When I first came to the U.S. Department of Energy (DOE) in 1993 to help oversee research and development (R&D) in clean energy, hydrogen R&D did not even have its own separate budget line but instead was nestled inside the renewable energy budget. For the previous decade, hydrogen research funding had languished in the $1-$2 million per year range, some one one-hundredth of 1 percent of the overall departmental budget—a penny in every $100.

Only ten years later, all the major car companies had hydrogen vehicle programs, the major oil companies had hydrogen production programs, dozens of new companies had been formed to develop hydrogen-related technologies with venture capital funding, and President George W. Bush had announced a major hydrogen initiative in his January 2003 State of the Union address:

Tonight I’m proposing $1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles. A single chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car—producing only water, not exhaust fumes. With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so
that the first car driven by a child born today could be powered by hydrogen, and pollution-free.¹

What caused this sea change in ten short years? I believe there are three reasons: a series of technological advances in the fuel cells most suitable for cars; growing concern about a variety of energy and environmental problems, especially global warming; and advances in technologies needed for greenhouse-gas-free hydrogen production.

Advances in Transportation Fuel Cells
Fuel cells are one of the Holy Grails of energy technology (see Chapter 2). They are pollution-free electric "engines" that run on hydrogen. Unlike virtually all other engines, fuel cells do not rely on the burning of fossil fuels. Hence, they produce no combustion by-products, such as oxides of nitrogen, sulfur dioxide, or particulates—the air pollutants that cause smog and acid rain and that have been most clearly documented as harmful to human health.

Fuel cells have been reliably providing electricity to spacecraft since the 1960s, including the Gemini and Apollo missions as well as the space shuttle. The leading manufacturer of fuel cells for the National Aeronautics and Space Administration (NASA), United Technologies Corporation, has sold commercial units for stationary power since the early 1990s, with more than 200 units in service.

But finding a fuel cell with the right combination of features for powering a car or truck has proved much more difficult. Why is that hard? To begin with, you need a fuel cell that is lightweight and compact enough to fit under the hood of a car but that can still deliver the power and acceleration drivers have come to expect. You also need a fuel cell that can reach full power in a matter of seconds after start-up, which rules out a variety of fuel cells that operate at very high temperatures and thus take a long time to warm up. You also need cost and reliability comparable to that of the gasoline-powered internal combustion engine, which is an exceedingly mature technology, the product of more than a hundred years of development and real-world testing in hundreds of millions of vehicles.

Further, these hardware hurdles are all quite separate from the way in which the fuel for fuel cells—hydrogen—would be produced and delivered to the vehicle. Hydrogen, first and foremost, is not a primary fuel, like natural gas or coal or wood, which we can drill or dig for or chop down and then use at once. Hydrogen is the most abundant element in the universe, true enough. But on Earth, it is bound up tightly in molecules of water, coal, natural gas, and so on. To unbind it, a great deal of energy must be used.²

For all these reasons—plus the sharp drop in both the price of oil and government funding for alternative energy—hydrogen fuel cell vehicles received little attention through most of the 1980s. Still, a few government and industry laboratories (together with a small and ardent group of hydrogen advocates and state energy experts) kept plugging away, particularly on proton exchange membrane (PEM) fuel cells.

PEM fuel cells were developed in the early 1960s by the General Electric Company for the Gemini space program. Fuel cells require catalysts to speed up the electrochemical reaction, and PEM fuel cells use platinum, a very expensive metal. An early 1981 analysis for the DOE had presciently argued that PEM fuel cells would be ideal for transportation if the catalyst loading could be significantly reduced.³ By the early 1990s, Los Alamos National Laboratory (and others), did succeed in cutting the amount of platinum by almost a factor of ten, a remarkable improvement. This still did not make PEM fuel cells cost-competitive with gasoline engines—we are a long way away from that—but it did dramatically reinvigorate interest in hydrogen-powered vehicles because PEMs were exactly the kind of low-temperature fuel cell that could be used in a car.

In 1993, DOE funding for PEM fuel cells was just less than $10 million. Within days of my arrival, I was briefed on Los Alamos' PEM work and began pushing for increases in funding for PEM fuel cells as well as for the development of a transportation fuel cell strategy. President Bill Clinton's entire team was very supportive of R&D for fuel-efficient technologies, including PEMs. Funding for hybrid vehicles, including fuel cells, was significantly increased. So, too, was funding for hydrogen R&D.
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In mid-1995, I moved to the DOE’s Office of Energy Efficiency and Renewable Energy. I was principal deputy assistant secretary, the number two slot, in charge of all budget and technology analysis. In that capacity, I was able to work with other fuel cell advocates in and out of the administration, especially my DOE colleagues Brian Castelli and Christine Ervin, to keep the PEM fuel cell budget creeping upward even as the entire budget for the office was cut 20 percent by a 1995 Congress that was extremely skeptical of all energy R&D.

It seemed likely that long before PEM fuel cells would be cost-effective for powering cars, they would be cost-effective for providing electricity and hot water to buildings. Yet Congress had repeatedly rejected our office’s request to start a small ($1 million) program to advance the effort to put fuel cells into buildings. In 1997, when I was acting assistant secretary, we managed to launch the program for stationary PEM fuel cell research, the budget for which ultimately grew to several million dollars.

By 1998, the year I left the DOE, the hydrogen budget was ten times larger than in 1993, and the proposed PEM fuel cell budget was more than three times larger. The investment paid off: The cost of fuel cells (PEM and others) had steadily declined as performance increased. Harry Pearce, vice chairman of the General Motors Corporation, said at the North American International Auto Show in January 2000, “It was the Department of Energy that took fuel cells from the aerospace industry to the automotive industry, and they should receive a lot of credit for bringing it to us.”

There were promising developments in hydrogen production and storage. Hydrogen budgets were ballooning everywhere in a race for patents and products. William Clay Ford Jr., chairman of the Ford Motor Company, said in October 2000, “I believe fuel cells will finally end the 100-year reign of the internal combustion engine”—a poignant statement from the great-grandson of the man whose manufacturing innovations had begun that reign a century ago with the Model T.

The federal government’s increasing commitment to hydrogen and fuel cells, together with the technological successes already spawned by that funding, has spurred private sector interest, much as similar support does in medicine and national defense. Since the late 1990s, hundreds of millions of dollars from venture capitalists and investors in the stock market have flowed into start-up companies and divisions of existing companies, all working to develop hydrogen-related technologies and fuel cells, although, as discussed in Chapter 3, this investment funding has proved as erratic as the stock market.

The U.S. government was hardly the only source of funding for hydrogen and PEM fuel cells. Governments in Europe and Asia have major programs, as do Japanese car companies such as Toyota and Honda. Canada has a significant program because of the leadership of Ballard Power Systems Inc. in PEM technology.

Growing Energy Risks

Many other trends have driven the renewed interest in hydrogen. At the top of the list are worries about oil consumption and air pollution, including global warming. America’s dependence on imported oil has accelerated since the mid-1990s, as many people predicted—including Charles Curtis, then deputy secretary of the DOE, and me in a 1996 Atlantic Monthly piece titled “Mideast Oil Forever?” By 2002, we were importing more than half our oil, an outflow of $200 billion per year to foreign governments, including those in the politically unstable Persian Gulf region.

The terrible September 11, 2001, terrorist attacks heightened this concern. Less than two weeks later, the DOE was commenting publicly. “It is clear that our reliance on imported oil—56% of the oil we use—has complicated our response to the terrorist attack,” noted David Garman, the Bush administration’s assistant secretary for energy efficiency and renewable energy, on September 24, 2001. “There is also little doubt that some of the dollars we have exported in exchange for foreign oil have found their way into the hands of terrorists and would-be terrorists.”

These seismic problems, together with worldwide population growth, economic growth, and urbanization, will dramatically
increase global oil consumption in the coming decades, especially in the developing world. If by 2050 the per capita energy consumption of China and India were to approach that of South Korea, and if the Chinese and Indian populations increase at currently projected rates, those two supergiant countries by themselves would consume more oil than the entire world did in 2003.9

Since oil is a finite, nonrenewable resource, analysts have attempted to predict when production will peak and start declining. Some believe this will occur by 2010. The Royal Dutch/Shell Group, probably the most successful predictor in the global oil business, adds fifteen to thirty years to that gloomy forecast. Worry about oil supplies is one of the factors behind Shell's growing research into hydrogen (see Chapter 7). This debate will not be resolved here, but it does appear credible that oil production will peak in the first half of this century and will possibly decline at a relatively rapid rate thereafter, even as demand increases. Thus, delaying action until we are past the peak may put us at significant risk.

Growing Environmental Risks

A whopping two-thirds of U.S. oil consumption is in the transportation sector, the only sector of the U.S. economy wholly reliant on oil. The energy price shocks of the 1970s helped spur growth in use of natural gas for home heating and drove the electric utility sector and the industrial sector to reduce their dependence on petroleum. But roughly 97 percent of all energy consumed by our cars, sport utility vehicles, vans, trucks, and airplanes is still petroleum-based.

Not surprisingly, a high priority of R&D funding by the United States—and by any country, state, or company that takes the long view—is to develop both more fuel-efficient vehicles and alternative fuels. Only a limited number of fuels are plausible alternatives for gasoline, and one enormous benefit of hydrogen over others is that it can be generated by a variety of different sources, thus potentially minimizing dependence on any one. Most important, hydrogen can be generated from renewable sources of energy such as wind power, raising the ultimate prospect of an inexhaustible, clean, domestic source of transportation fuel. Also, since fuel cells are more efficient than gasoline internal combustion engines, hydrogen fuel cell vehicles are, potentially, a double winner in the race to replace oil.

Hydrogen fuel cell vehicles would seem to be the perfect answer to our burgeoning and alarming dependence on imported oil. For some, like Peter Schwartz, chair of the Global Business Network, they are almost the deus ex machina—the quick, pure technological fix—that will avoid the need for difficult policy choices, such as federal mandates for increased vehicle efficiency.10 That is overoptimistic hype, as we will see.

The pollution generated by internal combustion engine automobiles is another key reason why so many people are drawn to hydrogen fuel cell vehicles. The transportation sector remains one of the largest sources of urban air pollution, especially the oxides of nitrogen that are a precursor to ozone smog and the particulates that do so much damage to our hearts and lungs. Vehicle emissions of such pollutants, however, have been declining steadily, and, by 2010, federal and state standards will have made new U.S. cars exceedingly clean.

Yet, even as new internal combustion engine vehicles dramatically cut the emissions of noxious urban air pollutants by automobiles, their contribution to global warming has begun to rise. In the 1990s, the transportation sector saw the fastest growth in carbon dioxide (CO2) emissions of any major sector of the U.S. economy. And the transportation sector is projected to generate nearly half of the 40 percent rise in U.S. CO2 emissions forecast for 2025.11

When the United States takes serious action on global warming, the transportation sector will need to be a top priority. The two most straightforward ways to reduce vehicle CO2 emissions are, first, by increasing the fuel efficiency of the vehicles themselves and, second, by using a fuel that has lower net emissions than gasoline. Again, the attractiveness of hydrogen fuel cell vehicles is that they afford the possibility of pursuing both strategies at the same time: Fuel cells are more efficient than traditional internal combustion
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engines, and hydrogen, when produced from renewable energy sources, would create no net greenhouse gas emissions.

Hydrogen without Greenhouse Gases

The possibility that hydrogen and fuel cells could play a key role in combating pollution, particularly global warming, is, I believe, the strongest argument for expanded efforts in research and development. John Heywood, director of the Sloan Automotive Laboratory at the Massachusetts Institute of Technology, argues, “If the hydrogen does not come from renewable sources, then it is simply not worth doing, environmentally or economically.”

The idea that hydrogen could be generated without releasing any pollution is not a new one. In 1923, John Haldane, who later became one of the century’s most famous geneticists, gave a lecture predicting that Britain would ultimately derive its energy from “rows of metallic windmills” generating electricity for the country and, when there was excess wind, producing hydrogen. “Among its more obvious advantages will be the fact that... no smoke or ash will be produced.”

The problem with the vision of a pure hydrogen economy has been that, until recently, most greenhouse-gas-free sources for hydrogen have been far too expensive to be practical. Haldane himself was imagining a future “four hundred years hence.” Even today, nuclear, wind, and solar electric power would produce hydrogen that is far more expensive than hydrogen from fossil fuels. But for more than two decades, renewable energy, especially wind and solar energy, has been declining in price sharply. That has created a renewed interest in renewable hydrogen, although it will still be two or more decades before this is a competitive way to generate hydrogen.

There is another, more unexpected possible source of greenhouse-gas-free hydrogen: fossil fuels. In the mid-1990s, Princeton University professor Bob Williams (and others) produced detailed reports arguing that fossil fuels could be both a cost-effective and an environmentally benign source of hydrogen if the CO₂ released during the production process could be captured and stored in underground geologic formations so that it would not be released into the atmosphere and thereby accelerate global warming. His briefings to DOE officials and others in government were a major reason why the department launched a major effort to explore this possibility. Today, carbon capture and storage is the subject of considerable research as well as demonstration projects around the globe and is widely seen as a potentially critical strategy for addressing global warming in the longer term (see Chapters 7 and 8).

With ongoing advances in transportation fuel cells and pollution-free hydrogen production, hydrogen vehicles would seem to be the perfect answer to global warming. Yet one of the conclusions of this book—the one that surprised me the most, as it was not my view before starting the current research—is that hydrogen vehicles are unlikely to make a significant dent in U.S. greenhouse gas emissions in the first half of this century, especially if U.S. energy policy is not significantly changed (see Chapter 8). Still, hydrogen-fueled stationary power plants could be critical in reducing greenhouse gas emissions much sooner. Further, hydrogen may well be the essential vehicle fuel in the second half of this century if we are to achieve the very deep reductions in CO₂ emissions that will almost certainly be needed then or if we are past the peak of oil production.

We are not used to thinking or planning in such giant, multi-decade time steps. But then again, we have never faced such a giant problem as global warming.

The Long Transition to a Hydrogen Economy

The term “hydrogen economy” describes a time when a substantial fraction of our energy is delivered by hydrogen made from sources of energy that have no net emissions of greenhouse gases. These would include renewable sources of energy, such as wind power and biomass (e.g., plant matter), but it could also include the scenario of converting fossil fuels into hydrogen and CO₂ and then permanently storing the carbon. It could also include generating hydrogen from nuclear power, should that prove practical.
We are unlikely to know whether a hydrogen economy is practical and economically feasible for at least one decade and possibly two or even more. A hydrogen economy would require dramatic changes in our transportation system because, at room temperature and pressure, hydrogen takes up three thousand times more space than gasoline containing an equivalent amount of energy. We will need tens of thousands of hydrogen fueling stations, and, unless hydrogen is generated on-site at those stations, we will also need a massive infrastructure for delivering that hydrogen from wherever it is generated.

Substantial technological and cost breakthroughs will be needed in many areas, not the least of which is fuel cells for vehicles. In 2003, fuel cell vehicles cost $1 million each or more. Were we to build a hydrogen infrastructure for fueling vehicles, the total delivered cost of hydrogen generated from fossil fuel sources would likely be at least triple the cost of gasoline for the foreseeable future. Hydrogen generated from renewable energy sources would be considerably more expensive. Hydrogen storage is currently expensive, inefficient, and subject to onerous codes and standards. The DOE does not foresee making a decision about commercializing fuel cell vehicles until 2015. One detailed 2003 analysis of a hydrogen economy by two leading European fuel cell experts concluded, “The ‘pure-hydrogen-only-solution’ may never become reality.”

And if the imposing technical and cost problems can be substantially solved, we will still have an imposing chicken-and-egg problem. Who will spend hundreds of billions of dollars on a wholly new nationwide infrastructure to provide ready access to hydrogen for consumers with fuel cell vehicles until millions of hydrogen vehicles are on the road? Yet who will manufacture and market such vehicles—and who will buy them—until the infrastructure is in place to fuel those vehicles? A 2002 analysis by Argonne National Laboratory found that “with current technologies, the hydrogen delivery infrastructure to serve 40% of the light duty fleet is likely to cost over $500 billion.” I fervently hope to see an economically, environmentally, and politically plausible scenario for bridging this classic catch-22 chasm; it does not yet exist.

So, despite much hype to the contrary, a hydrogen economy is a long way off. Widespread use of fuel cells, particularly for stationary applications, may be just around the corner, however, so they are the subject of the next two chapters.
Hydrogen is the best of fuels. Hydrogen is the worst of fuels.

On the plus side, hydrogen is the most abundant element in the universe by far. Hydrogen can be made from many things, which offers us the potential to replace our reliance on limited and insecure energy sources, such as oil, with the use of diversified, domestic, and, ultimately, limitless sources. Hydrogen can power highly efficient fuel cells that generate both electricity and heat with no emissions other than pure, drinkable water. Hydrogen represents one of the few substitutes for oil as a transportation fuel that will not contribute to global warming—if generated by renewable sources, such as wind power, or even by coal, should the capture and storage of carbon dioxide (CO₂) on a massive scale prove practical and affordable.

Hydrogen is widely used in industry today, and we have decades of experience in generating, storing, and transporting it. Although it has a reputation as a dangerous fuel, it has a good safety record in industrial settings.

On the minus side, hydrogen is not a readily accessible energy source, as are coal, oil, natural gas, sunlight, and wind. Hydrogen is bound up tightly in such molecules as water and natural gas, so it is expensive and energy-intensive to extract and purify. Transportation fuel cell costs in 2003 exceeded internal combustion engine
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costs by far more than a factor of thirty. Hydrogen from renewable sources is especially expensive. The practicality of carbon sequestration is as yet unproven.

Hydrogen is difficult and costly to compress, store, and transport. It has one of the lowest energy densities of any fuel, one-third that of natural gas. It is expensive and energy-intensive to liquefy; moreover, a gallon of liquid hydrogen has only about one-quarter the energy of a gallon of gasoline. Hydrogen has major safety issues—it is flammable over a wide range of concentrations and has an ignition energy twenty times smaller than that of natural gas or gasoline—so leaks are a significant fire hazard. One of the most leak-prone of gases, hydrogen is subject to a set of strict and cumbersome codes and standards.

To paraphrase Charles Dickens again: We were all going directly to hydrogen, we were all going directly the other way. This chapter looks at options for producing hydrogen today and in the future—but first a little background on this most indispensable element.

A Brief History of Hydrogen

"If God did create the world with a word, the word would have been hydrogen," said Harlow Shapley, one of the twentieth century's greatest astronomers. In our current theory of the origin of the universe, when atoms first formed out of the sea of particles created in the big bang, basic hydrogen—one electron and one proton—constituted some 92 percent of the atoms, while virtually all of the rest was helium. Today, some 15 billion years later, about 90 percent of all particles are hydrogen and 9 percent are helium.

Hydrogen is everywhere. In the near-vacuum of interstellar space, every cubic centimeter contains a few hydrogen atoms. In the interior of planet Jupiter, every cubic centimeter contains more than 10 million billion billion hydrogen atoms. Every second, our sun fuses 600 million tons of hydrogen into helium, providing the light and the warmth that make life on Earth possible. The hydrogen-driven process of stellar birth and death has generated all the heavier elements that make up our bodies and our planet, including the oxygen that, with hydrogen, composes water. As physicist John Rigden puts it in his delightful 2002 book Hydrogen: The Essential Element, "hydrogen is the mother of all atoms and molecules."

Hydrogen's first "discovery" on Earth is often credited to Theophrastus Bombastus von Hohenheim (1493–1541), better known as Paracelsus, Renaissance physician and alchemist. Paracelsus observed that when acids react with metals, a flammable gas is emitted. But English nobleman Henry Cavendish (1731–1810) is typically given credit for discovering in 1766 that hydrogen is a separate substance and for characterizing a number of its qualities. He called hydrogen "inflammable air" and was the first chemist to produce water from oxygen and hydrogen. French scientist Antoine Lavoisier (1743–1794) learned of Cavendish's work in 1783 and repeated and expanded upon his experiments. Lavoisier, who died on the guillotine in 1794, named the element hydrogene, from the Greek words for "water" and "generate."

Now remarkable, then, that hydrogen not only generates water when combined with oxygen but also helped generate the oxygen in stars in the first place. How doubly remarkable it would be if the sun's hydrogen-generated power were ultimately used to electrolyze that water to generate hydrogen to power the planet.

The idea of hydrogen as the ultimate fuel, limitless and powerful, stoked the imagination of nineteenth-century fiction writers. In his 1874 book The Mysterious Island, the ever-present writer Jules Verne has his characters discuss what would happen to America's "industrial and commercial movement" when the world runs out of coal in hundreds of years. The engineer, Cyrus Harding, explains that the world will turn to another fuel, "water decomposed into its primitive elements... doubtless by electricity, which will then have become a powerful and manageable force." Harding goes on to say:

Yes, my friends, I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable. Some day the coalrooms of steamers and the tenders of locomotives will, instead of coal, be
stored with these two condensed gases, which will burn in the furnaces with enormous calorific power. There is, therefore, nothing to fear. As long as the earth is inhabited it will supply the wants of its inhabitants, and there will be no want of either light or heat as long as the productions of the vegetable, mineral or animal kingdoms do not fail us. I believe, then, that when the deposits of coal are exhausted we shall heat and warm ourselves with water. Water will be the coal of the future.¹

Verne neglected to tell us where the primary energy to electrolyze the hydrogen would come from, but his prediction stands as one of uncanny foresight.

A few years later, in 1893, British novelist Max Pemberton published a prophetic best seller, The Iron Pirate. In the book, a speedy and powerful pirate ship terrorizes the Atlantic Ocean. The source of its power baffles the narrator: “Neither steam nor smoke came from her, no evidence, even the most trifling, of that terrible power which was then driving her through the seas at such a fearful speed.” Ultimately, we learn that the ship is based in Greenland and hydrogen from coal fuels “the most powerful engines that have yet been placed in a battle-ship.” Interestingly, Pemberton writes, “the gas itself was made by passing the steam from a comparatively small boiler through a coke and anthracite furnace, the coke combining with the oxygen and leaving pure hydrogen.”² As we will see, generating hydrogen from coal is one of the principal areas of focus for public and private sector research and development (R&D).

As the twentieth century dawned, hydrogen became an intense focus of scientists, both theorists and experimentalists. “To understand hydrogen is to understand all of physics,” one physicist said. The study of hydrogen was critical to our understanding of the atom and the evolution of the universe, to the development of quantum mechanics and quantum electrodynamics, and to such practical devices as magnetic resonance imaging (MRI) medical equipment. Rigden’s book is the best recent recounting of all this work.

In the middle of the twentieth century, scientists and governments expended tremendous effort in trying to replicate on Earth the awesome power of the sun’s hydrogen fusion. Strikingly, we have been all too successful in tapping fusion energy in uncontrolled reactions—unleashing the horrific power of the hydrogen bomb—but unsuccessful in efforts to create practical energy sources from a controlled fusion reaction to generate electricity. Controlled, earthbound fusion is still many decades away. For this century, the fusion energy we will most likely be tapping will be from the sun, in the form of its renewable radiating energy.

Efforts to harness hydrogen on a smaller scale, through direct combustion or fuel cells, gathered momentum throughout the twentieth century. An excellent history of those efforts can be found in Peter Hoffmann’s 2001 book Tomorrow’s Energy. The large investments made by the National Aeronautics and Space Administration to develop compact, lightweight engines and energy storage devices for space travel were especially important. As discussed in earlier chapters, making practical and affordable fuel cells has proven more difficult than expected. And even if we can develop transportation fuel cells that can potentially replace automobile engines, a true hydrogen economy will require the generation of enormous amounts of hydrogen from CO₂-free sources, which is not currently practical or affordable.

### Hydrogen Generation: Today and Tomorrow

Hydrogen production is a large, modern industry with commercial roots reaching back more than a hundred years.³ Globally, hydrogen is produced primarily for two purposes. The first is to synthesize ammonia (NH₃), especially for fertilizer production, by combining hydrogen with nitrogen. The second is hydro-formulation, or high-pressure hydro-treating, of petroleum in refineries, a process that, for instance, converts heavy crude oils into usable transportation fuels or that produces cleaner reformulated gasoline.

Global annual production is about 45 billion kilograms (kg) or 500 billion Normal cubic meters (Nm³). A Normal cubic meter is a cubic meter at one atmosphere of pressure and 0°C. Hydrogen is produced through a variety of processes discussed below using traditional fuels (see Table 4.1).⁴
Natural gas (methane, or \( \text{CH}_4 \)) is by far the most common source of hydrogen.\(^\text{10}\) Steam methane reforming (SMR) generates about half of global hydrogen and more than 90 percent of U.S. hydrogen (representing some 5 percent of U.S. gas consumption).\(^\text{11}\) Conventional SMR is a multi-step process. In the first step, natural gas reacts with water vapor (\( \text{H}_2\text{O} \)) in tubes under high pressure (15 to 25 atmospheres) and high temperature (750°C–1,000°C), which are filled with a catalyst (typically nickel), forming carbon monoxide (CO) and hydrogen:

\[
\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2
\]

In the second reaction, called the water-gas shift, the CO is shifted with steam to produce \( \text{CO}_2 \) and extra hydrogen:

\[
\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2
\]

This reaction can be accomplished in one or two stages at temperature levels ranging from 200°C to 475°C.

The flue gas that leaves the shift reactor is some 70 to 80 percent hydrogen, together with \( \text{CO}_2 \), \( \text{CH}_4 \), water vapor, and CO. The hydrogen is then separated from the mixed gas stream for final use, typically using pressure swing adsorption (PSA), achieving high purity. (For proton exchange membrane, or PEM, fuel cells, a CO removal system is needed, since PEMs tolerate only a few parts per million of CO.) The \( \text{CO}_2 \) is usually vented to the atmosphere, but as concerns over global warming continue to grow, it might well be captured and sequestered. Both SMR and PSA are mature commercial processes. For SMR, the overall energy efficiency (the ratio of the energy in the hydrogen output to that in the fuel input) is about 70 percent.

Although SMR is by far the most widely used means of producing hydrogen on an industrial scale, small-scale SMR might also be used at local hydrogen filling stations. Currently, however, it is far too costly a process for providing a major source of hydrogen for transportation. Today, SMR plants have significant economies of scale—not only are large plants relatively cheaper to build (per unit output), but they also would very likely command a far lower price for natural gas than would smaller SMR plants at local urban filling stations. Partly offsetting that extra cost, local produc-
ion would avoid the need to transport hydrogen from a central generation facility to the filling station (see Chapter 5). The cost of producing and delivering hydrogen from an SMR is currently projected to be $4 to $5 per kilogram, comparable to a gasoline price of $4–$5 per gallon. Not surprisingly, a considerable amount of R&D is being focused on efforts to reduce the cost of SMR as well as its alternatives, such as partial oxidation and autothermal reforming.

While natural gas is both the least expensive source of hydrogen today and the most straightforward to scale up quickly for fueling PEM vehicles, we must answer these questions before pursuing this path:

- Is there enough natural gas to both meet the growing demand for gas-fired power plants and supply a significant fraction of a hydrogen-based transportation system?
- What would happen to the prices of natural gas, hydrogen, and electricity with a dramatic increase in the demand for natural gas to make hydrogen?
- Can the delivered cost of hydrogen from natural gas become competitive with the delivered cost of gasoline?
- Can the infrastructure costs be reduced to manageable levels? Current estimates are as much as a trillion dollars or more.
- Which will be cheaper and/or more practical, reforming methane at small local filling stations or at large centralized plants? Could technological advances change the answer to that question?
- Are the global warming benefits from methane-based hydrogen sufficient to justify building an infrastructure around SMRs, or should we wait until we can build the infrastructure around a CO₂-free source of hydrogen?

These basic questions are in addition to the fundamental question that applies to all means of generating hydrogen: Can automakers build an affordable and practical PEM vehicle that will use the hydrogen?

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**Water**

Water is another common source of hydrogen. Electrolysis, the process of decomposing water into hydrogen and oxygen using electricity, is a mature technology widely used around the world to generate very pure hydrogen. It is, however, an extremely energy-intensive process, and the faster you want to generate hydrogen, the more power you need per kilogram produced. Typical commercial electrolysis units require about 50 kWh per kilogram, which represents an energy efficiency of 70 percent—that is, more than 1.4 units of energy must be provided to generate 1 energy unit in the hydrogen. And since most electricity comes from fossil fuels, and the average fossil fuel plant is about 30 percent efficient, the overall system efficiency is close to 20 percent (70 percent times 30 percent)—four units of energy are thrown away for every one unit of hydrogen energy produced. That is a lot of energy to waste.

As with SMR plants, larger electrolysis plants are relatively cheaper to build (per unit output)—and they would very likely command a far lower price for electricity—than smaller ones at local urban filling stations (sometimes called “forecourt plants” because they are based right where the hydrogen is needed). Hydrogen could be generated at low nighttime off-peak rates, but that is easier to do at a centralized production facility than at a local filling station, which must be responsive to customers who typically do most of their fueling during the day and early evening, peak power demand times. “To circumvent peak power rates,” Dale Simbeck and Elaine Chang noted in their July 2002 analysis for the National Renewable Energy Laboratory (NREL), “forecourt plants have to be built with oversized units operated at low utilization rates with large amounts of storage. This option would require considerable additional capital investment.”

Simbeck and Chang estimate the cost today of producing and delivering hydrogen from a central electrolysis plant at $7–$9/kg. They put the cost of production at a forecourt plant at $12/kg. High cost is probably the main reason why only a small percentage of the
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world’s current hydrogen production comes from electrolysis. Moreover, to replace all the gasoline sold in the United States today with hydrogen from electrolysis would require more electricity than is sold in the United States today.¹⁴

From the perspective of global warming, electrolysis makes little sense for the foreseeable future because both electrolysis and central-station power generation are relatively inefficient processes, and most U.S. electricity is generated by the burning of fossil fuels. Burning a gallon of gasoline releases about 20 pounds of CO₂. Producing 1 kg of hydrogen by electrolysis would generate, on average, 70 pounds of CO₂.¹⁵ A gallon of gasoline and a kilogram of hydrogen have about the same energy, and even allowing for the potential doubled efficiency of fuel cell vehicles, producing hydrogen from electrolysis will make global warming worse. Because of these economic and environmental problems, it seems unlikely that the nation will pursue generation of significant quantities of hydrogen from the U.S. electric grid anytime soon.

Hydrogen could be generated from renewable electricity, but the renewable system most suitable for local generation — solar photovoltaics — currently makes hydrogen that is far too expensive. The least expensive form of renewable energy — wind power — still constitutes only a few tenths of 1 percent of all U.S. generation, although that figure is rising rapidly.¹⁶ These basic questions need to be answered before we pursue this enticing path:

• Is generating hydrogen from electrolysis powered by renewables a good use of that power from economic and environmental perspectives?
• How long will it be before the United States has enough excess low-cost renewable generation that it can divert a substantial fraction to production of hydrogen?
• What are the prospects that forecourt hydrogen generation from solar photovoltaics will be wise or practical in the first half of the century?
• If hydrogen is generated from the vast wind resources in the Midwest, what would be the infrastructure costs for delivering it?

Gasoline

Gasoline can be used as a source of hydrogen. Hydrogen can be produced from hydrocarbons such as gasoline (and methane) with partial oxidation and autothermal reformers.¹⁷ The toughest practical problem for onboard gasoline reformers — other than high cost — is that the high temperature at which they operate does not allow a rapid start for the automobile, a design feature we have all come to expect.

In May 2003, Nuvera Fuel Cells announced that in conjunction with the U.S. Department of Energy (DOE) and a European automaker, the company had demonstrated a 75 kW gasoline reformer with more than 80 percent efficiency.¹⁸ This device cannot start up in less than a minute, but the company is working on a next-generation device aimed at beating a thirty-second start time. Since the 75 kW reformer is not a commercial product, the company did not announce its price. Prashant Chintawar, Nuvera’s executive director for business development and strategic R&D, has told me that it would be at least ten years before the device would achieve a cost of $25–$30/kW, the range needed for an affordable car.

When I was at the DOE in the mid-1990s, we thought this area of R&D was valuable because it was far from clear that we could solve all the technological problems related to building a pure hydrogen infrastructure, including practical and affordable onboard storage of hydrogen, or that we could solve the chicken-and-egg problem between the hydrogen fueling infrastructure and the hydrogen-powered vehicles. Gasoline fuel cell vehicles (FCVs) seemed like a worthwhile interim step. As a comprehensive 2001 study on commercializing fuel cell vehicles concluded, “a major potential advantage of gasoline FCVs is the prospect of a conventional fuel . . . that requires essentially no infrastructure changes or investment for FCV use.” The study, undertaken for the California Fuel Cell Partnership (CAFCP), notes, “It would also eliminate the new health and safety concerns of other fuels.”¹⁹

Nonetheless, many people questioned this strategy when it was first developed, and many continue to do so. For instance, follow-
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ing the 2003 Nuvera announcement, David Redstone, editor and publisher of the Hydrogen & Fuel Cell Investor's Newsletter, wrote:

What is the point of a gasoline reformer? Isn’t the point of “the hydrogen economy” to eliminate carbon from the fuel chain (thereby eliminating CO₂ emissions) and to end our dependence on foreign energy sources (Saudi-Kuwaiti-Iraqi oil)? How is switching from burning gasoline in ICES [internal combustion engines] to reforming it for use as H₂ in fuel cells going to get us where we need to go, especially when the fuel cells currently being contemplated for car engines are barely more efficient than ICES and the reforming process involves a loss of 20 percent of the energy contained in the gasoline?20

These are reasonable questions. Several additional questions need to be answered before we pursue a path of generating large volumes of hydrogen from gasoline reformers on board fuel cell vehicles:

• Can we build an affordable and practical gasoline reformer?
• Is the chicken-and-egg problem solvable, or will we need this technology to achieve significant market penetration of fuel cell vehicles before we build the hydrogen infrastructure?
• Are the net energy and environmental benefits of gasoline-powered fuel cell vehicles worth the extra cost of the system?

Methanol

Methanol, also known as wood alcohol, is another widely discussed potential source (or carrier) of hydrogen.21 Chemically, methanol, CH₃OH, is a clear liquid, the simplest of the alcohols, with one carbon atom per molecule. Methanol is extensively used today—U.S. demand in 2002 exceeded 2 billion gallons. The largest U.S. methanol markets are for producing the gasoline additive MTE (methyl tertiary butyl ether) as well as formaldehyde and acetic acid.

Methanol is already used as a transportation fuel. It has been the fuel of choice at the Indianapolis 500 for more than three decades, in part because it improves the performance of the cars but prima-

rily because it is considered much safer. It is less flammable than gasoline and, when it does ignite, causes less severe fires; one 1990 study for the U.S. Environmental Protection Agency (EPA) concluded, “Pure methanol is projected to result in as much as a 90 percent reduction in the number of automotive fuel related fires relative to gasoline.” Methanol appears to biodegrade quickly when spilled. It dissolves and dilutes rapidly in water. It has been actively promoted as an alternative fuel by the EPA and the DOE, in part because it has reduced urban air pollutant emissions more effectively than gasoline. Most methanol-fueled vehicles use a blend of 85 percent methanol and 15 percent gasoline called M85.

Methanol has a number of advantages for powering fuel cell vehicles. As the 2001 study for the CARCP noted, these include methanol’s “immediate availability without new upstream infrastructure, high hydrogen-carrying capacity, and ability to be readily stored, delivered, and carried on-board without pressurization.”22 In short, our transportation system and its infrastructure favor liquid fuels. Fuel cell vehicles with onboard methanol reformers would have very low emissions of urban air pollutants. Daimler-Chrysler has introduced demonstration fuel cell vehicles that convert methanol to hydrogen on board.

A key advantage of methanol is versatility. Methanol reformers operate at much lower temperatures (250°C–350°C), so they are more practical than onboard gasoline reformers. Also, methanol reformers could be used at fueling stations to generate forecourt hydrogen. Most intriguingly, considerable research is aimed at developing a direct methanol fuel cell (DMFC), which could run on methanol without a reformer—although practical, affordable DMFCS for cars and trucks appear a long way off. And while methanol is primarily synthesized from natural gas, it can also be produced from a number of CO₂-free sources, including municipal solid waste and plant matter.23

On the other hand, many features of methanol would make its widespread use as a transportation fuel problematic. It is very toxic. As the EPA has noted, “a few teaspoons of methanol consumed orally can cause blindness, and a few tablespoons can be fatal, if not treated.” Methanol is also very corrosive, so it requires a special fuel-
handling system. Most major oil companies currently responsible for delivering our transportation fuels are at best unenthusiastic about creating a methanol economy, and some have expressed outright opposition.

Some environmentalists and former environmental regulators I have spoken to are reluctant to embrace a dramatic increase in methanol use, in part because it is used to make MTBE, a gasoline additive now being phased out in California because of environmental concerns such as groundwater contamination (although in fairness to methanol, which exists in nature and degrades quickly, MTBE, in contrast, is a complex, man-made compound that exhibits little degradation once released into the environment).

For any dramatic increase in U.S. methanol consumption, most of the supply would have to be imported. While biomass-generated methanol might be economical in the long term, there is a considerable amount of so-called stranded natural gas in distant locations around the globe that could be converted to methanol and shipped by tanker at relatively low cost, should increased demand warrant such investment. Methanol from natural gas would have little or no net greenhouse gas benefits in a future fuel cell vehicle, as compared with future hybrid electric vehicles (see Chapter 8).

These questions need answering before we pursue a path of building a transportation system around a methanol economy:

- Is there enough natural gas both to meet the growing demand for gas-fired power plants and to supply a significant fraction of a transportation system built around methanol?
- Can the price of methanol remain competitive with that of gasoline if methanol demand increases sharply in the coming decades?
- What would be the overall health and safety effect of large-scale use of methanol as a consumer product?
- What are the prospects for generating a substantial fraction of methanol cost-effectively from renewable or CO₂-free sources?
- Will direct methanol fuel cells be affordable and practical anytime soon?

Coal

Coal is a major source of hydrogen. To produce hydrogen, typically coal is gasified, impurities are removed, and then its hydrogen is recovered. This process results in significant emissions of CO₂, and so, from a global warming perspective, current coal gasification technology could not serve as a basis for a hydrogen economy. In addition, Simbeck and Chang estimate that producing and delivering coal-generated hydrogen would cost $4.50–$5.60/kg, several times the cost of U.S. gasoline on an equivalent energy basis.

Coal is the most abundant fossil fuel in the United States and a great many other countries. For instance, coal constitutes some 95 percent of the nation’s fossil energy reserves, and it is estimated that, with the use of existing technology, known recoverable coal reserves could sustain the nation’s current level of coal consumption for more than 300 years. Major developing countries such as China and India also have vast coal reserves. However, burning any significant fraction of global coal reserves using current power plant technology would almost certainly cause devastating and irreparable harm to the global climate (see Chapter 7). Hence, many countries and companies are pursuing R&D into generating hydrogen, electricity, or both from coal without releasing CO₂.

Here is one strategy being pursued by the DOE: Use a gasification and cleaning process that combines coal, oxygen (or air), and steam under high temperature and pressure to generate a synthesis gas (syngas) made up primarily of hydrogen and CO, without impurities such as sulfur or mercury. The water-gas shift reaction described earlier is then applied to increase hydrogen production and create a stream of CO₂ that can be removed and piped to a sequestration site (see Chapter 8). The rest of the hydrogen-rich gas is sent to a PSA system for purification and transport. The remaining gas that comes out of the PSA system can be compressed and
sent to a combined cycle power plant (similar to the natural gas combined cycle plants now in widespread use). Hydrogen can also power a combined cycle plant (as can syngas), so this system can be configured to generate more hydrogen and less electricity or vice versa.

In February 2003, the Department of Energy announced FutureGen (the Integrated Sequestration and Hydrogen Research Initiative), a ten-year, billion-dollar project to design, build, and construct a 273 MW prototype plant that would cogenerate electricity and hydrogen and sequester 90 percent of the \( CO_2 \). The goal of the system is to “validate the engineering, economic, and environmental viability of advanced coal-based, near-zero emission technologies that by 2020” will produce electricity that is only 10 percent more expensive than current coal-generated electricity and produce hydrogen that is competitive in price with gasoline (although this does not include the cost of delivering the hydrogen). Initially, the hydrogen would be used to generate clean power, perhaps using a solid oxide fuel cell (SOFC).27

A 2002 study for the National Energy Technology Laboratory found that coal gasification systems with \( CO_2 \) capture could achieve efficiencies of 60 percent or more in cogenerating hydrogen and electricity using various combinations of turbines and SOFCs.28 Nonetheless, just as commercializing fuel cells has taken much longer and has proven far more difficult than was expected, so, too, may building large commercial coal gasification combined cycle units. One 2003 analysis described the “embarrassingly poor history” traditional power generators have had with far simpler chemical processes.29

Sequestering the \( CO_2 \) will be another technological challenge. Sequestration is the process of locking up \( CO_2 \) (for instance, in large underground formations) so it cannot enter Earth’s atmosphere. While \( CO_2 \) separation and capture are a common part of many industrial processes, existing technologies would not be cost-effective for large-scale sequestration. Estimates of sequestration costs using current technology are exceedingly high. Moreover, the practicality and environmental consequences of many pathways for sequestration are not yet proven from an engineering or scientific perspective. Sequestration remains a focus of active research and development and is discussed in greater detail in Chapter 8.

These questions need answering before we can pursue the path of generating large volumes of hydrogen from coal and sequestering the \( CO_2 \) produced:

- Can cogeneration of hydrogen and electricity from coal, coupled with \( CO_2 \) extraction, be made into an affordable and practical system for cost-effectively generating both energy carriers?
- If hydrogen is generated from large coal plants outside cities, perhaps close to existing coal mines, what would be the infrastructure costs for delivering the hydrogen to consumers?
- Can \( CO_2 \) sequestration on a massive scale be practical, economical, and permanent?

Biomass

Biomass could become a major source of hydrogen.30 Biomass is any material that has participated in the growing cycle. It includes agricultural, food, and wood waste as well as trees and grasses grown as energy crops. Biomass is of interest from a global warming perspective because when it is transformed into energy, by burning, for instance, it releases \( CO_2 \) that was previously sequestered from the atmosphere (temporarily) in the growing cycle, so the net \( CO_2 \) emitted is zero.31 Biomass thus represents a potentially sustainable way of providing energy without accelerating global warming.

Biomass can also be converted to a liquid fuel, such as ethanol, which is then used as a gasoline blend. Today, the major biofuel is ethanol produced from corn, which yields only about 25 percent more energy than was consumed to grow the corn and make the ethanol.32 The future holds the promise of ethanol from sources other than corn, dedicated energy crops such as switchgrass, which can be grown and harvested with minimal energy consumption so that overall emissions are near zero (see Chapter 8).

Biomass is of special interest because it seems likely to be the
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lowest-cost renewable source of hydrogen in the near term and because it may be a viable renewable source of hydrogen on a large scale in the long term. Biomass can be gasified and converted into hydrogen (and electricity) in a process very similar to coal gasification, described earlier. A number of biomass gasification processes are being demonstrated, although a practical commercial system remains technologically challenging. Biomass can also be gasified together with coal; the Royal Dutch/Shell Group has commercially demonstrated a 25/75 biomass/coal gasifier.

Perhaps most intriguing, if CO₂ sequestration is possible, one could imagine extracting the CO₂ stream from the biomass gasification process, as is being contemplated for coal gasification. This would turn biomass into a potent net reducer of CO₂—it would mean extracting CO₂ from the air while growing and then injecting that CO₂ into underground reservoirs through the gasification and sequestration process.

Another promising approach is pyrolysis, the use of heat to decompose biomass into its constituents. The ultimate idea is to create a "bio-refinery," analogous to a petroleum refinery, where biomass is converted into many different useful products. In one version of this process, biomass is dried and heated, coproducts are removed, and the hydrogen is produced via steam reforming.

Like coal, biomass seems unlikely to serve as a source of small-scale on-site hydrogen production. Simbeck and Chang estimate the cost of delivered hydrogen from biomass gasification at $3.00–$6.50/kg, depending primarily on the means of delivery. Other studies by NREL suggest a lower cost, especially for pyrolysis, should we achieve significant technological improvements and successful commercialization of biomass and hydrogen infrastructure technologies.

Waste biomass, such as peanut shells or bagasse (the residue from sugarcane), tends to be the most cost-effective source, but the ultimate supply is limited. Even in a country with as much arable land as the United States, a large fraction of agricultural land would need to be devoted to biomass production if that were to serve as the major source of transportation fuel.

Nuclear Power Plants

Nuclear power plants can also be a source of hydrogen. Straight electrolysis of water with electricity from a nuclear power plant is one possibility, but that seems unlikely to be economically efficient for the foreseeable future. On the other hand, nuclear power plants, like most central-station power plants, generate a considerable amount of heat that they end up throwing away. This creates an opportunity because it is more efficient to generate hydrogen at higher temperatures, for instance by thermochemically decomposing water into hydrogen and oxygen through a set of chemical reactions.

Thermochemical water-splitting processes at temperatures exceeding 750°C could theoretically achieve 40 to 52 percent efficiency in hydrogen production. Cogeneration of electricity could raise the overall efficiency to as high as 60 percent. The fact that a process could be efficient, however, does not mean it would be economical, and we are a long way from knowing whether this approach can compete with other emerging hydrogen generation technologies. The DOE is currently pursuing thermochemical hydrogen production systems using nuclear power, with the goal of demonstrating commercial-scale production by 2015.
No plausible strategy for generating hydrogen that is potentially 
$\text{CO}_2$-free can be dismissed out of hand, but I am skeptical that 
nuclear-generated hydrogen could be a practical solution, at least in 
the United States, especially since 100 or more nuclear water-splitting 
plants would be needed to replace a significant fraction of U.S. 
transportation fuel with hydrogen. A major 2003 interdisciplinary 
study by the Massachusetts Institute of Technology, *The Future of 
Nuclear Power*, highlighted many of the “unsolved problems” that 
have created “limited prospects for nuclear power today.” The study 
found that “in deregulated markets, nuclear power is not now cost 
competitive with coal and natural gas.” The public has significant 
concerns about safety, environmental, health, and terrorism risks 
associated with nuclear power. The study also found that “nuclear 
power has unresolved challenges in long-term management of 
radioactive wastes.” The study described possible technological and 
other strategies for addressing these issues, but noted, for instance 
that “the cost improvements we project are plausible but 
unproven.”

These questions need answering before we pursue a path of generating large volumes of hydrogen from nuclear power:

- Can nuclear power be a safe and economical source of hydrogen capable of attracting enough investment capital to build so many new plants?
- If hydrogen is generated from nuclear power plants outside cities, what would be the infrastructure costs for delivering the hydrogen to consumers?
- How much additional nuclear power capacity would need to be added to meet the needs of the hydrogen economy? How would the nuclear waste be disposed of?

**Other Sources of Hydrogen**

Novel strategies for generating hydrogen abound. For instance, research is being conducted into using solar energy to directly facilitate the production of hydrogen, such as by using photovoltaic devices to split water directly. Considerable research is also taking place into producing hydrogen through active biological processes, such as adapting photosynthesis processes for hydrogen production and using existing or bioengineered bacteria to decompose organic compounds into hydrogen. As noted in an editorial in the special 2002 issue of the *International Journal of Hydrogen Energy* devoted to biohydrogen, this is still a relatively small and long-term area of research because “so far efficiencies obtained are low, productivity is low and costs are high compared to alternative technologies.”

Finally, fuel cells themselves, especially high-temperature ones, could trigenerate electricity, heat, and hydrogen. FuelCell Energy Inc. is pursuing this strategy for its molten carbonate fuel cell, as are solid oxide fuel cell (SOFC) companies. Fuel cells running on natural gas typically use about three of the four hydrogen atoms in methane ($\text{CH}_4$) for power generation. The remaining hydrogen goes into the flue gas or stack effluent with various amounts of $\text{CO}_2$, CO, and water vapor, depending on the type of fuel cell. That flue gas is sometimes vented to the atmosphere, sometimes combusted for heat, and sometimes used to facilitate the reforming process.

Hydrogen could, however, be separated and purified from the flue gas at a relatively low cost if high-temperature fuel cells can be made into successful commercial products. That is, when an SOFC or molten carbonate fuel cell can cost-effectively generate electricity and heat, the fuel (natural gas) and the fuel cell are already paid for. The cost of the hydrogen generation would then be just the incremental cost of the purification and separation system. A future SOFC system might cogenerate hydrogen for about $2.00 per kg. This is still somewhat more expensive than gasoline, but it is potentially a very attractive price, since these fuel cells could be sited at an urban fueling station, thus avoiding the need for a costly hydrogen delivery infrastructure.

This promising strategy will, however, require fuel cells to have achieved significant technological and cost improvements while overcoming the numerous barriers to commercialization discussed in Chapter 3.
Conclusion

There are many different promising technologies and strategies for producing hydrogen, each with its own great advantages and severe disadvantages. It is possible that one will come to dominate. It is possible that multiple means will be used. These are still very early days in the transition to a hydrogen economy, and no one can know.

The most cost-effective existing technologies are, unfortunately, the ones that generate the most greenhouse gas pollution and thus face the greatest risk of stranded investment—of needing to be replaced when government policies change, as I believe they inevitably will (see Chapters 7 and 8). For instance, if by 2020 we were to build a hydrogen infrastructure around small steam methane reformers in local fueling stations, and then decide that greenhouse gas emissions must be dramatically reduced, we would have to replace that infrastructure almost entirely.

At this time, no set of commercial technologies appears able to deliver hydrogen to vehicles at a price much below about four times the current cost of gasoline (untaxed) on an equivalent energy basis. Nor does onboard reforming of gasoline appear likely to be a cost-effective and practical interim strategy without significant technological advances. Centralized hydrogen production far away from cities is the least expensive way of generating hydrogen for the foreseeable future, but that would entail a considerable investment in a delivery infrastructure, which is the subject of the next chapter.
During my five years at the U.S. Department of Energy (DOE), the two questions I was asked most often were “How expensive will it be to reduce U.S. greenhouse gas emissions?” and “What role can clean energy technologies play in reducing that cost?” These questions became increasingly important in the months leading up to the 1997 international negotiations in Kyoto, Japan, as President Bill Clinton’s administration tried to determine what level of emissions reductions it could agree to without jeopardizing the U.S. economy.

Many traditional economic analyses concluded that the cost of reducing U.S. greenhouse gas emissions to 1990 levels by 2010 would harm the economy and cost jobs, with carbon dioxide (CO$_2$) permits costing $60 per metric ton or more, which would raise energy prices by as much as 40 percent. These results made use of “top-down” economic models that rely on macroeconomic assumptions about how fast technology changes and are thus especially weak in their ability to characterize the effects of technology. Years earlier, most of these same models had wildly overestimated the price of industrial permits to emit sulfur dioxide that would result from the Clean Air Act restrictions, some by a factor of five or more.1

After I was put in charge of technology analysis at the DOE’s Office of Energy Efficiency and Renewable Energy (EERE), it
seemed more practical to have a “bottom-up” analysis that considered in detail the specific technologies that could reduce U.S. CO₂ emissions and their likely cost and benefit to the nation.

Expert technologists at the national laboratories were the ideal authors for such a study. The laboratories, together with EERE staff, are responsible for the vast majority of federal research and development into hydrogen and fuel cells; energy-efficient building and industrial technologies; cogeneration and distributed energy; and all forms of renewable energy, including solar, wind, and biomass. These are a large fraction of the core technologies that will be vital to reducing greenhouse gas emissions.

For a full year, I supervised an effort by some of the best analysts at five U.S. national laboratories. The result was the September 1997 report *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond*. It concluded that significant emissions reductions were possible for the country with no net increase in the nation’s energy bill, plus a much lower price for CO₂ emissions reductions, $7 or $14 per ton—a long way from the $60 per ton predicted by others. Achieving this would take a significant effort by the government to accelerate the deployment of a variety of clean energy technologies, but the conclusion was based on existing commercial or near-commercial products—energy-efficient lighting, cogeneration, hybrid electric vehicles, wind power. It would require no major technology breakthroughs.

In November 2000, the DOE released an even more comprehensive analysis by our national laboratories extending out to 2020, which showed that U.S. CO₂ emissions could, with serious government effort, be reduced dramatically below 2000 levels, again with a price for CO₂ of less than $15 per ton and with reductions in energy bills to consumers and businesses that exceeded the economic costs. Other benefits included reductions in urban air pollution and oil imports.

One conclusion I draw from all this analysis is that, in the near term, hydrogen almost certainly will not be able to compete with the myriad alternative strategies for reducing greenhouse gas emissions. Why? Four reasons:

- The competition—more fuel-efficient internal combustion engine vehicles—is getting tougher, so the incremental benefits of using fuel cell vehicles will be smaller than if they were replacing existing vehicles.
- In the near term, hydrogen is likely to be made from fossil fuel sources, which entails significant greenhouse gas emissions.
- The annual operating costs of a fuel cell vehicle are likely to be much higher than those of the competition for the foreseeable future.
- The fuels used to make hydrogen for transportation could achieve larger greenhouse gas savings at lower cost if used instead to displace the dirtiest stationary electric power plants.

In this chapter, I examine each of these points as well as other potential drivers of a transition to a hydrogen economy. I end with my own scenario for the transition.

The Competition

Underestimating the competition may be the single biggest reason why new clean energy technologies achieve success in the market much more slowly than expected. Consider renewable energy, which has been the focus of considerable public and private research and development (R&D) in the past few decades. In a 1999 study of five major renewable technologies as well as conventional power generation, Resources for the Future concluded:

In general, renewable technologies have failed to meet expectations with respect to market penetration. One exception to this trend is wind, which has met projections from the 1980s, although earlier projections were overly optimistic. The other exception is biomass applications, for which market penetration has exceeded previous projections.
The study noted that these failures came in spite of the fact that R&D efforts did reduce the cost of renewables:

Renewable technologies have succeeded in meeting expectations with respect to cost. For every technology analyzed, successive generations of projections of cost have either agreed with previous projections or have declined relative to them.

Government R&D for renewables has been exceedingly successful, bringing down the cost of many renewables by a factor of ten in only two decades—in spite of the fact that the R&D budget for renewables was cut by 50 percent in the 1980s and didn't return to comparable funding levels until the mid-1990s. For example, a separate, earlier analysis in *The Technology Pork Barrel*, which examined more than a dozen major government R&D efforts, including the space shuttle and the nuclear breeder reactor, concluded, "Unlike the other technologies discussed in this book, PV [photovoltaics] had very good outcomes."

Why, then, have most renewables not achieved the level of marketplace success that was projected? The authors conclude, "To a significant degree, the difference in performance in meeting projections of penetration and cost stem from the declining price of conventional generation, which constitutes a moving baseline against which renewable technologies have had to compete." The competition got tougher.

In fact, not only did traditional electricity generation reduce costs in the 1980s and 1990s (rather than increasing costs, as had been projected in the 1970s), but it did so while reducing emissions of urban air pollutants. Also, as noted in the discussion in Chapter 3 of on-site power generation, which involves many forms of renewables, utilities place many barriers in the path of new projects, and these technologies typically receive little or no monetary value for "the contributions they make to meeting power demand, reducing transmission losses, or improving environmental quality."

The competition from renewables does drive the entire power generation industry to improve its performance. And renewables, especially wind power, have become a major marketplace success in

Europe, providing 20 to 40 percent of electric power in parts of Germany, Denmark, and Spain. Although renewables have been slow to achieve market share in the United States, they will very likely become essential components of the nation's and the world's efforts to avoid catastrophic global warming. As such, they represent a significant long-term success for government R&D.

The internal combustion engine, running on gasoline, has dominated the transportation market for nearly a century. Significant advances in both the engines and their fuels (such as reformulated gasoline) have dramatically reduced the urban air pollution of internal combustion engine cars, helping them fight efforts by competitors such as electric battery cars and natural gas vehicles. In the area of reduced greenhouse gas emissions, the direct competition to fuel cell vehicles includes hybrid electric vehicles and diesels, which themselves are the subject of considerable R&D today.

Hybrid gasoline-electric cars can be twice as efficient as regular cars. The onboard energy storage device, usually a battery, increases efficiency in several ways. It allows "regenerative braking"—recapture of energy that is normally lost when the car is braking. It also allows the engine to be shut down when the car is idling or decelerating. Finally, because gasoline engines have lower efficiencies at lower power, the battery allows the main engine to be run at higher power and thus more efficiently more of the time, especially in city driving.

The first-generation Toyota Prius has a city mileage of 52 miles per gallon (mpg) and a highway mileage of 45 mpg. The second-generation Prius, debuted in 2003, has even better mileage. Toyota plans to introduce a great many more hybrid models in the coming years, and most automakers will be coming out with their own hybrid vehicles. Imagine how good hybrid vehicles will be by 2020, when they might first have to face fuel cell vehicles in the marketplace.

The high efficiency that hybrids have in urban settings poses particularly tough competition for fuel cell vehicles because, at least initially, fuel cell vehicles are likely to be used mainly for urban driving, for several reasons:
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- Early models probably will not have the driving range of regular vehicles.
- Early models probably will be used by fleets, which operate mainly in cities.
- The limited number of fueling stations early in their deployment will restrict long-distance travel.

Fuel cells typically have higher efficiencies at lower power, so hybridizing a fuel cell vehicle (by adding a battery) does not improve its efficiency as much as does hybridizing a gasoline engine.

The other major competition to fuel cell vehicles is diesels. Diesel engines are the workhorses for big trucks and construction equipment because of their high efficiency and durability. Modern diesel engines are quite different from the smoky, noisy engines of the 1970s and 1980s, with advances such as “electronic controls, high-pressure fuel injection, variable injection timing, improved combustion chamber design, and turbo-charging.” Although they represent less than 1 percent of car and light truck sales in the United States, diesels are becoming the car of choice in Europe, where gasoline prices are much higher, fuel taxes favor diesel use, and tailpipe emissions standards are less stringent. Diesels have some 40 percent of the market for cars in Europe, and by 2001 they represented the majority of new cars sold in a great many European countries. They are 30 to 40 percent more fuel efficient than gasoline vehicles. Also, producing and delivering diesel fuel releases 30 percent lower greenhouse gas emissions than producing and delivering gasoline with the same energy content.

While diesels currently have higher emissions of particulates and oxides of nitrogen, they are steadily reducing their emissions. Many believe that with the large amount of R&D funding currently aimed at diesels, they will be able to meet the same standards as gasoline engines.

Building a clean hybrid diesel-electric vehicle will require advances in technology, but ones that seem less daunting than the major breakthroughs that will be required for a practical and affordable hydrogen fuel cell vehicle, such as advances in hydrogen production and storage technology as well as in proton exchange membrane (PEM) fuel cells. It would be unwise to assume that such a hybrid car cannot be built by 2020. Trucks have less stringent emissions requirements than cars. FedEx Express and Environmental Defense teamed up in 2000 to develop a new generation of pickup and delivery trucks running on hybrid diesel-electric engines. These trucks are expected to improve fuel efficiency by 50 percent, reduce emissions of particulates by 90 percent, and reduce emissions of nitrogen oxides by 75 percent. By September 2002, two suppliers had delivered prototypes.

If Hydrogen Comes from Natural Gas

In a near-term deployment scenario, hydrogen would almost certainly be produced from natural gas and probably at local fueling stations (see Chapter 5). This has three effects on greenhouse gas emissions. First, the extraction and delivery of natural gas to a fueling station entails very small leaks of natural gas, important because methane—the primary component of natural gas—has twenty-one times the global warming effect of CO₂. Second, reforming natural gas into hydrogen not only produces CO₂ but also is an inefficient process, particularly for the kind of small reformers that would be seen at filling stations. You might expect to lose as much as one-third of the energy in the natural gas. Third, compression of hydrogen, the likely near-term approach for onboard storage, requires lots of electricity, the production of which also releases significant greenhouse gases. The life-cycle well-to-wheel efficiency of such a fuel cell vehicle, in terms of energy delivered to the wheels divided by total energy input, might be only 25 percent, according to one 2002 analysis, though future advances might increase that a little.

In 2003, the Massachusetts Institute of Technology did a comprehensive “assessment of new propulsion technologies as potential power sources for light-duty vehicles that could be commercialized by 2020,” focusing on life-cycle energy consumption and greenhouse gas emissions. The assessment analyzed hydrogen generated from natural gas and concluded that a diesel hybrid...
would have greenhouse gas emissions more than 10 percent below those of a hydrogen fuel cell vehicle and would have roughly the same emissions as a hybridized fuel cell vehicle. Equally noteworthy, the projected gasoline hybrid for 2020 has roughly the same life-cycle greenhouse gas emissions as the hydrogen fuel cell vehicle. This is one of many reasons arguing against significant investment in natural gas reforming and local fueling stations.

Annual Operating Costs

Cost savings—economic payback—appears to be the single biggest determinant of success for a new energy technology. Renewable energy has many superior attributes similar to those of fuel cells, including zero emission of urban air pollution, but renewables have been slow to catch on in the United States because of their high cost. On the other hand, the other major area of R&D conducted by DOE’s office of Energy Efficiency and Renewable Energy—developing energy-efficient technologies that reduce energy bills—has been wildly successful.

The national laboratories, funded by EERE, developed a host of more efficient devices, including a more efficient refrigerator, improvements to the compact fluorescent light bulb, solid-state lighting controls for office fluorescent lights, and super-efficient windows. Many of these products have achieved very significant market penetration. The National Academy of Sciences examined dozens of case studies of EERE-funded technologies and found that they had cumulatively saved American businesses and consumers $30 billion in reduced energy bills.

The products that were most successful not only reduced pollution from electricity generation but also had a good economic payback combined with equivalent or superior attributes to the products they replaced. For instance, solid-state lighting helps businesses cut lighting energy use in half or more while delivering higher-quality light without the annoying flicker of earlier fluorescents. Likewise, greenhouse gas emissions from lighting are cut in half, often with paybacks of less than two years.

Unfortunately, for the foreseeable future, hydrogen cars will almost certainly be unable to compete with alternative strategies for reducing greenhouse gas emissions. As we saw in Chapter 6, we do not even know today whether a practical and affordable fuel cell vehicle can be built. A 2002 analysis for the DOE concluded that even with optimistic assumptions about technology improvements, future fuel cell vehicles will probably cost 40 to 60 percent more than conventional vehicles.\(^{15}\)

Also, hydrogen will be much more expensive than gasoline. As previously discussed, hydrogen provided at fueling stations would probably cost $4 or more per kilogram (kg). The equivalent-energy price of gasoline hovers around $1.50–$2.00, including taxes, in the United States today (since a kilogram of hydrogen has about the same energy content as a gallon of gasoline). Ultimately, if hydrogen were to be the main transportation fuel, it would itself have to be taxed unless we found a new source for funding road projects. So, even with a more efficient engine, the annual fuel costs are likely to be considerably higher, perhaps by a factor of two.

Moreover, compared with the competition, hybrids and diesels, the cost differential is even more. While hybrid and clean diesel vehicles may cost more than current internal combustion engine vehicles, at least when they are first introduced, their greater fuel efficiency means that, unlike hydrogen fuel cell vehicles, they may pay for that extra up-front cost over the lifetime of the vehicle. This means that hybrids and diesels will very likely have roughly the same annual operating costs as current internal combustion engine vehicles, a significant marketplace advantage over fuel cell vehicles.

Hence, from a policy perspective, hybrids and diesels would reduce transportation CO\(_2\) emissions at a far lower cost per ton. The average new car today generates about four to five metric tons of CO\(_2\) per year. Perhaps the key reason for replacing gasoline engines is to lower that number. A fuel cell vehicle in 2020 might reduce CO\(_2\) emissions at a price of more than $200 per metric ton (regardless of what fuel the hydrogen was produced from).\(^{16}\) An advanced gasoline engine could reduce CO\(_2\) for far less and possibly for a net savings because of the reduced gasoline costs. Energy efficiency strategies in other sectors are similarly
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low in cost. A June 2003 analysis in the journal *Science* by David Keith of Carnegie Mellon University and Alexander Farrell of the University of California, Berkeley, put the cost of CO₂ avoided by fuel cells running on zero-carbon hydrogen at more than $250 per ton, even with optimistic reductions in fuel cell costs.¹⁷

Moreover, we still have the question of who will pay for the hydrogen infrastructure, which in the early going could easily come to $5,000 per car.¹⁸ Those who believe, as I do, that global warming is the most intractable and potentially catastrophic environmental problem facing the nation and the planet this century—and therefore the problem that requires the most urgent action on the part of government and the private sector—may conclude that spending this kind of money on building a hydrogen infrastructure could take away a massive amount of resources from far more cost-effective measures. Ultimately, a hydrogen infrastructure may be critical to helping us achieve the kind of deep CO₂ reduction that we will need in the second half of this century, but probably not before then.

Better Uses for the Fuels

In the first half of the twenty-first century, the fuels used to make hydrogen for transportation could achieve far larger greenhouse gas savings at lower cost, displacing emissions in electricity generation, as several analyses have shown.¹⁹ This is true not only for natural gas but also for renewable power in the foreseeable future.

Let's start with natural gas. As we've already seen, a fuel cell vehicle running on hydrogen produced from natural gas will have little or no net greenhouse benefits compared with the likely competition in 2020, hybrid vehicles. Natural gas, however, has a huge benefit when used to avoid the need to build new coal plants—or to displace existing ones. Coal plants do not merely have much lower efficiencies than natural gas plants—30 percent versus 55 percent. Compared with natural gas containing the same amount of energy, coal has nearly double the CO₂ emissions, whereas gasoline has only about one-third more CO₂ emissions than natural gas. A megawatt-hour (MWh) of electricity from a combined cycle gas turbine releases about 810 pounds (370 kg) of CO₂, whereas the same megawatt-hour of even relatively new coal plants can release more than 2,200 pounds (1,000 kg) of CO₂. And the savings would be even larger if the natural gas were used in a future stationary fuel cell and gas turbine system that might have 70 percent efficiency. If the nation had an unlimited supply of cheap natural gas, we could use it for all purposes, but we do not.

The United States has recently been sprinting to build new natural gas power plants because they are so efficient and clean. As of 2003, the country had more than 800 gigawatts (GW) of central station electric power generation. A gigawatt is equal to 1,000 megawatts (MW) and is the size of one very large existing power plant or three typically sized new power plants. Of the 144 gigawatts added between 1999 and 2002, 138 gigawatts is natural-gas-fired, including 72 gigawatts of efficient combined-cycle capacity and 66 gigawatts of combustion turbine capacity, which is used mainly when demand for electricity is high," as noted by the U.S. Department of Energy's Energy Information Administration (EIA) in its *Annual Energy Outlook 2003*. As rising demand leads to rising prices for natural gas, however, the EIA forecasts an increase in coal-powered production. The EIA projects that between 2001 and 2025, 74 GW of new coal-fired capacity will come online. Significantly, "as natural gas prices rise later in the forecast, new coal-fired capacity is projected to become more competitive, and 91 percent of the projected additions of new coal-fired capacity are expected to be brought on line from 2010 to 2025."²⁰

From a global warming perspective, the right approach would be to defer that increased coal-fired capacity and to spur the retirement of existing coal plants. Yet not only is coal-fired capacity projected to grow, but also the EIA projects that existing coal plants will be used far more. From 2001 to 2025, the EIA projects a remarkable 40 percent increase in coal consumption for electricity generation, which by itself would increase U.S. greenhouse gas emissions by 10 percent. Dale E. Heydlauff, senior vice president for governmental and environmental affairs at American Electric Power (AEP), a leading U.S. producer of coal-fired power, said in August
2003, “The amount of AEP’s coal plant retirements will be driven primarily by the price of natural gas.”

Unfortunately, by 2003, rising demand for natural gas had already hit North American supply constraints, driving up prices. In June 2003, Alan Greenspan, chairman of the Federal Reserve Board, took the unusual step of testifying before the House Energy and Commerce Committee about natural gas, warning, “We are not apt to return to earlier periods of relative abundance and low prices anytime soon.” While robust government efforts to push more efficient use of natural gas and to accelerate renewable power are the policies that I would recommend (see the Conclusion), such approaches lack political support, and Greenspan himself did not propose them. Noting that “Canada, our major source of imported natural gas, . . . has little capacity to significantly expand its exports,” he endorsed an expansion of the capacity to import liquefied natural gas (LNG).

While not as energy-intensive a process as liquefying hydrogen, cooling natural gas to a temperature of about -260°F and transporting the resulting liquid has “an energy penalty of up to 15%,” according to the Australian Greenhouse Office. So if LNG represents a significant fraction of incremental U.S. natural gas consumption in the future, the energy lost in the process of making and shipping LNG provides one more reason why we should not make hydrogen from natural gas, which already offers little or no energy or greenhouse gas benefit over hybrid vehicles. And since we should start thinking of the energy resource base as a global one, it would be far better to use foreign natural gas to offset foreign coal combustion than to import it into the United States in order to turn it into hydrogen to offset domestic gasoline consumption. That’s especially true because projected growth in global coal consumption is an even bigger greenhouse gas problem than projected growth in U.S. coal consumption.

By 1999, the world had just more than 1,000 GW of coal-fired electricity generating capacity, of which about one-third was in the United States. Between 2000 and 2030, more than 1,400 GW of new coal capacity will be built, according to the International Energy Agency, of which 400 GW will represent replacement of old plants (see Figure 8.1).

These plants would commit the planet to total CO₂ emissions of some 500 billion metric tons over their lifetime, unless “they are backfit with carbon capture equipment at some time during their life,” as David Hawkins, director of the Natural Resources Defense Council’s Climate Center, told the U.S. House Committee on Energy and Commerce in June 2003. Hawkins continued:

To put this number in context, it amounts to half the estimated total cumulative carbon emissions from all fossil fuel use globally over the past 250 years! If we build any significant fraction of this new capacity in a manner that does not enable capture of its CO₂ emissions we will be creating a “carbon shadow” that will darken the lives of those who follow us.

The carbon shadow is not merely the long lifetime of coal plants (many decades) but also the long lifetime of heat-trapping CO₂ in the atmosphere (more than a century).

**FIGURE 8.1.** Two-thirds of world coal capacity in 2030 is not yet built.

*Source: IEA, NRDC.*
Carbon capture and storage (CCS) is an important focus of research, but on a massive scale it is unlikely to be practical and economical for more than two decades (as discussed later in this chapter). To defer as many of these plants as possible until CCS is ready, we will have to use our electricity more efficiently (thereby slowing the demand for such power plants) and build as many cleaner power plants as possible. Again, natural gas is far more critically needed for this task than for generating hydrogen. So, too, with renewable power—for the foreseeable future, we will need it in order to avoid building coal-fired plants, not to generate hydrogen for transportation.

As discussed in Chapter 4, converting electricity from renewable sources to hydrogen through electrolysis is a relatively inefficient process, immediately costing some 30 percent of the energy in the electricity. Transporting and storing the hydrogen costs another 10 to 20 percent of that energy. This wasted energy would be better used to displace fossil fuels, according to a November 2002 study by three leading analytical groups in the United Kingdom. That study calculated that 1 MWh of electricity from renewables, if used to manufacture hydrogen for use in a fuel cell vehicle, would save slightly less than 500 pounds of CO$_2$. That is some 300 pounds less than the savings from displacing a future gas plant and 1,700 pounds less than the savings from displacing coal power (see Figure 8.2). And, as we’ve seen, we are going to build a lot more coal plants unless we can displace them with efficiency, natural gas, and renewables.

The British study concluded, “Until there is a surplus of renewable electricity, it is not beneficial in terms of carbon reduction to use renewable electricity to produce hydrogen—for use in vehicles, or elsewhere. Higher carbon savings will be achieved through displacing electricity from fossil fuel power stations.” The July 2003 Keith and Farrell analysis in Science comes to a similar conclusion: “Until CO$_2$ emissions from electricity generation are virtually eliminated, it will be far more cost-effective to use new CO$_2$-neutral electricity (e.g., wind or nuclear) to reduce emissions by substituting for fossil-generated electricity.”

When will we have a surplus of renewable power and a virtual elimination of CO$_2$ emissions from electricity generation? The British authors conclude that, in the United Kingdom, it is likely to be “at least 30 years.” Significantly, the United Kingdom’s electric grid already has a CO$_2$ intensity (CO$_2$ emitted per megawatt-hour of electricity produced) that is lower than that of the United States by more than one-third. Moreover, the United Kingdom has moved sharply away from coal generation in the past two decades and is aggressively pursuing renewable energy and cogeneration. The U.S. government, in contrast, has been unable as of 2003 to pass a law requiring that 20 percent of electricity come from renewable...
power in 2020, even though the environmental benefits are very large and the economic costs small. In fact, a key reason why the costs are so small is that such a law would reduce the pressure on the natural gas supply, which would reduce prices by just about the amount of the extra electricity costs.31 A May 2003 analysis in Windpower Monthly argues that having excess U.S. wind power generation to use for hydrogen production is "a situation not likely before 2050 at the earliest."32

As but one example of how far the United States and the world have to go on clean energy, consider the results of a March 2003 analysis by scientists at Lawrence Livermore National Laboratory, the University of Illinois, and New York University.33 They concluded that if the world is to stop global temperatures from rising by more than 2°C as a result of our greenhouse gas emissions, we should be building between 400 and 1,300 MW of zero-carbon electricity generation capacity per day for fifty years. Yet current projections for the next thirty years are that we will build just 80 MW per day.34 And 2°C would still very likely have a devastating effect on the planet, as we have seen. Strikingly, "if climate sensitivity is in the middle of the IPCC range," the analysis also concludes, "even stabilization at 4°C warming would require installation of 410 megawatts of carbon emissions-free energy capacity each day."35

I think it is possible that the United States could have virtually carbon-free electricity before 2050—with hydrogen playing a key role, as I will discuss in my scenario at the end of this chapter—but it will require both major technological breakthroughs and a sea change in U.S. government policy on global warming. First, let's examine some of the other potential drivers of the hydrogen transition.

Hydrogen and Urban Air Pollution

Another driver of a shift to hydrogen is concern about urban air pollution. The transportation sector remains one of the largest sources of such pollution—especially (1) the oxides of nitrogen (NOx) that are a precursor to ozone smog and (2) particulates—especially those less than ten microns in size, which do so much damage to our hearts and lungs.

In the United States, vehicle emissions (other than greenhouse gas emissions), however, have been declining steadily. Toxic emissions are being reduced through the combination of ever stricter federal and state regulations coupled with the steady turnover of the vehicle fleet. The oldest and dirtiest vehicles ultimately go out of service and are replaced by the newest and cleanest vehicles. The federal Clean Air Act Amendments of 1990 set in motion a two-pronged process. In the 1990s, Tier 1 standards dramatically reduced tailpipe emissions of new light-duty vehicles (such as cars and most sport utility vehicles, or SUVs). By 2010, Tier 2 standards will even further reduce vehicle emissions and will extend the regulations to larger SUVs and passenger vans while mandating the use of gasoline with lower sulfur content (which not only directly reduces emissions but also makes it easier for automakers to design cars that achieve further reductions). Due to its infamously smogged-in cities, California has even tougher standards for automobiles than does the United States as a whole; these standards will also be phased in during this decade.

When all these standards are in place, new U.S. cars will be exceedingly clean, at least from the perspective of emissions of urban air pollutants (the current Clean Air Act standards do not address vehicle CO2 emissions). Many new cars, so-called partial zero-emissions-vehicles, will actually have tailpipe emissions cleaner than Los Angeles air. Hydrogen fuel cell vehicles, though, have no emissions besides water and thus are the ultimate in a clean car. On the other hand, they will be more costly in the beginning and will require a significant investment in infrastructure. Here is the question for any such breakthrough clean technology: Are the benefits received proportional to the money spent? Put another way, can emissions reductions beyond Tier 2 standards be achieved for less money using other strategies? In the short run, the answer is yes.

For instance, remote sensing of vehicles at a major intersection in Denver, Colorado, showed that "the worst polluting 10% of cars
and trucks emit 6% of the carbon monoxide pollution, while the 50% of clean, new cars emit less than 6%.” Those dirty vehicles are primarily “older, poorly maintained automobiles.” This evidence strongly suggests that until we make a serious effort to either repair or scrap these gross polluters, we won’t affect urban air pollution much by focusing on further emissions reductions in new vehicles. Trying to lower that already low 6 percent just won’t have much effect. The 2003 analysis by Keith and Farrell estimates that fuel cell vehicles would reduce oxides of nitrogen at a cost 100 to 500 times greater than that of current strategies. Also, in terms of overall emissions of urban air pollutants, for the next two decades at least, we can achieve pollution reductions far more cost-effectively by cleaning up power plants and large off-road vehicles, such as construction equipment, than by investing in fuel cell vehicles. The George W. Bush administration has proposed new, tougher emissions regulations for off-road vehicles.

The long-term answer to the cost-effectiveness question will require a far better understanding of what is now unknown—the cost of super-clean vehicles, their hydrogen fuel, and the necessary infrastructure. Research, development, and demonstration of hydrogen fuel cell vehicles remain the only ways to find the ultimate answers.

Hydrogen and Energy Independence
In a February 2003 speech on hydrogen, President Bush said, “It jeopardizes our national security to be dependent on sources of energy from countries that don’t care for America. . . . It’s also a matter of economic security, to be dependent on energy from volatile regions of the world.” You might think that after fighting two wars in the Persian Gulf since 1990, after enduring a major terrorist attack funded in large part by Persian Gulf oil money, and with imports accounting for more than half of our oil consumption and our sending $100 billion per year offshore, that our first call to action would be to significantly reduce those imports. And yet we have done essentially nothing.

The two most effective strategies for permanently reducing dependence on imports—raising gasoline taxes and raising fuel efficiency standards—simply lack political support, even though they both have the added benefit that they would help address global warming and other environmental problems. The gasoline tax strategy is the one Europe has used to help constrain fuel consumption. The United Kingdom and countries such as France and Germany have gasoline taxes of more than $2.00 per gallon, more than five times the gasoline tax in the United States. Such tax hikes are essentially inconceivable in this country for the foreseeable future. For instance, by the end of the Clinton administration, it was not possible to suggest increasing gasoline taxes by even a few cents—tax increases of all kinds were considered political suicide.

The fuel efficiency approach is the one this country used so successfully in the late 1970s and early 1980s, when we doubled the fuel efficiency of our fleet while making our cars safer, mandating that new cars have a fuel efficiency of 27.5 mpg. In a 2002 report to President Bush, the National Academy of Sciences concluded that automobile fuel economy could be increased by 12 percent for small cars and up to 42 percent for large SUVs with technologies that would pay for themselves in fuel savings. That study did not even consider the greater use of diesels and hybrids. Studies undertaken by the national laboratories for the DOE, by the Massachusetts Institute of Technology, and by the Pew Center on Global Climate Change have concluded that even greater savings could be cost-effective while maintaining or improving passenger safety. The Europeans have a voluntary agreement with automakers that will reduce CO₂ emitted per mile by 25 percent from 1996 to 2008 for the average light-duty vehicle, which equates to a vehicle fuel efficiency of almost 40 mpg. Japan has a mandatory target with similar goals. Yet most observers consider such new fuel efficiency standards in this country politically infeasible for the foreseeable future: The auto companies have actively lobbied against any such standards, the White House is opposed to them, and there is little evidence of broad political support in Congress or elsewhere.
Because of this inaction, as of 2002 the fuel economy of the average vehicle on American roads was at its lowest level in two decades and likely to get worse. The fuel economy laws have a loophole allowing SUVs and light trucks to average 20.7 mpg, 25 percent lower than the standard for new cars. This has allowed overall vehicle efficiency to drop as the SUV share of new vehicle sales has grown. Ford, for instance, has backed off a voluntary commitment to increase SUV fuel efficiency, and, in fact, its 2003 model year SUVs will be less fuel efficient than those of the previous year. Moreover, companies known for fuel efficiency, such as Honda and Toyota, both of which have introduced hybrid vehicles into the U.S. market, have also introduced gas-guzzling SUVs.

From my years of working to influence policy on this issue, both in and out of government, the conclusion I draw from all this is that "energy independence" is a phrase to which politicians and policy makers give lip service but which is exceedingly unlikely to speed up the transition to a hydrogen economy. If the actions of Saddam Hussein and Osama bin Laden and record levels of oil imports couldn't induce lawmakers, automakers, and the general public to embrace existing vehicle energy efficiency technologies that will actually pay for themselves in fuel savings, I cannot imagine what fearful events must happen before the nation will be motivated to embrace hydrogen fuel cell vehicles, which will cost much more to buy, cost much more to fuel, and require massive government subsidies to pay for the infrastructure.

Ultimately, I believe, it is not fear about the growing level of oil imports that will bring about change but the inevitable exhaustion of the world's finite oil resources. Worldwide population growth, economic growth, and urbanization will dramatically increase global oil consumption in the coming decades, especially in the developing world. As farmworkers move to urban centers, much more oil will be needed. The key elements of urbanization are commuting, transport of raw materials, and construction of buildings and other infrastructure. All consume huge amounts of oil. At the same time, fewer farmers will have to feed more people, so the use of mechanization, fertilizer, and transportation will increase, consuming even more oil. In spite of all this growth in the developing world, no country will overtake the United States in oil consumption anytime soon. The EIA projects that between 2000 and 2025, we will increase our oil demand by nearly 50 percent.

This acceleration in global oil demand will eventually bump up against the reality of oil as a finite, nonrenewable resource, causing global production to peak and start declining, much as production in the continental United States did decades ago. Some believe this will occur by 2010—or sooner. In a 2003 speech, Matthew Simmons, energy investment banker and Bush administration advisor, said that his analysis was leading him more and more to "the worry that peaking is at hand; not years away. If it turns out I'm wrong, then I'm wrong. But if I'm right, the unforeseen consequences are devastating. But unfortunately the world has no Plan B if I'm right." In his 2001 book *Hubbert's Peak: The Impending World Oil Shortage*, Princeton University geophysicist Kenneth Deffeyes states bluntly, "There is nothing plausible that could postpone the peak until 2009. Get used to it."

The Royal Dutch/Shell Group, probably the most successful predictor in the global oil business, adds a few years to those gloomy forecasts. According to Shell, "a scarcity of oil supplies—including unconventional sources and natural gas liquids—is very unlikely before 2025. This could be extended to 2040 by adopting known measures to increase vehicle efficiency and focusing oil demand on this sector." Whether we will adopt these known measures or not remains to be seen. Moreover, producing conventional liquid fuels from either natural gas or unconventional sources of oil (such as Canadian oil sands) is relatively energy-intensive, and relying on these sources will significantly increase greenhouse gas emissions.

I have found that this issue—the possibility that we are nearing a production peak—gets even less traction in Washington, D.C., as a driver of energy policy than the call for energy independence. The argument is inevitably dismissed with a wave of the hand: "We've heard that for decades." In 1996, at my first congressional hearing representing the DOE, a researcher from the Massachusetts Institute of Technology testified that "you really can't see a peak, because
the peak keeps moving out further and further into the future. And, people who do this kind of work are always sort of explaining that the previous peak was wrong, but now they have a new peak and it's the real peak. So, I wouldn't give too much credence to that.\textsuperscript{89}

What would happen if we started running out of oil? Prices would start spiking, possibly with destabilizing effects on the economy. On the one hand, Deffeyes and others argue that after the peak, production may well decline at a relatively rapid rate even as demand increases, so delaying action until that moment may risk significant economic damage. On the other hand, most European countries have gasoline prices that are double ours already, with no obvious harm to their standard of living. In either event, such a peak would eventually force us to switch to much more efficient vehicles and alternative fuels. So the possibility of a production peak in the near future is an argument for being prepared with alternatives to oil through an aggressive R&D effort. But again, if we were seriously concerned about this issue, we would take up Shell's suggestion and aggressively adopt "known measures" for vehicle efficiency, such as hybrids, diesels, and biofuels, discussed later in this chapter.

Hydrogen and Sequestration

Carbon sequestration—permanent carbon storage—is a potentially crucial strategy for reducing net atmospheric CO\textsubscript{2} emissions and one that could dramatically accelerate introduction of hydrogen into the economy. CO\textsubscript{2} can be removed from the atmosphere and stored biologically in trees and other biomass, a strategy I will return to shortly. Sequestration can also involve removing CO\textsubscript{2} from power plants and storing it within the planet's physical systems, which, as discussed earlier, is sometimes called carbon capture and storage (CCS). The CO\textsubscript{2} can be captured either before or after combustion.

Geologic sequestration is the storage of CO\textsubscript{2} in vast, sealed underground places. Costs for geologic sequestration are currently quite high, more than $30 per ton of CO\textsubscript{2}, according to the DOE.\textsuperscript{50} The technical challenges of reducing those costs are significant. The report of a February 2003 workshop on carbon management by the National Academy of Sciences concluded, "At the present time, technology exists for the separation of CO\textsubscript{2} and hydrogen, but the capital and operating costs are very high, particularly when existing technology is considered for fossil fuel combustion or gasification streams."\textsuperscript{51} Significant R&D is being carried out to bring the costs down.

Capturing CO\textsubscript{2} from a gasification stream is potentially the most intriguing option for a hydrogen economy, especially for a world awash in coal but needing to restrain greenhouse gas emissions. As discussed in Chapter 4, coal can be gasified and the resulting synthesis gas (synthesis gas) can then be chemically processed to generate a hydrogen-rich gas for fuel and a stream of CO\textsubscript{2} that can be piped to a sequestration site. This hydrogen-rich gas can be combusted directly in a combined cycle power plant, or it can power a high-temperature fuel cell.

Some hydrogen can also be purified and shipped out for other uses, such as transportation. From a global warming perspective, though, the same analysis that applied to renewable energy applies here: Until the U.S. electric grid is virtually CO\textsubscript{2}-free, this hydrogen-rich gas is far better used to displace electric power derived from fossil fuels than to be converted to very pure hydrogen, shipped hundreds of miles, and used as a transportation fuel. And, in fact, the DOE's FutureGen project for coal gasification and CO\textsubscript{2} sequestration envisions using the hydrogen to generate clean power, at least initially, perhaps using a solid oxide fuel cell (SOFC).\textsuperscript{52} Coal gasification systems with CO\textsubscript{2} capture could achieve efficiencies of 60 percent or more using various combinations of turbines and SOFCs.\textsuperscript{51}

The key question is where to put the CO\textsubscript{2}. The largest potential physical reservoir is the deep oceans. However, ocean sequestration poses serious environmental risks and is unlikely to be a viable climate mitigation strategy. Tens of millions of tons of CO\textsubscript{2} are already injected into oil fields to enhance recovery. This strategy can be expanded for early, low-cost sequestration efforts, but oil fields are limited in size and location, and transporting CO\textsubscript{2} over long dis-
stances will be costly. To meet a potential demand to sequester several billion metric tons of CO$_2$ per year, especially in places that do not have conventional storage formations, research is focusing on finding much larger reservoirs.

Recent attention has focused on pumping highly compressed liquid CO$_2$, so-called supercritical CO$_2$, into geologic formations such as deep underground aquifers. As the report of the National Academy workshop noted, "less dense than water, CO$_2$ will float under the top seal atop the water in an aquifer and could migrate upward if the top seal is not completely impermeable." The problem here is that even very tiny leakage rates can undermine the environmental value of such sequestration. If we are trying to stabilize CO$_2$ concentrations at twice preindustrial levels, a 1 percent leakage rate could add $850 billion per year to overall costs by 2095, according to an analysis by Pacific Northwest National Laboratory. That study concluded, "Leakage of CO$_2$ from engineered CO$_2$ disposal practices on the order of 1% or less per year are likely intolerable as they represent an unacceptably costly financial burden that is moved from present generations to future generations." If we cannot be certain that leakage rates are below 1 percent, "the private sector will find it increasingly difficult to convince regulators that CO$_2$ injected into geological formations should be accorded the same accounting as CO$_2$ that is avoided"—avoided, that is, directly through technologies such as wind power. The study notes that, "there is no solid experimental evidence or theoretical framework" for determining likely leakage rates from different geologic formations.

How long will it take before CCS emerges as a major solution to global warming? That remains uncertain. As Princeton's Bob Williams wrote in 2003, "one cannot yet say with high confidence that the CO$_2$ storage option is viable." The technology itself is very challenging, and just as commercializing fuel cells has taken much longer and has proven far more difficult than was expected, so, too, may building large commercial coal gasification combined cycle units. The DOE is aiming to "validate the engineering, economic, and environmental viability" of a system by 2020.

Ultimately, this integrated gasification combined cycle (IGCC) technology will require leadership by the private sector. Yet, as the National Coal Council reported to the secretary of energy in its May 2003 report titled Coal Related Greenhouse Gas Management Issues, "vendors currently do not have an adequate economic incentive to invest R&D dollars in IGCC advancement" because "IGCC may only become broadly competitive with" current coal and natural gas power plants "under a CO$_2$-restricted scenario." Thus, "power companies are not likely to pay the premium to install today's IGCC designs in the absence of clear regulatory direction on the CO$_2$ issue." Absent near-term restrictions on CO$_2$ emissions, this option will be pushed much further out to the future.

As for storing CO$_2$ in underground aquifers, much testing will have to be done before this approach can be considered for widespread use. Each potential major site will very likely need to be the subject of intensive long-term monitoring to guarantee it can permanently store CO$_2$. Very sensitive and low-cost in situ assessment and monitoring techniques must be developed to provide confidence that leakage rates are exceedingly low.

Analysis suggests that CCS could potentially eliminate a large fraction of emissions from the U.S. electricity sector for $20 to $40 per ton of CO$_2$, whereas using the carbon-free hydrogen as transportation fuel to cut emissions in cars could cost more than $200 per ton. Ultimately, leak-proof CCS may be an essential strategy for combating global warming, one that will accelerate the transition to hydrogen economy. But, at this point, it seems unlikely to be widely used until after 2030—after the world has built an additional 1,000 GW of coal plant capacity and dramatically enhanced the prospect of catastrophic global warming.

In the near term, biological sequestration can, with appropriate accounting rules and environmental criteria, play a role in reducing atmospheric concentrations of CO$_2$. Probably the best-known form of sequestration is the planting of trees (or other plants) to remove CO$_2$ from the atmosphere and store it inside that biomass. This biological sequestration is temporary because when the plant or tree dies, it decays, returning the CO$_2$ to the atmosphere. Even massive
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planet-wide reforestation would have a limited effect on CO₂ concentrations.⁶¹ A biological sequestration strategy with enormous potential is to plant trees and crops for the purpose of harvesting them as renewable energy, either electric power or liquid fuel.⁶² If the planting and harvesting are done in a sustainable fashion, with relatively low energy inputs, the net CO₂ released will be close to zero. Biomass can be gasified and converted to hydrogen (and electricity) in a process very similar to coal gasification. A number of biomass gasification processes are in the process of being demonstrated, although a practical commercial system remains technologically challenging. If carbon capture and storage is practical, then one could also imagine extracting the CO₂ stream from the biomass gasification process. This would turn biomass into a potent net reducer of CO₂—extracting CO₂ from the air via photosynthesis while growing and then injecting that CO₂ into underground reservoirs through CCS. This may be a critical option for the United States and the world, given the increasing risk of rapid and catastrophic climate change.⁶³

Biomass can also be used to make a zero-carbon transportation fuel, such as ethanol, which is now used as a gasoline blend. Today, the major biofuel is ethanol made from corn, which yields only about 25 percent more energy than was consumed to grow the corn and make the ethanol, according to some estimates. Considerable R&D is being focused on producing ethanol from sources other than corn. This so-called cellulosic ethanol can be made from agricultural and forest waste as well as dedicated energy crops, such as switchgrass or fast-growing hybrid poplar trees, which can be grown and harvested with minimal energy consumption so that overall emissions are near zero.⁶⁴ All cars today can use a mixture of 10 percent ethanol and 90 percent gasoline, known as E10. Some 4 million flexible fuel vehicles, which can run on either gasoline or a blend with 85 percent ethanol, E85, are on the road today, but few use E85 because of its high price.

If hybrids and diesels are the toughest competition for transportation fuel cells, then cellulosic ethanol is probably the toughest competition for hydrogen in the race to develop a transportation fuel with low or no greenhouse gas emissions. The big advantage ethanol has over hydrogen is that it is a liquid fuel and thus is much more compatible with our existing fueling system. Existing oil pipelines, however, are not compatible with ethanol, so significant infrastructure spending would still be required if ethanol were to become the major transportation fuel.⁶⁵ As with hydrogen, production of ethanol will require major technological advances before it can come close to the price of gasoline on an equivalent energy basis.⁶⁶

Probably the biggest drawback to biofuels, and to biomass energy in general, is that biomass is not very efficient at storing solar energy. Therefore, large land areas are needed to provide enough energy crops if biofuels are to provide a significant share of transportation energy. One 2001 analysis by ethanol advocates concluded that to provide enough ethanol to replace the gasoline used in the light-duty fleet, “it would be necessary to process the biomass growing on 300 million to 500 million acres, which is in the neighborhood of one-fourth of the 1.8 billion acre land area of the lower 48 states” and is roughly equal to the amount of all U.S. cropland in production today.⁶⁷ That amount of displaced gasoline represents about 60 percent of all U.S. transportation-related CO₂ emissions today, but less than 40 percent of what is projected for 2025 under a business-as-usual scenario. If ethanol is to represent a major transportation fuel in the coming decades, then U.S. vehicles will need to become much more fuel efficient. Moreover, given the acreage needed, using it for these purposes would obviously have dramatic environmental, political, and economic implications. As of 2003, there were no commercial cellulosic biomass-to-ethanol plants.

Hence, ethanol, like hydrogen, is no near-term panacea. In the long term, however, biomass-to-energy production could be exceedingly efficient with bio-refineries that produce multiple products. Lee Lynd, professor of engineering at Dartmouth College, described one such future bio-refinery where cellulosic ethanol undergoes a chemical pretreatment and then fermentation...
converts the carbohydrate content into ethanol as CO₂ bubbles off. The residue is mostly lignin, a polymer found in the cell walls of plants. Water is removed, and the biomass residue is then gasified to generate electricity or to produce a stream of hydrogen and CO₂. The overall efficiency of converting the energy content of the original biomass into useful fuel and electricity would be 70 percent, even after accounting for the energy needed to grow and harvest the biomass. The CO₂ can be sequestered. Also, this process could be used to generate biodiesel. This is admittedly a futuristic scenario, but it is the subject of intensive research and could make ethanol competitive with gasoline and make electricity competitive with other zero-carbon alternatives, especially when there is a price for avoiding CO₂ emissions.

The Global Warming Century

I take issue with the many scenarios that place us in the safe harbor of a hydrogen economy in just a decade or two. I do think such a transition may well be essential, for all the reasons I have described, but I think it will happen very differently from the way most analysts have suggested.

Here is my own scenario for the transition. Scenarios are not predictions; rather, they are credible and relevant narratives designed to challenge our thinking. This scenario assumes major technological advances but recognizes that the energy system changes slowly. As Shell noted in its most recent scenarios, "typically it has taken 25 years after commercial introduction for a primary energy form to obtain a 1% share of the global market."

As in Shell's, the environmental driver in this scenario is global warming. I draw on the most recent science and apply the lesson of the 1990s, when the hottest decade in 2,000 years drove most developed countries to a commitment to reduce their greenhouse gas emissions.

Although our scientific understanding of the climate will continue to improve in the coming years, this scenario plays out what a growing number of scientists see as the current warming trajectory. This scenario is called "The Global Warming Century." It is a world driven by reaction to bad environmental news and good technological news. Here are some of the highlights through 2050:

2000–2009: The hottest decade in 2,000 years. Many developed countries (other than the United States) begin making modest greenhouse gas reductions, creating a robust market for CO₂. Lack of leadership in the United States and the developing world stalls broader action on emissions. Growing R&D efforts and the prospect of major sales in Europe and Japan for climate-mitigating energy technologies bring about steady advances in fuel cells, renewables, energy efficiency, and hydrogen. CO₂ emissions in the United States rise by more than 10 percent, and in the world they rise by more than 15 percent.

2010–2019: The hottest decade in 2,000 years. The Intergovernmental Panel on Climate Change (IPCC) raises its warming estimate in its fifth assessment, projecting that 2100 will be 3.5°F–12.5°F hotter than 1990. The IPCC acknowledges in 2016 that stabilization of CO₂ concentrations below 550 ppmv (twice preindustrial levels) by 2100 is "for all practical purposes, impossible." The National Academy of Sciences declares that 60 percent of the world's coral reefs will be lost by 2030 and that most of the rest are "unsavable, given current knowledge." The success Europe and Japan have in achieving small reductions at moderate costs inspires the first global climate treaty. Major developing nations refuse to accept absolute emissions reductions and insist that a nation's climate targets reflect cumulative emissions since 1900. The U.S. government refuses to accept a CO₂ reduction target before 2030. Solid oxide fuel cells and hybrid cars emerge as major commercial successes, delaying entry of PEM fuel cells into both the stationary and transportation markets. CO₂ emissions in the United States rise by another 10 percent, and worldwide they again rise by more than 15 percent. Global concentrations exceed 400 ppmv by the end of the decade.

2020–2029: The hottest decade in 2,000 years. The IPCC's seventh assessment projects that, by 2100, sea levels will be
twelve to sixty inches higher than in 1990. After a piece of Antarctica the size of Connecticut breaks off in 2024, the National Academy of Sciences warns that disintegration of the entire Western Antarctic Ice Sheet now “appears likely within 200 years” and that a complete melting of the Greenland Ice Sheet is “virtually inevitable,” which would raise sea levels more than twenty feet. In the United States, a major push for the most cost-effective climate solutions—energy efficiency, cogeneration, hybrid vehicles—leads to a peaking of U.S. primary energy demand in 2027. Fuel cell vehicles appear in a few fleets mandated by states such as California. Significant advances occur in hydrogen storage, coal and biomass gasification, and solar power. An electricity standard is proposed requiring that 50 percent of U.S. electricity be from renewables by 2040. The standard passes in 2025, after a “grand bargain” amendment allows CO₂ capture and storage to constitute as much as one-third of the requirement. A major effort is launched to characterize all significant potential geologic reservoirs for CO₂. Emissions of CO₂ in the United States remain flat, but global emissions rise by another 10 percent.

2030–2039: The hottest decade in 2,000 years. The IPCC’s ninth assessment projects that 2100 will be 4.5°F–15°F warmer than 1990. The United States experiences its first 1,000-tornado month. In mid-decade, Hurricane Elisa hits Miami with winds raging at 200 miles per hour, killing 800 people and causing $100 billion in damage. In 2037, the National Academy of Sciences’ Panel on Abrupt Climate Change, noting that the three previous years were a full 1°F warmer than the past decade, urges CO₂ stabilization at 650 ppmv within fifty years. Coal gasification together with carbon capture and storage (CCS) becomes cost-effective, with the resulting hydrogen-rich gas used to generate electricity in SOFC and gas turbine plants with efficiencies exceeding 80 percent. Global oil production peaks and starts to decline significantly in mid-decade as CO₂ restrictions limit development of unconventional resources. In 2038, China intro-