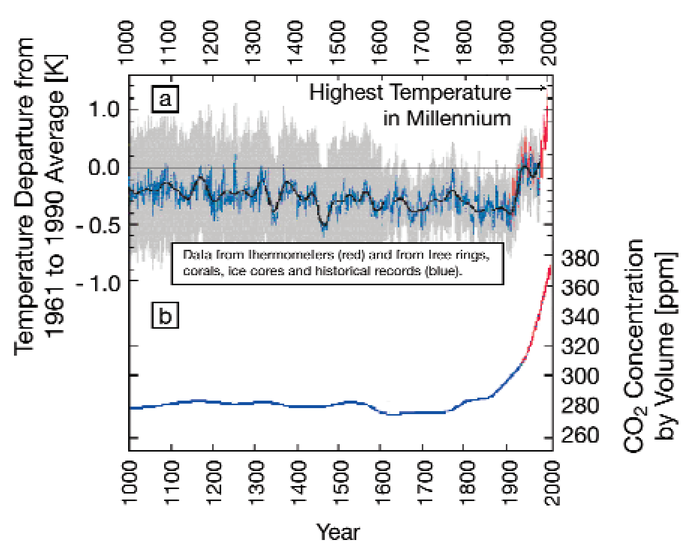

Figure 2. Global warming over the past millennium, by temperature and CO_2 level. (a) Data from thermometers (red) and from tree rings, corals, ice cores, and historical records (blue); (b) data from measurements at Mauna Loa Observatory: Hawaii (red) and ice core records (blue). Courtesy of Marty Hoffert of New York University.

https://doi.org/10.1557/mrs2005.124 Published online by Cambridge University Press

top 10 problems, with energy at the top, we can see how energy is the key to solving all of the rest of the problems—from water to population:

1. Energy
2. Water
3. Food
4. Environment
5. Poverty
6. Terrorism and war
7. Disease
8. Education
9. Democracy
10. Population

Take the second problem on the list, for example: water. Already billions of people around our planet live without reliable access to clean water for drinking and agriculture. As population continues to build and the depletion of existing aquifers worsens, we will need to find vast new sources of clean water. Luckily, our planet has huge resources of water, but most has salt in it, and it is often thousands of miles away from where we need it. We can solve this problem with energy: desalinate the water and pump it vast distances. But without cheap energy, there is no acceptable answer.

Without abundant fresh water, how are we going to provide the food for our burgeoning worldwide population? Without cheap energy, how are we going to produce the fertilizer, till the soil, harvest the crops, process them, package them, and deliver them to markets?

Energy likewise plays the dominant role in determining the quality of our environment, the prevention of disease, and so on, down the entire list of global concerns.

In short, energy is the single most important factor that impacts the prosperity of any society. In today's world, with about six and a half billion people, only about one and a half billion of us enjoy modern energy at the level to which we in this audience are accustomed. It is impossible to imagine bringing the lower half of the economic ladder of human civilization—about three billion people—up to a modern lifestyle without abundant, low-cost, clean energy.

Right now, we do not have the technology to enable that. If we do not solve the energy problem for these billions of people who are basically disenfranchised, how can we imagine that we are going to avoid a future that has ongoing war and terrorism at levels that exceed what we have already known in this past unprecedentedly violent 20th century, a century in which we had less than half the population we have now, a century that was blessed with ever-abundant cheap oil?

"To give all 10 billion people on the planet the level of energy prosperity we in the developed world are used to, a couple of kilowatt-hours per person, we would need to generate 60 terawatts around the planet—the equivalent of 900 million barrels of oil per day."

Continuing down the list of problems, we can make strong arguments that energy would be tremendously enabling in solving all of these issues, even population. The good news about population is that around the planet, the fertility rate is dropping. Whenever a nation begins to develop, the fertility rate generally drops. In fact, in many sections of the developed world, fertility rates are now so low that we need to increase them. During our lifetime, we will see worldwide population growth continue to slow down, then level out at somewhere around 10 billion people. It probably will not go higher than that. Our challenge then is to make it possible for 10 billion people to live a reasonable lifestyle on this planet. That is certainly our charge to keep.

The Terawatt Challenge

To provide the technology for accomplishing our energy goals, what we need to do is to find the "new oil"—a basis for energy prosperity in the 21st century that is as enabling as oil and gas have been for the past century. The sheer magnitude of the energy industry makes this an extremely difficult task. Studying the problem in depth, we come to appreciate the fundamental nature of the scientific breakthroughs necessary to activate these new energy sources.

In 2004, we consumed on average the equivalent of 220 million barrels of oil per day to run the world. Or, if we convert that into watts, what ran the world was about 14.5 terawatts. The vast majority of this energy was from oil, gas, and coal. Fission and biomass were significant players. Most of this biomass was the energy source for the bottom half of the global economic ladder, three billion people or so. A great deal of that was unsustainably burned vegetation, cow dung, and other materials that are used where modern energy is not available or affordable. Quite a bit of the 14.5 terawatts was hydropower, but we have already tapped most of the available hydropower. An incredibly small amount of that energy, about 0.5%, was solar, wind, and geothermal, with geothermal composing the largest part.

To solve the energy challenge, we will have to find a way to produce, every day, not just what we are producing right now, but at least twice that much. We will need to increase our energy output by a minimum factor of two, the generally agreed-upon number, certainly by the middle of the century, but preferably well before that—despite the fact that oil and gas will have long since peaked. Considering that many people on the planet are not using much energy at all and that new energy sources have yet to be developed, billions of people would still be living without modern energy. To give all 10 billion people on the planet the level of energy prosperity we in the developed world are used to, a couple of kilowatt-hours per person, we would need to generate 60 terawatts around the planet—the equivalent of 900 million barrels of oil per day.

Where could that amount of energy ever come from? The goal of finding it seems impossible. Nevertheless, we need to acquire the ability to produce energy at this magnitude in a sustainable, continual way and do it at a low-enough cost—a couple of pennies per kilowatt-hour—to enable global prosperity.

Searching for the enormous amounts of energy that could accomplish this goal, we find, remarkably, that our biggest resources are in the areas where we generate hardly any energy at all right now—solar, wind, and geothermal.

Reversing Current Energy Trends

By 2050, if we have solved the problem, the world's energy breakdown will probably look like a reverse of what it is today. Oil, hydroelectric, coal, and gas (in that order) would supply the least amount of energy, with fusion/fission and biomass processes being somewhat larger players, and solar/wind/geothermal resources providing the majority of the world's energy. This new breakdown represents a revolution in the largest enterprise of humankind, an energy industry that currently runs about $3 trillion per year.

Getting there will be incredibly difficult. If we knew today how to transform the makeup of our energy mix by exploiting fission/fusion, solar, or wind, it would take an inordinate amount of time. If I could go out tomorrow and turn on the switch of a new power plant that would produce a thousand megawatts of power from some new, clean, carbon-free energy source, I would have to turn on a new plant every day for 27 years before I generated even 10 terawatts of new power.

https://doi.org/10.1557/mrs2005.124 Published online by Cambridge University Press

Ten terawatts plus 14 terawatts does not add up to even half of the 60 terawatts we will eventually need. Of course, we do not currently have the technology to build a fleet of nuclear fission breeder reactors—let alone a solar or geothermal plant—that could produce that amount of energy cheaply. I believe that if we do not find a way to build such power plants over the next decade, or at most two, this 21st century is going to be very unpleasant.

Finding Alternatives to Oil

Where are we going to find new energy? The list of possible sources will not produce enough of an energy impact. True, early on we could achieve some progress with conservation and efficiency. In the developed world, with its top billion people, it is possible that we could effect substantial energy savings. In the undeveloped world, however, conservation is meaningless, because so little energy is used. Even with high efficiency, then, we are still going to need vast new energy sources. Hydroelectric, as I mentioned, is mostly tapped out. Biomass could be very significant were we not confronted with a global food and water crisis. Essentially, we are trying to move from a situation where we pull our energy out of the ground in oil and gas to one where we must grow energy crops every year at a very high rate in order to produce just one terawatt. This would require a revolution in agriculture at a time when we are struggling just to sustain our current production levels for food.

There has been a lot of talk about the hydrogen economy, which I believe is, despite its virtues, likely to remain a distraction from the real, practical solutions to our energy needs. Hydrogen is not a basic energy source. Rather, hydrogen is a way of storing energy and moving it from here to there. Unfortunately, it does not do either of these tasks very well. For these tasks, electricity is a much better answer. Electrical power transmission is a superb way to move energy from one place to another, and at least on a small scale, electrical power can be stored.

The biggest resources right now are in fossil fuels—oil, gas, and coal. We certainly have enough coal for another five decades or so, if we expand production. But we cannot simply burn all that coal and assume that the CO_2 problem is going to go away, or that we can ignore it, or get around it. The only way now imagined to deal with the enormity of this issue is sequestration, finding places where CO_2 can be securely stored. Given that the average lifetime of CO_2 in the atmosphere is greater than 100 years, we would need to store it so that much less than 1% escapes from the ground every year. We could certainly build such storage facilities in special locations for small amounts of CO_2, but to solve the problem for the planet, we would need to build them all over the world and be able to verify that they will safely store tens of gigatons of carbon per year, and do this year after year. There is no known way to do this. Putting CO_2 in the ground does not generate any money; instead, it is more like taking money and throwing it down a hole. I have yet to hear a compelling business case for sequestration.

Solar Solutions

I do not believe that our energy problems can be solved through the burning of fossil fuels. Yet, these fuels currently represent our primary energy resources, the only ones we know how to use to our economic advantage. The energy sources that could genuinely respond to our future needs are all basically from nuclear sources, either human-made nuclear fission or nuclear fusion reactors, or the nuclear reactions resulting from the spontaneous decay of uranium and thorium in the rocks of the earth (geothermal energy). Then there is that great big hydrogen fusion reactor up in the sky, the sun. That is where the truly big resources can be found.

Yet, the mention of "solar energy" in any kind of conversation about world energy will sometimes elicit a wry smile from certain people—for example, from some people in my home town of Houston, where the favorite unit of energy is the barrel of oil. By saying "solar energy," we show that we know nothing about how big the energy industry is, or what the "real" energy people are doing.

Solar is not now a major player in worldwide energy. To those people with wry smiles, however, I would like to point out that if they like nuclear reactors as a big-time, big-boy energy solution, they should be impressed by a nuclear reactor that has been going strong for billions of years. Without doing anything, we enjoy the effect of 165,000 terawatts of power hitting the earth's disk every moment of every day. This vast nuclear reactor has gone through over 4 billion years of shake-down trials, and it is probably going to continue providing stable performance for at least another couple of billion years. We are bathed in energy.

The truth is that there is plenty of energy hitting the surface of the earth. Nate Lewis of the California Institute of Technology likes to demonstrate that we could cleanly meet the world's entire energy needs, two kilowatts per person for 10 billion people, by applying the following elegant solution (shown in Figure 3). On a global map, identify six rectangular spaces located in areas of high solar radiation, create 10% efficiency, then collect that power, which would be about 20 terawatts of electrical power, the equivalent of 60 terawatts total energy power at a 30% energy conversion. That would totally solve humanity's energy problem and

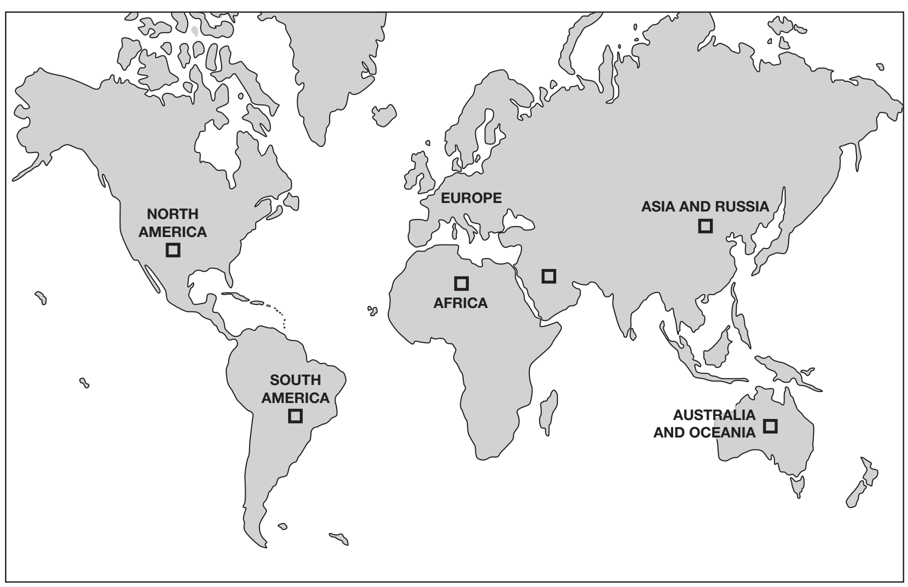

Figure 3. Solar cell land area requirements in which the six boxes (100 km on a side), located in areas of high solar radiation, can each provide 3.3 terawatts of electrical power to a total of ~20 terawatts of electrical power. Courtesy of Nate Lewis of the California Institute of Technology.

allow us to concentrate on other problems for the rest of this century.

Although there is plenty of solar energy, we do not have the technology to develop it at a few pennies per kilowatt-hour. Right now we could do it at about 20–50 cents a kilowatt-hour (averaged over a day/night cycle), but that would be far too expensive. If you believe with me that we absolutely need to provide the planet's 10 billion people with the potential to pursue a fulfilling lifestyle, where they have a roof over their heads, enough food to eat, sufficient mobility, communications, and the capability to build homes and develop cities, then you will agree that we have to revolutionize the world's energy system. We need cheap, clean energy in vast amounts.

The Distributed Energy Grid

The hardest problem will be finding viable replacements for the energy sources we have been relying on for decades, oil in particular. Oil is not only a great primary energy source, it is also the best form in which to transport energy over continental distances and across oceans. Most of the oil we import comes across the sea in what has become a very efficient process—putting the oil in tankers. When we buy a gallon of gas, the actual dollar cost for that transportation is less than 10%.

In contrast, it is much less efficient to transport natural gas in this way. Natural gas has to be cooled to liquefy it to form LNG before it goes into the tank. That in itself takes a lot of energy. The LNG tanker is more expensive, resulting in much higher transportation costs, and it takes more energy to re-gasify and compress the gas for storage, pipeline transportation, and use when it reaches its destination. We are going to find out exactly how high these costs will be as time goes on, since most of our natural gas will eventually have to be imported. Transporting liquid hydrogen would be vastly more expensive.

"Energy as Energy"

How, then, around the year 2050, are we going to transport energy over vast distances while minimizing the costs and getting the amount of power we need? The best answer would be to transport energy as energy, not as mass. Instead of storing energy in some chemical form, keep it as pure energy. There are essentially only two ways to do that. We could microwave energy up to a satellite and bounce it back down, or we could run it along wires on the earth's surface. We will do both, but mostly we will use wires.

Enabling the Grid: Local Energy Storage

With this energy distribution model, the entire North American continent, all the way from the Arctic Circle down to Panama, would be wired together in a giant interconnected electrical energy grid. Indeed, we are already very close to that now, except that in the new grid, by the middle of the century, there would be two critical additions. The first would be local energy storage. Every one of the hundred million or so sites consuming energy in this grid would have its own storage unit—the equivalent of an uninterruptible power supply that not only gives a home computer a few minutes of power during an outage, but also can supply each of our houses or businesses with 12–24 hours of full operation.

> *"There has been a lot of talk about the hydrogen economy, which I believe is, despite its virtues, likely to remain a distraction from the real, practical solutions to our energy needs."*

Imagine that by mid-century, nanotechnologies, new materials, and possibly new physics will have enabled us to create local storage units for electrical energy that are not much bigger than this lectern. The units would store 100 kilowatt-hours, which is enough to run a normal house for 24 hours. If we tried to run this type of unit right now using a lead acid battery, the unit would have to be about 20 times this volume—the size of a small room. The cost would be around $10,000. I believe that if we really put our minds to it, we could think of a way to shrink the unit volume significantly and drop the cost dramatically. There must be many technologies that would fit inside this "box" and store that amount of energy.

On the other hand, if we think about storing energy on a much larger scale—say, that of a big power plant that produces a gigawatt of power—the possibilities are very limited. We could pump water uphill and run it back down again (if we had the water and the land), or we could compress air (if we had large caverns to store it in). Large-scale energy storage technologies do exist, but, except in special locations, they lack the practicality and desirability of small-scale storage.

Commercializing Local Energy Storage

I believe that creating an efficient local storage solution should be one of our prime energy targets. Let us develop what effectively would be a new major-appliance industry. Since our proposed unit is very small, it could be easily marketed to each one of those hundred million or so energy customers who are seeking local storage. Since the unit would have to be inexpensive—a few thousand dollars at most—customers who were not satisfied could replace their units or trade up to a better model, as they do now with other technical products such as computers. It would be a way to "PC" this critical aspect of the energy industry. Every five years or so, on average, customers would opt to upgrade their storage unit, based on local economic incentives and newly available product improvements driven by free markets and entrepreneurship. Inventive minds would be continually evolving the best possible answer to what fits inside this box.

Then, every one of those sites in the electrical energy grid would be able to use one of these units to buffer the grid's energy fluctuations. Real-time pricing for individual electrical power usage would give each customer the incentive to buy a unit that could absorb the power needed to generate 100 kilowatt-hours of electricity in the six-hour time period when energy is cheapest on the grid. People who needed more than 100 kilowatt-hours of power or needed virtually trouble-free energy for longer periods could simply buy additional or larger units. That would be the customer's decision.

Basically, this local unit would solve the energy storage problem. With that solved, it would now be possible to get most of the energy on the grid from "unreliable" or episodic sources, like wind or solar. Without a local storage solution, however, we could not rely on these "other" energy sources to supply large amounts of energy on the grid, at least not at levels above 10–20%. Above those levels, we would need to have all the reserves in place, ready to provide electrical power when the sun stopped shining or the wind stopped blowing. Local energy storage would get us past that problem and give us an extremely robust, terrorist-resistant, delocalized electrical energy system.

Completing the Grid: High-Voltage Transmission Lines

In addition to a local system, one other innovation is needed on the grid to make it work. We need the capability to transport electrical power in hundreds of gigawatts over thousands of miles. High-voltage transmission lines would be very efficient for this purpose. In fact, we already have dc lines that carry electricity for 1500 miles with fairly low loss. They carry only about 1 gigawatt, or 1000 megawatts, however, not the 100 gigawatts we need. If, through new technology, we could figure out how to transport electricity over wires that would deliver power thousands of miles away from where it is generated, and do that for several pennies per extra premium, we could make the whole North American continent energy– self-sufficient.

Everybody Gets to Play

That goal is not as impossible as it might seem. There are places on this continent that experience extremely intense solar radiation that is very reliable. There are also highly remote places that most people would not object to as sites for nuclear power plants—places that would not be in anybody's backyard. Today, most people are not even aware of what fraction of their electrical power comes from a nuclear plant, or where that plant is located. They would be even less aware if the facility were out in, say, Hanford, Washington, my favorite place to put nuclear power plants. So, combining long-distance electrical power transmission with efficient local electrical storage gives us access to energy produced by any new technologies, as well as any existing power plants regardless of their technology or precise location. In the brave new energy era, everybody gets to play.

Conclusion

Innovations in nanotechnology and other advances in materials science would make it possible to transform our vision of plentiful, low-cost energy into a reality. By developing new technologies, marshaling the excellent resources of organizations like the Materials Research Society, and developing the talents of a new generation of scientists and engineers, I believe that we can solve even our most critical energy problems.

For Further Reading: David Goodstein, *Out of Gas: The End of the Age of Oil* (W.W. Norton & Co., New York, 2004); Paul Roberts, *The End of Oil: On the Edge of a Perilous New World* (Houghton Mifflin, New York, 2004); Daniel Yergin, *The Prize: The Epic Quest for Oil, Money, & Power* (Free Press, New York, 1991); Kenneth S. Deffeyes, *Hubbert's Peak: The Impending World Oil Shortage* (Princeton University Press, Princeton, N.J., 2001); Matthew R. Simmons, Simmons & Company International, www.simmonsco-intl.com (accessed April 2005); Association for the Study of Peak Oil & Gas, www.peakoil.net (accessed April 2005); Gal Luft, Institute for the Analysis of Global Security, www.iags.org (accessed April 2005); Amory Lovins, Rocky Mountain Institute, www.rmi.org (accessed April 2005); M.I. Hoffert et al., *Science* **298** (November 1, 2002) p. 981; and "Basic Research Needs for the Hydrogen Economy: Report of the Basic Energy Sciences Workshop on Hydrogen Production, Storage, and Use, May 13–15, 2003," www.sc.doe.gov/bes/hydrogen.pdf (accessed April 2005).

Richard E. Smalley *is the 1996 Nobel Laureate in chemistry and a University Professor and professor of chemistry and physics at Rice University. He received his BS degree in 1965 from the University of Michigan. After a four-year period as a research chemist with Shell Chemical Company, he earned a master's degree in 1971 and his PhD degree in 1973 from Princeton University. At Rice University, he rose rapidly through the academic ranks, being named to the Gene and Norman Hackerman Chair in Chemistry in 1982. Smalley was a founder of the Quantum Institute in 1979 and served as chair from 1986 to 1996. In 1990, he became a professor in the Department of Physics and was appointed University Professor in 2002. Smalley was the founding director of the Center for Nanoscale Science and Technology at Rice in 1996 and is now director of the university's Carbon Nanotechnology Laboratory. Among Smalley's other awards and honors are election to the National Academy of Sciences (1990) and to the American Academy of Arts and Sciences (1991), the International Prize for New Materials (1992), the E.O. Lawrence Award of the U.S. Department of Energy (1992), the Franklin Medal (1996), the Distinguished Public Service Medal from the U.S. Department of the Navy (1997), the Glenn T. Seaborg Medal of the State of Texas (2002), and the Lifetime Achievement Award from* Small Times Magazine *(2003).*