Powering the Planet

Nathan S. Lewis

The following article is an edited transcript based on the plenary presentation given by Nathan S. Lewis (California Institute of Technology) on April 11, 2007, at the Materials Research Society Spring Meeting in San Francisco.

I am humbled and honored to be here to tell you about a topic that is dear to everyone's heart—and vital to the future of our planet. My colleague, Richard Smalley, gave a presentation[1] on this topic several years ago, at a similar MRS plenary session. Over the last few years of Dr. Smalley's life, he and I worked together, traveling across our country to deliver a message about a subject that we—like many others, both scientists and lay people—have come to believe is unequivocally the most important technological problem in the world: our global energy future. That is an incredibly powerful statement, one that during the next hour I hope to ably defend.

My presentation will offer a perspective similar to Dr. Smalley's, although through a different lens. In this talk, I will not focus on the science that my team is doing in the laboratory. That will be left for the specific venues where we, as scientists, talk about science. Instead, I am going to talk about the bigger picture of our energy challenge. I believe that we researchers, the modern-day spokespeople for this challenge, have a responsibility to understand it and its terms so that we can help communicate why it is critically important, do something about it through our own research efforts, and present our message effectively to the general public. Compared with all the other technical issues facing us in the world today, why is energy the most important? I believe that energy, not the dollar, is the currency of the world. It is the joule that drives every economy and gives people a way out of poverty. Without energy, we cannot find or administer medicine to cure disease, we cannot purify water, we cannot drive our cars; we cannot go to work, operate computers, or even study at night. Because our modern lives run on various forms of energy, we need to find a way to manage our energy challenges before they begin to manage us.

To provide some balance to this talk, I would like to state that I am not the only one saying that energy is the most important technological problem in the world. Scientists are saying it, journalists are saying it, the pundits are saying it. Dr. Smalley testified in Congress that energy is indeed the most critical of current-day issues. He stated that it "is the single most important challenge facing humanity today."[2] *Chemical & Engineering News* described energy as "the single most important scientific and technological challenge facing humanity in the next century."[3] Author and syndicated public affairs columnist Thomas L. Friedman believes that the need to achieve energy independence in America is "blindingly obvious."[4] Susan Hockfield, president of the Massachusetts Institute of Technology (MIT), in her inaugural address, said that "it is our responsibility to lead in [this] mission" to deal with the energy problem. As a country, we are not pursuing solutions to our energy problems with anywhere near the same intensity that we are, for example, leading in efforts to cure disease. It is up to researchers, therefore, to help formulate and lead the initiative to aggressively address our energy issues. Otherwise, as many reports have unequivocally shown—including the report[5] that Richard Smalley and I contributed to and the solar report from the U.S. Department of Energy[6] that I co-authored—it will simply be too little, too late. That is something we simply cannot afford to have happen.

This presentation will comprise three parts. The first part will focus on the scale of our energy challenge, which is what makes the problem truly severe and difficult. The second part will be a reasonable scenario of what the future is likely to bring, a description of the problem. The third part will center on the possible solutions to the problem.

Scaling the Problem

The problem of producing energy in a sustainable way is such an enormous one that we need to calibrate its scale. Looking at powers of 1000, PDAs have a mean load of about 1 W. Toasters are 1000 times more energy-intensive, about 1 kW, which is, by the way, about the average typical home electricity demand. A thousand toasters would consume about a megawatt, the power required to run a small jet engine. A thousand jet engines would consume a gigawatt, which is about the electrical output rate of a typically sized nuclear fission power plant. Moving to a much grander scale, consider a photo of the world at night, from space, showing the millions of pinpoints of light on Earth. A thousand nuclear power plants would be required to generate enough electricity to satisfy global demand, which represents about 1 trillion watts, or 1 terawatt, of electricity.

That 1 trillion watts, however, is only a fraction of the total thermal load of human energy consumption on our planet. We now actually use over 10 times more energy than that to run the world. Taking the number of joules of energy consumed by humans in a typical year, and dividing that by the number of seconds in a year, yields an average burn rate of about 13 trillion watts, or 13 TW. This unit analysis, which Martin Hoffert and I have tried to popularize, is the basis for what Dr. Smalley brilliantly adopted as "the terawatt challenge." That challenge is for humans to sustainably produce enough energy to meet that global 13 TW need.

Out of that 13 TW, the United States consumes about 3.2 TW, or about a quarter of the total. The U.S. National Energy Policy report[7] expresses that amount in quads (a quadrillion Btu), stating that the U.S. annual energy consumption is about 99 quads. Recalculating that figure in SI units, however, yields the same result: an average burn rate of 3.2 TW. From this point on, I will not discuss the United States' energy concerns in isolation—although that topic is a vital part of our national political debate—because our concerns about energy stem primarily from our concerns about national security. Historically, humans have always been willing to go to war to acquire or defend natural resources. If, for example, another country has resources that we need, but refuses to sell them or grant access to them, human experience has shown that we may see this as a clear mandate to challenge them militarily in order to attain those resources.

Sources of Current Global Energy Consumption

Taking a global rather than national perspective, I am going to focus on the 13 TW that are consumed worldwide to run our planet (see Figure 1a). Eighty-five percent of that amount is represented by fossil energy, with oil, gas, and coal contributing

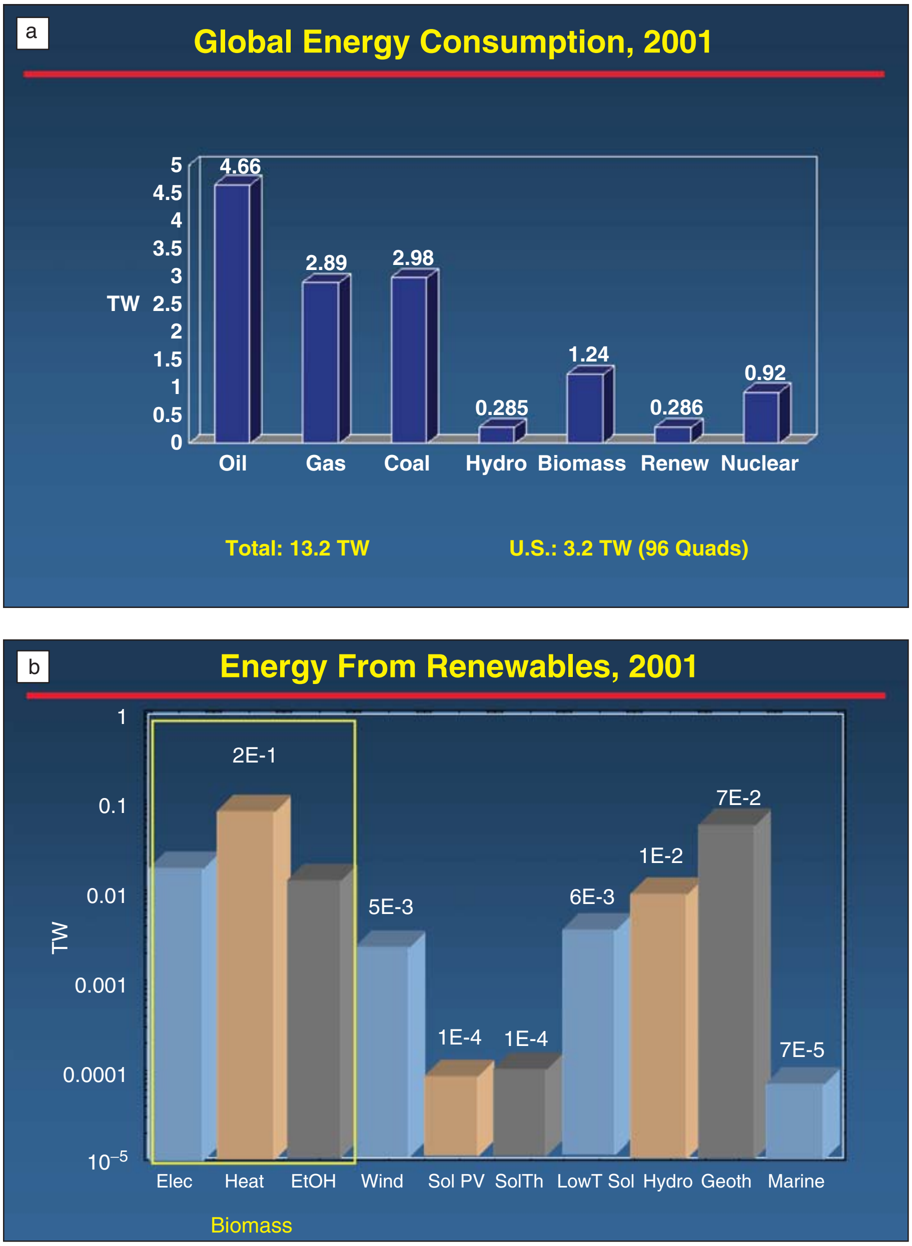

Figure 1. (a) Global consumption of various energy sources (2001). (b) Renewable forms of energy represented 2% of global energy consumption in 2001.

roughly equal amounts. Hydroelectricity accounts for a small part, about two-tenths of a terawatt. The segment of biomass that is unsustainably burned constitutes 1.2 TW of our total rate of energy consumption. However, the total amount of sustainably burned biomass is part of the total categorized as "renewables" which represents 0.28 TW. Biomass is renewable when replanting and reforesting of crops are taking place at a rate commensurate with the burning of those crops for energy. The heat produced by nuclear power represents 0.9 TW out of the 13 TW.

It is interesting to note that of the 0.9 TW of power generated by nuclear fission plants, only 400 GW, or about 30%, is converted into electricity. To put it another way, that 0.9 TW is the heat content produced by the nuclear fission process, in the same way that 2.98 TW is the heat content of burning all the coal consumed in a given year. This example dramatically illustrates the difference between the amount of primary energy consumed relative to the amount of secondary energy delivered to the end user.

Renewable forms of energy represent 2% of our total energy consumption. I have used a logarithmic scale to put these various renewable contributions into relative context (see Figure 1b).

- For biomass—divided somewhat evenly between electricity, heat, and ethanol—the total sustainable mean power produced is only 10^{-1} TW out of the 13 TW global primary power consumption. Here, we are referring only to the sustainably burned portion of biomass that comes from sources such as energy farms in Brazil.
- Wind produced one part in 10^4 of our energy consumption.
- Solar electric power production, or solar photovoltaics, is growing rapidly, but from a small base, providing 10 parts in a million of our total global primary power.
- Other renewable resources—solar thermal, geothermal, marine, and tides—are all small players, representing only fractions of the overall primary energy supply.

At this point, an obvious question arises: Why does renewable energy not compose a greater fraction of the current total energy production? One of the major reasons is an economic one. Energy is a commodity, and its use is shaped not only by policy but also, in large part, by cost. Consider a comparison of the estimated costs for electricity production from various primary energy sources for the year 2002 (Figure 2a). These estimates are average three-year fully amortized costs in the United States, but they are representative of trends around the world.

Coal, on average, is the least expensive way to make electricity today, costing 1–4 cents per kWh. The 4 cents incorporates the cost of capitalizing, building, and operating the coal-fired plants over their 40-year lifetime, while the 1 cent is the short-run marginal cost, or the cost of literally adding more coal to the fire.

Next in line on our scale is electricity from natural gas, which costs 2.3–5 cents per kWh. Natural gas was favored in the United States for some time, when we had certain SOx and NOx regulations, but gas has now been replaced by coal as the

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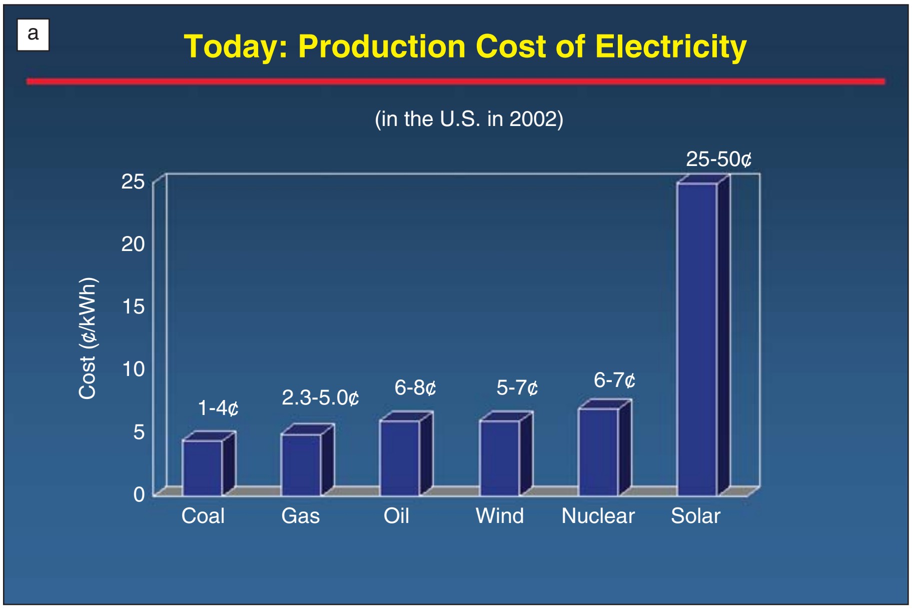

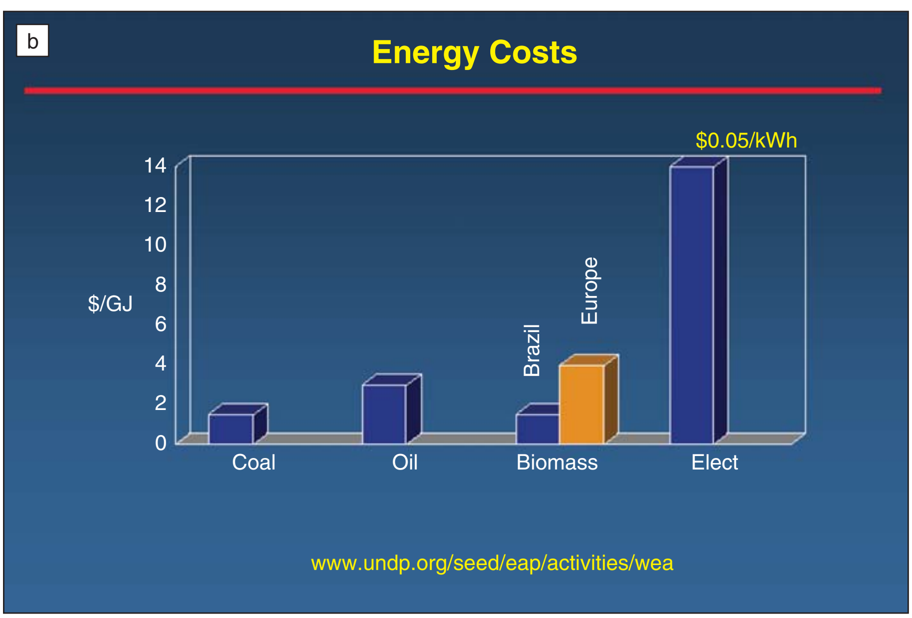

Figure 2. (a) Estimated costs for electricity production from various primary energy sources in the United States (2002), in cents per kilowatt-hour. (b) In a comparison of the values of coal, oil, biomass, and electricity, coal is the least expensive (at about $2/GJ), followed by oil, then biomass. Electricity, at $0.05/kWh, actually costs $14/GJ. When electricity is made from coal, it will be more than three times more expensive per joule delivered than the cost of coal.

favored economical choice for electricity generation.

Producing electricity from oil costs 6–8 cents per kWh. It is foolish to burn oil at a fixed site to make electricity, which we did at one time in the United States. During the oil crisis of the 1970s, much of the energy that we conserved from oil resulted not from conserving vehicle mileage, but from eliminating oil as a fuel in the electric power system. Now that we have accomplished this, there should be no going back.

Wind, in favorable sites, can produce electricity for 5–7 cents per kWh. That cost may seem comparable to the cost of electricity from coal or gas, but in all fairness, it does not involve any expenses for storage and is not base-loaded. Wind power peaks when the wind blows strongly in a favorable site.

The cost of nuclear electricity generation at scale, 6–7 cents per kWh, is predicated on the construction of 1000 new nuclear fission plants. A study at MIT led by John Deutch and Ernie Moniz[8] showed that if 1000 nuclear power plants were built, the cost of the electricity produced by them could then probably be brought down to 6–7 cents per kWh. It must be added, of course, that the world, thus far, has built only about 430 such plants. If you ask the CEOs of electric utilities in the United States why we have not permitted a new nuclear power plant to be built in this country in the past 30 years, they will not cite a lack of public acceptance as the prime reason. Virtually all of them will say that, right now, cost is the major factor, because electricity from nuclear power is more expensive to produce than electricity from coal or gas.

The most expensive electricity comes from renewable sources. Solar electricity (solar photovoltaics) costs 25–50 cents per kWh to produce, while solar thermal electricity, in peak sites, can be generated for 10–15 cents per kWh.

There is a conventional wisdom that says that renewable wind, solar, and nuclear sources could compete fairly with fossil fuels for energy (not electricity, high-value energy) production if the production costs of the renewables could be brought down by only a few cents per kWh. That is unfortunately not true. Again, in the photo of the world at night, the millions of lights shining from earth represent a part of our electricity usage, which is in total only 10% of our total energy consumption. That 10% is high-value energy, while the 90% of the energy that runs the rest of our economy is low-grade energy. That 90% represents the heat used to make products in factories, the heat used to heat and cool our buildings and homes, and the energy used to drive our cars.

To assess the true value of electricity against lower-grade forms of energy, we will evaluate its cost per joule, expressing that cost as dollars per gigajoule (see Figure 2b). In a comparison of the values of coal, oil, biomass, and electricity, coal is the least expensive (at about $2/GJ), followed by oil, then biomass. Electricity, at $0.05/kWh, actually costs $14/GJ. At a nickel per kWh, then, electricity is expensive energy. When electricity is made from coal, it will be more than three times more expensive per joule delivered than the cost of coal, because a coal-fired power plant is only 30% efficient. In another example, using $0.05 per kWh of electricity to heat a house would result in a monthly home heating bill of about $1000, which is not a realistic solution even for the developed world.

For the developing world, the picture is even grimmer. Because the cost of $14/GJ electricity is greater by a factor of five than the cost of $2/GJ for coal, renewable energy costs would have to decrease by a factor of 25–30, rather than by a factor of 4–5, in order for them to compete economically in the total energy picture, as opposed to the portion of secondary energy that is consumed as electricity. Creating viable forms of renewable energy for developing countries such as China or India would therefore require another factor of five to make their economies run on a fair energy basis.

The Impact of Energy Reserves and Resources

Some people think this scenario of global energy consumption will change naturally. In that view, pure market forces will raise the price of our existing energy technology just as our supply of fossil fuels is nearing depletion, then the curves will cross at some point in the future and renewables will become the market favorites. We can best evaluate that possibility by taking a detailed look at our current energy reserves and resources.

"Proven reserves" are the quantities of fossil energy that the U.S. Securities and Exchange Commission allows a company, with 90% confidence, to book and to tell its stockholders it has in the ground. "Resources" are fossil energy supplies that the U.S. Geological Survey (USGS), with 50% confidence, estimates are still left to be discovered in the ground. The critical factor here is understanding not just what energy sources we know are there now, but also what sources are available for humans to consume on our planet. That is the resource base.

To determine how long our current energy supply is likely to last, I will leave aside economic and geopolitical considerations and focus on a purely geologic estimate of the global energy picture. If you take the proven reserves and the estimated resource base of the various fossil fuels—oil, gas, and coal—and divide that number by the burn rate for each of those fuels, you can compute approximately how long each fuel will be available for energy production. To do this calculation, I used peer-reviewed numbers for both the proven reserves and the estimated resource base, and fuel burn rates for 1998, for which there are solid consumption data for each type of fuel. Looking only at proven reserves, the results—depending on whether or not you include unconventional resources—show that we have 40–80 years of oil supplies, 60–176 years of natural gas globally, and more than 200 years of coal, both globally and within the United States.

Some people use the oil reserves figure to claim that we are going to run out of oil in 40 years. To understand why this is not accurate, it helps to look closely at some of the challenges faced by oil companies in finding and extracting oil. If, for example, the cost of drilling an oil well is $1 million a day, and only one in every four wells will be "wet"—that is, will yield oil—it is not surprising that oil companies allocate only enough capital to prove out 40 years' worth of reserves, and then find other ways to invest their money. Investing in the discovery of oil 100 years out simply does not pay because that investment and asset is evaluated on a net present value basis, yielding very little immediate profit. Even more compelling is the fact that we have had 40 years' worth of proven reserves of oil literally since the day after oil was discovered, and that ratio has remained stable for the past 100 years.

What really matters is the amount of oil, along with coal and natural gas, that is still available in our resource base. Significantly, we have from 50 to 150 years of oil resources, with oil discovery going on continuously. We also have about 200 to 600 years of natural gas and almost 2000 years of coal in our resource base. In our fossil-fungible world, there are vast amounts of hydrocarbon energy resources that can last us for many centuries, if not millennia. This does not even include the methane clathrates, off the continental shelves, which are estimated to exist in comparable quantities to all of the oil, coal, and gas on our planet combined.

Even if, at some point, we started to peak in oil (which is, of course, eventually inevitable), we have the expertise to get around that. For example, we already know technologically how to convert both natural gas and coal into liquid hydrocarbons. Right now, ExxonMobil Corporation and Shell Oil Company are spending over $10 billion to develop gas-to-liquid-hydrocarbon conversion plants. Historically, this type of conversion has been shown to be a viable alternative to oil. During World War II, when Germany was denied oil by the Allies, the country was able to flip its economy on a dime and ran by liquefying coal to run its war machine. Thus, a limited global supply of one fossil energy source can be compensated for, in principle, by the additional consumption of another fossil fuel.

Fossil fuel still remains the cheapest energy resource available as a commodity on the world market. Regarding oil, for example, we have already produced, in history, about 1 trillion barrels of oil at relatively low per-barrel rates. Extracting the next trillion barrels from the ground is estimated to cost around $20 per barrel. The next trillion barrels could be had for under $30 per barrel, and the next trillion barrels for under $40 per barrel. When oil was only $9 per barrel, people looked at projections like these and declared that the age of cheap oil was over, and that things could only get worse. Today, $40 per barrel looks like a bargain!

From all of these considerations, it is clear that we have an abundant, inexpensive resource base of fossil energy that is not going to run out any time soon. The Stone Age did not end because of a shortage of stones. Likewise, the Fossil Energy Age is not going to end any time soon because we have run out of cheap fossil energy. Neither then are renewables going to play a large role in primary power generation unless or until some technological breakthrough is achieved, or some externality is introduced into energy pricing. In short, the market will not drive us into using non-fossil forms of energy for a long time. These are controversial conclusions to some audiences, but I believe that the numbers presented here support the conclusion analytically.

Energy and Sustainability

Factors that Impact Energy Demand

What I believe is more probable is that other events and conditions will prevent us from using all of our fossil energy—despite its abundance, availability, and cheapness. What, exactly, might be the "game-changers" related to energy? Over 100 articles exist on the topic of sustainability, but I will recap just one, published in 1998 in *Nature* and authored by Martin Hoffert et al.[9] This article, which summarized work from the 1992 report of the Intergovernmental Panel on Climate Change (IPCC),[10] is not really about climate, but about energy. Even though the report came out nearly 15 years ago, the

> "There are about six major climate models, all differing from each other in detail. As scientists and engineers, we know, therefore, that in detail at least five of them must be wrong."

data compiled then now still illustrate dramatically the enormous scale of our energy challenges.

A major factor is population growth, which is a key driver for energy demand. In order to reasonably predict how much energy will be needed in the future, we need to know how many humans are going to be on our planet. This can be estimated by a chart showing data on a logarithmic scale, since population growth will, in fact, be a key factor in driving energy demand. The current global population is approximately 6 billion, and is estimated to increase to about 10 billion in the year 2050, which I will use as the representative "out" date for this discussion.

I chose 2050 for two reasons. First, achieving results in the energy industry is a much longer-term endeavor than, say, achieving results in the information technology business. In IT, for example, you can build a Web site and only a few years later become a Google. If you build a coal-fired power plant, however, it will take about 40 years to pay itself off and deliver a reasonable return on investment. The energy infrastructure that we build in the next 10 years, therefore, is going to determine, by and large, what our planet's energy mix is going to look like in 2050. The second reason for choosing 2050 is that today's population wants to know what our planet's energy picture is going to look like within a timeframe meaningful to them—the next 30 to 40 years.

Instead of analyzing global energy consumption purely on a per person basis, I am also going to factor in economic productivity, which is strongly correlated to energy consumption. The U.S. President's Council on Economic Advisors, along with most other policy-making groups, would first break down energy consumption according to per capita gross domestic product (GDP) growth, which globally has been about 1.6% per year, on average, historically. According to the IPCC—and I believe their extrapolation to be a conservative one—in a "business-as-usual" scenario we can expect the future to be similar, on average, to what we have experienced over the past 100 years. Thus, we can expect to enjoy about 1.6% or so economic growth for the next 50 years.

One can debate about whether a sustainable GDP growth rate is 1%, 2%, or 4%. The developed countries believe about 4% is sustainable, and few, if any, countries have a policy *against* economic growth. Nobody, however, at the time when these estimates were made, could have foreseen that China, along with India, would be growing at 7%–10% per year. While we can only hope that the global growth rate will not go negative, 1.6% therefore seems to be a representatively conservative number.

Evaluated by themselves, economic growth and population growth would conspire, through the magic of exponentials compounded, to lead unabated to a tripling of energy demand between now and 2050. Considered in terms of energy consumption per unit of GDP, however, we are actually saving energy, and at a rate of about 1% per year globally. Energy consumption in the United States, as well as in other developed countries, is declining somewhat more rapidly. We can accomplish this because we operate from such a high base that it is much easier for us, as compared with developing countries, to implement energy-saving technologies like compact fluorescent light bulbs. It is difficult to save much energy if you are lighting your home at night with only two candles. Because the developing countries are not sustaining the same rate of declining energy consumption per unit of GDP as the developed ones, the global average rate of decline is about 1% per year.

Looking at energy demand in terms of these three separate factors—population growth, economic growth, and energy consumption per unit of GDP—is useful because it builds energy efficiency into the demand side of the equation. Developments related to increased energy efficiency—the efforts materials researchers are putting into creating better fuel cells, light-emitting-diode–based lighting, solar thermal technology, and passive insulation for homes—are thus incorporated into our assumptions about demand reduction. The 1% per year global demand reduction can be plotted on a chart to extrapolate what the average thermal energy load would be on our planet in 50 years if we kept to this demand reduction rate (see Figure 3). It would be at 2 kW/person, represented by the horizontal dashed line in the figure. Significantly, the average recent thermal energy load for the United States is 10 kW/person. The 2 kW/person figure thus requires that every country's average is one-fifth the current U.S. per person energy demand. To reach this goal, we would need to start today to do everything possible—

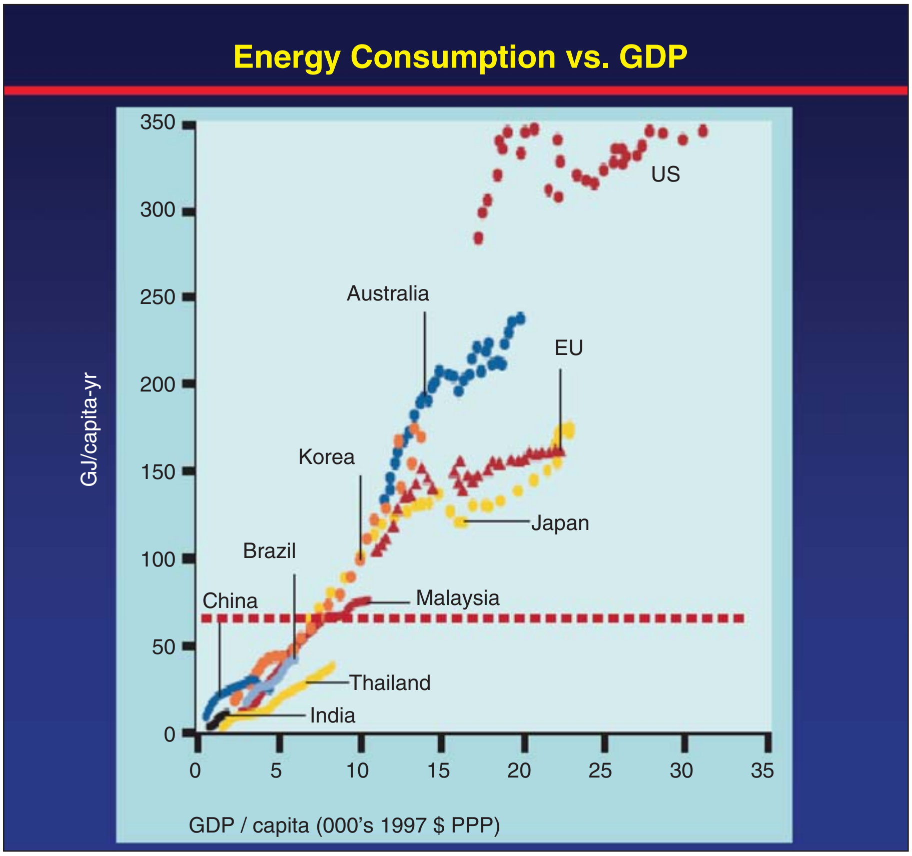

Figure 3. Energy consumption versus gross domestic product.

including using 100 mpg cars and zero-energy homes—to conserve energy.

For calibration, the 2 kW/person average turns out to be about twice as much as it takes in energy just to eat. If you convert a 2000 calorie per day diet into wattage, that works out to be about 100 W. But, the energy needed to produce a certain amount of food—to grow, fertilize, distribute, and refrigerate it—is 10 to 20 times greater than the energy embedded in that amount of food. Thus, 1 kW/person is required in our highly mechanized Western society just to eat. Assuming that the world average energy consumption is only 2 kW/person (i.e., twice as much as it takes to eat), twice as much energy will be needed roughly to meet demand within 50 years. This is in accord with the most optimistic projections of the World Energy Assessment and the International Energy Agency. Some say that demand will go higher than this.

The 2 kW/person energy need can be expressed another way, that 28 TW of total global power will be needed by 2050. Even though we currently use only 13 TW, we will be able to make up the difference by consuming more of our fossil energy, oil, gas, and coal, of which ample supplies will be available for centuries. As stated previously, the availability of fossil energy is not the problem that is of primary concern.

Sustainability Indicators

Our energy problem lies in the effects caused by the CO_2 produced when fossil fuels are burned. A useful measurement in studying this problem is the mean carbon intensity of the energy mix, the amount of carbon emitted to the atmosphere as CO_2, averaged over our planet, over the energy mix, during the past century. A more specific way to express the mean carbon intensity is how many kilograms of carbon are emitted to the atmosphere as CO_2 per year per watt of power produced from fuel. Figure 4a of the mean carbon intensity from 1890 through 2100 (projected) shows that this figure has been steadily declining. As we have evolved into an industrial society, we have used, and then de-emphasized, a series of fossil fuels. From wood unsustainably burned in caves, producing the largest carbon emissions per joule from the source, we have gone to coal burned in locomotives, producing large amounts of CO_2 from a carbon-rich source. Following coal in carbon intensity is oil, then natural gas.

Today, we are doing better. Part of our energy comes from natural gas, or CH_4, which, when burned, produces 1 molecule of CO_2 for every 2 molecules of H_2O.

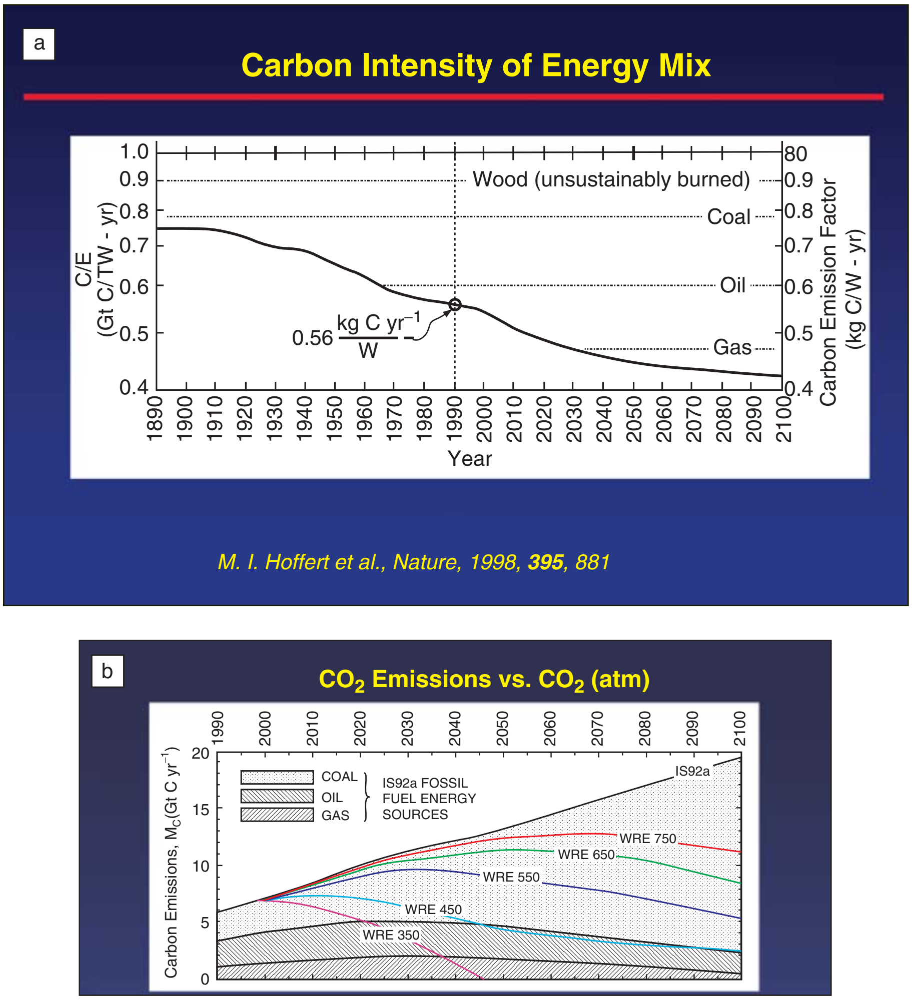

Figure 4. (a) Carbon intensity of the energy mix from 1890 through 2100 (projected), i.e., kilograms of carbon emitted to the atmosphere as CO_2 per year per watt of power produced from combined sources of fuel. The average in 1990 is shown as an open circle on the carbon intensity curve. (b) CO_2 emissions versus CO_2 in the atmosphere, projected through 2100. See text for discussion.

Methane is carbon-light in terms of the carbon emissions per unit of energy delivered to the end user. Oil has a chemical formula of about CH_2, so it is between coal and methane for CO_2 emissions. The lines in Figure 4a representing coal, oil, and gas we can do nothing about, because they are simply properties of the chemical stoichiometry and the heats of combustion of coal, oil, and gas. The average, in 1990, is represented by a small circle on the carbon intensity line. The IPCC projected, I believe optimistically, that in a business-as-usual scenario we will continue along the historical trend of declining mean carbon intensity, all the way through to 2050, in terms of adopting a cleaner-burning energy fuels mix, from a carbon emissions standpoint.

If we were able to continue this decarbonization trend, the projected carbon intensity in 2050 would be 0.45 kg of carbon per watt-year, which is lower than that of any of the fossil fuels. The only way one can reach this value of the mean carbon intensity is through a significant contribu-

"As scientists, then, we can say that what humanity decides to do about energy is an experiment, the biggest experiment that humans will have ever done."

tion of carbon-free power to the total energy mix. In other words, to obtain a mean carbon intensity below that of an economy based entirely on natural gas requires significant amounts of power produced by carbon-free or carbon-neutral sources. To the extent that the mix of fossil fuels used to generate energy is not 100% natural gas, but also includes roughly equal parts of oil and coal, even more carbon-neutral energy is needed to maintain the average of the total mix at the 0.45 kg C/Wyr value.

Let us assume, however, that indeed we follow this line and that we are able to decarbonize the mix to better than a pure natural gas economy within our lifetimes. If we know the amount of energy demanded in every year and the amount of carbon that we produce from the energy that we demand every year, then we need only multiply those two functions together to get the amount of carbon that will be emitted into our atmosphere every year under this scenario. This amount leads to the top curve in Figure 4b. That curve is significant, because under this arguably highly optimistic scenario, the atmospheric concentrations of CO_2 still are not stabilized at any reasonable value. To stabilize the concentrations of CO_2 at 350 ppm by 2050 would necessitate reducing the carbon emissions on our planet to zero by that date. To hold CO_2 concentrations to 450 ppm would still require aggressive reductions, better than the scenario I just described. To achieve a limit of even 550 ppm would still involve extremely high reductions.

We do not know, except through climate models, what the implications of driving the atmospheric CO_2 concentrations to any of these levels will be. There are about six major climate models, all differing from each other in detail. As scientists and engineers, we know, therefore, that in detail at least five of them must be wrong. Complicating the matter even further, these climate models are based on the averages of many paths, because of sparse initial data for the last 100 years of temperatures and cloud formations. Earth, however, is on one path, and nobody knows which one. If we wait for a climate model that can exactly predict the climate in 2050, then I will make the only rigorously true prediction about when we will exactly be able to do that scientifically—when we open our doors on New Year's Day, January 1, 2050, and look outside.

We do, however, have data from the past. An excellent collection of information about the past is the Vostok Ice Core data from over 400,000 years, recently extended in other ice cores to over 600,000 years, showing that CO_2 levels have been in a narrow band of between 200–300 ppm, but not higher. We know from simple calculations that under the scenario I described, within our lifetime the atmospheric concentrations of CO_2 are going to be twice as high as they have been in the last million years, are already higher than in the past 20 million years, and will probably be higher than in the last 100 million years.

We do not know precisely what the effects of these increased concentrations of CO_2 will be upon our planet, but we do know what we can see now for ourselves, with the naked eye. One of the visible "markers" is that every glacier on earth but a few is melting. A photo of Upsala Glacier, the largest glacier in the Southern Hemisphere, in 1928, compared with a photo of that same glacier in 2004, shows that what was originally a field of ice has now become a lake. In August of 2006, I visited Alaska to see the Portage Glacier, taking a boat ride from the visitors' center to the glacier. The disturbing fact here is that the visitors' center originally was built at the edge of the glacier, and as late as 1985, there was no lake.

In Greenland, there are great quantities of ice. Sea level is predicted to rise by 20 feet if that ice continues to melt. We do not know for sure that CO_2 is the cause of this; we only know that there is simply one way to find out.

We know that more than just thermal management is at issue here because the pH of the near-surface oceans is changing—20% of the coral is already bleached. Many models predict that from half to all of it will be bleached within our lifetime, as we acidify the oceans and change their carbonate equilibrium. Anyone who wants to see coral in its pristine state should probably visit coral reefs sooner rather than later.

No climate model rigorously incorporates the nonlinear effects of CO_2. An example of these effects is the melting of the permafrost, which we know is happening because we can isotopically date the helium being released. This He has not been released from the permafrost in at least 40,000 years. As the ice melts, it also releases methane and CO_2. Enough methane and CO_2 is contained there that, if the melting process continues, the levels could go up by a factor of 10. This has already happened once before, 230 million years ago in the Permian Era. There was an isotopically light, massive, quick release of carbon. CO_2 levels then rose by factors of 10, temperatures spiked by factors of from 4 C to 8 C, and according to the fossil record, about 90% of the species that existed on Earth at the time went extinct. We do *not* know that this would happen again, but we do know that there is only one way to find out.

Another important fact is that CO_2, unlike ozone, for example, does not have a natural destruction mechanism. Ozone, when formed, is then destroyed. CO_2, which is the most oxidized form of C in our oxidizing atmosphere, equilibrates with the near-surface oceans and the biomass. That process takes about 10 to 30 years, and that is accounted for in the models I discussed previously that showed how much CO_2 will be emitted versus how much will remain in the atmosphere. CO_2 has great staying power because it has to move from the near-surface ocean to the deep ocean to be depleted from the air. At the levels of CO_2 that we are emitting today, our best knowledge says that the equilibration time of mixing, from the near surface to the deep ocean, will take from 500 to 5,000 years. A good number for the CO_2 lifetime is estimated to be about 3,000 years. As scientists, then, we can say that what humanity decides to do about energy is an experiment, the biggest experiment that humans will have ever done. Unless someone finds a technically credible, cost-effective way to get rid of CO_2, it is an experiment whose effects, whatever they may be, will be with us for a time scale comparable to modern human history.

Carbon-Free Energy Needs

Assuming that we continue to use roughly equal amounts of oil, coal, and gas, the exact breakdown of how much carbon-free power would be needed in 2050 to meet the business-as-usual 0.45 kg of C/Wyr carbon mean intensity value is about 10 TW. Stabilizing the atmosphere at 550 ppm of CO_2, which is twice the pre-anthropogenic levels, under the demand-reduction scenario I described, would require more than 10 TW. To hold CO_2 emissions to 450 ppm and meet demand would require an even greater amount of carbon-neutral power. By any reasonable measure, to stabilize CO_2 concentrations at reasonable levels, we need to make as much energy from carbon-neutral sources, within our lifetimes, as all of the oil, coal, gas, and nuclear power we produce today combined.

It becomes obvious, then, that waiting 50 years for scenarios to play out is an issue because, in the meantime, CO_2 will have accumulated in our atmosphere to a level no human has ever experienced and, given the long lifetime of CO_2, it will remain there for generations to come. This outcome, according to Martin Hoffert, underscores the pitfalls of the "wait-and-see" solution, which involves waiting for market forces to take over.

On the other hand, where can 10 or 20 trillion watts of carbon-free power be found? The physics of our planet dictates that 10 TW of carbon-free energy can be obtained only from certain primary sources, three to be exact: nuclear power, carbon sequestration, and renewable carbon-neutral energy sources.

Nuclear Power. The only existing carbon-free technology that can scale to the 10 TW or greater level is nuclear fission, our first possibility. I am not personally for or against nuclear power, but I believe we should understand what its ramifications would be before making decisions about it, especially since it will be the only source to fall back on if we decide not to do anything else.

One challenge presented by nuclear fission—one that you seldom hear about in the press—is that its capacity to generate enough power to meet our needs is dwarfed by the sheer magnitude of our carbon-free energy requirements. The "just build a few nuclear power plants" solution falls completely short. Given the limits at which structural materials can be developed to handle the heat and radiation flux in a fission reactor and make it viable commercially for a 50-year lifetime, safe reactor designs are rated at 1 GW of electricity output. Since the world needs 10 TW, at minimum, 10,000 such reactors would need to be built. In other words, we would need to build a new nuclear power plant somewhere in the world every other day, continuously, for the next 50 straight years. Even building 1000 nuclear plants at that rate would not begin to solve the problem, because 95% of the world's energy needs would still be unmet. Furthermore, if demand cannot be reduced to the 2 kW/person level we discussed earlier, even more nuclear plants would have to be built merely to hold the atmospheric CO_2 concentration at double what any human has ever experienced on our planet.

Complicating this picture is the availability of nuclear reactor fuel. The proven reserves and the resource base of all terrestrial uranium combined would be enough to provide only 10 years of operation for the 10,000 necessary nuclear power plants under once-through operations. Uranium could be mined from seawater, but the equivalent of 3,000 Niagara Falls would be needed, running constantly, to mine uranium, which is very dilute in sea water (nanomolar levels) at this scale. One solution might be to develop a uranium—thorium cycle, but that has not yet been proven technically at scale. Another solution is to use plutonium and reprocessing, and enough plutonium and reprocessing fuel exist to make this possible. Plutonium, then, is the only possible fuel solution now available, when combined with the nuclear plant-building schedule of a plant every other day for the next 50 years. One clearly would need to evaluate the implications of building thousands of plutonium-based power plants before pursuing this option seriously.

Carbon Sequestration. Another approach to producing carbon-free power is to sequester the CO_2. In this process, CO_2 would be captured when it is emitted from a power plant, and then sequestered through burial in the deep ocean or in geological reservoirs, or perhaps through conversion to carbonates. Burial of gigatons per year of CO_2 in the deep ocean has largely been discredited because it would eventually change the pH of the ocean, thereby inducing potentially radical ecological changes in the biosphere.

Sequestration in geologic reservoirs—oil and gas reservoirs and aquifers—is much more promising, provided that the reservoirs will remain intact. The collective leak rates of the reservoirs must be significantly lower than 1%, sustained over a century-to-millennium-type time scale. Otherwise, after 50 to 100 years of sequestration, the yearly emissions will be comparable to the emission levels that were supposed to be mitigated in the first place. CO_2 geysers can form naturally and have been known to harm life when the CO_2 migrates out. Furthermore, because every underground geologic aquifer is different, being able to verify that billions of tons of CO_2 could be sequestered in one or two particular aquifers for centuries to millennia at a 0.1% leak level would not be sufficient. We would need to perform such verification for every one of the hundreds or thousands of places that sequestration took place.

A significant fraction of the existing fossil-derived power plants could be retrofitted to allow for sequestration if it worked on the needed scale. An equally significant fraction, however, are too remote from the location of suitable geologic reservoirs, requiring that either the CO_2 would have to be pumped long distances or entirely new plants would have to be suitably sited and constructed. In addition, significant additional costs would be incurred in converting the entire energy distribution system to either electricity or to the required non-carbon-containing fuel, presumably H_2. From a CO_2 emission viewpoint, clean coal is not clean at all unless the carbon can be safely buried.

Sequestration, then, should definitely be explored as an option, but it is far from clear that it will technically work at scale, or what its actual overall energy system cost would be. A lot of research is still needed in modeling materials and testing interactions of CO_2 in the subsurface in order to understand whether this will technically work. The United States is building a plant called FutureGen, scheduled to go online in 2012, that is geared to demonstrate that CO_2 can be buried. The U.S. Department of Energy is doing work on carbon sequestration, with the goal of creating 1 gigaton of storage by 2025 and 4 gigatons total by 2050. Since the United States' annual carbon emissions are 1.5 gigaton per year, the total DOE goal for 50 years from now is commensurate with a few years' worth of current emissions. There is clearly a large mismatch between our goals and what would be needed to solve this problem, a gap that we need to close quickly.

Renewable Carbon-Neutral Energy Sources. Leaving aside nuclear fission and clean coal, the other approach to producing carbon-neutral power is to use carbon-neutral renewables, of which there are six often-mentioned sources: hydroelectric, geothermal, oceans/tides, winds, biomass, and solar.

Hydroelectricity is a model renewable energy resource. It is relatively cheap, fairly abundant, and relatively benign. The total hydrological energy potential of the planet, however, including the energy in the water flow from every river, lake, and stream, amounts to a rate of approximately 4.6 TW. Since it is not technically practical to build dams on every small creek, all of that power cannot be extracted. The amount of technically feasible hydroelectric power globally has been estimated to be about 1.5 TW. The amount of economically feasible hydro is only about 0.9 TW, and 0.6 TW capacity of that has already been installed. While hydroelectricity is an attractive renewable resource that should continue to be exploited wherever possible, it will not make a significant contribution toward our 10–20 TW global carbon-free energy requirement in the mid-21st century.

> "Producing 2 TW of wind power would require the operation of 2 million state-of-the-art wind turbines, starting today."

In a few places on Earth, we are able to take advantage of geothermal energy directly, using steam as it comes up out of the ground to run turbines and produce electricity. In most places, however, it is necessary to exploit the 200-degree thermal gradient of the Earth by going down about 10 km, injecting cold water into a well, and having the hot dry rock heat it up and convert it to steam for running a turbine.

The Earth contains an enormous amount of heat, which can be located on geothermal maps. The amount of heat, however, that can be sustainably used is equal to the total geothermal heat flux at the Earth's surface, which is 57 mW/m^2 over land. Multiplying that figure by the area of all of the land on Earth results in 11.6 TW of sustainable global heat energy. Of course, there is a small problem involving the second law of thermodynamics, which will prevent us from getting 100% efficient heat engines at a low temperature difference, that will practically let us extract much less than a few terawatts sustainably.

In terms of oceanic and tidal energy, all the energy in all the currents, all the tides, and all the waves on our planet combined falls far short of the 10–20 TW needed.

Wind could be an important player in producing our total carbon-free energy mix, but it has constraints. The National Renewable Energy Laboratory did a study[11] in the 1990s showing that if windmills are sited at 4%–5% spacing (which is about their optimal spacing for not obscuring each other), and nothing is excluded other than environmentally sensitive lands or urban areas, a significant amount of electricity could be produced. For example, if windmills were deployed in all of the suitable sites in all of North Dakota, 36% of U.S. domestic electricity production for the year 1990 could be produced. That 36% figure, however, represents only the fraction of the 1990 electricity consumption of the United States, 0.3–0.4 TW, which constitutes about only 10% of our total primary energy consumption, which is now 3 TW.

On a global scale, adding all of the marginal-to-high potential wind areas in the world, and considering practical site constraints, windmills could produce a total of 2–4 TW of electricity. The offshore electrical power potential of wind is greater than 2–4 TW, but transmitting significant amounts of power from offshore installations to the land-based regions that need it would be a major problem. In addition, realistically the 2–4 TW of global wind power is an overestimate, because it is based on point-source measurements. As the wind travels through windmill installations, its initial energy is depleted to the point where, far into an installation the length of, say the entire state of North Dakota, very little wind energy would remain to turn the turbines and produce power. Multiplying the point-source wind energy potential values by arbitrarily large areas, therefore, produces skewed estimates. Producing 2 TW of wind power would require the operation of 2 million state-of-the-art wind turbines, starting today. Wind energy could be marginally material, providing perhaps approximately 10% of our total energy needs, if used exhaustively on suitable land around the globe.

Although biomass is attracting a lot of attention today as a possible carbon-neutral energy source, it is fundamentally inefficient. Plants using photosynthesis store less than 1% of the total incident energy they receive from sunlight, under optimal growing conditions, averaged over the year. In addition, to prevent oxidative damage, photosynthesis shuts itself down at higher light intensities. Those two things conspire to make even the fastest growing plant, on a yearly average over large areas, store only 0.3% of the energy hitting it from the sun, relative to the amount of insolation (incoming solar radiation) involved. The result is that incredibly large areas of land would be needed to provide the 20 TW of total energy we need: 30% of the total land on Earth would have to be covered with energy farms devoted solely to producing biomass to meet the carbon-neutral energy demand requirements.

A good way to calibrate the area demands is from the bottom up, starting with the fact that not all of that 30% of needed land can support crops. Begin, then, with all the rain-fed cultivatable land on Earth, figure how much of that is currently used for food production, increase that amount by about 50% to meet estimated 2050 food production needs, and then allocate all the remaining cultivatable land for biomass production. Assuming that all of the rain-fed cultivatable land not required for food was functioning as an energy farm—with no need for any energy coming in or going out—the result would be about 5 TW of power. One way to increase this energy output would be to genetically modify the plants used on energy farms, making them absorb more energy from the sun and grow more quickly. After some improvements in growth rates, however, by a factor of two or so, plants will run out of CO_2 from the atmosphere to use, due to mass-flux limitation, and will not be able to grow much faster.

The above output of 5 TW assumes that the net energy return from biomass farms is equal to the gross energy production, with minimal energy inputs. That result remains only a best-case scenario. It is well known, for example, that the corn-to-ethanol conversion is not energy-efficient. The numbers are simple: in 2006 in the U.S., 20% of the corn crop provided 2% of our transportation fuel. And it used almost as much energy input, in the form of coal, as the energy it produced. The challenge here for materials science is how to convert nature's version of coal, lignocellulose, into something that humans can use as an energy source. A cellulose-to-ethanol conversion cycle, for example, could be accompanied by the development of a fuel cell that would utilize the ethanol efficiently. Biomass could be a significant contributor to the overall carbon-neutral power requirements, but it cannot be relied on alone to meet the estimated demand.

The last renewable energy resource to consider is solar energy. The sun is simply the champion of all energy sources. The sun provides Earth with 120,000 TW. To put that another way, more energy from the sun hits the earth in one hour than all of the energy consumed on our planet in an entire year. When talking about solar energy, I like to cite what I call the "Willie Sutton principle" of materials science and energy. Willie Sutton was a bank robber who robbed many banks and managed to elude the law for years before he was finally caught. When asked why he robbed banks, he replied, "Because that's where the money is." If Sutton were presented with our energy problem, he would obviously say that we should use the sun because, quite simply, that's where the energy is. Solar energy is, in fact, the only renewable resource that has enough terrestrial energy potential to satisfy alone, with room to spare, the 10–20 TW carbon-free supply constraint in 2050. No other source comes even close.

The actual land area required to produce 3 TW of carbon-free power from solar energy can be represented as a single box superimposed on a map of the United States (see Figure 5). This map, which is on my Web site, has been used in many venues—including Dr. Smalley's presentations—to demonstrate solar energy requirements. The box shows the amount of land that would be required for a solar energy "farm" operating at 10% efficiency, at a representative mid-latitude, to supply 3 TW of power. In reality, the solar energy sites would be widely distributed, but the area represented would still cover 1.7% of U.S. land, comparable to the land devoted

Figure 5. The red square shows the amount of land needed for a solar energy farm operating at 10% efficiency to match the 3 TW of power currently consumed in the United States.

to the nation's numbered highways. From a global perspective, six 3.3 TW boxes would be needed to represent the needed amount of land. This is, by no means, a small area or a small project.

One possibility would be to use solar panels to generate electricity. Since putting a 10% efficient solar energy conversion unit on every U.S. home rooftop would generate only 0.25 TW, it becomes obvious that our global 10–20 TW requirement cannot be met by covering everyone's house with solar panels. In fact, to meet a 3 TW goal, the U.S. would have to install about a half-million typically sized (2 kW peak power) solar roof systems every day, continuously from now until 2050.[1]

Even if widespread use of solar technology were possible, the cost would currently be prohibitive. Science, however, while it cannot fix the fact that there simply is not enough practically available geothermal energy or enough wind energy to solve our energy problems, can develop ways to lower the cost of solar energy products. Of course, a lot of work remains to be done for truly cost-effective solar to become a reality. The amount of energy available from the sun is a constant. If 10% of that energy is extracted as solar power, how much product energy can be sold to customers? That concept could be charted as the cost in U.S. dollars per square meter of photovoltaic technology at various efficiency percentages. If it costs \$300 to install 1 m^2, then another equal amount for the balance of systems, that will set the amount that must be charged to customers in order for solar energy providers to break even. Amortizing that amount results in a cost of \$0.25 to \$0.35 per kWh for solar technology that is about 10%–20% efficient. Lowering the price to pennies per kWh would not be possible solely by improving efficiency. The cost must be lowered dramatically, to a range within \$10–\$100/m^2, probably closer to \$10/m^2, to provide cost-effective energy, not just cost-effective peak energy. As a comparison, the cost of house paint now at a typical building supply store is \$1/m^2. The cost of the average carpet is \$10/m^2. Solar technology, in whatever forms it might take, would have to cost not much more than painting a house or buying carpet. My colleague, Harry Atwater, phrases the problem this way: "Do not think 'silicon chip,' think 'potato chip.'"

Ironically, though, even if solar cells were cost-free, the problem of producing enough carbon-free power to satisfy our energy needs by 2050 would still not be solved. Sunlight is intermittent, but our collective energy needs are continuous. The sun can readily be a peak-generating power source, only at certain segments of the day, and on sunny days. And importantly, solar power produces electricity, and there is no viable cost-effective way to store massive quantities of electricity. So parallel challenges in storage still exist and remain unsolved today.

Energy Solutions for the Future

Other options exist that could make solar energy a reasonable way to fulfill the mismatch between energy supply and demand, should the CO_2-based environmental constraints come into play. From a cost standpoint, the least expensive way to store solar-produced electricity would be to pump water uphill. That method works well when you are emptying a reservoir in the summer and filling it in the winter. To buffer the day/night cycle would require filling up every reservoir every day and emptying them every night. To see this, the energy density in a kilogram of gasoline is 45 MJ, whereas that in a kilogram of water at a height of 100 m is 1 kJ. So for every gallon of gasoline that we use, storing that same amount of energy in pumped water requires moving uphill by 100 m more than 50,000 gallons of water!

Current energy storage, in fact, is accomplished not by kinetic- to potential-energy conversion, but by storing energy in chemical bonds. We get most of our energy not from making electricity, but from storing and dispatching energy in the form of chemical fuels, which by far are the most cost-effective stored energy sources. Assuming that biomass could be produced in sufficient quantities, for example, the best way to extract energy from it would be to refine it, make biodiesel, ethanol, or other liquid fuels, and consume that again, in a carbon-neutral cycle. Similarly, the best way to manage supplies of electricity would be to sell them when they are available, as opposed to holding on to the elec-

"... in 2006 in the U.S., 20% of the corn crop provided 2% of our transportation fuel. And it used almost as much energy input, in the form of coal, as the energy it produced. The challenge here for materials science is how to convert nature's version of coal, lignocellulose, into something that humans can use as an energy source."

tricity. The key missing link in solar power utilization, then, is a way to capture, convert, and cost-effectively store the energy from the sun.

At present, there are three technology approaches to producing a "black box" for the conversion of sunlight to stored energy (see Figure 6). One method, photovoltaics, can be very efficient but has a high cost per watt of electricity produced. Biomass produced through photosynthesis is another method. Since photosynthesis is relatively inefficient, biomass farms require extremely large areas per unit of output energy produced. A third approach is the use of semiconductor/liquid junctions, which is an active area of research in my group at the California Institute of Technology, as well as in others around the world. Each approach has its own advantages and issues to be dealt with.

The efficiency of photovoltaic devices is increasing, but the industry is still exploring different technologies on a cost per watt basis. The materials cost dominates in energy conversion applications because installed capacity scales linearly with the area of the device. Put simply, one needs to pay the price to produce more material to cover larger areas. The net result is that one can ride anywhere on this cost/efficiency tradeoff, but nevertheless ends up with the same figure of merit, within a factor of 20%.

Inexpensive materials do not produce very efficient photovoltaics, while the expensive materials produce efficient solar cells, with the result that the cost per watt installed of both systems is about the same, to within a factor of 20%–30%. The photovoltaic materials now available basically all suffer from the same fundamental physical limitation, that the large-grain materials (the pure materials) that have the long lifetime necessary for making efficient solar cells are costly to produce. Using cheap materials, which have a small grain size, results in inefficient solar cells, because the grain boundaries act as recombination sites.

A similar tradeoff is found for organic ("plastic") photovoltaics. If pure inorganic single-crystal materials like silicon and GaAs are replaced with much cheaper organic materials, which are inherently disordered, the cheaper materials lie on the same cost per watt curve. The resulting cells are cheaper, but less efficient.

This does not have to be the case, however. A cogent argument can be made that, in order to bring this technology down by the needed factors to be competitive in cost with other sources of primary stored energy, we need to employ disruptive

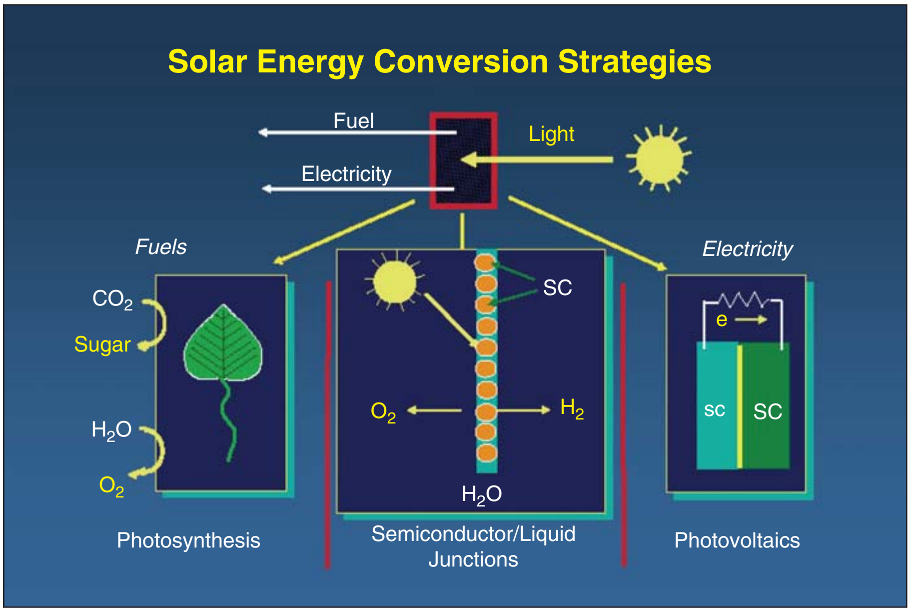

Figure 6. Three technology approaches for converting sunlight to stored energy.

technologies that are very different than the technology curve that is being developed now. From a physics point of view, there are at least two approaches that have the potential to provide such a technology solution.

One approach would be to utilize chemical methods to "fool" inexpensive materials into performing as if they were expensive single crystals, with no cost involved to actually grow large, single crystals. Basically, all common solar cell designs are constrained to have planar junctions, so as to have a certain thickness needed to absorb all the sunlight. The material then has to be pure enough to let those excited states move to the planar contacts, otherwise they will recombine and generate heat. On the other hand, if we were to use particles of inorganic materials, the grain boundaries would serve as sources of carrier recombination and cheap materials would not work very well. It remains for researchers, therefore, to find a way to passivate the surface atoms of these particles, "fool" them into thinking they are chemically bonded like the atoms in the bulk, and get electrons to hop from particle to particle. Indeed, dye-sensitized TiO_2-based solar cells work because the electrons do hop from particle to particle. This method is the basis for work being done by scientists in my group, and in others, to passivate small-grain Si particles to make a binder that allows electricity to flow right through the "stepping stones" while fooling the surface atoms.

The other approach is to relax the physical constraint and produce so-called interpenetrating networks. To do this, we will relax the usual constraint in which the carriers must exist long enough in their excited states to traverse the entire distance of the cell. A way to do this is to make structures that look like nature's version of grass, but on the nanometer scale, obtaining long absorption depths through rods, but very short collection distances, by moving carriers sideways and letting them be collected over short distances, in an orthogonal direction to where they are absorbed (see Figure 7). This method for getting off of the existing cost per watt curve, which my research group is now working on, was pioneered by, among others, Michael McGehee, the 2007 MRS Outstanding Young Investigator.[12]

Both of these photovoltaics approaches are emerging technologies, and neither of them is economically or technologically viable today. They do, however, seem like feasible solutions in the long run. In the end, whatever approaches are used must be almost as inexpensive as painting the house, as engineered as making layers of film, and as mass-producible as both of the previously mentioned technologies.

Even if solar electricity could be successfully stored, would we be living in the "solar hydrogen economy?" We could track the sun every day using the most cost-effective method, a solar thermal concentrated two-axis parabolic dish. The dish would utilize a thermal working fluid, a sterling engine or, in the example

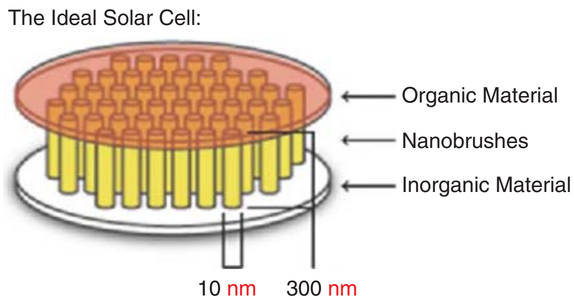

Figure 7. Nanotechnology-based solar cell design.

here, a high-efficiency multijunction concentrator cell. These dishes can be 30% efficient, using solar energy to produce electricity that would go into an electrolysis unit, which, however, would need to contain huge amounts of platinum. Every day the electrolyzer would fill a tank with H_2. The problem is that, to produce the needed minimum of 10 TW of carbon-free power, one of these structures would have to be built every second for the next 50 years. The world's supply of steel or aluminum would be needed just to build the structures. This technology would not scale, even in a limited way, as currently practiced, to our 10–20 TW needs.

The following process, however, might provide a workable alternative. Instead of putting fuel in a fuel cell across a membrane, sunlight could be used as the energy source across that photoactive membrane. Instead of making electricity and electrons through wires, the incipient electricity would be used to make and break chemical bonds just as nature does in photosynthesis, thereby both capturing/converting and storing the energy for later dispatch and delivery.

That is something a solar cell by itself now simply cannot do, because we currently do not have good catalysts for making fuel directly from sunlight, with no wires. Nature has such catalysts, however, utilizing in hydrogenases, for example, Fe, a cheap metal. Nature's catalysts are not poisoned by CO and S, as platinum fuel cell catalysts are, because they have CO and S in the molecule. Scientists have just recently learned the structure of these catalysts from x-ray crystallography. Some chemists are extracting these enzymes and trying to build models that are both inspired by, and mimetic of, the natural catalytic process. Instead of using the incipient electricity to make H_2 or fix CO_2, they are using that energy to make better fuels directly. An example of such a fuel would be methanol, a liquid fuel produced from abundant raw materials. We do not know how to efficiently make O_2 from water, except in nature in the Mn site of the oxygen-evolving complex of photosystem II. Another challenge for materials scientists is to develop catalysts that make O_2 from H_2O at low overpotentials, because if this cannot be done, it is impossible to make a useful, scalable fuel, no matter what is done on the reducing side of the chemical transformation.

A Vision for an Energy Program

The greatest energy challenge facing researchers now is, of course, scale. As time goes on, we will need increasing amounts of energy. There has never been a year in which we as a planet have used significantly less energy than the year before. Even if energy use were held constant, in the face of population and economic growth, that would just take a triangularly increasing ramp, and make it a constant function. Because CO_2 emissions, however, are cumulative, the day when our CO_2 emission levels produced 550 ppm of CO_2 would merely be pushed back from 2050 to around 2065. We will not be able to buy ourselves out of this problem even by holding demand close to where it is now. The case, therefore, for producing significant, if not daunting, amounts of carbon-neutral power is either plausible or imperative, depending on how much risk we, as a society, are willing to take. This is an experiment at which we will have only one chance. If we do not do this experiment, we will never know what we missed, and if we do, we will never know if we could have stopped it instead.

Any realistic energy program would start with energy efficiency, because saving energy costs much less than making energy. Because of all the inefficiencies in the energy supply chain, for every 1 J of energy that is saved at the end, 4–5 J is avoided from being produced. To the extent that the energy demand reduction requirement is not met, the supply-side problem becomes that much harder. In addition to saving money, energy efficiency is necessary for our security, both national and environmental, because the less energy used, the less CO_2 emitted.

Any realistic energy program will be built on a cornerstone that combines technology and policy. To put in place the mechanisms necessary to conserve energy usage, drastically reduce emissions, and conduct research on clean sources of energy production, there needs to be agreement about the urgency of the problem and how it might be addressed. But energy efficiency can go only so far. We will still have to make enormous amounts of clean energy. No amount of saving energy ever turned on a light bulb or put food on someone's table. We need to both save as much energy as we now make, and make as much clean energy as all the energy we now use, to meet a doubling or more of demand and drastically cut emissions of CO_2 as well. In considering solutions to our energy supply problems, three "big cards" remain to be played: (1) technically prove that carbon sequestration works at scale; (2) create an enormous amount of nuclear power from plutonium; and/or (3) find a way to cheaply capture, convert, and store the energy from the sun, so that it can be used wherever it is supplied, and whenever it is demanded.

Conclusions

Thus far, I have presented only peer-reviewed technical numbers. I have not ventured into the realm of policy. Before I close, however, I will discuss one critical policy question: what is the true cost/benefit analysis for developing clean energy sources? This issue rests on two divergent views: one, that we cannot afford to invest massive amounts in clean energy, and two, that we cannot afford *not* to do it. Advocates of the former view believe that engaging in large-scale energy developments will ruin our economy. Obviously, switching from an existing mature infrastructure to a new one will cost a tremendous amount of money, like any major project would. The real issue here is how much the project is worth in terms of future security, both energy security and environmental security.

"Solar technology, in whatever forms it might take, would have to cost not much more than painting a house or buying carpet."

Advocates of developing carbon-free energy alternatives believe that this is a project at which we cannot afford to fail because there is only one chance to get it right. For them, the question is whether or not, if the project went ahead, it could be completed in the time we have remaining. Because CO_2 is extremely long-lived, there are not actually 50 years left to deal with the problem. To put this in perspective, consider the following comparisons. If we do not build the next "nano-widget," the world is going to stay the same over the next 50 years—it will not be better, perhaps, but it will not be worse, either. Even if we do not develop a cure for cancer in 50 years, the world is going to stay basically the same, in spite of the tragedy caused by that disease. If we do not fix our energy problem within the next 20 years, however, we can, as scientists, say with absolute certainty that the world will simply not be the same, and that it will change in a way that, to our best knowledge, will affect life on our planet for the next 3,000 years. What this change will be, we do not precisely know. That is a risk management question. We simply know that no human will ever have experienced what we will within those 50 years, and the unmitigated results will last for a time scale comparable to modern human history.

If, on the other hand, we decided to do something about our energy problem, I am fairly optimistic we could succeed. As I have outlined, there are no new principles at play here. This challenge is not like trying to figure out how to build an atomic bomb, when we did not know the physics of bomb-building in the first place—which was the situation at the start of the Manhattan Project. We know how to build solar cells; they have a 30-year warranty. We have an existence proof with photosynthesis. We know the components of how to capture and store sunlight. We simply do not yet know how to make these processes cost-effective, over this scale.

Here, our funding priorities also come into the picture. In the United States, we spend $28 billion on health, but only about $28 million on basic solar research. Currently, we spend more money buying gas at the pump in one hour than we spend funding basic solar research in our country over an entire year. Yet, in that same hour, more energy from the sun is hitting the Earth than all of the energy consumed on our planet in that year. The same cannot be said of any other energy source. On the other hand, we need to explore all credible energy options that we believe could work at scale because we do not know which ones will work yet. In the end, we will need a mix of energy sources to meet the 10–20 TW demand, and we should be doing all we can to see that it works and works at scale, now and in the future.

We have established that, as time goes on, we are going to require energy and we are going to require it in increasing amounts. I can say with confidence therefore, as Dr. Smalley did, that energy is *the* biggest scientific and technological problem facing our planet in the next 50 years.[13] Clearly, the Materials Research Society is going to play a major role, if there is one to be played, in developing the technology that will enable us to drastically reduce the amount of carbon emissions to our atmosphere, while accessing enough clean energy to run the world.

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References

1. R.E. Smalley, "Nanotechnology for Energy Prosperity," presented at Symposium X, MRS Fall Meeting (Boston, Mass., December 2, 2004). An edited transcript of Smalley's presentation was published in *MRS Bull*. **30** (6) (June 2005) pp. 412–417.
2. R. Smalley, testimony to the U.S. Senate (April 2004).
3. *Chem. Eng. News* (August 22, 2005).
4. T.L. Friedman, *The New York Times* (September 23, 2005).
5. "Basic Research Needs to Assure a Secure Energy Future," Report of the Basic Energy Sciences Advisory Committee (February 2003), www.sc.doe.gov/bes/reports/files/SEF_rpt.pdf (accessed September 2007).
6. "Basic Research Needs for Solar Energy Utilization," Report of the Basic Energy Sciences Workshop on Solar Energy Utilization (April 18–21, 2005), www.sc.doe.gov/bes/reports/files/SEU_rpt.pdf (accessed September 2007).
7. "National Energy Policy," Report of the National Energy Policy Development Group (May 2001), www.gcrio.org/OnLnDoc/pdf/nep.pdf (accessed September 2007).
8. J.M. Deutch, E.J. Moniz, *Sci. Am*. **295**, 76 (September 2006).
9. M.I. Hoffert, K. Caldeira, A.K. Jain, E.F. Haites, L.D. Harvey, S.D. Potter, M.E. Schlesinger, S.H. Schneider, R.G. Watts, T.M.L. Wigley, D.J. Wuebbles, *Nature* **395**, 882 (1998). Adapted from J. Leggett et al., "Climate Change: The Supplementary Report to the Scientific IPCC Assessment" (Cambridge University Press, Cambridge, UK, 1992) p. 69.
10. "Climate Change: The Supplementary Report to the Scientific IPCC Assessment (Cambridge University Press, Cambridge, UK, 1992).
11. National Renewable Energy Laboratory Home Page, www.nrel.gov (accessed September 2007).
12. M. McGehee, "Nanostructured Polymer-Titania Solar Cells," Outstanding Young Investigator presentation, MRS 2007 Spring Meeting (April 12, 2007).
13. The Lewis Group Home Page, http://nsl.caltech.edu/energy.html (accessed September 2007).

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