are likely to find residuals on the person carrying it, or on that person's suitcase. Keep the cockpit door locked.

The greatest unknown in my mind is the danger of a biological attack. Making anthrax or mutating a bacterium is relatively easy compared to assembling or even operating a nuke. I suspect that anthrax will not be used, because of the evident failure of the 2001 anthrax attack to kill large numbers of people. If another anthrax attack does occur, make certain you don't overreact to reports of huge numbers of "lethal doses." A greater danger would be the release of a virus or bacterium—maybe one from a remote region of the world, one that has been genetically engineered to be more dangerous. Students with a master's degree or less in biology could know all the procedures necessary to make such a bug. A terrorist who spreads a disease runs the risk of killing more people in the developing world than in the United States, but some terrorists may not care. Good data collection methods would be essential to locate the source of the spread and to isolate it. Such procedures may serve a dual purpose if a "natural" pandemic such as bird flu begins to spread.

Most of the unknowns related to future terrorism are not physics questions. They have to do with the terrorist mind, the possible fears and reactions of our own people, probabilities, weighed risks and costs. As president, you need to have a proper sense of the physics aspects: how hard is it to make a nuclear bomb, how bad is a dirty bomb, what are the dangers of high explosives and gasoline, and what is the threat of a biological attack? You will have to allocate resources, and your decision on how to do this will depend on numerous other issues, many of which are not technical. That's why we have a president in charge and not a physics professor.

II

ENERGY

COUNTRIES go to war over energy. When the Japanese invaded China in 1941, we responded with an embargo on their oil imports. Once we had done that, many experts believed that an attack from Japan was inevitable. Pearl Harbor followed later that year. In the 1970s the oil cartel OPEC embargoed the United States, creating a crisis felt by every US citizen. We are currently at war in Iraq, in part to bring freedom to the Iraqi people, but also because Iraq is the keystone of the Middle East oil region.

Energy is important because it is linked to national wealth. As an astonishing example, consider the United States and China. We have a gross domestic product 20 times theirs. Our energy use is also about 20 times theirs. Wealth seems to equal energy use. The correlation is truly amazing—and something that China has noticed. No wonder the Chinese are frantically building new power plants, averaging over one new giant (gigawatt) plant per week.

As a future president, you undoubtedly ponder the future of the developing world. The economy of China is small per person but large in total, *and growing rapidly. Most caring people in the world are happy to see the growth of the developing countries, with the associated reduction of poverty, poor health, and poor opportunity that has plagued them. As they grow, however, their energy use will undoubtedly grow too. What about their pollution? In particular, we worry about their emissions of carbon dioxide, the notorious greenhouse gas that is linked to global warming and to acidification of the oceans. China probably passed the United States in the total of such emissions in 2007. Moreover, China emits far more greenhouse gases per GDP than does any other country in the world—over 3 tons of CO_2 for every thousand dollars; US emissions are nearly six times lower. After China, the second worst polluter per GDP is India, emitting nearly 2 tons of CO_2 per thousand dollars GDP. It is absolutely critical that these pollution rates drop as the GDPs of these countries grow.*

If their economies expand (as we hope they will), then soon the developing countries will dominate in pollution. What can we do? To answer that question, we must first have a realistic picture of energy—what it is, where it comes from, and where it goes.

5

KEY ENERGY SURPRISES

NO FIELD of physics can beat energy for the number of things that *folks know that ain't so.* Let me illustrate this in a positive way with some key energy facts that surprise most people and that are important for making good policy decisions:

- Gasoline delivers 15 times the energy of an equal weight of TNT.
- Coal is 20 times cheaper than gasoline, for the same energy.
- A square mile of sunlight at midday could provide a gigawatt of electric power[1]—the same as a large coal, electric, or nuclear power plant.
- A square yard of sunlight delivers about a horsepower when it hits the ground, the same as the average electric power used by a US household.
- Gasoline has 1000 times as much energy as an equal weight of flashlight batteries, and 100 times as much as an equal weight of expensive computer batteries.
- Liquid hydrogen, the key fuel for a future "hydrogen economy," has 4.5 times *less* energy per gallon than gasoline has.
- Energy from nonrechargeable batteries costs about 10,000 times as much as from the wall plug.

Future presidents need to know, understand, and feel comfortable with these facts, just as much as they need to know the difference between Shiite and Sunni, or the history of the Japan–China conflict. We'll begin with the most important issue: the physics reasons why we love gasoline so much.

Why We Love Oil

It's a cliché that Americans have a love affair with automobiles, but it could also be said that our affair is really with the oil that makes the autos possible, or maybe with the refined oil called gasoline. Yet in many ways our relationship with gasoline is more like an unhappy marriage. Gasoline stinks. It pollutes the atmosphere with carbon dioxide, and it is blamed for global warming and for nitrous oxides that cause smog. It finances totalitarian dictatorships and terrorists, and drives us to war.

We seek a divorce, but the steps seem too difficult or too painful, and what would we be left with, particularly if our standard of living is tied to our energy consumption? Are we really trapped in a doomed marriage? Many people think yes, and the only questions are how long it will last and what kind of terrible consequences we will suffer. After all, isn't oil about to be used up, any decade now? Isn't the skyrocketing price of oil simply a symptom of this looming disaster?

These questions have economic, political, sociological, historical, and psychological dimensions. Some people would add their contention that oil is also driven by national and international conspiracies—or at least by monopolies. But it turns out that the past and future of oil, and of the alternatives, have a very large physics component. These physics dimensions are sometimes more important than the others, so it is essential to know and understand them. And the alternatives to oil also have key physics aspects. I'll bring in engineering and economic aspects as they are needed, but the focus here will be on the science. Laws of countries can be changed, but laws of physics are pretty much set.

The fundamental physics reason for our addiction (or marriage) to oil is the same reason that oil was the weapon of choice for the 9/11 terrorists: it carries huge amounts of energy. Consider the fact that our best rechargeable batteries hold only 1% of the energy of gasoline. Now ask, Why don't we drive electric autos? Were they killed by a conspiracy? Conspiracy or not, it hardly matters. This energy storage discrepancy provides a huge physics barrier. Batteries simply do not store much energy—not when compared to gasoline.[2] We love gasoline because it is so energetic!

Here is another example that illustrates the enormous energy of gasoline: For the same weight, gasoline delivers 720 times the energy of a bullet.[3] Are you surprised by this number? It makes physics sense, if you think about it in the following way. Bullets are driven by the explosion of gunpowder or other similar explosives, but these typically have about 15 times less energy than gasoline. Moreover, they don't put all their energy into the motion of the bullet; much is lost to heat of the expanding gas. (The longer the rifle is, the more energy is transferred to the bullet.) Add to all that the fact that the explosive charge usually weighs much less than the bullet itself, and you should not be too surprised that bullets carry so little energy compared to an equal weight of gasoline.

To provide its energy, gasoline must combine with oxygen. In an auto, the fuel is mixed with air by the fuel injector or carburetor. Part of the energy advantage of gasoline comes from the fact that we don't have to carry oxygen with us; it is as free as the air. Let's compare the chemistry of gasoline and gunpowder. Gasoline consists of atoms of hydrogen and carbon—about two hydrogens for each carbon. When it burns or explodes, the hydrogen combines with oxygen to make water (H_2O), and the carbon combines with oxygen to make carbon dioxide (CO_2). If the combustion is incomplete, gasoline also makes carbon monoxide (CO). In contrast, gunpowder uses potassium nitrate in place of oxygen, as its *oxidizer*, so it doesn't need to pull in any air. That allows the reaction to occur in condensed form and much faster than with gasoline. Rockets also must carry an oxidizer, sometimes in the form of liquid oxygen or hydrogen peroxide.

Gasoline is even better than food. (No, I don't mean the taste, I mean in energy per pound.) Here are some less astonishing but maybe still somewhat surprising facts. For the same weight, gasoline delivers approximately

- 4 times the energy of steak
- 2 times the energy of chocolate chip cookies
- 1.4 times the energy of butter

Perhaps the most surprising result is that food has even this much energy, almost as much as gasoline and much more than TNT. Here is the direct comparison between food and explosive: steak has almost four times the energy of TNT; chocolate chip cookies, eight times as much. No wonder we are addicted to food! If you find this high energy content implausible, watch a hummingbird. It uses enormous energy to flap its wings just to sip a tiny amount of nectar. Clearly the energy in the nectar must be more than enough to cover the work being done by those rapidly beating wings that hold the bird in front of the flower. It is. Food is almost as good as gasoline.

You probably eat between 1 and 2 pounds of food each day. (I know it seems like more, and if you are under age 20 it may be more, but add it up and see. Don't count the water.) Yet all your work, your thinking, your accomplishments are achieved on the energy in that remarkably small amount of food.

On the downside, the enormous energy content of food is what makes it so difficult to lose weight without serious dieting. One 12-ounce can of soda contains, typically, 150 food calories. A person can work that off with a half hour of vigorous exercise (running, not jogging; basketball, not baseball; swimming, not golf), provided, of course, that he doesn't reward himself with a can of soda. The best way to lose weight is to eat less, not to exercise more.[4]

What about other energy sources? Here is a comparison with four important alternative fuels. For the same weight, gasoline delivers approximately

- 2 times the energy of coal
- 2 times the energy of methanol (wood alcohol)
- 1.5 times the energy of ethanol (drinking alcohol)
- 1.1 times the energy of butanol (a likely future biofuel)

These facts are important when you consider alternatives to gasoline. If you live in a state that sells ethanol as a substitute, or perhaps ethanol mixed with gasoline in a combination called *gasohol*, then you've possibly been intrigued by the fact that it costs less per gallon than gasoline. But look at the numbers that I just gave. Per pound and also per gallon, alcohol delivers less energy. In fact, when computed per mile, alcohol sold in the United States is more expensive than gasoline. Of course, some people use alcohol or mixed fuels not because they are cheaper, but because they believe that these fuels are better for the environment. They sacrifice wealth for the good of the world. They may be wrong, however. Ethanol made from corn saves the world very little pollution; we'll discuss this more when we discuss biofuels. Butanol looks attractive because of its high energy density—comparable to that of gasoline—and for this reason butanol may be the biofuel of the future.

Let's wind up this introduction with a few more numbers, several of which are important, and one of which (the last one) is just amusing. The following fuels do *beat* gasoline in energy per pound:

- *Natural gas* is 1.3 times better
- *Hydrogen gas or liquid* is 2.6 times better
- *Uranium or plutonium fission* is 2 million times better
- *Hydrogen fusion* is 6 million times better
- *Antimatter* is 2 billion times better

The 2.6 value for hydrogen gas is what inspires people to talk about the hydrogen economy. With 1 pound of hydrogen fuel, you can go 2.6 times farther than with gasoline. Yet a pound of hydrogen, even in its liquid form, takes up a lot more space. That's why hydrogen has 4.5 times less energy per gallon, as I stated at the beginning of the chapter.

The uranium number may not surprise you; the high value is why it is used in nuclear bombs and nuclear reactors. Fusion is even better, and it uses as its fuel heavy hydrogen, a component of ordinary water—something we will not run out of. (Of course, the same was once believed about wood from forests.)

I included antimatter in this list only because it is so prominent in science fiction. That number will be most useful for future presidents to know when they talk to teenagers. Someday (in a few hundred years?) we might actually use antimatter as fuel, if we can figure out a good way to bottle it; that is a problem, since it explodes when it contacts ordinary matter. Antimatter has an important feature in common with hydrogen gas: Neither one is a source of energy. Rather, they are both means of transporting energy. To use antimatter as a fuel, we first have to create it, and that takes more energy than we get back. To use hydrogen as a fuel, we must first extract it from its natural compounds.

Unlike oil, we can't mine hydrogen gas from the Earth. The hydrogen that is present has all already "burned"—that is, combined with oxygen to make water (H_2O), or with carbon to make sugars, starches, and hydrocarbons (including plant matter, wood, oil, and natural gas). To use hydrogen we have to separate the hydrogen from the other atoms. We can remove the hydrogen from water by running electric current through it—a process called *electrolysis*. But that process takes energy, and when we use the released hydrogen as a fuel, we get back only 30% to 40% of the energy that we put in; the rest is wasted as heat. Beware of inventions that claim to use ordinary water as fuel; these usually obtain the hydrogen by using other energy to separate it from water, by electrolysis or use of another fuel such as a purified metal.

There is one way to get net positive energy from hydrogen: obtain it from natural gas. This is, in fact, the way we get most of our hydrogen today. Natural gas is mostly methane, CH_4, with molecules that

consist of one carbon atom and four hydrogen atoms. When methane is reacted with water, out comes hydrogen and carbon monoxide (along with some carbon dioxide). This hydrogen can be used as fuel, but the energy we get is less than we would have obtained directly from the methane.

Power

If TNT contains so little energy, why do we use it at all? The answer is that it delivers a lot of *power*. In popular parlance, power and energy mean the same thing, but scientists like to make a distinction—one that will be useful for future presidents to know: power is the *rate* at which energy is used. Power can be measured in terms of calories per hour or joules[5] per second. TNT has less energy than gasoline, but it delivers what little it has with such speed that it can shatter rock. Gasoline has more energy than TNT, but TNT can deliver more power than gasoline can.

The same amount of energy can be delivered at different rates—that is, at different powers. In the chapter on 9/11 we discussed a hammer as a force multiplier. Now let's take another look, to see that it can also be considered a power multiplier. When you accelerate a hammer, you are putting energy into it over the length of the swing. You do this relatively slowly because your arm has limited power. Just before hitting the nail, the head of the hammer has all the energy that you are going to put into its motion. This energy is called *kinetic energy* because it is stored in the movement of the hammer. When the head finally makes contact, it delivers that energy very quickly to the nail. The energy that the hammer puts out is the same that you gave it with the swing, but because it gives up that energy much faster, we say it has more power. Of course, it delivers the higher power for a shorter time. The greater power means that the hammer will put a larger force on the nail than you put on the handle of the hammer; thus the force is multiplied, and the greater force splits the wood.

James Watt was the first person to measure the power that a healthy horse can deliver, and he called that unit the *horsepower*. The term is used most commonly today to describe the power of the thing that replaced the horse: the automobile. Another unit of power was named after Watt himself, and is called the *watt*. A thousand watts, one *kilowatt*, is approximately one horsepower.[6] That fact is so useful that a future president should memorize it:

1 horsepower = 1 kilowatt

This rough equality will prove very useful in getting a feel for power. Solar power, for example, is about 1 kilowatt per square yard (or square meter, if you prefer). You can now visualize the power in a square yard by thinking of it as the power of a horse. That sounds like a lot, and it is, but it is not enough to run a modern car. Typical cars have engines that can deliver 50 to 200 horsepower.

Watts are usually used to measure electric power. Lightbulbs are labeled by how many watts they use. If you turn on ten 100-watt lightbulbs, you are using $10 \times 100 = 1000$ watts = 1 kilowatt of electric power. That's about one horse, and one square yard of sunlight.

Now for the confusing part: measuring energy. If you use a kilowatt for an hour, you have used an amount of energy that we call a *kilowatt-hour* (abbreviated *kWh*). What makes the term confusing is the presence of the word *watt*. But you should be no more confused by these two words than you are by *miles* and *miles per hour* (*mph*). One is an amount (miles), and the other is a rate (miles per hour). For power and energy, the kilowatt is the rate of energy delivery (the power), and the kilowatt-hour is the total amount of energy delivered. A similar confusion arises from the term *light-year*, which is not a measure of time, but refers to the *distance* that light travels in a year. A light-year is a distance, and a kilowatt-hour is an amount of energy.

The average US household uses about a kilowatt of power. In a 24-hour day, the same household will use 24 kilowatt-hours of energy. Most future presidents are wealthier than average and probably use more. If you use a kilowatt for an hour, the electric utility will charge you for 1 kilowatt-hour of energy. The cost depends on your location, but the average in the United States is about 10 cents for that kilowatt-hour. That is a lot cheaper than renting a horse for an hour! Twenty-four hours of using a kilowatt would cost you \$2.40. A 30-day month would cost \$72. A year, 365 days, would cost \$876. It adds up. And your household probably uses more than a kilowatt.

A thousand houses will use 1000 kilowatts—also called a *megawatt*, meaning a million watts. Intermediate-sized power plants produce 50 to 100 megawatts of electricity, and they often serve local communities. The largest electric power plants produce about a billion watts of electric power, called a *gigawatt*. To avoid using yet another term, however, some energy experts talk about "thousands of megawatts" rather than gigawatts. The total electric power of the United States averages about 450 gigawatts. The electric power used by California amounts to about 40 gigawatts. These are useful numbers to know. Imagine 40 large power plants supplying all of California's power. To remember the value for the United States, remember that the whole country uses just over 10 times that amount: 450 big power plants, each producing one gigawatt.

Here is a conversion to our old energy unit, the food calorie. One watt-hour is equivalent to about one food calorie.[7] In other words, a flashlight turned on for an hour consumes one calorie. If we multiply by 1000, we get the following approximate conversion:

1 kWh ≈ 1000 food calories

A typical adult consumes 2000 food calories per day. That's equivalent to 2 kilowatt-hours, or about 20 cents of electricity. Are you surprised that electric energy is cheaper than energy from food? Actually, food isn't very expensive if we stick with basics. Enough rice to provide your 2000 calories—1.3 pounds—costs about 70 cents in a US grocery store. If you buy it by the ton, you can buy that 1.3 pounds of rice for less than 10 cents. You can live on about a dime a day of food! It is only the fancier food that is really expensive.

Energy Alternatives

When thinking about alternatives to petroleum and other fossil fuels, it is important to know how the United States uses its current supplies. About 5% is used to manufacture materials such as fertilizer, chemicals, and plastics. The rest is used to generate energy. Here's roughly how that breaks down for the US use of fuel:[8]

- 28% is used for transportation (gasoline and jet fuel).
- 40% is used to generate electric power.
- 20% is used for direct heating (natural gas, coal).
- 32% is used by industry.

These numbers add to more than 100% because of overlap; some of the electric power, for example, is used by industry.

Rather than learning these specific numbers, all you really have to know is that fuel is used in four different ways—transportation, electricity, heat, and industry—all in comparable amounts. That fact has important policy implications for future presidents. For example, if you are concerned that we are polluting the atmosphere by driving automobiles and you decide to solve this problem by replacing all gasoline with biofuels (alcohol made from plants), you will affect only 28% of the total.

Equally important (and interesting) is the broad spectrum of US energy sources:

- 29% from imported oil
- 11% from domestic oil
- 24% from coal
- 19% from natural gas (methane)

- 8% from nuclear
- 8% from others (solar, hydro, wind, biomass, geothermal)

Again, the diversity of sources is the most important fact. Here is an example of the way you might use these numbers for an important policy decision: Suppose someone proposes to replace all of our fossil fuel electric power plants with nuclear power, in an effort to reduce CO_2 emissions. The first list tells you that 40% of our energy is used to create electricity. The second list tells you that 8% is already coming from nuclear. So making the change would affect only the remaining 32% of our power use. Remember, if we are going to reduce fossil fuel emissions, we have to address several sectors, not just one.

The Bottom Line: The Cost of Energy

Not all energy sources are equally expensive; in fact, you may find the differences more astonishing than any of the astonishing numbers I've shown so far. Here is the most important fact: for the same energy, coal in the United States is 20 times cheaper than gasoline. That number is important for future presidents to consider. It implies that some developing nations are likely to rely on coal for their energy needs, rather than on oil or natural gas.

Here are some details. The following list compares the cost of energy per kilowatt-hour from various sources. The list does not include the cost of the plant and the power lines that deliver the energy.

- Coal: 0.4–0.8¢ ($40–80 per ton)
- Natural gas: 3.4¢ ($10 per million cubic feet)
- Gasoline: 11¢ ($3.70 per gallon)
- Car battery: 21¢ ($50 per battery to replace)
- Computer battery: $4 ($100 per battery to replace)
- AAA battery: $1,000 ($1.50 per battery)

It is odd that energy cost depends so much on the source. If the marketplace were "efficient," as economists sometimes like to postulate, then all these different fuels would reach a price at which the cost would be the same. This hasn't happened, because the marketplace is *not* efficient. There are large investments in energy infrastructure, and the mode of delivery of the energy is important. We are willing to spend a lot more for energy from a flashlight battery than from a wall plug because the flashlight is portable and convenient. Locomotives once ran on coal, but gasoline delivers more energy per pound, and it does so without leaving behind a residue of ash, so we switched from steam to diesel locomotives. Our automobiles were designed during a period of cheap oil, and we became accustomed to using them as if the price of fuel would never go up. Regions of the world with high gas prices (such as the countries of Europe) typically have more public transportation. The United States has suburbs—a luxury that is affordable when gas is cheap. Much of our way of living has been designed around cheap gasoline. The price we are willing to pay for fuel depends not only on the energy that it delivers, but also on its convenience.

The real challenge for alternative energy sources is to be more economically viable than coal. When we talk about global warming (in Part V), we'll discuss how coal is one of the worst carbon dioxide polluters that we use. To reduce our use of coal, we could, of course, tax it. But doing that solely in the developed nations would not accomplish much, since the ultimate problem will be energy use by nations such as China and India. Leaders of such countries might choose to get their energy in the cheapest possible way so that they can devote their resources to improving the nutrition, health, education, and overall economic well-being of their people.

6

SOLAR POWER

SOME experts say that solar power has no future. They claim that useful power sources must be compact, as if reciting a law of physics. But there is no such physics principle, and even people who appear to be experts can have their numbers very wrong. Let me tell you a true story that illustrates the kind of confusion that reigns over solar power.

An Anecdote

Liz, a former student of my class in Berkeley, came to my office. She was eager to share an experience that she had had a few days earlier. Her family had invited a physicist over for dinner, someone who worked at the Lawrence Livermore National Laboratory. He regaled the family throughout dinner with his stories of controlled thermonuclear fusion, its use for national security testing, and its great future for the power needs of our country. According to Liz, the family sat in awe of this great man describing his great work. Liz knew more about fusion than did her parents, because we had covered it in our class, but still not very much. She said she learned a lot.

After a period of quiet admiration at the end, finally Liz spoke up. "Solar power has a future too," she said.

"Ha!" the physicist laughed. (This is as related to me by Liz. He didn't mean to be patronizing, but this is a common tone that some physicists affect.) "If you wanted enough power just for California," he continued, "you'd have to plaster the whole state with solar cells!"

Liz told me that she answered right back. "No, you're wrong," she said. "There is a gigawatt in a square kilometer of sunlight, and that's about the same as a nuclear power plant."

Stunned silence followed. Liz said he frowned. Finally he said, "Hmm. Your numbers don't sound wrong. Of course, present solar cells are only 15% efficient . . . but that's not a huge factor. Hmm." He then said he would rethink the issue.

Yes! I have never been prouder of a student. Liz did exactly what a future president needs to be able to do. Not integrals, not roller-coaster calculations, not pontifications on the scientific method or the deep meaning of quantum physics. What she did was far more important: she was able to shut up an arrogant physicist who hadn't done his homework. Liz hadn't just memorized facts. She knew enough about the subject of energy that she could confidently present her case under duress when confronted by a supposed expert. She remembered the important numbers because she had found them fascinating and important. They had become part of her, a part she could bring out and use when she needed them, even a year later.

As a future president, you should aspire to no less.

Basic Facts

With a few basic numbers memorized, a future president can think more clearly about the potential of solar power. We discussed the power in sunlight earlier; now let's look into it a little more carefully. Overhead sunlight delivers to the ground approximately

- 100 watts per square foot
- 1 kilowatt per square yard (or square meter)
- 1 horsepower per square yard (or square meter)
- 1 gigawatt per square kilometer
- 3 gigawatts per square mile

Consider the fact that sunlight delivers a horsepower in just a square yard. Think about that. Visualize it. Does that sound like too much? If it does, try thinking about the intensity of sunlight. Sunlight dries clothes much faster and far more thoroughly than a household clothes dryer. Every cold camper appreciates the morning appearance of the sun. Watch a sunrise and experience the sudden warming of your face once the sun peeks above the horizon. Sunlight delivers enormous power density. No wonder many early peoples worshiped the sun!

A kilowatt per square yard is large, but in another sense it is remarkably small. Let's consider a solar-powered auto. Put a large solar cell on the roof of the car. A reasonably expensive solar cell can convert about 15% of the solar power into electric power. So if the cell has an area of 1 square yard, it will deliver about 15% of a horsepower—that is, about 1⁄7 horsepower. That's about the same as the power that a healthy person can produce by pedaling a bicycle.

Little wimpy cars, like the 1966 Volkswagen Beetle that I owned for many years, deliver a maximum of 50 horsepower. That's 350 times as much as we could get from the square-yard solar cell. Big muscle cars deliver 200 horsepower. That's 1400 times as much as we get from our solar cell. So, although solar power is intense, a whole horse in just 1 square yard, it is feeble compared to the power we need to drive an auto. Here's the bottom line: solar autos will never be a realistic technology to replace our gasoline-driven cars. This conclusion is a consequence of physics, with only a little bit of sociology: my assumption that you will not be satisfied with a car that delivers no more power than you could pedal.

Could solar cars become practical if solar cells improve? The best solar cells tested in the laboratory today have an efficiency of about 41% and cost about $100,000 per square yard. Let's be optimistic and assume that we can one day actually get 100% efficiency and that the solar cell will be cheap. Even so, we will get only 1 horsepower for our car, regardless of the price. Double the size of the solar cells to 2 square yards, and we'll get 2 horsepower. There's no room to put up more solar cells.

Piddling horsepower doesn't mean that solar autos don't exist. In fact, several races every year are dedicated to such vehicles. Some of them use expensive solar cells, with efficiency of 30%—double the cheap cell number. But all the autos are low and sleek to avoid air resistance, because it is hard to go very fast with only a fraction of a horsepower. To go up a hill in such cars requires accumulating energy on the flats by charging a battery with whatever excess power can be spared. I repeat: solar autos are not in our future.

An average US house uses 1 kilowatt, about 1 horsepower. Could a house be powered by a solar cell? Solar cells are typically 15% efficient. Moreover, the sun is not always out, and it is rarely overhead. Combining these factors shows that the solar cell average efficiency is only a few percent. So you could do it, if you had, say, 20 square yards of solar cells. That area of cells will fit on the roof of many homes. Some people are already doing it. It is environmentally very clean, and it sounds very cheap.

Why doesn't everyone put solar cells on the roof? Let's consider the cost. As of 2008, the typical expense (in sunny California) is $3.50 per installed noontime watt. Average in the time when the sun isn't overhead, and that amount becomes $14 per installed watt, $14,000 for your one-kilowatt home. That still sounds pretty good. You invest $14,000, and you don't have to pay the utility. How much do you save? Energy from the electric power companies averages about 10 cents for 1 kilowatt for 1 hour. Since there are 8760 hours in a year,[9] the power company's typical charge amounts to $876 per year. That is how much you would save if you installed the solar cells on your roof. In effect, you are *earning* $876 per year on an investment of

$14,000. That works out to a 6.2% average return on the investment—better than you can do with a typical savings account. So you are making money, as long as you don't have to replace the cells.

Suppose, on the other hand, that the cells last only 10 years. Then there is an additional replacement cost that averages $1,400 per year. Instead of making a yearly profit of $876, when you subtract the cost of replacement you suffer a net $524 yearly loss. To break even, an actuarial calculation[10] (assuming a 3% interest rate) shows that the cells would have to last 22 years. If they last that long, then you are just breaking even by investing in solar cells. If they require replacement or repair sooner than that, then you are losing money. If they last longer, then you are coming out ahead.

Right now, these are the economic and physics reasons that are delaying our transition to solar power. People who are wealthy enough can convert, and feel good about the societal good they are accomplishing. What is the prognosis for more widespread use? Improving efficiency might help, but that will be only a small factor. The real potential comes from a possible substantial reduction in the cost of the cells.

Part of the problem with solar power is that it is so inefficient to turn it into electricity—only 15% for inexpensive cells. If you don't need to convert it, however, but just use the heat directly, then it becomes much more attractive. For heat it is effectively 100% efficient,[11] and it doesn't require expensive solar cells. For this reason, solar-powered water heaters make good economic sense in many parts of the country. But when you add in the cost of the plumbing, do you really save money? That depends on the alternatives. Let's consider a few. A ton of coal costs only $40, and it will supply a kilowatt of heat for most of a year. Electric heating is the most expensive, but for short periods even electric costs are tolerable. For example, you can warm your bedroom on a cold night with a kilowatt electric heater. At 10 cents per hour, that will cost less than a dollar for the night. That sounds like a bargain, but it does add up. A dollar per night is $365 per year.

Solar Power Plants

So far we have been talking about using solar power for personal use—automobiles and houses. What about large power plants? There are two main approaches to using solar power to generate electricity. The first is to use solar cells similar to the ones we've been discussing, but to deploy them in huge numbers over large areas. The second method is called *solar thermal conversion*.

Let's begin with the solar cell approach. The key material in these cells is silicon, a very abundant element on Earth and the heart of our semiconductor industry. Most of our modern computer electronics are based on the electric properties of silicon, and that's what gave rise to the name *Silicon Valley*. When sunlight hits silicon, it knocks an electron out of the silicon crystal and transfers at most 25% of its energy to the electron. (The rest goes into heat.) That electron can then be drained off to supply electric current. Silicon solar cells are now in widespread use. As I said earlier, inexpensive solar cells aren't as efficient as the best ones, and achieve only 10% to 15% energy conversion to electricity.

More efficient solar cells are possible, but making them requires complex manufacturing methods and expensive materials. The trick is to make multiple layers, one for each different color in the spectrum of sunlight. The best efficiency achieved so far, 41%, has been with a "triple junction" cell[12] that has separate layers for different colors of light. But they are expensive, about $65 per square inch. If the cost can be brought down, and if we don't run out of the specialized materials needed to make them,[13] then solar could become an important source of energy in the future. I'll come back to this issue when I discuss global warming and alternative energy in Part V.

The second method to produce electricity from sunlight, solar thermal conversion, begins with reflectors or lenses to concentrate the sunlight. Just as a large magnifying glass can be used to start a fire, this focused sunlight can be used to boil water. The resulting steam

then runs a steam engine that generates electricity. Figure 6.1 shows a solar thermal conversion plant situated near Seville, Spain. It produces 11 megawatts of electric power, enough for 60,000 people.[14]

Although the rays in the photo look like they are emanating from the tower, in fact they are reflecting off 624 large mirrors on the ground, each one more than 1000 square feet in size. The sunlight is

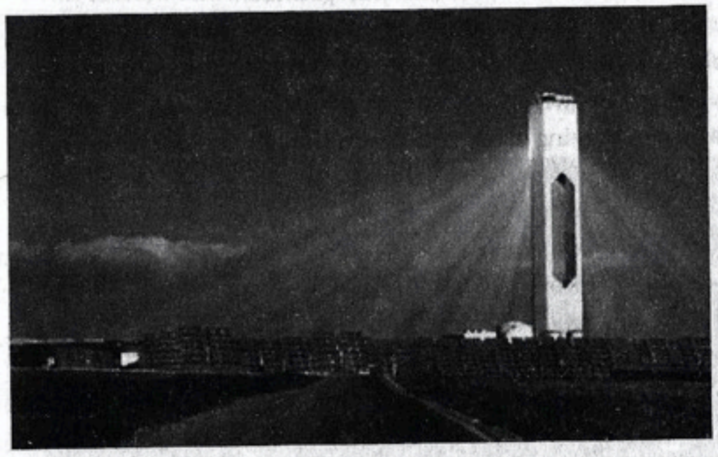

***Figure 6.1.** Solar power plant near Seville, Spain. The mirrors focus sunlight onto a boiler, and the resulting steam runs a turbine that produces electricity.*

directed onto a central boiler that sits on the top of the 377-foot tower (taller than the Statue of Liberty). The sunlight heats the water to 750°F. The whole system is reasonably efficient, converting about 15% of the intercepted solar power to electricity. There are plans to expand the plant to 300 megawatts in the near future.

The Seville solar power plant seems to set an example for the rest of the world to follow. Why aren't we doing this? What's the catch? Is there an anti-solar conspiracy? No. It's the same old catch: cost. The electricity from the plant costs about 28 cents per kilowatt-hour (versus 10 cents from fossil fuels). This uneconomical plant was made possible by the Spanish Royal Decree 436/2004, which subsidizes the operation. The Spanish government did this to help meet its requirements under the Kyoto Protocol limiting CO_2 emissions. (I'll discuss Kyoto further in Part V, which covers global warming.) It was also hoped that building the technology will eventually reveal ways to save money.

Solar Airplanes

Solar cars, with less than 1 horsepower, are just for hobbyists. It is therefore somewhat surprising to discover that solar airplanes have real value, serving some very practical applications. Their main use in the future will probably be for continuous spying on critical areas of conflict.

Solar aircraft (drones, actually, with no passengers) have already flown. One of the most successful was called *Helios*, shown in Figure 6.2. The solar cells are on the upper and lower surfaces of the wings; the cells on the undersides use light reflected off the Earth. The *Helios* vehicle carried fuel cells, a kind of rechargeable battery, that were charged during the day to allow continued flight at night. The payload was 100 pounds, enough for a good telescope, camera, and radio. In 2001, *Helios* achieved an amazing altitude of 96,863 feet (commercial airliners fly at about 40,000 feet). It was built by AeroVironment, a company started by engineer Paul McCready, who designed the human-powered airplanes the *Gossamer Condor* and the *Gossamer Albatross*.

Many follow-up solar-powered planes are now under test or development. The most prominent of these is called *Pathfinder*. It is somewhat smaller than *Helios*, and designed for shorter missions. The maximum power delivered by its solar cells is 17 horsepower. It flies at the leisurely speed of 20 miles per hour.

Imagine that you are president and you need a surveillance system above a particular country, perhaps North Korea or Iraq. You want to send a camera there that can circle above one location, maybe a nuclear test site, to watch for suspicious activity. You want it to stay there, perhaps for months. Your secretary of defense says that's

impossible; no craft can carry enough fuel. You ask, "What about solar energy?" A solar plane can get through the night by stored battery energy, or just by gliding. It flies so high that it is well beyond the range of manned aircraft. In fact, with its low velocity, it doesn't really stand out in a radar scan. It's possible that no one will even notice that it is there. The secretary of defense asks whether it could carry the camera and radio equipment needed for such a mission. You reply, "The *Helios* mission had a payload of 100 pounds. See if your scientists and engineers can squeeze what they need into such a package."

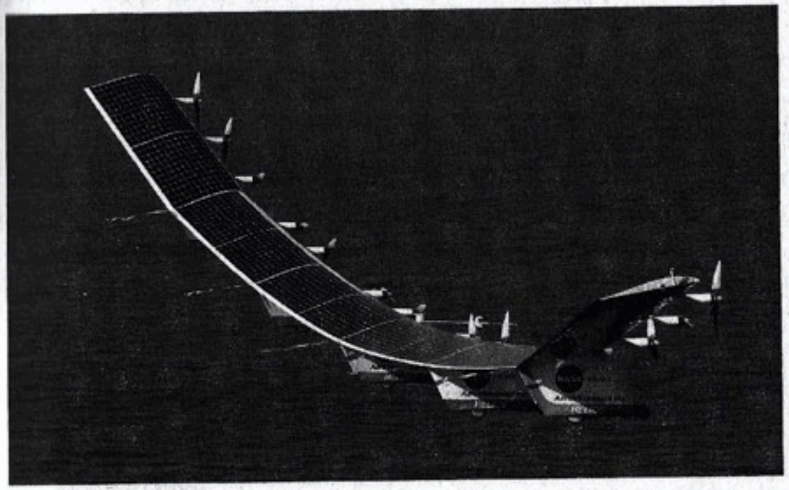

Figure 6.2. **Helios** ***in flight. In this image, the curvature of the wings is exaggerated by the fact that it was taken from an angle with a telephoto lens. The wingspan is 247 feet, 36 feet longer than that of a 747.***

rock. All sorts of ideas have been tried to overcome this problem—from pumping detergents down, to injecting polymers that make the oil less viscous. It has even been suggested that bacterial biofilms could be grown at the oil–rock interface to make the surface slippery.

Hubbert originally thought that the world production of oil would peak in the mid 1990s, about a decade earlier than seems to be happening. The delay was largely a result of the development of new technologies and the willingness of the world to buy oil at above $100 a barrel. In 1956, when Hubbert wrote his paper, the total recoverable oil in the world was thought to be less than a billion barrels. That much has already been pumped out of the ground. With enhanced oil recovery, and the possibility of recovering oil from oil shales and oil sands, the total recoverable reserves now appear to be an additional 5 billion barrels.

Because of the limited pumping capacity of the world's oil wells, demand has now outstripped the ability of the existing wells to keep up. In particular, the rapid growth of the economies of China and India has sopped up most of the available oil-pumping capacity. Competition among buyers pushes the price higher. Oil drilled in Saudi Arabia for $2 per barrel is sold to the United States for $100 per barrel and higher.

In the past, the OPEC cartel did not let prices rise high. OPEC's public reason for this control was that it wanted the Western economies to stay vibrant. However, most experts think that OPEC's motive was more self-serving. Once the price of oil reaches $50 per barrel, there are many alternatives. In the 1970s, OPEC's primary competition was energy conservation; that led to the drop in oil prices in the early 1980s. But ultimately, the competition that OPEC fears most is coal.

Oil From Coal: Fischer–Tropsch

Coal is cheap and—unfortunately for OPEC—abundant in the countries that need the most energy: the United States, China,

India, and Russia. Once the price of oil rises above about $50 per barrel, these countries can take their coal reserves and convert them to oil, using a series of chemical reactions known as the *Fischer–Tropsch process*. The basic method is to combine the carbon with the hydrogen from water to make hydrocarbons—the basic molecules of oil.[17] This process was used by Nazi Germany during World War II, when the Germans could not get oil because of the Allied blockade. It was used by South Africa during the era of apartheid for similar reasons, and because the plants still exist, South Africa is still converting coal to oil today. The only reason that we are not yet doing this in the United States is that building Fischer–Tropsch plants is expensive, and nobody wants to make the investment unless it is certain that the price of oil will stay high. Several companies, in fact, want to go ahead and build such plants, but they fear they cannot take the risk unless the US government guarantees that it will cover their losses if oil prices drop again.

Our ability to manufacture oil from coal means that as long as we can afford a price as high as $50 a barrel, we are not going to run out of liquid fuel at that price, not for centuries—at least not once we have our Fischer–Tropsch plants built. The Hubbert Peak for oil does not take into account the availability of the Fischer–Tropsch method. If we are driven to other fuels, it will not be because we can't get oil. Rather, it will happen for one of two reasons: either the alternatives will become cheaper than oil, or we will be forced to use them anyway because of the environmental consequences of the continued use of fossil fuel.

How soon will we run out of coal? The United States has enormous reserves. About 2 trillion tons of coal are known, but twice as much coal might be present. We consume about a billion tons per year. If our coal use doesn't grow, the supply will last over 1000 years. If we wind up using a great deal more—to replace expensive oil, for example—then it might last only several hundred years. Of course, by then we may be using fusion power or solar.

7

THE END OF OIL

MANY people believe that we are soon going to run out of oil. Actually, according to a famous analysis by Marion Hubbert done in 1956,[15] we will never completely run out. The plot in Figure 7.1 shows the historical oil production up to 2004, and then the expected production until the year 2050. Although the amount of oil recovered each year will go down, it drops by only a factor of two by 2050.

Although the general shape of the curve was not widely antici-

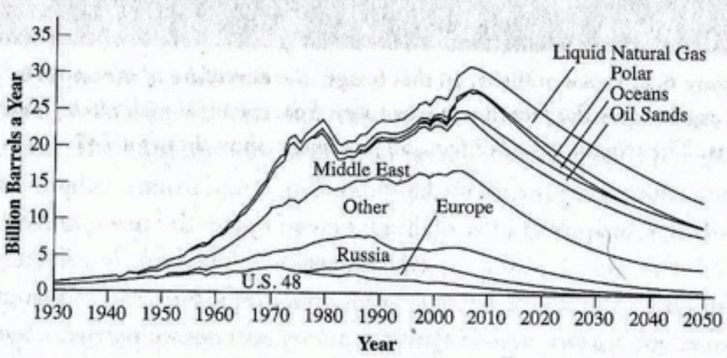

Figure 7.1. The Hubbert curve for oil. The plot shows the growing consumption of oil in the past, the peak (occurring about now), and the predicted drop in usage as world supplies are depleted.[16]

pated prior to Hubbert's paper, the reason for the shape now seems obvious. When oil was first used as a commodity, it was rare and expensive, and only little was produced. Thus, people were encouraged to search for more, and as they succeeded the production rose; that's the left side of the plot. The world is finite, however, so after a few decades little additional oil was being found. (The North Slope of Alaska, one of the more recently discovered sources, produced only 2 billion barrels of oil in its maximum year, and it yields less than 1 billion barrels per year now. That's only 3% of the total world production of 30 billion barrels per year.) For that reason, the production peaks and eventually drops. That happened for US oil in the mid 1970s, and it should happen for the world total productivity soon—maybe as soon as 2008. The maximum is called the *Hubbert Peak*. You need to know that term. You'll hear politicians (your rivals) using it to show their erudition. It is becoming so widely used in popular analysis that an episode of the TV series *The West Wing* was named after it.

Notice how slowly the Hubbert curve drops. Hubbert did not predict the slowness of that drop, although he was careful to state his limited assumptions. Part of the reason for the slow decline is that as time passes and the price of oil remains high, new technologies emerge that enable more oil to be recovered. Moreover, oil usage can fluctuate, as it did in the 1970s because of the oil embargo, suddenly dropping and then rising again.

Underground oil is not found in caves or large openings, but in microscopic cavities in porous rock. When the oil is first drilled, it tends to come up of its own accord, from the enormous pressure as the weight of the material above squeezes the saturated rock. Only 20% to 30% comes up that way, however. To get the rest, gas such as carbon dioxide or liquid such as water is pumped down into the rock. (Pumping carbon dioxide into these wells will prove to be a useful means to keep it out of the atmosphere; we'll describe this further when we discuss global warming.) With these methods, an additional 30% to 60% of the oil can be pushed out. What about the rest? Getting it out is difficult because the oil tends to stick to the

The Price of Oil

To discuss the real price of oil (versus the perceived price), we have to start with a little economics. Economists try to account for inflation so that they can compare prices in *constant dollars*. The plot in Figure 7.2 shows the price of oil, in dollars per 42-gallon barrel, from 1970 to 2007. Note that the high price of oil, over $100 per barrel in 2008, is not unprecedented. The cost approached similar levels during the Iran crisis in the early 1980s. Prior to 1970, the price had been less than $20 per barrel for decades.

There is much more that a future president needs to know about energy. Part III will be devoted entirely to one key field: nuclear energy. Energy will also be at the center of our discussion of global warming in Part V.

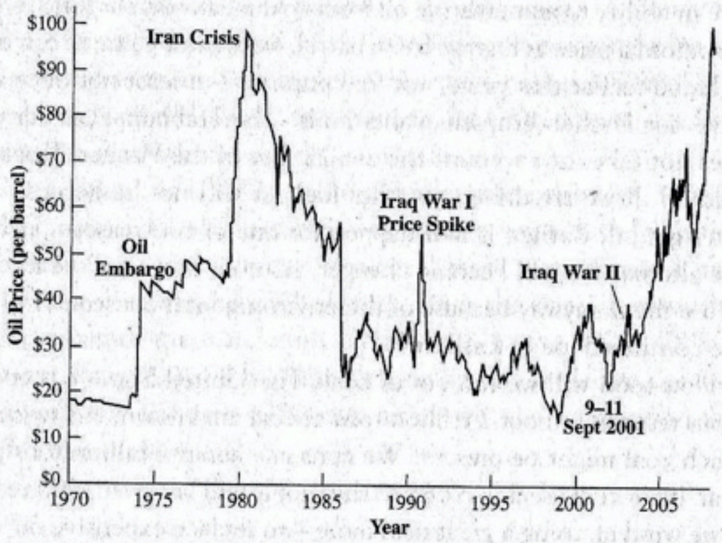

Figure 7.2. Oil prices (adjusted for inflation) from 1970 to the present.[18] Notice that the current price for 2008, when measured in constant dollars, is only a bit higher than the price in the early 1980s.

ENERGY: PRESIDENTIAL SUMMARY

IN DEALING with energy, you will be confronted with the fact that the public has a vast amount of misinformation. Many of the facts I gave in the previous three chapters are directly useful for policy decisions, whether they relate to battery-driven autos or energy storage with hydrogen, but equally important are the facts that most people think are true but aren't. Our love affair with fossil fuels ultimately derives from the fact that they are so cheap.

It is important to realize that we are not running out of fossil fuels—but only out of oil. Our coal will last centuries. That is both the good news and (from a global-warming perspective) the bad news. We'll defer our in-depth discussion of global warming to the end of this book. Coal can be converted to gasoline, but we don't presently have the factories to do that. If you want such factories to be built, you may have to guarantee their profit, because otherwise investors will be wary of OPEC's ability to drop prices (as in an old-fashioned gasoline price war) just long enough to put Fischer–Tropsch plants out of business.

There are many alternatives to fossil fuel. We've discussed some of them, and we'll be discussing more in the coming chapters. The key issue will be cost. We have been having a love affair with gasoline not because it smells good, but because it has been very cheap and abundant. Shifting to coal will be expensive (at first) and potentially dangerous, especially from the environmental point of view. There are no simple, obvious solutions, despite hype about the hydrogen economy and the imminent expansion of solar. Coal is the front-runner precisely because it is so cheap. From the environmental point of view, coal is perhaps the worst source of energy. Even if the United States votes in favor of the environment, however, it is not obvious that the developing countries—especially China and India, but also Russia—will go along. That is the conflict you will have to resolve. Only one approach satisfies everyone: conservation. A deeper discussion of that approach will have to wait for Part V.