



# THE FUTURE OF FOSSIL FUELS

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KENNETH S. DEFFEYES

A **PRINCETON SHORTS** selection from *Hubbert's Peak*

As debates about the effects of fossil fuels on our climate and foreign policy intensify, the question of just how much longer we can depend on this finite source of energy becomes more and more pressing. This selection from *Hubbert's Peak*, the leading book on the limits of our oil supply, forecasts what the future will bring for fossil fuels and what the alternatives are likely to be.

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## *The Future of Fossil Fuels*

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Years ago, a visitor to Switzerland asked how people earned a living in those high Alpine villages. “Each village gets paid for doing laundry for the next village.” Today, an equally silly answer would be, “Each village uses the Internet to sell toilet paper to the next village.” The lesson for the global village: we can’t all work in the service economy; somebody has to be down grubbing at the base of the economic pyramid. The list of fundamental activities is short: agriculture, ranching, forestry, fisheries, mining, and petroleum.

Consider the names on some great art museums: Getty (oil), Guggenheim (copper), de Menil (oil services), Gulbenkian (oil). Huge wealth used to be accumulated at the base of the economic system. Today’s dot.com billionaires up at the apex of the pyramid may not be able to see all the way down to the base. They might have the illusion that everyone can earn a living by selling software to the next village.

A permanent drop in oil production will pull one of the blocks out from underneath the pyramid. The previous chapter strongly suggests that the drop will happen in this decade. Major disruptions are likely to follow. What should we do? The question exists at two levels:

- 1 What can individuals and institutions do, in their enlightened self-interest, to minimize the impact of a global oil shortage?
- 2 As a society, how can we rearrange the global economy to lessen our dependence on oil?

Republicans choose line 1; Democrats pick line 2. The division is not that simple. I’m a registered Democrat, but I still feel authorized to protect myself while the world gets its act together. That’s why line 1 says “*enlightened* self-interest.” This chapter discusses fossil fuels; chapter 10 treats alternative energy sources.

A “fossil” is the remains of an ancient organism. A fossil fuel is solar energy stored by organisms in ancient times. A major lesson: the source of the world’s oil accumulated over hundreds of millions of years; most of the world’s oil has been discovered during my lifetime. Large-scale use of fossil fuels began with the Industrial Revolution, of which coal was an integral part. In a sense, the fossil fuels are a onetime gift that lifted us up from subsistence agriculture and eventually should lead us to a future based on renewable resources.

A fad of 10 years ago was “finding oil on Wall Street.” Publicly traded companies with undervalued oil and gas reserves became targets for stock traders and merger-and-acquisition specialists. An individual today could offset his or her family’s petroleum consumption by purchasing oil and gas company shares. But “petroleum consumption” is not just gasoline and home heating. Many other goods and services include an energy cost. Only comparatively wealthy individuals have the flexibility to offset future oil price rises by owning oil stocks. Many of us in the middle class have the majority of our assets tied up in home equity and managed retirement funds; we have little

flexibility to change investments.

~~My friends would love to have a short list of trading symbols for companies with undervalued U.S. oil reserves. Unfortunately, professional traders have their computers monitoring these opportunities. Several large oil companies are ready to swallow smaller companies to acquire additional reserves. I'm not likely to find anything in a three-month-old copy of *Oil and Gas Journal* that the full-time traders have overlooked.~~

Colleges and universities are substantial energy users; the more fortunate schools have sizable endowments. Investing a block of the endowment, directly or indirectly, in oil and gas reserves could be a prudent choice. I can report, however, that I got absolutely nowhere when I tried to explain that to Princeton University in 1980. Two universities have their energy problem solved in advance: the University of Texas at Austin and Texas A&M share revenues from state-owned oil lands.<sup>1</sup> The University of Texas at Austin has an endowment second only to Harvard; an oil price rise increases UT Austin's income.

Here is a second limitation: we can't all buy Texaco. For years, Texaco has been a Wall Street favorite: large oil and gas reserves, few employees, low costs. Texaco is disappearing as a investment opportunity; it is being acquired by Chevron. In fact, the entire stockholder equity for all U.S. petroleum companies combined is not large enough for all of us to offset the threatened oil price rise. Equities are, at best, an opportunity for smart money to get in during the early rounds.

Gradually, the role of the major oil companies has changed. They are becoming more like enormous service companies, although they do bring along their own investment capital. The majors appear to be vertically integrated companies, active in everything from exploration to marketing. However, production, transportation, refining, and marketing are almost independent activities. The oil has a defined price in between each stage. I was disappointed when I learned that the gasoline sold in a Shell station might come from a Conoco refinery. Shell writes specifications and analyzes the gasoline to see that it meets the specifications, but another company may do the actual refining. There is no equivalent of a chateau-bottled wine.

In the past 10 years, major oil companies have been getting as little as 10 percent of the oil from their share in new overseas ventures.<sup>2</sup> Much of the oil revenue goes to the producing nation, usually through the participation of government-controlled oil companies. At the marketing end, a substantial part of the price of gasoline at the pump is another round of taxes. Let's face it, oil used to be a highly profitable business, and governments figured out how to cut themselves in for a big piece of the action. As world oil production decreases, some governments may feel more pain than the major oil companies.

Years ago, the New York Times Company bought enough Canadian forestland to grow pulpwood as fast as it prints newspapers. Heavy petroleum users among large corporations, like FedEx and UPS, could attempt a takeover of an oil company large enough to offset their consumption. In the past, a useful way of insuring major producers and consumers against the effect of a price change was purchasing futures contracts. However, the ordinary futures contracts extend for a year or two. The oil problem extends for 10 years or more. Anyone who agrees to supply oil 10 years from now, for a price agreed on today, very likely will disappear into bankruptcy before the contract matures.

The financial world has reorganized since 1980. Effects of oil price rises, during the late 1970s, took months to years to spread from industry to industry; from price increases to wage demands. In the new economy, the shock of an oil price rise will spread in milliseconds. Detailed computer models of the world economy will flash messages to buy or sell everything from AT&T to Xerox, from aluminum to zinc, from bahts to zlotys.

Oil and gas companies have split personalities. Finding a new oil field is an investment that

generates income for 20 years, but Wall Street has a fixation on the most recent quarterly earnings. The stock market has preempted the time horizon for most corporations, especially for those outside the natural resource industries. The CEO is assigned stock options on a two-year time scale. His motivation is to get the stock price up in two years: one way is to close the research lab, fire the engineers designing the upcoming product, make the quarterly profits look great, retire and cash out. Of course, I have overstated the case, but the top managers should not be given heavy personal incentives to ignore long-term goals.

A second struggle about the time horizon comes from interest rates. A potential project, in any industry, is judged by the present-day discounted value of the expected future cash flow.<sup>3</sup> At times of high inflation, and high interest rates, the future barely exists. During the 1980 oil crisis, interest rates reached 20 percent. At a 20 percent discount rate, a dollar earned 10 years in the future has a present-day value of only 11 cents. Long-term efforts, like designing a new aircraft or exploring for new oil, become difficult to justify. ExxonMobil is not designed to be a charity. In the existing system, ExxonMobil is not asked to take on uneconomic projects to provide us with future oil. Discounting the future is more than a problem for the oil industry. Economists and the Sierra Club have opposing philosophies.

The dichotomy between the short and long time scales affects employees, including the professional staff. Oil companies have to survive boom-and-bust cycles. This one circulated around Denver in 1970:

**Q:** How do you address a petroleum geologist?

**A:** Waiter!

Usually at a time of low prices, all the companies in the industry are hurting simultaneously. Of the 200 largest U.S. oil and gas companies, 133 had a net loss for the year 1998. Employees who are let go rarely find employment at another oil company; many of them leave the industry and never want to return.

At the other extreme, around 1980 our geology undergraduates were starting out at salaries higher than those of their professors. Some were very capable, but some were not our best students. Boom years can be just as distorted as lean years. However, falling oil production is not necessarily bad news for individual petroleum geologists. My rough calculation shows that geologists' salaries amount to about two cents for each barrel of U.S. oil. There's plenty of room to raise that to four cents per barrel.

In 1997, I looked into direct investment in wells. Could I set up a company to buy and operate wells? During 1998, inflation-corrected oil prices approached the levels of the 1930s Depression. At the same time, a terrible drought was affecting the midcontinent. Rumor had it that the Oklahoma City police chief reported the good news that only 13 women in Oklahoma City were trying to earn a living as prostitutes. His bad news was that 7 of them were still virgins. It seemed like a good time to be shopping for oil wells.

I picked out one category of wells that might be made marginally profitable, but my major motivation was holding the wells for five years until world oil production peaked. The search focused down to certain counties and a particular depth range. (Don't ask! Just because I am writing a book doesn't mean I have to tell *everything*.) The potential investors I approached had two reactions: (1) oil was a severely depressed industry, and (2) you could make a gazillion dollars in 1997 by buying Internet stocks. In the year 2000, potential investors told me that oil prices had recently doubled and oil wells would be too expensive to buy. So it goes.

In the long run, the eventual use for oil will be for manufacturing useful organic chemicals. I expect our grandchildren to ask, “You burned it? All those lovely organic molecules, you just burned them?” Sorry, we burned it. Originally, the feedstock for synthesizing organic chemicals was a tar by-product from treating coal. The change from coal tar to oil, roughly from 1930 to 1950, gave the name “petrochemical” to the industry. Today, about 7 percent of world oil production goes into petrochemical manufacturing.<sup>4</sup>

The modern state of Israel is, in one limited sense, a product of the synthetic chemical industry. During World War I, a shortage of the solvent acetone was severely limiting British production of gunpowder. Chaim Weizmann, a young chemical engineer working in England, developed a successful method for synthesizing acetone.<sup>5</sup> After the war, as a thank-you gift for Weizmann, the British carved out an independent country in the Middle East, which they named Palestine.

Natural crude oil consists of relatively stable molecules. No surprise, over geologic time all the unstable molecules break down. Early petroleum refineries simply sorted out those stable molecules into salable products. Oil production, and oil refineries, had been running for 50 years before the automobile was invented. Originally, their most marketable product was kerosene, primarily for light from kerosene lanterns. The Oklahoma City oil field was discovered by the Indian Territory Illuminating Oil Company, founded before Oklahoma became a state. *Oil for the Lamps of China* was a novel and a movie of the 1930s.<sup>6</sup>

Introducing the automobile generated a huge market for gasoline, but the amount of gasoline that could be separated from crude oil was low, 10 or 20 percent. The original separation process was distillation, sorting out molecules that boiled at different temperatures. Later, commerce copied nature; thermal cracking was introduced to make smaller molecules, salable as gasoline, out of large molecules.<sup>7</sup> The route to petrochemicals was opened because thermal cracking produced some unstable molecules, molecules that would participate in further chemical reactions. Before World War II, both American and German companies developed commercial petrochemical products. After the war, petrochemical production expanded enormously, in both the range of products and the tonnage produced. A whole range of plastics and synthetic fibers became part of our daily lives. (An unusual application: to clean a lens, use the freshly broken surface of a white foam-plastic packing “peanut.” The plastic is made from oil and gas; there is no grit in it.)

A major early petrochemical complex grew up around the Houston Ship Channel. Large petroleum refineries supplied hydrocarbons. Salt from the salt domes was turned into hydrochloric acid, chlorine, and sodium hydroxide. Sulfur, originally from the caps of salt domes, was a source for sulfuric acid. Bromine came from seawater. Portions of the complex were owned and operated by various companies; a local maze of pipelines conveyed intermediate products from one plant to another.

We don’t usually think of oil processing as a source of fertilizer. However, nitrogen compounds are important in plant nutrition; the first of the three numbers on a fertilizer bag gives the nitrogen content. Mineral sources of nitrogen compounds are quite rare. The obvious source is the atmosphere: air is 76 percent nitrogen. In 1908, Fritz Haber reacted atmospheric nitrogen with hydrogen gas to produce ammonia; other nitrogen compounds could in turn be produced from the ammonia.<sup>8</sup> Today the cheapest source of hydrogen gas is hydrocarbons: oil and gas. Virtually all our nitrogen compounds are indirectly petrochemicals.

Major oil companies, such as ExxonMobil, are vertically integrated; they explore for oil, drill wells, transport oil, run refineries, and their gasoline hose reaches all the way to your car’s fuel tank. On the side, major oil companies are also petrochemical producers. Profits, or losses, happen all along the chain from exploration to marketing. Oil-producing countries soon realized that crude oil was



leaving their borders and refining and petrochemical profits were appearing elsewhere. Gradually, oil-producing countries arranged for the building of local refineries and petrochemical plants. Today petrochemical plants in Saudi Arabia use about 10 percent of the country's oil production.<sup>9</sup>

As the global economy eventually converts to renewable energy, oil and gas will continue to be produced for petrochemicals, lubricants, and specialty products. An example of a specialty product is "Vaseline," a trade name for petroleum jelly, is made by Chesebrough-Ponds. One of the companies that split up in 1911 from the original Rockefeller-owned Standard Oil was Chesebrough, along with Exxon, Mobil, Chevron, Arco, and Amoco.

If there is a continuing use for oil, what can we do to extend the supply? More oil can be squeezed out of existing fields, oil can be produced from tar sands and oil shales, and natural gas production can expand.

Conventional primary and secondary recovery methods typically leave half of the oil still in the ground. A depleted oil field can be acquired cheaply; lots of clever people have devised methods for recovering the second half of the oil. In 1980, when oil reached \$37 per barrel, projects known as "tertiary recovery" or "enhanced recovery" were initiated. By 1986, 512 projects were operating in the United States.<sup>10</sup> Tertiary recovery looked like the wave of the future. Since 1986, however, the total amount of U.S. oil produced from these enhanced methods has been roughly constant at 700,000 barrels per day, compared with U.S. production of 6 million barrels per day. The number of operating projects dropped from 512 (in 1986) to 199 (in 1998).<sup>11</sup>

Rather than listing all the tertiary recovery methods, real and imaginary, here are the most successful methods in terms of U.S. oil production in 1998:

- 1 Steam injection, either into separate injection wells or as "huff-and-puff" intermittent injection into production wells: 420,000 barrels per day. Steam is the oldest of the enhanced methods; it is used to recover thick, viscous oil, largely in California.
- 2 Carbon dioxide injection to increase the volume of the oil and to reduce its viscosity: 179,000 barrels per day.
- 3 Hydrocarbon injection: 102,000 barrels per day.
- 4 Eleven other methods combined: 58,000 barrels per day.

Of course, the lack of growth was partially explained by the 1997 drop in crude oil prices. If there are major price rises associated with a drop in conventional oil production, we can expect that the enhanced methods will be dusted off and expanded once again. However, the 1980s experience shows that it is not duck-soup easy to pull out the second half of the oil.

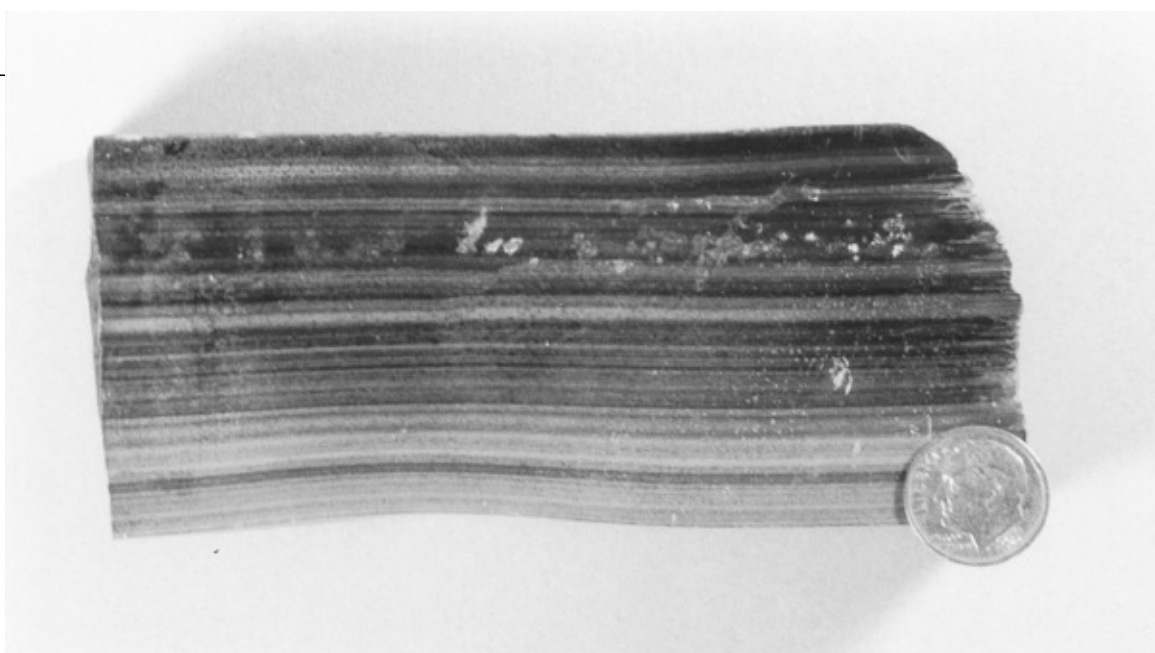
Of the unconventional sources of oil, recovery from tar sands is being expanded rapidly. A tar sand is essentially a dead oil field. When erosion brings an oil field to the surface, the small molecules evaporate, and a nearly solid tar is left in the reservoir rock. Although tar sands exist around the world, Alberta contains two enormous tar sand deposits: Athabaska and Cold Lake. Tar sand oil is extracted by mining the sand, contacting it with hot water, and separating the oil. To tell the truth, the oil isn't all that great; it contains a lot of sulfur. The original tar sand recovery plant, opened in 1978, was profitable in the sense that oil sales paid the operating costs, but the plant took forever to pay back the capital investment.<sup>12</sup> Improved methods followed; as of 1999, 2 billion dollars is being invested in new tar sand operations in Alberta. Closely related to tar sands are reservoir rocks filled with "heavy" oil, oil that is too viscous to move using ordinary production practices.

If a tar sand is a moribund oil field, an oil shale is an unborn oil field. An "oil shale" contains

neither oil nor shale; it is an ordinary petroleum source rock that has never been buried into the oil window. A particularly large oil shale deposit exists where Utah, Colorado, and Wyoming come together. As the first transcontinental railroad reached the town of Green River, Wyoming, a work crew gathered up a circle of rocks to surround their campfire. The rocks caught fire. They were not coal; the heat from the campfire caused thermal cracking to produce oil, and it was the oil that was burning. The rock unit, the source rock, was eventually named the Green River Formation. After the formation was deposited, mountain ranges arose that broke the original lake basin into several pieces. The Wyoming portion is the Green River Basin, in Utah it is the Uinta Basin, and in Colorado it is the Piceance Basin. ("Piceance" is a local name, made to look French again by early map makers. The word is pronounced "piss ants.") In the western Uinta Basin, some of the source rocks have been buried into the oil window; two midsize oil fields produce oil whose source is the Green River Formation.



In the Athabaska tar sands of Alberta, huge trucks are used to haul tar-impregnated sand from open-pit mines to the processing plant. Economies of scale are very important in making a previously marginally profitable activity profitable. © Jonathan Blair/CORBIS.



The Green River “oil shale” is an oil source rock deposited in a nonmarine lake. The bottom water of the lake was depleted in oxygen, organic matter was preserved, and there were no bottom-dwelling animals to churn up the thin layers of sediment.

The Green River Formation turned out to be unusual in several ways. It was not marine; it was formed in a saline lake. Almost half of the world’s supply of sodium carbonate is mined from the Green River Formation.<sup>13</sup> Unique minerals occur in the Green River Formation. Spectacular fossils occur because no scavengers could live on the oxygen-free lake bottom. And, for our purposes, the oil that could be released from the Green River oil shale is roughly equal to all the world’s conventional oil.

When I was an undergraduate, crude oil sold for \$2.50 per barrel, and everyone expected that if oil got to \$5.00 per barrel, oil shale would come on the market and put conventional oil fields out of business. However, each time the price of oil increased, the imaginary oil shale price was always about \$3 per barrel above the current price. I’ve been waiting for 50 years; what’s wrong? Several pilot plants have operated, mostly in western Colorado. The rock has to be mined, crushed, and heated in closed containers. The leftovers after the oil is recovered fluff up to more than their original volume; the hole where the rock was mined isn’t big enough to hold the waste. Several variations of the theme were developed, but none of them seemed economic at \$25 per barrel. Research continues.

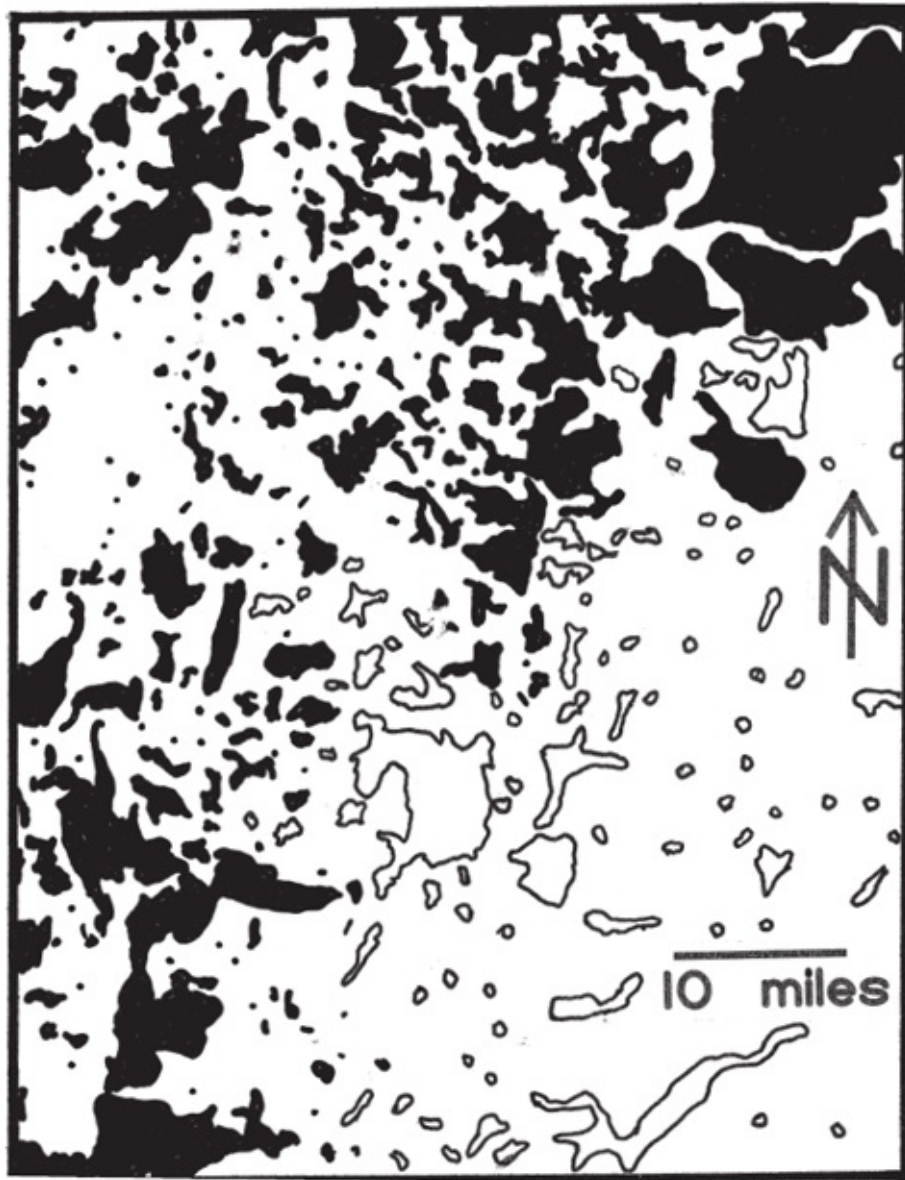
Up until 1953, natural gas sold for less than 10 cents per 1,000 cubic feet. One barrel of oil has the same energy content as 6,000 cubic feet of gas. In 1953, oil sold for \$2.70 per barrel; 6,000 cubic feet of gas cost 60 cents. If you were a consumer, natural gas was a bargain. If you were drilling for oil, gas was a nuisance. Gradually, the school of hard knocks identified areas that produced oil and natural gas as places to stay away from. Usually, these were areas that had been buried beneath the ocean window at some time in their history. Natural gas prices went above \$2 in 1981. Blow the dust off the old maps; there’s a new ball game in town! Places that were now too deep, or had once been too deep, were ripe for drilling. In contrast to oil, future supplies of natural gas can be expanded by additional exploration and deeper wells.<sup>14</sup>

Natural gas has some advantages over the other fossil fuels. Of the fossil fuels, natural gas adds the smallest amount of carbon to the atmosphere. In natural gas there are four hydrogen atoms for each carbon; gasoline and diesel fuel average two hydrogen atoms per carbon, and coal can be almost

pure carbon. When burned, hydrogen produces water, which for the moment has not been listed as a harmful substance. Sulfur removal from natural gas is cheaper and more complete than sulfur removal from oil or coal. As a fuel for house heating and for power generation, natural gas causes the least environmental damage of the fossil fuels. Not zero damage, the *least* damage.

The big advantage of gasoline is portability; the gasoline tank does not occupy much space or weight in an automobile. A tank of gasoline will take the car 300 to 400 miles. The only way to make natural gas portable is to compress it to high pressure in thick-walled tanks. Even at high pressure, a car with half the trunk filled with natural gas tanks will travel only 150 miles between fuel stops. Commuters, school buses, and construction vehicles typically travel much less than 150 miles per day.

The eye opener is this: natural gas costs 57 cents for the equivalent of a gallon of gasoline. That's based on the retail price of natural gas delivered recently to my basement for the furnace, stove, and hot water heater. At a meeting on natural gas, one of the exhibits was a compressor previously used to fill scuba divers' air tanks, modified to compress natural gas. We all crowded around that exhibit fantasizing about driving around on cheap fuel. The government hasn't figured out how to tax natural gas as a motor fuel, which made the fantasy even sweeter. In Italy and New Zealand, roadside natural gas filling stations have been around for 20 years.



Sometimes on an oil and gas map, it is possible to locate the former base of the oil window at the line where oil and gas production changes to all gas. On this map of a portion of southeastern Oklahoma

oil fields are shown in solid black, and natural gas fields are outlined.

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High-pressure tanks being installed to convert a conventional pickup truck to run on compressed natural gas. A typical configuration consists of two tanks at the front of the pickup bed. Additional tanks are in the background. © Sergio Dorantes/CORBIS.

Of course, I wondered about safety. What happens if I have my trunk half filled with compressed natural gas tanks and I am in a rear-end collision? I was told that the gas tanks are so strong that the car will crumple around the gas tanks like so much aluminum foil. Also, a gas flame burns upward. The ghastly hazard with gasoline is the fuel pouring down on the ground, then burning upward on the people.

Except for the portability problem, natural gas is a wonderful automotive fuel. The efficiency of an ordinary automobile engine increases with the compression ratio: how much the fuel-air mixture can be compressed before the spark plug initiates burning. However, burning can begin spontaneously and prematurely (called “pinging”) if chemical bonds between carbon atoms in the fuel start to break. The compression ratio that a fuel will tolerate is the “octane” number displayed on a filling station pump. The scale is based on two standard molecules: isooctane taken as 100 on the scale and heptane taken as 0. Regular gasoline is about 85 octane, premium gasoline is 90 octane, and top grades of aviation gasoline are 100 octane. Natural gas is 135 octane. An automotive engine designed from the beginning to run on natural gas can have a high compression ratio and a high efficiency. Of course, we all respond to our gut feelings more than to numerical arguments: in the hotel lobby at a petroleum engineers meeting a year ago was a full-size, mean-looking drag racer that ran on natural gas.

Diesel engines avoid the pinging problem by compressing only air, then squirting in the fuel to initiate burning. There are hybrid diesels that compress a mixture of natural gas and air and then squirt in a little diesel fuel to act as a spark plug. I thought the hybrid diesel was a really clever new idea. I was told that the hybrid diesel was patented by Rudolph Diesel.

As of 1965, there were two last hopes for finding an oil province that might rival the Middle East.

Those two were western Siberia and the South China Sea. As pointed out earlier, we don't yet know about the South China Sea. Western Siberia turned out to contain entirely natural gas, almost no oil. One-third of all the world's known natural gas reserves are in western Siberia.<sup>15</sup> The Russians could market some of that gas in Europe, but a lot of clarification of the Russian economic and political situation is required before the resource is fully utilized. As with oil from Iraq and Iran, interruptions of exploitation now may preserve a portion of the resource for future generations.

Coal is the worst possible fossil fuel. Most of the fuel value comes from carbon, with the carbon dioxide added to the atmosphere. Sulfur and mercury are difficult to remove from coal; they are released to the air in ordinary burning. However, the world has at least a 300-year supply of coal. The United States and the former Soviet Union have the largest reserves of coal; the third world has comparatively little coal. That didn't seem fair, but I realized that the two largest industrial economies were originally built on coal.

China is going to be a particular problem with regard to coal burning. China has extensive coal deposits and more than a billion people. I heard a talk presented at a geology meeting that illustrated how difficult the problem can be. In one area in China there are local coal beds, but the coal contains significant amounts of arsenic. The coal is burned on raised, but open, platforms inside the homes. Slides projected at geology meetings are usually quite pleasant: interesting rocks, beautiful mountains. But the talk on arsenic-bearing coal was illustrated with horrible pictures of lesions on people's hands and feet from arsenic poisoning. The government had tried to sell the people stoves with chimneys to get the arsenic out of the house. The stoves were rejected, in part because the open fire did a better job of drying vegetables hung from the rafters. I have a suggestion that has only a slight chance of working. Often arsenic mineralization is associated with gold. If there is a decent trace of gold in that coal, I could give them the stoves and pay them for the coal ash. They avoid the arsenic poisoning and I get to keep the gold.

Our political discussions often become debates about the wrong topic. Sometimes, a subsidiary issue is a proxy for a deeper concern:

- Preserving ANWR, not because we love caribou but because we don't want the oil companies to get rich from our public lands.
- Opposing disposal plans for radioactive wastes because of our fears of nuclear power plants.

Discussions about increasing the supply of crude oil get sidetracked into debates about whether government action is needed or whether the invisible hand of economics will guide us to bigger and better oil fields. We can argue endlessly about the details without asking first whether searching for additional crude oil would be worth the effort.

When my parents retired to a farm in Oklahoma, they hired a bulldozer and built a pond. Stocked it with bass. Good fishing, good eating. Gradually, however, they began catching fewer bass, and catching enough for dinner required longer and longer hours. There are two possible reactions:

- Buy ever more expensive fishing tackle, because there might be a great lunker of a bass still hiding deep in the pond.
- Substitute fish from the grocery store and take up something other than fishing for a hobby.

The finite supply of world oil is, in my opinion, written in stone. It's not engraved on the facade of the

Treasury Building. It's written in the reservoir rocks, in the source rocks, and in the cap rocks. No amount of fancy fishing tackle is going to satisfy our appetite for oil.

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## *Alternative Energy Sources*

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There are plenty of energy sources other than fossil fuels. Running out of energy in the long run is not the problem. The bind comes during the next 10 years: getting over our dependence on crude oil. This chapter begins by discussing two nonrenewable energy sources, followed by the renewable resources.

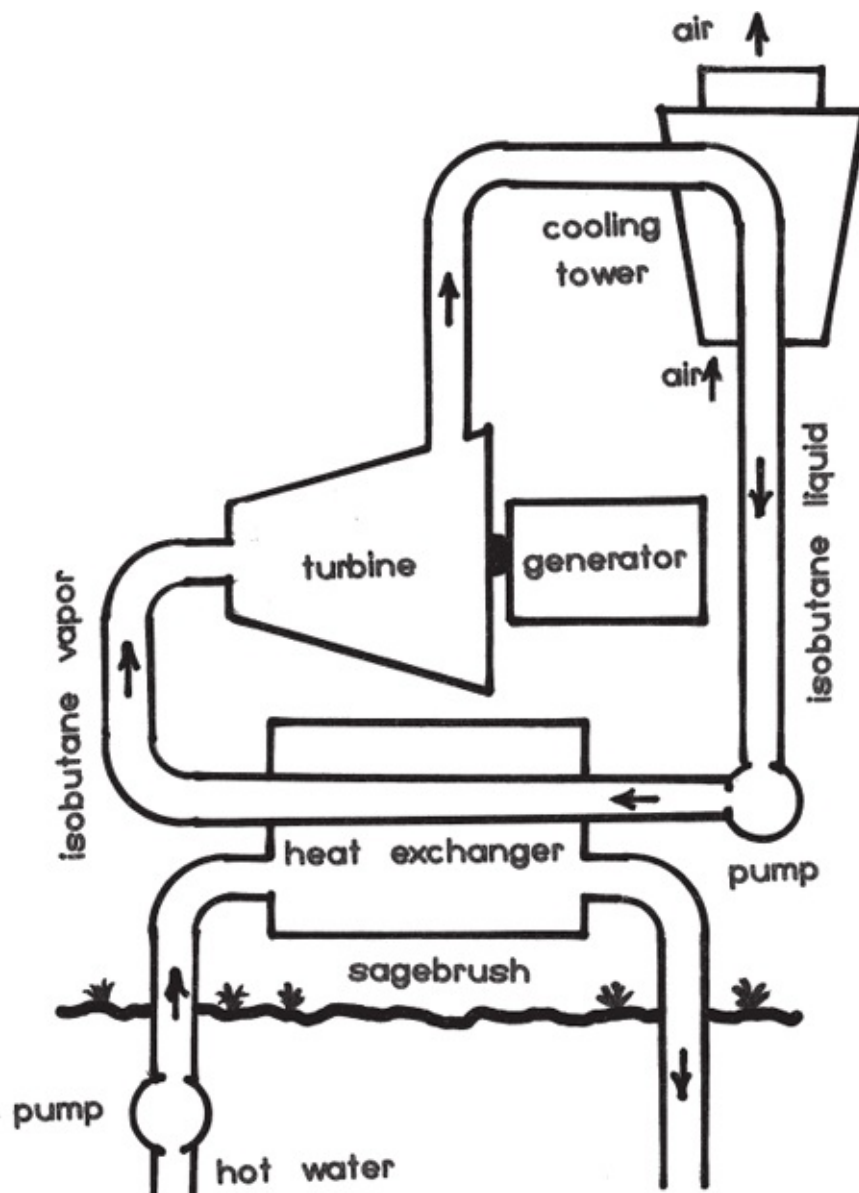
“Geothermal” energy is just what its name implies, heat recovered from within the Earth’s crust. Just as with oil fields, there are a few high-grade geothermal areas, a larger number in the middle, and an extensive low-grade heat sources that may not be economic in this century. Before 1960, three high-grade geothermal fields were generating electric power: Lardarello, Italy; the Geysers, north of San Francisco; and Wairakei, New Zealand (pronounced wy-RACK-ie). Each area was originally identified from hot springs at the surface, and ordinary oil-well-drilling technology was used to exploit the resource.<sup>1</sup> The water from these three areas was hot enough to boil, giving an impressive yield of steam. Passing the steam through turbines generated electrical power; the steam was condensed back to water on the downstream side of the turbine to increase the energy yield. The Geysers geothermal field produces about half of the electricity used by the city of San Francisco.

There are some additional high-temperature geothermal fields, but none of them seems to be as attractive as the first three. However, stepping down in both temperature and size opens up a large number of geothermal fields. Even though the water temperature in these lesser deposits is hot enough to boil, letting 10 percent of the water convert to steam cools the rest of the water down below the boiling temperature. Also, boiling extracts a price: dissolved minerals come out of the water and clog up the equipment. The older high-temperature deposits put up with the problem; Lardarello even sold boron chemicals as a by-product.<sup>2</sup> For a leaner deposit, the cost of the labor and downtime for cleaning the pipes is unacceptable.



A geothermal area about 80 miles north of San Francisco, called the Geysers, generates enough electricity to supply about half of the city of San Francisco. © Bob Rowan; Progressive Image/CORBIS.

A clever process for recovering geothermal energy without the consequences of boiling became commercial during the 1980s. Hot water from geothermal wells was used to boil an organic liquid, but the water itself was returned back to the ground without being allowed to boil. The organic vapor goes through turbines to generate electricity, and the vapor is condensed back to liquid and circulated to contact more hot water. These are called “binary” geothermal plants because both water and a low-boiling liquid are used.



A binary geothermal plant uses hot water from the ground to boil an organic liquid. The water is returned to the ground, and the organic vapor goes through a turbine to generate electricity.

The beauty of a binary geothermal plant is zero emissions to the atmosphere and returning the water to the ground. You don't need an Environmental Protection Agency permit to pump arsenic, mercury, and antimony back into the ground if you just took the water out of an adjacent hole. The binary process opens a range of geothermal opportunities that would not otherwise be economic. Since the late 1980s, I have been taking 20 first-year students during fall break to study geology around Mammoth Lakes, California. One stop on the trip is at an elegantly designed and profitable binary geothermal plant. Hot water from wells drilled into a welded tuff (with connected pores) is used to boil isobutane, which boils at 11°F. One of my students asked the plant engineer what would happen if one of the geothermal wells got out of control. He said that he would call a company named Halliburton. Right! Call Duncan, Oklahoma. The engineer also pointed out that the plant, over its lifetime, would replace 3 million barrels of imported oil. After he left, I had to tell the students that the United States was importing 6 million barrels of oil a *day*. That plant solves the U.S. energy problem for one half of one day.

Drilling for geothermal energy utilizes the same equipment and skills that were developed for the oil industry. It comes as no surprise that oil companies looked at geothermal resources as an extension

of their existing activities. There are rumors that at least one major oil company is holding leases on U.S. geothermal areas as a way of extending its business into an era of energy shortage.

Everywhere, the temperature in the Earth's crust increases with depth; that observation underlies the oil-window paradigm. In a sense, there is geothermal energy everywhere. The U.S. Department of Energy sponsored one test to get energy out of hot dry rock.<sup>3</sup> At the edge of a major volcanic area west of Los Alamos, two vertical holes were drilled, and oil field hydrofrac equipment was used to open a fracture between the two holes. Cold water was pumped down one hole, heated by the rock, and hot water came up the other hole. When I was taken on a group tour to see this operation, someone in the audience asked whether the hot water coming up carried more energy than the pumps consumed. The tour guide didn't know which was larger, but he gave the pump pressure in pounds per square inch, the flow rate in gallons per minute, and the temperatures in degrees. A geophysicist, whose work I greatly admired, turned around and started mumbling; he was trying to work the problem in his head. Game time! Could I beat him to the answer? I had recently done some similar calculations for another purpose. We finished at almost the same time. (I like to think that I was one second ahead.) The hot water would not produce enough energy to run the pumps.

Drilling for geothermal energy has its unpleasant surprises. The federal government and the state of California jointly sponsored a geothermal test right in the center of the Mammoth Lakes–Long Valley volcanic area. Nearby volcanoes are only 400 years old. A drilling rig was brought in. Whenever I took my students to see it, I described the rig as “medium large.” In truth, that particular rig held the American depth record: drilled beyond 30,000 feet in the Anadarko Basin of Oklahoma. The Mammoth Lakes “geothermal” hole got down to 12,000 feet, and the drillers were not even touching volcanic rocks. They were drilling cold dry rock typical of the adjacent Sierra Nevada. A year ago the rig was cut up and sold for scrap iron.

Today, nuclear energy is about as unfashionable as the hoop skirt. The incidents at Three Mile Island and Chernobyl converted a widespread uneasy feeling into an almost universal fear of nuclear power plants. On other side of the nuclear argument: no carbon dioxide emission to the atmosphere and a 100-year supply of uranium. It's going to be a gut-wrenching debate. Are painfully high electric bills the cure for nuclear phobia?

No press agent would have advertised nuclear power by blowing away Hiroshima and Nagasaki. It could have happened another way. In 1972, the French found that uranium from the Oklo Mine in Gabon was missing most of its fissionable uranium 235. After some investigation, they established that a natural nuclear fission reaction had occurred.<sup>4</sup> In effect, a billion years ago in nature there were six (count them, six) water-moderated, enriched-uranium nuclear reactors. All natural ingredients. The “enriched” uranium existed because a billion years ago less of the uranium 235 had decayed. Suppose the natural reactors at Oklo had been discovered in 1935 instead of 1972. Wow! A wonderful gift from nature. Best thing since Prometheus discovered fire. The nuclear age would have opened with a whimper instead of a bang.

Earlier, I mentioned the grip that the internal combustion engine has on the automobile and the rotary drilling rig has on the oil business. Similarly, the enriched-uranium, water-moderated nuclear reactor dominates the market for nuclear power plants. Actually, the standard commercial nuclear power reactors are derived from the U.S. Navy nuclear submarine reactors. However, there are about a dozen fundamentally different designs for nuclear reactors.<sup>5</sup> I once heard Eugene Wigner lecture on reactor designs. During World War II, Wigner designed the reactors at Hanford; later he won the Nobel Prize for bringing group theory into physics. Back when new power reactors were being built, the Canadians built and operated several reactors that used natural uranium and “heavy water” (deuterium) as the moderator that slowed down the neutrons. The Canadian deuterium reactors were

by the overly clever name of CANDU. The CANDU reactors had an outstanding track record for reliability. I suspect that if we sat down today to reinvent the nuclear power industry, we might not choose the standard American design.

Reactors have two options for their used uranium. The spent fuel elements can be disposed of in their entirety as radioactive waste. Or the used uranium can be “reprocessed” to recover unburned uranium and to recover plutonium. Plutonium is evil stuff. Besides being exceedingly toxic, plutonium can be used as the core of a nuclear bomb. Ted Taylor, who was the leading American designer of nuclear weapons, left Los Alamos to campaign against nuclear proliferation because he felt that it was entirely too easy to build an effective nuclear bomb out of stolen plutonium. There is a continuing debate about whether you need a large staff of whizzbang scientists to build a nuclear weapon or whether you could build one in your garage. No question that Ted Taylor could build one in his garage.

Despite the scary aspect, some spent fuel from commercial power reactors has been reprocessed and the plutonium recycled for additional reactor fuel. A dilemma over reprocessing arose for the Australians around 1980. Huge uranium deposits had just been discovered in northern Australia; the Jabilinka deposit by itself contained more uranium than the United States had mined since 1940.<sup>6</sup> The Australians preferred not to encourage worldwide growth of nuclear power plants. But as the specter of reprocessing and commercial plutonium shipments arose, the Australians switched their position. Australian uranium is cheap enough, nobody will want to reprocess spent fuel.

Very likely the safety problems and the radioactive waste problems could be handled adequately if our society were willing to make the appropriate investments. Maybe the hoop skirt will come back. The emotional problem remains. There is one possible psychological boost. The United States has been converting surplus weapons-grade uranium and plutonium, some of it purchased from the Russians, into reactor fuel. Would getting rid of nuclear weapons be an incentive for accepting nuclear power plants? “They shall beat their swords into plowshares and their spears into pruning hooks. They shall burn their warheads to warm their toilet seats.” OK, OK, so Ecclesiastes was a better writer than I am; it’s the thought that counts.

It is difficult to store electrical power. There are a few facilities that use electricity to pump water uphill to a reservoir at times of low demand and generate power when needed by running the water back down. Only a few sites are suitable for pumped storage; most electric power is generated at the time it is needed. Typically, nuclear power plants carry the base load, the minimum power demand that exists all the time. At the intermediate level, hydroelectric and fossil-fuel steam-generating plants carry the normal increase. For the few peak hours, a hot summer afternoon with all the air conditioners running, the preferred power source requires a low capital cost but can tolerate a high fuel cost. A gas turbine, similar to a jet aircraft engine, powered by oil or natural gas is a typical peak load power generator. Some of the renewable electric sources, like solar and wind power, have their own built-in schedules; the difficulty of storing power is a serious problem.

Hydroelectric power has a number of attractions. It is renewable, you can turn it on when it is needed, and it does not pollute the atmosphere. Enthusiasm for hydropower was enormous during the first half of the twentieth century. Wild rivers, salmon runs, and the glens of Glen Canyon were sacrificed in exchange for cheap electric power. Of course, mountainous areas have the greatest hydroelectric opportunities. Hydroelectric power is the leading export of Kyrgyzstan; most of the country consists of the Tien Shan mountain range. Locally generated hydropower supplies electricity in remote Himalayan valleys. Aluminum ore is hauled halfway around the world to get to cheap hydroelectric power at Kitimat, British Columbia.<sup>7</sup> Right now, there is a growing enthusiasm for tearing down dams, instead of building more. In mountainous areas with high rainfall, new

hydroelectric facilities might be acceptable, but the total of all the remaining hydroelectric opportunities will make only a modest dent in the need for electricity.

Solar and wind power participate in what I call the energy-material paradox. If materials were cheap, I could build large energy collectors. If energy were cheap, I could produce large amounts of raw materials. If neither materials nor energy is cheap, I have a problem. At the moment, solar and wind power are developing in specialized areas. Neither is an immediate, large-scale solution to the energy problem.

The power per square foot in the sunshine is essentially identical to the power per square foot of the wind. At first, I thought that this was just an accident, but solar energy may crank up the wind velocity until the average energy density in the wind equals the average solar energy density. Wind and sun don't appear together at the same place or the same time. As an example: wind often is stronger at a gap in the mountains. At the southern end of the Sierra Nevada, there is a huge array of windmills. They don't look like Dutch windmills, or like my grandmother's daisy wheel; they are slender, three-bladed propellers on tall stands.

The low energy density in solar and wind power requires large energy collectors. A normal-size nuclear or fossil-fuel power plant generates 1,000 megawatts. At typical efficiencies around 1 percent, a solar or wind collector has to occupy five square miles to deliver 1,000 megawatts. I can direct you to any of several Nevada basins where you can get the five square miles; your problem is the capital cost of paving five square miles with solar collectors.

During the 1980 energy crisis, a variety of different ways were considered for converting solar energy to electric power. The two major approaches were:



The engineering design for generating electricity from windmills is not as simple as it might sound. After the engineering problems were solved, large arrays of windmills could be built by replicating a single design. © Bob Rowan; Progressive Image/CORBIS.

1 Trap solar heat and use the heat to generate electricity. For instance, boil a liquid with solar heat and run the vapor through a turbine. High efficiency requires a large temperature difference.

between the solar-heated source and the air or water where the waste heat is dumped.

~~2 Direct generation of electricity, typically by using semiconductor solar cells. In 1980, the efficiency of solar cells was about 6 percent; today's cells are about 13 percent efficient.~~

The materials for solar and wind collectors are not scarce. Silicon (for solar cells) and aluminum (for windmills) are the second and third most abundant elements in the Earth's crust. However, producing either silicon or aluminum from their ores requires lots of energy. It's the energy-material dilemma that was mentioned earlier.

During the 1980 oil crisis, exotic energy schemes popped up like dandelions in my lawn. Examples are (1) solar cells in Earth orbit, sending down solar power by microwave, and (2) exploiting the temperature difference between warm surface seawater and cold deep sea-water. None of the schemes are to be ignored, but the inventor usually wants to see an immediate full-scale implementation of the idea. It takes real judgment to sort the sheep from the goats. It is all too easy to say, "It won't work." Rather than make decisions in a closed committee, we need an open competition to propose detailed implementations of each concept, followed by another competition to look for serious flaws in the designs.

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