CNA

Working Paper

Version 1.1 11 June 2001

Oil as a Strategic Factor

The supply of oil in the first half of the 21st century, and its strategic implications for the U.S. [1]

William D. O'Neil
analysis.williamdoneil.com

Oil—liquid hydrocarbons derived from natural petroleum—has long been a commodity of great importance. It is so fundamental, indeed, as to be truly *strategic,* affecting the relationships among nations to a major extent. Several of the great conflicts of the 20th century were shaped in large measure by issues of oil supply.

In this paper I ask how natural and economic factors will affect the supply of oil in the first half of the 21st century and examine likely strategic effects.[2]

---

[1] This is a product of The CNA Corporation, a not-for-profit research and analysis organization. The opinions expressed are those of the individual author and do not necessarily represent those of CNA as a whole.

[2] To conserve space and avoid tedious repetition, citations have not been provided where material is from standard sources, except in a few special cases. The standard sources employed have chiefly been [AccessScience] and [EB]. An effort has been made to cite readily accessible sources where possible. Where a still-current review source is cited that provides references to more detailed studies, I have not repeated these even when the individual studies have been consulted, except as needed to document a critical specific assertion. In some cases where somewhat obscure sources have been cited, I am in a position to provide a copy for study and reference.

I want to express particular appreciation for the advice and assistance provided by Tom Ahlbrandt of the Department of the Interior, U.S. Geological Survey, World Energy Assessment Team, and by Gary Long and David Morehouse of the Department of Energy, Energy Information Administration. I have responsibility for the interpretation and presentation of their data, however, and for any errors thus introduced.

While the paper may seem very lengthy, the main text in fact ends on page 20. The rest is appendices offering supporting and amplifying information and explanation. Cross-references are provided to make it easy to find the background for any issue of interest.

Note: two ways to read this paper

This paper has been formatted for ease in reading either as an ordinary printed document or as an on-screen document. Reading it on line offers some significant advantages, by making cross-referencing easier. For hints on how to read it most easily on screen, look at Appendix H, page 137. (If you're already looking at this on screen in Adobe Acrobat Reader (or Adobe Acrobat), click in the blue box around the number "137" in order to jump right to the appendix.)

Summary

I conclude that oil could well present one of the great strategic challenges of the 21st century, for the U.S. and for the world as a whole. The challenge is likely to unfold fairly slowly for a while. Oil should remain in good supply at reasonable prices for several decades. Like any commodity, its price will be subject to swings—sometimes sharp swings—resulting from short-term imbalances between demand and supply, but difficulties in supply from one source can be made good, with a little investment and some lapse of time, from any of a number of others.

There will be some development of alternatives to oil as a source of fuels as well as of means to conserve oil resources. There are many possibilities, some of which already are being exploited in small ways, and growth seems assured. But all are costly relative to oil today, and few show clear potential for competitiveness at current oil prices, even over the very long term. Thus the impetus for their development will remain limited as long as oil is relatively plentiful, barring some government action to tilt the scales. In the meantime, oil consumption will continue to grow—currently at a rate a bit less than 2% per year, worldwide.

But while oil will indeed remain plentiful for several decades to come, it is likely that the distribution of its sources will change, and very possible that they will become much more concentrated in the region that is richest in oil: the area around the Persian Gulf. Today, this region supplies less than 30% of the world's oil production, but this could climb to 50% or more within two to three decades. Iraq and Iran, which have large reservoirs of oil that are being produced at relatively low rates today, are likely to become particularly prominent producers in the future.

Scientists have made estimates of how much oil may lie within the Earth. There is a broad band of uncertainty. But whatever the ultimate amount may be, by the time the world's "oil gauge" gets down to somewhere in the vicinity of the 20% mark, geological and technical factors will act to make it a great deal more expen-

sive to expand production markedly. The world will be like the United States is today: oil will continue to be produced, but at a rate that falls off steadily despite ongoing and even accelerated drilling and development. Oil prices will rise as it becomes more expensive to find and produce more, and this will in turn stimulate more efforts to find and produce oil. But it seems most likely that sharply diminishing returns will limit the effect of these, so that production will nevertheless drop off, perhaps quite sharply.

It also seems likely that prices will rise not in a smooth and continuous curve but in a series of sharp shocks.

The world won't go dark. Eventually, other sources of fuels will be brought on line to replace the reduction in oil production, albeit at significantly higher cost. And ways will be found to get along with less fuel use. But this is unlikely to be a smooth or immediate process. The remaining major producers of crude oil will retain a great deal of market power for a long time after the peak of oil production is passed, because their costs will remain much lower than those for alternatives.

None of this is certain. Many things will happen over the coming decades and many of them will be unexpected, or prove to have implications and consequences we cannot now foresee. But there is at very least a significant risk that a crisis in oil supply will be reached before the midway point of the 21st century, and that it will be accompanied by a further heightening of the strategic tensions and dangers focused on the Persian Gulf region. The U.S. should take measures both to ameliorate these tensions and to prepare to respond to the dangers.

The rise of oil[3]

Petroleum has been known and used by humankind for thousands of years, but large-scale commercial development dates from the mid 19th century. The era of oil is conventionally taken to have begun with the completion of a well in northwestern Pennsylvania by Edwin Drake in August of 1859. Drake's enterprise led to history's first oil rush and establishment of an industry.

The initial markets were primarily for lamp oil, displacing the better and safer but expensive whale oil. This was a strong market by the standards of the day and production volumes grew rapidly into the tens of millions of barrels annually.[4] Commercial production soon began at similar scale in southern Russia and Indonesia.

---

[3] The material of this section is drawn principally from [API 1999], [BP 2000], [EIA 1999], [EIA 2000a], [WTRG 2000] and [Yergin 1991]. For the period since 1965 or so, however, I have relied mainly on [Adelman 1995].

[4] The "barrel" (abbreviated *bbl)* is the conventional unit for measuring oil volume, equal to 42 U.S. gallons, equivalent to about 159 liters. The density of oil varies, but on average a barrel of crude oil weighs about 300 lbs or 136 kg. A deadweight ton (a common measure of tanker capacity equivalent to 2,240 lb) will contain roughly 7.5 bbl.

Gas and then electricity began to take over oil's illumination market toward the end of the century, but the development of the internal combustion engine and its application to automobiles brought a major new market and transformed the industry.[5] In the U.S., at the center of the automobile revolution, crude production climbed steeply to about the 100 million bbl/yr mark by 1903 and kept on going. Production topped 1 billion bbl/yr (gbbl/yr) in 1929, fell back in the Great Depression, and then surged up again over 1 gbbl/yr from 1936 onward. Domestic production peaked at 3.5 gbbl/yr in 1970, and now has declined to about 2.2 gbbl/yr. World production now is more than ten times as great.

Before the 20th century, the coal-fired steamship and steam locomotive were the only significant mechanical transport vehicles. But the automobile, truck, and aircraft quickly became huge consumers of oil products, and even ships and many locomotives soon came to be fueled with oil. Oil became essential for a modern economy—and for modern war.

Even though oil was found in many areas, the U.S. remained the dominant force the industry through the early 1950s. None of the Axis powers in World War II enjoyed good access to oil and this exerted a major influence on their strategy and some of their decisions for war in the first place. The Allies, by contrast, enjoyed significant advantages as a result of good supply.

While it had long been recognized that there were large deposits of oil in the region around the upper Persian Gulf, difficult geography, lack of local infrastructure, and refining challenges associated with the oil's relatively high sulfur content delayed full appreciation of the potential. But following World War II, more intensive exploration established this region as the most richly endowed in all the world. Because of the size and concentration of oil deposits, production costs were very low even after taking account of the need to build a great deal of infrastructure. U.S. and European oil firms invested in Persian Gulf oil, gaining *concessions* from local rulers that gave them a free hand in exploration, development, and production in return for fees and a tax on production (and a bit on the side). Long a focus of interest for European powers, the Gulf started to assume importance for American policy-makers.

By 1951, oil had overtaken coal as the dominant fuel in the U.S., and only a few years later natural gas also surpassed coal in importance. While U.S. oil production continued to climb, by the 1960s the nation had become a net importer of oil for the first time. In 1960, OPEC (Organization of Petroleum Exporting Countries) was formed. U.S. imports remained small relative to its total consumption throughout the 1960s, although they increased incrementally.

In 1930, at the start of the Great Depression, vast new fields were discovered in East Texas. It was the largest discovery ever made in the lower 48 states, and one of

[5] In most cases, 19th century gas lighting used *producer gas* or *town gas,* made from coal by treating it with steam, rather than natural gas.

the largest in the world. The nature of the reservoirs made production very cheap. Coming on line at the start of a period of unprecedented economic decline, the East Texas fields raised a spectre of "overproduction" and "glut" that could cause market chaos. This brought an intensification of a trend toward market structures that would in effect make the oil world safe for producers and guarantee that all owners of oil properties got a share of the market—at the expense of consumers. Because the price of oil remained low enough to make it a fairly minor item in most user's budgets, this did not evoke sharp opposition.

For decades, the price of oil was set, in effect, by the Texas Railroad Commission, in its role as regulator of the oil industry in the largest producing State. Everywhere the price of crude was the price at Texas ports, plus shipping (with adjustment for quality)—even if the oil had come from someplace much closer than Texas. Following World War II, competition gradually crept into the market, forcing downward pressure on prices, measured in real terms (exclusive of inflation).

Even at the lower (real) price, oil remained an exceptionally profitable business, with a large margin between costs and prices. There were risks, but those who accepted them generally were handsomely compensated. In 1970, the U.S. produced nearly 10 mbbl/day. But production from older wells was declining at about 10% per year while demand was growing at rates of 5% per year or more. No huge new fields had been discovered in decades—the 1930s had been the peak decade for U.S. discoveries. To raise U.S. production to meet demand would require greatly accelerated drilling in order to tap numerous smaller pools, thus increasing costs. It was much more attractive to import oil from the Middle East and Venezuela, where costs were a great deal lower. After 1970, U.S. domestic production began to fall off. (Even the large Alaskan fields which entered production in the mid 1970s only slowed the decline.) A widening gap between growing demand and declining domestic production was filled by imports.

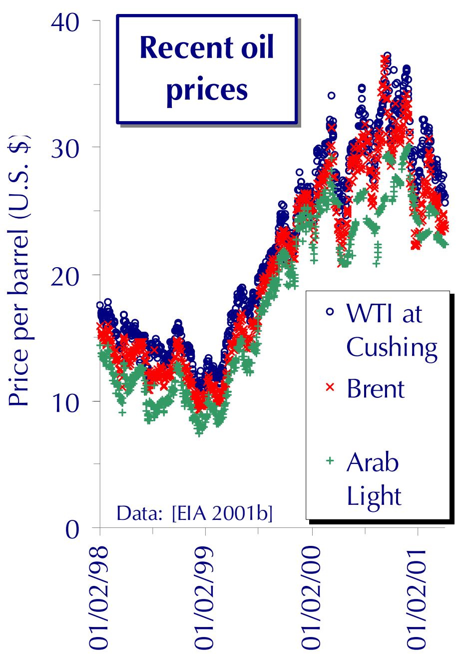
The OPEC nations had economic and political situations that were very different from those of the U.S. Their economies were small with little diversification, and their political systems were generally weakly legitimized and lacking in mechanisms for orderly and nonviolent change. Saudi Arabia was the dominant OPEC member because its oil reserves were much the largest; its economy was notably primitive and its government was controlled by a narrow family elite. They could afford to pursue extreme oil-centered policies that would be out of the question for a nation with broad economic and political interests.

By 1973 dominance of oil and oil pricing had passed from U.S. hands. With U.S. import demand increasing sharply, OPEC's market share rose. The organization had not originally been intended to function as a cartel but now became one, with the leverage to raise prices. Political turmoil in the Mid East led to a supposed "embargo" on oil shipments to the U.S. by Arab nations in 1973 and a 50% increase in prices.[6] Major OPEC nations ended the concessions that had been granted to Western oil firms and took control of their own oil industries. Believing that users could not cut back consumption, they sought to raise prices to levels just short of the cost of hydrocarbons from sources such as coal, tar sands, and oil shales.

Then, in 1978, the Iranian revolution set off a train of events that allowed OPEC to raise prices to more than $70/bbl in today's prices—more than ten times what they had been before the embargo in 1973. To many people, it seemed as if OPEC could not lose: the less they produced the higher they could boost prices and the more they made.

But high prices gave users incentives to conserve. They invested in more efficient, less energy-consuming buildings and equipment, and substituted other goods and services for oil in their budgets. After a lag of several years the demand for oil slowed, then backed off. Prices slid, then plunged. By the end of the 1980s they had settled below $25/bbl.

Figure 1: 1999-2000 oil price rise



High oil prices also gave non-OPEC producers incentives to produce, and non-producers incentives to join the ranks of oil-lords. Many marginal fields that could not profitably be produced at the $5/bbl prices (in 2000 dollars) of the late 60s and early 70s were very attractive propositions at $30/bbl, let alone $70. This took quite a long time to take effect, however (in part because of perverse incentives resulting from government policies in the U.S. and elsewhere). As a result, the main effects of increased non-OPEC production were not felt until the 1980s, after the price decline was well underway.

In the Persian Gulf, most fields could be produced at costs (including generous return on investment) of substantially less than $5/bbl, leaving an enormous margin of profit for the producing countries. But in the 1970s their appetite had grown with the eating and they found it very difficult to live with profit margins that were "only" 200% to 300% above fully-allocated cost. OPEC negotiated to try to persuade members to curtail production and so raise prices. Saddam Hussein decided on more direct means, leading to wars with Iran, Kuwait—and thereby with a vast U.S.-led coalition.

[6] The embargo was a threat never carried into effective practice—and in practice was entirely hollow—but fear of it created memorable havoc, especially because it combined with anti-competitive domestic market regulation in the U.S. and elsewhere that impeded market solutions..

Through the 1990s, prices drifted downward to little more than $10/bbl—painful for marginal producers. Demand, which had been inhibited by high prices, began to resume its climb (although more slowly than in the 1960s). New technology helped marginal producers find savings, but the price and its downward trend made investment in oil seem less attractive. Exploration and development of new sources slowed. By 1999, the market had tightened enough to give the major OPEC producers the leverage to raise prices again as shown in Figure 1.

Some terminology

I'll try to avoid highly technical terms, but some words can have several meanings, and I want to be clear about how I will use them. There's a more extensive glossary in Appendix G, page 127.

- ***Petroleum.*** The literal meaning from the Latin roots is "rock oil", but *petroleum* has come to be used as a catch-all term for crude oil, natural gas, and some intermediate substances known as natural gas liquids. That's how I'll use it (although some people still use it as a synonym for *crude oil).*
- ***Crude oil.*** I'll shorten this to *oil* where there's little risk of confusion. It means the kinds of petroleum that are liquid under normal conditions.[7]

Price and supply

The price of oil is like the weather: we're all aware of it, if only as it affects how much we pay to fill our car fuel tanks. Most of us don't think of ourselves as living in tornado alley so far as oil prices are concerned—the worst we expect is an occasional squall. Is this realistic? How bad could the "hundred-year storm" be in our neighborhood? Economics is a bit like meteorology in this; it cannot provide confident predictions but can help us understand the processes in ways that outline the possibilities.

As shown in Figure 1, oil prices roughly tripled between the beginning of 1999 and the end of 2000. There was no very dramatic stimulus for this. Oil producers of course wanted to raise prices, but that had been true for more than a decade and a half.

This is not a fluke, nor evidence of defect or outside tampering in the oil market. It is the sort of behavior that markets in commodities often give rise to. For instance, the price of the metal platinum, after remaining in a narrow band for nearly a decade, jumped about 75% in less than 18 months recently [1].[8] Again, there were no dramatic events driving the rise.

---

[7] One ambiguity is the treatment of *condensates* and *natural gas liquids* (NGLs). For the most part, I have included them in statistics quoted. See the glossary.

[8] Where end-notes are used (figures in square brackets) it is only to indicate references, with no comment.

How much could oil prices jump in response to a serious disruption? There is some limit, no doubt, but how great this might be is not clear. Some market experts I've talked to say that 500% in a day would not surprise them, and that 1000% is not out of the question. Prices might return to normal levels very quickly. Or they might not.

The mechanisms and behaviors of oil markets are explored in Appendix A at page 23.

The end of the age of oil: some views

How is this all going to end? Or will it end? Are we in danger of running short of oil, or is there plenty not only for us but for our children and grandchildren?

There is a wide range of strongly-held views on this. I'm going to sketch three positions, which I call the doomster, cornucopian, and incrementalist viewpoints.[9] Those who I call the *doomsters* believe that the end is in sight, that oil supply is destined to get tighter rapidly, starting very soon. I could equally well have called this the *oleo-Malthusian* view.

Cornucopians are impressed with nature's abundance and humankind's ingenuity and resourcefulness in exploiting it. They don't believe that we will ever truly "run out" of oil, and think that any problems arising from exhaustion of the Earth's supplies of conventional liquid petroleum will be minor, transitory, and far in the future.

Incrementalists think we may eventually run short of oil, but not suddenly. They expect that any eventual tightening of supplies will prompt higher prices, which in turn will lead to incremental and orderly development and substitution of other energy sources. They see little reason to believe that this will take place soon—in a few decades, perhaps. Or perhaps later.

In the meantime incrementalists expect that oil should remain easily available at generally moderate prices.

At some point, incrementalists acknowledge, those who earn their livings producing oil may find that it is becoming harder and more expensive to find more oil to produce, regardless of where they look and regardless of how sophisticated the technology for such things may have become. Then (and only then) they expect the real economic value of oil to start to rise.

It will be easy to see that the costs of finding and developing oil are rising, they suppose, and people surely will take this as a signal to look for alternatives. As the price continues upward, other goods will progressively be substituted for oil. As their markets expand, the prices of some of these substitutes will come down, even as that of oil is rising. Eventually, oil will be priced out of all its markets and people

---

[9] I mean these labels to be convenient and evocative, but not prejudicial. None of these views is altogether without merit or reason, as I will show.

will stop producing it. How much oil may be left in the ground at this point is unknowable and unimportant, in the incrementalist view.

In Appendix B, at page 53, I describe and analyze these positions in greater depth.

Who's right?

A substantial majority of people, I've found, plant themselves pretty firmly in one of these camps. Most of those to whom this paper is especially addressed are likely to be incrementalists of one stripe or another. Anyone who is so strongly committed to his or her views that evidence can't sway them might as well stop reading right now, for this paper is going to reach some conclusions that aren't exactly in line with any of them. To show why, I need to introduce more evidence.

The facts of oil and its alternatives

This section very briefly summarizes the conclusions of several weighty appendices. Much of what is said here is controversial to one extent or another and it is important to consult the relevant appendix to see a summary of the various viewpoints and my rationale for how I resolve the issue.

- **Oil is a relic of earlier life.** Oil is mostly composed of hydrocarbons which, according to the best present evidence, were formed from the residues of plant and animal life that lived in bodies of water anywhere from a few thousand to tens of millions of years ago. A sequence of biological and geochemical processes transforms a very small fraction of these residues into liquid oil, and geological processes collect a still smaller fraction in reservoirs which can be reached by drilling. These processes continue to form new oil, but at a rate that is hugely slower than the rate at which we're extracting and using oil. So oil is essentially a limited resource. (Appendix C, page 59)
- **An alternative theory of oil's origin would make little practical difference.** There is an alternative *abiogenic* theory which has it that oil comes from hydrocarbons that were present deep within the Earth when our planet was formed, billions of years ago. There's very little clear evidence for this theory, and even if it were true it would make little practical difference. Abiogenesis would *not* automatically imply that there is a great deal more oil, that it should be easier to find, or that more oil is being created rapidly enough to have any practical effect. (Appendix C, page 61, & Appendix D, page 79)
- **We can't be entirely *certain* how much oil remains and where, but much is known with reasonable certainty.** There are significant unknowns, but less than often thought. There is still scope for companies to make vast fortunes on new discoveries of oil, but it is very unlikely that any new discoveries can be large enough to have much effect on the overall picture of Earth's remaining resources of oil. (Appendix D, page 71)

- **Roughly a quarter of Earth's oil has been consumed; the Persian Gulf region holds about 40% of what's left.** Best current estimates are that, after producing about 900 gbbl to date, there are still around 2,500 gbbl left—although the real number could be significantly higher or lower. Just about 40% of this is thought to lie in the Persian Gulf region, with the remainder concentrated most heavily in the area that formerly fell under the Soviet Union, in North America, and in Central and South America. (Appendix D, page 71)
- **Production falls with time; new reservoirs must be tapped to maintain and expand it.** Once a well is completed and in production, its production potential begins to fall off due to geophysical factors. Only by constant exploration and development efforts can oil production be maintained and increased. (Appendix C, page 64)
- **The superiority of oil fuels.** As fuels, the liquid hydrocarbons of oil are very hard to improve upon. There are no other common substances that make such compact, portable sources of energy. Gaseous hydrocarbons (from natural gas), alcohols, and gaseous hydrogen all have some potential as fuels, but have significant drawbacks relative to oil-based liquid hydrocarbon fuels. Oil fuels will be particularly difficult to replace for aircraft and for military vehicles generally. (Appendix E, page 87)
- **Liquid fuels can be produced from other sources—at greater cost.** Oil isn't the only potential source of liquid hydrocarbon fuels. With chemical processing, they can be made from other hydrocarbon-bearing minerals, including tar sands, coal, or oil shales. But the cost of mining the basic minerals adds to the cost of chemical processing to make these relatively expensive sources. It's also possible to transform alcohols to hydrocarbons, but this tends to be even more expensive. Hydrocarbons from natural gas can be transformed into liquid hydrocarbons, but also at considerable expense in most cases. Because of the expense that would be involved, no one has invested the massive amounts that would be necessary to produce these alternatives in large quantities. And until major investments are made, costs won't come down. (Appendix E, page 92)
- **Methane hydrates offer little help.** There may be vast stores of methane gas—the lightest hydrocarbon compound and chief component of natural gas—trapped in ice-like hydrate crystals beneath the floor of the oceans on the margins of the continental shelves. But the prospects for being able to extract this gas at all are quite uncertain, and the prospects of being able to turn it into liquid fuels at affordable overall cost seem dim at this point. (Appendix E, page 96)
- **Cheap sources of energy would help—when and if.** Alternative liquid fuels would be more affordable if there were cheap sources of energy other than oil and natural gas to aid in making them. This might come from solar energy in various forms. Many of these have real potential, but none is able to compete at the present state of the technology, except in niche applications. Nuclear fis-

sion reactors may make a comeback as energy sources, but are not significantly cheaper than gas-fired electric plants in most places. Thermonuclear fusion may become feasible as an energy source in the distant future, but there's no reason to expect it to be especially cheap. (Appendix E, page 97)

- **"Free energy" isn't.** Hopes have been raised for so-called "free energy" from "new physics"—notably from "cold fusion" or from zero-point vacuum energy. Detailed examination shows that neither offers any real prospects as practical sources of energy. (Appendix E, page 106)
- **Fuel cells may change the game, but not quickly.** Fuel cells have been under development for 160 years and may finally be nearing practicality. Despite various problems, their efficiency of operation may eventually make them as universal as piston gasoline and Diesel engines are today. Depending on how the technology develops, this may make hydrogen, methane, or methanol (wood alcohol) more attractive as fuels than liquid hydrocarbons, at least for many applications. (It is also possible that gasoline will prove to be the preferred fuel for fuel cells, however.) But it is virtually certain that this will be a process of decades, at best. (Appendix E, page 100)
- **Oil and oil users are running harder.** Part of the problem in knocking oil off its pedestal of importance is that it is a moving target. The technologies of finding, producing, and using oil keep improving. Because oil is so dominant, great effort is put into all of these technologies—vastly greater effort than is available to pursue alternatives to oil. (Appendix E, page 81)
- **Global climate change is a real issue, but its effects on oil are hard to predict.** There no longer is much room to doubt that the carbon dioxide and other products of oil burning affect Earth's climate through the *greenhouse effect.* But there is no certainty now about how far this can proceed without significant climate change, nor about how or how much such climate changes might affect humans. Because the costs of global climate change are uncertain and lie mainly in the future, while the benefits of continued oil burning are quite immediate and direct, it is not at all clear whether, when, or to what extent the world will develop a political will to curb oil consumption for the sake of ameliorating climate effects.

The two major points

- ***Oil will not diminish in importance.*** It is true, as often observed, that there are alternatives. But none of the alternatives will be broadly attractive as long as oil is plentiful and inexpensive. Today's prices qualify as inexpensive in this context, and so would significantly higher prices still.
- ***Oil won't run out soon.*** Even though the world is using it at a prodigious rate, there's a lot more left. Economic growth will spur consumption, but improvements in technology will improve the efficiency with which oil can be found,

produced, and used, and this will moderate the rate at which consumption eats into resources.

Oil production past and future

In Appendix C, at page 67, I display and discuss trends in oil production. Briefly, the main points are:

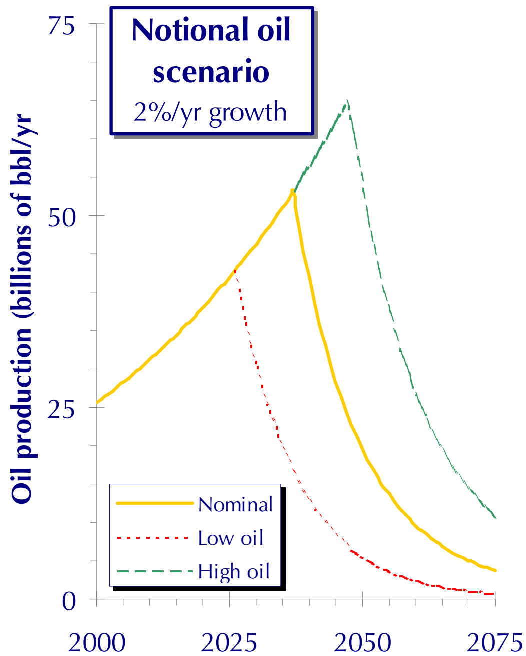
- The U.S. is still a major producer, but our production is on a long-term downward trend that is essentially irreversible. Accelerated exploitation of added resources in Alaska or deep continental shelf waters may temporarily slow the decline, but will not reverse it.
- In many nations, oil production has fluctuated greatly over the past few decades. This stems from a variety of causes: OPEC-induced instability, OPEC-stimulated increases, war and turmoil, and some technical factors.
- There are some "unknown" major producers, and some well-known non-majors. China, Norway, and the UK are among the nations that have become genuine major oil producers without a lot of public attention. All now substantially exceed Indonesia, Canada, or Nigeria. But while India has increased its production greatly in relative terms, it remains a rather minor producer.

Also shown are data on remaining oil resources in various regions and territories, and on the relative rates at which these resources are being pumped from the ground. There are uncertainties about the data, and of course production rates can change. But to the extent that relative relationships among rates remain reasonably constant, we can form a general idea of what the geographic distribution of oil may look like in the future.

Assuming that the production rates remain stable (in the sense not necessarily of remaining constant but of retaining the same relationships among themselves) then we can make the following observations:

- **The oil-rich are very rich, and likely to get relatively richer.** The region around the Persian Gulf not only has an exceptionally large fraction of the world's remaining oil (more than 40%) but actually is producing oil a bit more slowly, in relative terms, than other regions. Thus it could well have a somewhat greater proportion of the world's then-remaining oil in a decade or two than it has now.
- **The least richly-endowed regions are draining their resources relatively rapidly.** Europe and East Asia are pumping fast. North Africa, Southeast Asia, and South Asia are not far behind in the race to become "oil-free" zones.
- **The North American region still has a lot of oil, but is eating into it.**
- **The great "underproducers": Iraq and Iran.** Iran and particularly Iraq are producing slowly relative to their very large resources. If these trends were to con-

Figure 2: A possible oil scenario



tinue, they would eventually come to have much the greatest concentrations of oil resources remaining on our planet.

Scenarios for growth and decline

Figure 2 shows a hypothetical scenario for oil production growth in the 21st century. It is based on data from a study by the Energy Information Administration (EIA) of the U. S. Department of Energy which is described and discussed in Appendix A at page 38. The case shown in Figure 2 assumes that oil production will continue to grow at 2%/year—roughly its current rate.

Because the production rate of any given oil well will fall off with time, it is necessary to keep drilling new wells in order to expand—or even maintain—production rates. Eventually, the most productive reservoirs will have been tapped. New drilling will become less and less productive, so the rate of drilling will have to accelerate.

This sort of process cannot continue indefinitely. As the acceleration mounts, costs of drilling and production will rise increasingly rapidly. The price of oil must also rise very sharply in order to make this possible. At some point, falling demand in response to the steeply rising price puts a cap on new drilling. Without a continuing acceleration of drilling, production falls off.

Figure 2 shows is a very sharp production peak, followed by a steep drop-off. Many would argue for a more gradual and rounded peak, with a shallower drop-off. That may be so, and we'll consider the possibilities for this shortly. But Figure 2 assumes that essentially all of the technically recoverable part of world's oil endowment is actually produced. That is, the total area under the curve in the figure cannot change. Thus any rounding or flattening must come at the expense of moving the peak toward the left—closer to today.

Naturally, higher prices will stimulate more intensive efforts to find more oil. But this should not necessarily be viewed as "additional oil"; as described in Appendix D (page 71), geologists have made quite comprehensive efforts to account for the oil that has not yet been found, and the nature of oil deposits makes it improbable that they have missed anything really big.

It is important to recognize that this is not a matter that can be changed in any fundamental way through improvement in technology: technology can make it easier to find the oil that exists, but cannot alter the amount or distribution of that which does exist.

How much could better recovery help?

The net implication is that increases in oil prices associated with anticipated shortages will have only a fairly limited effect in increasing oil supplies. There is one aspect of the supply question which this does not address, however: *recovery,* or the percentage of the oil within the reservoir rock that can be recovered. Recovery varies a great deal with the geophysical conditions as well as the technology used, and yields of 50% or more are obtained in favorable conditions. But the general average recovery is more like 30% to 35%. If we accept the estimate that the world started out with about 3 trillion barrels of recoverable oil, then increasing recovery from 30% on average to 40% would provide an additional 1,000 gbbl.[10] Thus there might be potential to stretch supplies significantly through investment in production technology.

How much this can be relied upon to significantly change the story told by Figure 2 is another matter. This is the kind of technology which, so far, has not moved rapidly. And even once proven and put into practice, new production technology has not tended to result in major increases in overall production rates. The more usual effect has been to reduce the falloff in production.

But suppose that recovery could quickly be boosted on a worldwide basis to bring another trillion barrels within reach: how much would that do to resolve the problem? Surprisingly little, it seems. Because of the huge production rates envisioned by the middle of the 21st century, even an added trillion barrels is unlikely to delay a decline greatly. This seems surprising until we look at the curves of Figure 2 more closely. The difference in recoverable oil between the “mean” and “high” cases is about 900 mbbl—and the peak year for the “high” case comes only a decade later.

We can certainly expect that economics-driven technology advances will have significant effects on discovery and recovery of oil. But it is much less clear that this will bring major changes in the “falling-off-the-cliff” peaks shown in Figure 2. It’s possible, but it doesn’t seem as if we should count on it.

Smooth or jagged?

So long as there are many producers, none dominant, economic theory and experience suggest that their ability to raise prices will be disciplined by the free market. That is, prices in a competitive market will reflect oil’s real scarcity relative to demand, suggesting that, absent any sudden and sharp changes in demand or supply, competitive oil prices should change in a reasonably smooth manner as oil

---

[10] That is, the 3 trillion barrels represent the 30% of the total that is assumed to be recoverable, so increasing the recovery yield to 40% increases recoverable oil by 1 trillion barrels to 4 trillion.

demand rises. (Note that smooth doesn't necessarily imply slow; the accelerating need for more drilling is likely to prompt very rapid increase in prices at some point.) This in turn should lead to a progressive transition to alternatives.

But even with regard to the smoothness, there are two important questions:

- Will the market conditions be near enough to the ideal of perfect competition to allow this to happen?
- Will the stimulus of price rises be early enough and strong enough to ensure a smooth transition to alternatives to oil?

It seems, as we saw above, that the distribution of remaining oil resources will become yet more uneven as the century progresses. Many of today's significant producing nations are likely to enter their production decline phases within a decade or two at most. Some new resources will open up in remote areas of the Arctic, Antarctic, deep ocean, and elsewhere, but these probably will not have a large overall impact. It takes the equivalent of another new Mexico, Nigeria, or UAE to move the peak of production by a year, and it's unlikely that many new reservoirs on this scale will be found.

It could well be that at some time within the next two or three decades well over half of the world's remaining oil production capacity will come to lie in the hands of no more than three or four nations in single region: that around the Persian Gulf.[11] (In 1999, 28.5% of world oil production came from the Persian Gulf [2].) Competition in oil supply is already significantly limited by OPEC. This concentration of production in a few hands may very well lead to *much* less-than-perfect competition. It would seem to offer the producers an opportunity for a replay of the scenario of the 1970s, but with greater market power.

On the other hand, there is no prospect of perfect monopoly either. For consumers, alternatives may be expensive and painful, but there would be no way for producers to gauge consumer willingness to accept these penalties in advance.

The picture this suggests is one of a succession of price shocks, with price rises being followed in some cases by partial retreats. It will be in the interests of the suppliers to convey the impression that each rise is the one needed to attain "stability," since the prospect of continuing rises will tend to give consumers added incentives to seek alternatives.[12]

Will alternatives come forth promptly to fill the gaps?

As is made clear in Appendix E (page 83), there are a good many alternatives to dependence on crude oil as a source of fuels. Some of these are economically competitive today, to a limited extent, and it is likely that more economic competi-

---

[11] See [EIA 2000c], p. 58 *et seq.* and [EIA 2000a], p. 37 *et seq.* for analyses of some of the possibilities over the coming two decades.

[12] Indeed, we have already seen the OPEC nations criticizing consumers for their failure to rein in demand and citing this as a factor that compels them reluctantly to raise prices.

tors to crude oil will emerge over the next few decades, even if oil's price does not rise greatly. But the extent of these alternatives truly is very limited. World consumption of crude oil runs to more than 25 billion barrels each year today, while it appears that alternative liquid fuel sources and substitutes for liquid fuels total no more than a small fraction of this. It would take remarkably strong growth in development of alternative sources in order for them to reach even 10% of the fuels market within the next three decades, especially given that the fuels market is itself expected to grow vigorously in that period.[13]

So let us suppose that in the year 2035 (simply to take a concrete example) it comes to be widely believed that crude oil production is likely to begin falling within five years. We'll suppose that the gap between supply and demand is forecast to grow to more than 30 gbbl/yr by 2050, taking account not only of falling crude oil production but also of continuing (albeit slowing) demand growth. Foreseeing a great opportunity, firms around the world embark on crash programs to bring on line alternatives capacity equivalent to 10 gbbl/yr in 5 years, another 10 gbbl/yr in 10 years, and a further 10 gbbl/yr in 15 years. What's the likely result?

As can be seen from the discussion in Appendix E, the scope for sudden change-over to radical alternatives is limited. Most of any alternative to crude oil is going to have to involve the production of liquid hydrocarbon fuels from other sources—which might include tar sands, oil shales, coal, natural gas, and biomass. Here's a brief summary of what is involved in each, drawn from Appendix E:

- **Tar sands.** Where deposits are shallow and rich, tar sands are economical to mine in some cases already. Strip mining on the scale required for large-scale production with lower-grade ores raises significant environmental issues, however, and seems bound to make oil from tar sands quite costly
- **Oil shales.** Although there are experiential plants, it doesn't appear that there is any economically competitive production of oil from shales at this point. The issues are similar to those for tar sands, but processing tends to be more complex.
- **Coal.** Again, mining is the first step.[14] Processing is complicated and coal generally is less economic as a liquid fuel source than tar sands or oil shales. Experimentation continues under government auspices.
- **Natural gas.** Liquid hydrocarbons can be produced from natural gas feedstocks. There do not appear to be any commercial producers of liquid fuels

[13] Again, it must be kept in mind that alternative sources will have to compete with an oil-geared system whose technology is constantly being improved.

[14] Some investigations are being conducted of means of producing syngas or liquids from coal *in situ,* rather than mining the coal for conversion in an above-ground plant. The prospects are difficult to assess at this point.

from natural gas at this time, but the industry expectation is that this could prove economical for certain gas deposits.

- **Biomass.** It seems unlikely that biomass could be economically competitive as a source of liquid fuels under present conditions.[15]

Obviously, each of these alternatives involves investment in facilities to mine or produce the raw material as well as plant for processing—a rough estimate is about $200 billion per year for an extended period. Given that world economic output is likely to be something on the order of $50 trillion per year at that point, this seems ambitious, but certainly not out of reason.

Naturally, the risks and uncertainties would be enormous. OPEC will no doubt continue to obscure real economic conditions regarding petroleum, thus increasing investor uncertainties. Even if oil prices had already soared, investors would be bound to reflect on previous episodes of sharp price rises followed by price erosion.

It is important to recognize that the crude oil producers would hold considerable leverage for a long time, even well past the peak of crude production. They would have great scope to cut prices for a while in order to put high-cost alternative producers under pressure. This is sure to temper enthusiasm for investment in facilities for alternative production. Investor confidence in the accuracy of engineering forecasts of costs will also play a role, as will expectations regarding public acceptance of environmental impacts. Finally, unforeseen technical or construction problems could have an impact.

In the long run, there is little doubt that alternatives will be brought into production sufficient to meet fuels demands. (Naturally, these demands will be lower if prices are higher.) But there seems to be every reason to anticipate a very turbulent period near the peak of crude oil production, and for a decade or more thereafter. Much will depend on investor evaluations of risks, and their risk-reward calculus.[16] It would not be surprising if supply fell well short at some points. In fact, it would be rather surprising if it did not.

A scenario

To sum up so far, we can reasonably envision a possible course of events somewhat along the following lines:

- An increasing concentration of crude oil production capacity in the hands of a few nations—around the Persian Gulf especially, with Iraq and Iran very prominent. The Persian Gulf might come to hold more than 50% of the

[15] There is subsidized fuels production from biomass.

[16] I don't mean to restrict this discussion to private investors; governments also could choose to invest in alternatives, or not to.

world's remaining accessible oil by 2020 or so, and the proportion could increase further.

- A sharp narrowing of the gap between potential production and consumption. Eventually, the gap will close altogether and it will no longer be feasible to maintain production rates. The production peak might come as early as the 2020s or as late as the 2060s, depending on how much oil there actually is and how fast production grows.
- An increase in prices as the slack in supply is taken up. This could be gradual and smooth, but a series of sharp price shocks seems much more likely.
- Massive investment in facilities to produce alternative sources of fuels as the peak of crude oil production is approached and passed. As these facilities come on line they will cushion the impact of crude oil's decline by providing sources of fuel. But the fuel they produce will be costly and it is unlikely that new production capacity will match demand smoothly.
- Continued strong influence in the market by the crude oil producers for decades following the peak in crude production. While their share of fuels production will decline, they will have a large production-cost advantage that will give them market power.

None of this is certain, of course. But it seems very possible.

Strategic issues

Shifts and concentrations of power spell strategic trouble. It is unrealistic to expect that "the free market" can or will deal with all of the problems of the ending of the age of oil on its own. The concentration of wealth and potential power represented by oil is so great that some will no doubt be tempted to intervene. Even if the United States were entirely content to allow a market dominated by a few concentrated producers to determine the course of events, it might well be necessary to intervene in order to protect those producers from those whose commitment to market principles is less absolute.

Obvious risks include:

- **Intra-regional aggression.** We have seen Saddam Hussein attempt to increase Iraq's power and wealth through aggression against neighbors Iran and Kuwait. While he is unlikely to survive to see the last act of the oil drama, we have no reason for confidence that his successors (in Iraq and elsewhere in the region) will all be far-sighted or principled.[17]
- **Inter-regional aggression.** As the experience of World War II demonstrates, some states may be prepared to contemplate aggression in quite distant places to secure critical raw materials.

[17] Saddam Hussein was born in 1937.

- **Hybrid aggression.** A particularly disturbing possibility is that of one or more states from outside the Persian Gulf leaguing with one or more states in the region to seize control of it.

Aggressive actions would not necessarily require a major military effort, particularly if mounted by a state within the region. Suppose, for instance, that a local nation gained sufficient naval advantage over its neighbors to permit it to control the relatively narrow Strait of Hormuz. For Iran, in particular, this would require little effort. Without U.S. presence to ensure free passage of the Strait, small forces could effectively "blockade" any or all oil shipments to virtually any destination. Conversely, they could cut off the bulk of oil revenues to any state in the region.[18]

At present, our strategic position with respect to the Persian Gulf is complicated by the historic sense of grievance toward the West felt by the populations of the region. (Even when they can agree on little else, they all feel considerable estrangement from the West.) There is little firm basis for predicting the course of these sentiments over the coming decades, other than to observe that generally, revulsions of feelings like these have come only in response to dramatic watershed events. While the climate of opinion might improve, it seems imprudent to count on it doing so.

The other major complicating factor is distance, of course: more than 6,000 nmi from the nearest major centers of the U.S. by the most direct air route. Further compounding this is our lack of bases in the region. The U.K. shares facilities with us on their (quite small) island of Diego Garcia, 2,500 nmi to the south of the Persian Gulf. Beyond that, we depend on the willingness of states in the Gulf itself to allow us access.

Garrisons of foreign troops are always an irritant no matter how close the relations between garrisoned and garrisoning nations. Given the attitudes of local populations, states in the Gulf can entertain U.S. troop presence only at great risk to their legitimacy in the eyes of their own people. If Iraq did not pose so immediate and demonstrable a threat to its neighbors, it is difficult to see how any of them could tolerate even the current modest U.S. garrisons (consisting largely of headquarters units, light air forces, and very light ground combat elements with prepositioned matériel for larger forces).

We maintain substantial naval forces in the region, rotating them from the United States on six-month deployments. This is costly, since as much as half of a deployment period may be occupied in transit from the U.S. and back, and ships generally are unable to deploy more often than once in eighteen months. These rotationally deployed naval forces provide crucial advantages of freedom of action, security, and control of the sea approaches to the Persian Gulf. But there seems little prospect that we could strengthen them to the point that they would be able

[18] Some oil is shipped by pipeline, but the geography of the region tends to limit this.

to deal with major aggression in the region on their own, at least absent some major change in the structure or technology of these forces.

Naturally, it is much to be hoped that the peace and stability of this vital region can be preserved and our strategic and economic interests maintained without the need for force. But of course the likelihood that we will need to exercise force is inversely related to our ability to do so. The question of how best to improve our capabilities to exert force in the Persian Gulf seems sure to be one of the principal challenges for U.S. defense planning for decades to come.

Policy choices

A final appendix examines strategic issues and related policy matters in somewhat greater depth—see Appendix F at page 111. Here's a brief summary of what I suggest:

- Improve U.S. ability to exert military influence and power in the Persian Gulf region over the long term by making it easier to move forces to it and operate them there as may be necessary. There are a variety of technical improvements that should be pursued, and we should also investigate the potential for acquiring basing rights in helpful places.
- Continue to pursue diplomatic efforts to move the oil-producing states more strongly in line with the international order.
- Strengthen the operation of oil markets by regulation and taxation carefully designed to ensure that costs are borne directly by those who receive the benefits, and that cost and choice are aligned.
- Where it is necessary to impose societal needs regarding oil—as it almost certainly will be with respect to global climate change, for instance—do so insofar as possible through market incentives.
- Endeavor to compensate for the distortions in market information that are brought by the actions of OPEC and individual governments by strengthening the collection, analysis, and dissemination of objective information about supply, production, and cost.
- Initiate an ongoing program of research under government sponsorship aimed at quantitative understanding of how the oil market and production-consumption system is likely to respond to potential natural, economic, and political disturbances.
- Study when and how strategic petroleum reserves should be expanded to provide cushioning against the large oil supply and price shocks that are likely to accompany the peak of oil production.
- Strengthen and focus government sponsorship of fundamental research into the principles and phenomena which underlie potential alternatives to and substitutes for oil. But be cautious in sponsoring research into specific tech-

nologies (except as needed for military or other governmental purposes); this will normally be better left to private enterprise.

- Do not waver in sponsorship of research into climate change and other environmental aspects of oil production and consumption.

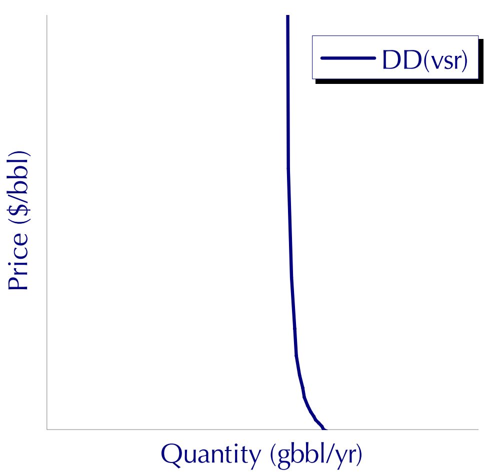
Appendix A
Oil economics

Oil is unique, both in its place in our society and in its technical problems and qualities. A full account of the economics of oil must take account of all of the aspects of its uniqueness. There are at least four current extended treatments of oil economics, but none even claim comprehensiveness.[19] Nevertheless, there are important insights to be gained also from viewing oil in the perspective of commodities in general.

Oil as a commodity

This section will draw on some widely-familiar basic ideas of economics to explore the general case of commodities and the specific case of oil economics.

Figure 3: Demand in very short run



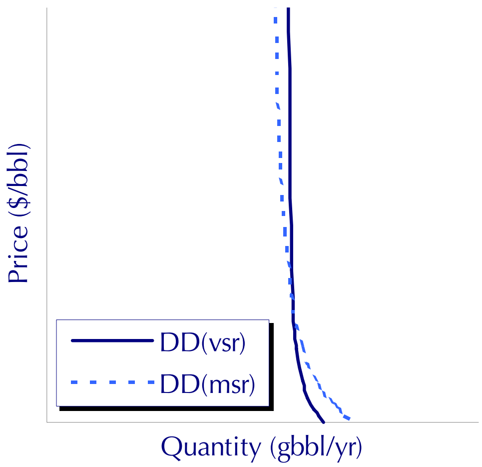
In Figure 3 the horizontal axis represents quantity and the vertical axis, price. The curve labeled DD(vsr) is supposed to depict the quantity that will be demanded by consumers for any given level of price, given a particular set of circumstances which does not otherwise change. (The axes are labeled to represent oil, but curves of this sort can be drawn for virtually all kinds of goods.)

The "vsr" in the label of the demand curve in the figure stands for "very short run". If we take this to mean one or two months—too short a time for users to make major changes in their technology or to scale back their fuel-using operations without major disruption—then we would expect that even a major change in price would result in only a fairly slight reduc-

---

[19] I have in mind [Adelman 1993], [Adelman 1995], [Heal & Chichilnisky 1991], and [Tippee 1993]. The last is (as its subtitle states) quite "nontechnical". The two Adelman books are essential for any serious student of oil economics. [Adelman 1995] is framed as an analytical economic history of oil in the age of OPEC but concisely presents most of the analytical apparatus which is developed in [Adelman 1993]. [Adelman 1997a] is a very brief overview that provides a clear summary of major points. [Adelman 1972] is an outstanding earlier treatment now superseded by the author's later works. [Heal & Chichilnisky 1991] is useful in that it endeavors to set the economics of oil in a broader context of international economics. It is marred, however, by approaching oil economics via a model—critiqued in the section below on "Hotelling and the theory of exhaustible resources"—that I argue does not fit the case of oil well enough to be very informative. As this listing suggests, I regard Prof. Morris Adelman as very much the most authoritative figure in the field.

Figure 4: Moderate short run demand

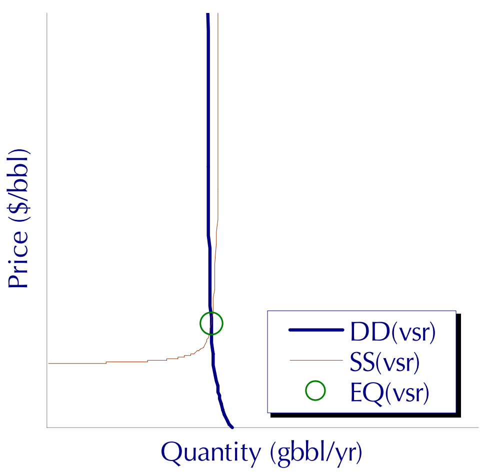


tion in oil usage, all else being equal. That's how the demand curve is drawn—nearly vertical. An economist would say demand is very *inelastic* to price.[20]

In Figure 4 I add a second demand curve, representing the moderately short run (say, a year or so in the case of oil)—again, all else remaining constant. In this somewhat longer period, users have more options, so the slope of DD(msr) isn't quite so steep as that of DD(vsr). But the moderately short run demand for oil remains pretty inelastic. This is typical of commodity classes in general, for in most cases they represent basic goods that users have structured their lives and businesses around.[21]

Returning strictly to the very short run, Figure 5 adds a supply curve, SS(vsr), to the demand curve. In the very short run, the supply of oil is almost entirely what is in dealer hands or well on its way to dealers; in most cases oil takes several months to make its way from well to final user. Since oil is storable and most dealers will have some storage capacity, a large fall in price will result in great fall in supply as dealers store oil rather than sell it below their cost. And even if price rises a great deal, there are physical limits to how much dealers can supply in the very short run. Thus the very short run supply also is quite inelastic to increasing price, assuming nothing else changes.[22] This, too, is typical of very short run supply of commodities as a whole (and many other kinds of goods as well).

Figure 5: Demand and supply in the very short run

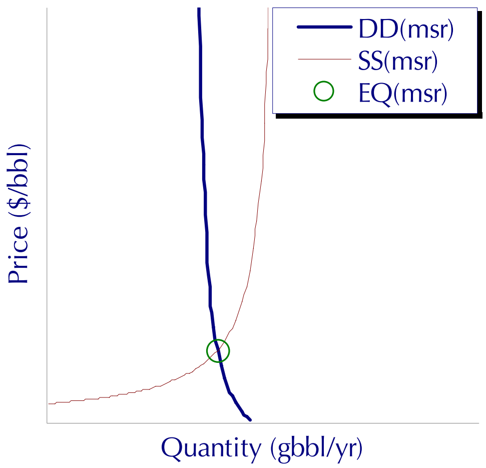


[20] At any point on a demand curve, its *price elasticity of demand* is percentage change in quantity of demand divided by percentage change in price level, in the limit as price change becomes very small. In symbols, $(\partial q/Q)/(\partial p/P)$, or $(\partial q/\partial p)(P/Q)$. When speaking of "small" elasticity, people usually mean absolute value—elasticity near zero, whether positive or negative in sign. Price elasticity of demand is negative for normal goods under most conditions, of course.

[21] Individual commodities within a broader class may have much more elasticity. That is, consumers who face a shortage of beef may buy more chicken or lamb rather than pay high prices, just as oil users may switch from Brent to Arab Light.

[22] *Price elasticity of supply* is defined in just the same way as price elasticity of demand. It's normally positive, of course.

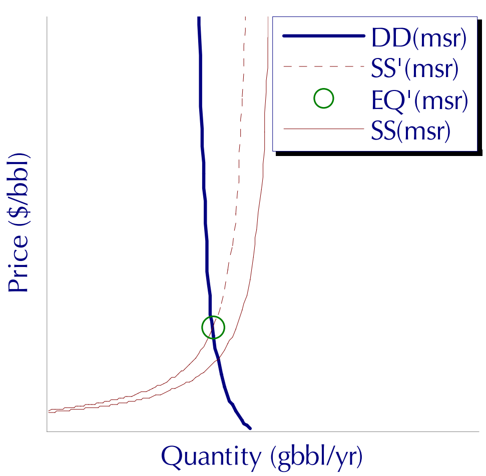
Figure 6: The moderate short run



Because both supply and demand curves are so steeply sloped in the very short run, it is obvious that even a slight shift in demand or supply will cause price movements. Commodities futures markets provide both buyers and sellers with means to stabilize the prices they have to pay or those they realize in the face of the continual nervous jiggling of prices that results from inelasticity.[23]

Demand, in particular, can occasionally react sharply in the very short run to changes in expectations. A sudden wave of concern about future supplies can evoke a "race to the exits" as users all seek to top up their fuel tanks, lest they run out of gasoline or heating oil. It's possible in such circumstances for demand to swamp all available supply in the very short run. Futures markets cannot help because they are structured only to hedge prices (and only for those who have bought or sold hedging contracts) and do not provide any added physical supply. In such circumstances, suppliers may run out, leading to heightened user anxieties. Forceful government action may be necessary to avert panic.

Figure 7: Constrained supply



In the moderately short run (say a year or so), matters look a bit different, as shown in Figure 6. User demand, represented by DD(msr), is more elastic (i.e., has a larger absolute value). And producer supply, SS(msr), is quite different. It's more elastic to increases in price due to increased demand, for one thing, because there is more time and opportunity for adjustment. Moreover, it extends to much lower price levels because it reflects the actual marginal cost of production rather than the prices paid by distributors.

Close examination will show another difference between Figure 5 and Figure 6—the

[23] Those who speculate in these markets are buffering hedging buyers and sellers against price movements, for which they receive the chance of a speculative profit. In essence, the speculator is arbitraging the inelastic short run demand and supply against the elastic long run. Commodities speculation can be profitable, but a great many speculators go to the wall because they haven't enough capital relative to their trading volume in order to weather shocks, or even normal fluctuations. Whether futures markets operate to stabilize prices generally is not altogether certain—see [Radetzki 1990], page 87 et seq.

equilibrium price is higher in Figure 5.[24] If this situation were to obtain in reality then we would expect that the very short run supply curve would loosen (move down and to the right) as distributors bought additional oil at lower prices, and that this would lead to a lowering in the equilibrium price in the very short run.

In Figure 7, however, we see a case in which the moderately short run supply tightens (moves left) by 10%, with all else remaining constant, moving from SS(msr) to SS'(msr). Now the equilibrium in the moderately short run, EQ'(msr), moves up to the price level of that in the very short run, EQ(vsr) in . In effect, this is more or less what is actually going on today: OPEC (with the cooperation of some major non-OPEC producing nations) is restricting supply in order to command higher prices. That is, in a sense the producer cartel is artificially forcing the moderate short-run supply from SS(msr) of to SS'(msr).[25]

As I say, in Figure 7, the constrained supply curve, SS'(msr), is simply translated by 10% to the left of the unconstrained supply, SS(msr). Yet EQ'(msr) in Figure 7 corresponds to a quantity of supply that is not even 3% less than that corresponding to EQ(msr) in Figure 6! This inelasticity of the quantity of demand to increases in price—which is to say the relative steepness of DD(msr)—reflects a willingness of consumers to pay significantly higher prices if necessary to avoid even 10% cuts in their fuel usage. With the curves as shown, the 10% reduction in supply from SS(msr) to SS'(msr) results in an increase of more than 40% in equilibrium price.

This series of diagrams helps to illustrate some important facts of the market for oil, and does much to illuminate the reasons for oil price behavior. But of course they represent a considerable simplification and abstraction from reality.

As I emphasized repeatedly in the discussion, this analysis makes sense only if the changes in price and quantity occur in a vacuum, unaccompanied by any other changes. But in reality, changes of more than a fraction of a percent in the prices and quantities of a good as important and widely consumed as oil can never occur in a vacuum. Significant changes will always be stimulated by, accompanied by, and stimulate other changes, and these also will affect the responses of buyers and sellers. So in reality there is a universe of different demand and supply curves, and which one gets followed in any given instance will depend on everything else that is going on at the time—both the objective circumstances and the beliefs people entertain about them.

Moreover, the analysis implicitly assumes perfectly competitive markets in which the equilibrium reflects the free interaction of a great many independent sellers with a great many independent buyers, all of whom have full information

---

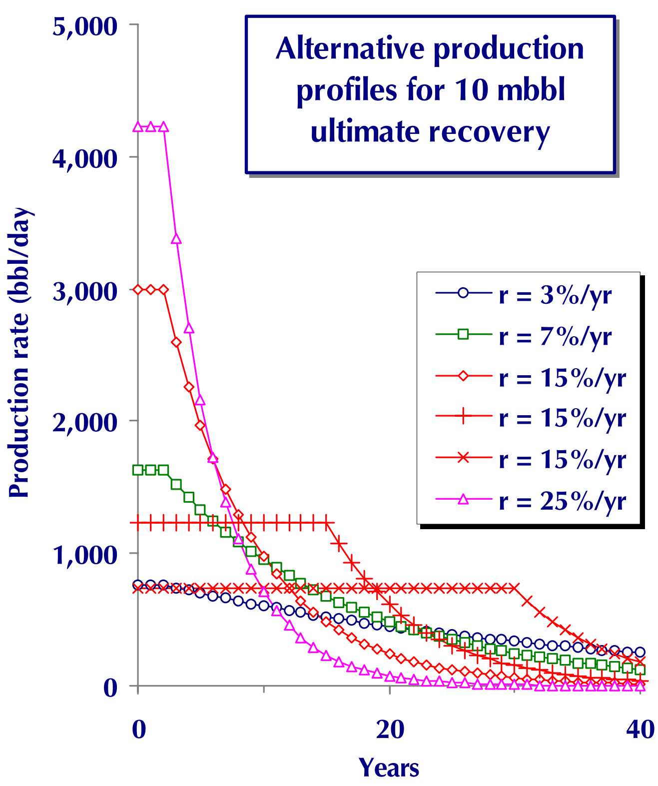
[24] While the scales are unlabeled, they are identical.

[25] Producer cartels can operate by setting either price or supply. In the case of oil, however, the structure of the market today—with oil traded on commodity exchanges—does not lend itself well to arbitrary pricing. So restriction of output is employed to the same end.

about market conditions. This is probably not a bad approximation to the conditions obtaining in day-to-day buying and selling of oil spot contracts on the NYMEX or the London International Petroleum Exchange in ordinary circumstances. But of course it does not apply to the case of collusive action by producers discussed in connection with Figure 7. In general, in fact, the concentration of supply in the oil market is great enough to call into question the assumption of perfect competition when discussing significant changes.

Despite these shortcomings, this simplified analysis is quite useful and illuminating. While price and quantity are not the only relevant factors, their action is very powerful. There are many different demand and supply curves, but most of them lie close to one another. And while departures from free competition may cause prices quantities to settle at some point distant from the intersection of underlying supply and demand, supply and demand remain powerful forces that need to be accounted for.

Figure 8: Typical production decline curves



Supply curves for oil

The demand curves in the figures don't need much explanation, but it may seem less obvious how the supply curves operate and why they are shaped this way. This is particularly so for the moderate short run curves, SS(msr) and SS'(msr), of Figure 6 and Figure 7. Here I will review some general considerations regarding supply and some data about petroleum supply in an effort both to make these curves seem more plausible and to lay groundwork for consideration of what may lie ahead for supply.

A dip in the oil pool[26]

The logical place to begin is with the individual petroleum pool or reservoir—the basic unit of petroleum production. The natural history of production at a pool level is described briefly in Appendix C at page 64. As explained there, production will normally fall off at a

[26] The analytical apparatus and specific data of this section follow closely on the lines laid down in [Adelman 1972] and [Adelman 1995].

roughly constant rate following an initial "flat" period (which usually is brief but in some cases may extend for many years)—much as shown in Figure 8.

The following equations form a convenient and reasonably accurate parametric representation of the typical production history of a reservoir:

$$q = q_0 t \,, \qquad \text{for } 0 \le t \le D \text{ (\textit{i.e.}, the "flat" period)} \tag{1a}$$

$$q = q_0 e^{-at} \,, \qquad \text{for } D < t \le T \text{ (the period of exponential decline)} \tag{1b}$$

where q_0 is the initial rate of production, D is the duration of constant-rate production, T is the total duration of production, and a is the effective (exponential) rate of decline subsequent to constant-rate production.[27]

These are the equations that, with different choices for the variables, generate the typical production decline curves shown in Figure 8. All four variables are constrained to some extent by natural conditions affecting the reservoir, and it's not likely that all of the choices represented in the figure would be options for any particular reservoir. But in general, the producer has freedom to vary each over a considerable range, at costs determined by natural, economic, and technological factors.

Each of the curves in Figure 8 would result in ultimate recovery of 10 million barrels (if carried to infinite time: $T = \infty$). This is a relatively modest sized reservoir. But the curves would have the same shape for a reservoir of any size—only the scale would change.

The volume of oil that can ultimately be produced from a given reservoir is its initial reserve, R_0. For instance, in Figure 8 we're assuming R_0 = 10mbbl. For a typical production profile, we can write

$$R_0 = q_0 \left(D + \int_D^T e^{-a(t-D)} dt \right) \tag{2}$$

A major fraction of expenditure for production normally takes place before significant production begins, thus taking the form of capital investment.[28] But the economic returns from a reservoir come over a period of years, as the oil it produces is sold. Suppose that a producer estimates that it will cost $1 million to complete a well that will produce at an initial rate of 1,000 bbl/day. Is this a sensible investment? How would he know?

---

[27] In mathematical terms this means that production rate, after the flat period, is represented by a *negative exponential* function: $q = q_0 \, e^{-at}$. The constant e, which is the base of the natural logarithms, is the limit as n tends to infinity of the quantity $(1 + 1/n)^n$ and has a value of approximately $e \approx 2.71828\ldots$ The rate of decline, a, is related to the annual decrease, r, by $r = e^a - 1$, or $a = \ln(1 + r)$, "ln" being the symbol for the natural logarithm function. For small values of a (say, $a \le 5\%$) we can approximate r very closely as $r \approx a$.

[28] A rough rule of thumb used for preliminary estimates in the industry is that normal annual operating costs will be 5% of the up-front investment. To this must be added any special investments for secondary or tertiary recovery. See [Adelman 1995], page 35.

There is a way to compare costs and returns at different times, known as a *net present value calculation.*[29] Suppose that the producer estimates the expenditures necessary in each future period to complete the well and keep it in operation, and the production in each period and the price he will receive. Let's take the periods to be successive and of equal length Δt, and number them from 1 to n. Also, let t_j be the time for the j^{th} period, k_j the expenditure, q_j the production, and p_j the price. We can write formal equations in a parameter d, which we call the *discount rate:*

$$NPR = \sum_{j=0}^{n} \frac{q_j p_j}{(1+d)^j} \tag{3a}$$

$$NPC = \sum_{j=0}^{n} \frac{k_j}{(1+d)^j} \tag{3b}$$

$$NPV = NPR - NPC = \sum_{j=0}^{n} \frac{q_j p_j - k_j}{(1+d)^j} \tag{3c}$$

These equations serve as definitions of *net present return* (NPR), *net present cost* (NPC), and *net present value* (NPV). If we set $NPV = 0$, we obtain a polynomial equation in d. If the subscripted variables obey suitable functional forms, it may be solved analytically for d; if not, it is straightforward to determine d by numerical means (such as Newton's method) for any given data. The producer considers the value of d that makes $NPV = 0$ and decides whether it is sufficient to compensate him for investing his money in this rather than alternative opportunities, having due regard for the risks and uncertainties that are involved. The d that is just sufficient is called the producer's *hurdle rate*—it's the "hurdle" that prospective investments must "get past" before the producer commits to them.

In practice, the producer employs relationships like (3c) to investigate how to make NPV as large as possible by changing investment within the limits set by nature (and governments). Looking again at Figure 8 we can see that high rates of pool drawdown, r, are helpful because they bring the returns closer to the present and so allow a higher d without driving NPV negative, other things equal. But this implies a high rate of initial production, q_0, which may involve added early expenditure, thus raising NPC. Manipulation of variables in equation (3c) allows the producer to find the best balance.

The variables q and p are pretty clearly defined, but a producer has many costs that must be considered yet are not directly linked to particular development projects. It is important that k reflect fully-allocated costs, so that the sum of all the k values for all the firm's efforts represents its full costs. In particular, it is necessary to allocate exploration costs. These have to cover not only the costs of finding the

---

[29] See [Nicholson 1985], Chapter 17—or virtually any other text dealing with microeconomics, business economics, or managerial accounting.

particular reservoir under consideration but the costs incurred in failing to find other reservoirs in other places. Sometimes producers simply buy rights to exploit reservoirs already discovered and proven, thus simplifying the accounting.

Investing in oil development involves uncertainties and risks that are larger than those in many other businesses. Uncertainties surround reservoir geology, future price of oil, and actions of governments. A hurdle rate of 20%/year is typical, and higher hurdles may well be set up for particularly risky tracks.[30]

Cost drivers for producers

If we restrict our attention to the conditions under which producers operate today, we can make some generalizations about the factors that affect the economics of production at the reservoir level. The costs of production can be broken down into drilling services, basic production-site equipment (*lease equipment*)[31], added investment for secondary recovery, and recurring operating costs.

- There is a base cost for both drilling services and lease equipment for any oil well, regardless of depth. Additionally, greater depth leads to increased costs for drill-rig time, tubular goods, pump rods, etc. Costs increase more than linearly with depth. For onshore wells in the U.S., total drilling and equipment costs of $500,000 are roughly typical [3].
- Offshore wells are naturally much more expensive. $5 million is not unusual for a U.S. offshore well [4].
- Wells are also more expensive to complete in areas which lack the dense infrastructure of the U.S. As a broad generalization, wells drilled outside the U.S. cost about twice as much [5].
- Wells differ enormously in initial production rates (q_0)—from less than 500 bbl/day in the smallest pools to more than 50,000 bbl/day in large freely-flowing reservoirs.[32] This has some effect on well cost. But because production rates tend to vary with area (being small in the U.S., for instance, and largest in the Persian Gulf), it's hard to get good data on the effect of production rate in isolation. One educated guess is that investment might vary like the square root of production rate [6]. If this is so, then a well that produces 50,000 bbl/day will cost 10 times as much as the 500 bbl/day well, while producing 100 times as much.
- In some reservoirs, the drive is sufficient to raise the oil to the surface, resulting in a *flowing well*, while in others the oil must be pumped up, with greater or

[30] As a rough rule of thumb, if the expected price averages p, the initial production rate is q_0, and the required initial investment is K then the project will pay so long as $K \leq 1000\ q_0\, p$. [Adelman 1995], page 238.

[31] The standard term in the industry is *lease equipment*, meaning not that it is leased but that it is deployed at the site leased for production.

[32] In the U.S., average production per in-place well is less than 15 bbl/day.

lesser assistance from natural drive. If secondary or tertiary recovery is employed, it will be necessary to pump water or gas down into the reservoir. Evidently, this affects the operating costs, since pumping requires energy. Naturally, this means that well operating costs are sensitive to energy costs. In certain locations, where there is no market for natural gas, gas extracted from the oil at the well site may provide "free" energy for well operations. But of course this means that there can be no sale of gas to improve return.

- The oil must be transported to the end user, via the refinery. Since crude oil is bulky and heavy relative to its value, transportation costs are a significant factor, even though marine and pipeline transport are highly efficient. Thus wells close to the site of demand have a cost advantage over those in remote areas.
- The costs of refining can vary significantly from one grade of crude to another. The hydrocarbon content, hydrogen content of the hydrocarbons, viscosity, and amounts of corrosive agents or catalyst poisons such as sulfur or heavy metals all have a significant effect on refining cost.

The net effect of these and other factors is to create a very wide dispersion in production costs, even if we restrict attention solely to "conventional" crude oil and neglect tar sands, shales, etc., and leaving aside any consideration of rents that may be demanded by the owners of the property rights to the oil. At any time, the most costly oil in production may cost tens of times as much to lift as the least expensive.

Generally, the least expensive place to produce oil is the Persian Gulf region. Although this region does have certain drawbacks, its very large and freely-flowing reservoirs make for very great economies, particularly on the western (Arabian) side of the gulf. The U.S. is for the most part a relatively high cost place to produce, mostly because its remaining oil is found in small pools. In a very few cases, oil is known or strongly thought to exist in areas so difficult and remote as to make production uneconomical at present prices.

At what price will a producer sell?

Consider the choices of the proprietor of an oil-producing firm that operates a single reservoir. Let's imagine that her costs are such that she can produce another barrel of oil at an added cost of $9.99, and that she finds that the market will currently pay $10 for a barrel of oil. Since the barrel she doesn't produce today will be available to produce tomorrow, she may perhaps choose to withhold her barrel from the market if she feels confident of a rise in prices. But if she expects the $10/bbl price to hold then it is rational for our producer to sell at this price. After all, the $0.01 that remains after expenses is money she wouldn't otherwise have.

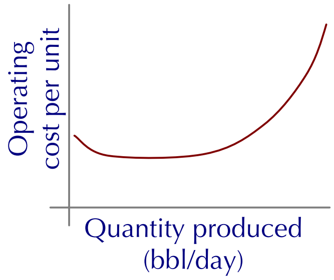
This is not to say that the $0.01 is profit. It may be that what our producer is getting for her oil in total is not sufficient to pay her overhead and return on capital in addition to current operating cost. But it is $0.01 less in losses, at very least.

By the same logic, it would not make sense for our producer to produce another barrel if she could get no more than $9.98 for it, since that would entail $0.01 less profit or more loss. In practice, again, expectations may modify this behavior somewhat, of course. But on the whole it is reasonable to say that producers are motivated to sell so long as the price is sufficient to cover the immediate costs of production.

If the total that our producer is getting for all of her barrels of oil is not sufficient to pay her overhead and cost of capital then she erred in her original estimates of price—those on which she based her investment decisions. If the situation continues, she will sooner or later be forced out of business. But in the meantime she is better off selling at any price over her operating cost than not.

If the producer is one among a great many, all acting independently, then there is virtually nothing she can do to affect the price she is offered for oil. It will be set by the equilibrating process illustrated in Figure 6; she is a *price taker,* for she must take the price as set by the market or else sit on the sidelines and withhold her oil from the market.

Figure 9: Notional producer supply curve



Of course we already know very well that some producers, tiring of price taking, have leagued under the banner of OPEC to refuse to take a price that is "too low" (even though far, far in excess of their production costs, even on a fully-allocated basis). In so doing, they force the price for all oil upwards. But even though we know that the oil market is by no means perfectly competitive, the study of a hypothetical competitive market for oil remains important because it tells us much about how the real market functions, and sets limits that the real market cannot transcend.

We can imagine that our oil producer finds that her operating costs per unit behave something like what we show in Figure 9. As she starts up from zero production, each unit produced is cheaper than the one before it for a while. Then the incremental cost levels out when her production system is operating at the rate for which it was designed. At high rates, costs increase with increasing rapidity until, finally, a limit is reached which she cannot exceed with installed equipment.

The curve of Figure 9 is our producer's supply curve. It shows the cost she will incur and thus the price she would be willing to take for each added barrel per day of production. We can imagine that there are a great many producers each of whom would have a supply curve that looked similar in shape. But the vertical position as well as the degree of horizontal stretching or contraction will vary a great deal from producer to producer. From these curves we may find the incremental cost of the j^{th} barrel per day of production from the k^{th} producer—let's call it $c_{k,j}$. We'll sort these numbers in the following special way: the first number in the series is the smallest $c_{k,1}$, and if $c_{k,j} < c_{k',j'}$ then $c_{k,j}$ goes ahead $c_{k',j'}$ of in our list *unless* there is some $j'' < j$ such that putting $c_{k,j}$ ahead of $c_{k',j'}$ would also move $c_{k,j}$ ahead of $c_{k,j''}$. (This condition is necessary so that our producer is not required to produce her second barrel before her first!) If we now renumber the sorted series in order, starting with c_1 and running out to c_N (where N for today will be of the order of 100 million, recognizing that more than 70 million barrels are produced worldwide each day, and that there is capacity to produce more) and plot it, we get a graph that will be somewhat lumpy, due to the higher costs for each producer at very low rates of production, but that on the whole will look a great deal like the curve SS in Figure 6. That is to say, the supply curve for the market as a whole is a certain kind of "horizontal sum" of the supply curves for each producer in it.[33]

Let's consider two oil producers. A is a low-cost producer. Even at his maximum rate of production, at the extreme upper right end of his supply curve, A's cost of production is far below current market price. B, on the other hand, is a moderately high-cost producer. At maximum rates of production, her most costly unit of output costs her only modestly less than she can get for it. Imagine now that both A and B are considering whether to expand production. For A it would seem that the answer is easy: if he can produce more oil at costs approaching his current levels, he is essentially guaranteed of a very attractive profit. Even if oil prices were to drop significantly for some reason, he would be well protected. But for B, it is not so clear. While there is a reasonable certainty perhaps that oil from the expanded facilities can be sold for enough to cover day-to-day operating costs, any unexpected leftward shift in demand or a surge in production by low-cost producers such as A might leave her unable to get enough to pay for her capital and overhead. Thus A should invest to expand without hesitation while B should check her calculations and assumptions very carefully.

OPEC and supply

But in practice the lowest-cost producers are those of OPEC, who have committed to a policy of restricting output in order to raise prices. They calculate that this will gain them more than will expanding their output to take market share from higher-cost producers. Whether this theory is correct is debatable, but they hew to it regardless [7].

At present there is plenty of oil available for development at all levels of production cost. So if the OPEC nations that own the least costly reservoirs will not develop and produce their resources, there are many owners of somewhat more costly oil who are willing to step in. Eventually, the entry of new producers attracted by high prices will stretch the supply curve to the right despite OPEC's efforts and lead to a fall in prices. But prices far above the economic equilibrium of

[33] One thing to note about this kind of supply curve is that it implies not one "marginal producer" but many. That is, while most producers will be producing at maximum output rate, there are likely to be a number of high-cost producers who can not reach maximum output at existing price levels.

the sort represented by Figure 6 may in fact be able to persist for much longer than conventional economic theory of the simpler sort might suggest [8].

In the U.S., cartels have long been in ill-odor, and "combinations in restraint of trade" have been a federal crime for more than a century. To a nation whose economy depends heavily on the production and sale of commodities whose prices are subject to wide swings, however, a cartel may seem quite a noble endeavor. Indeed, there is an entire United Nations agency, the UN Conference on Trade and Development (UNCTAD) which has devoted much of its energies over many years to promotion of agreements to stabilize commodity prices and the producer nations' terms of trade.[34]

OPEC has avoided calling itself a cartel, but it is no secret that it seeks to stabilize oil prices at levels exceeding those that would result from competitive market equilibrium. That is to say that it is a cartel at least in aspiration. It is not a notably effective cartel.[35] It has kept prices above their natural equilibrium, but this has been as much by bad management and waste as anything else and the benefits to the OPEC members are open to question, particularly in the case of Saudi Arabia, the leader of the cartel.

Certainly it does not seem that oil prices have been particularly stable in the age of OPEC. As a general principle, of course, it is not easy to stabilize systems at points far off equilibrium. In order to do so one has to have control forces that are strong enough to offset the disturbing forces, of course. But it is also essential that these control forces be precise in application and that their application not stimulate upsetting forces. The controls at OPEC's command are marginally adequate at best, simply because they hold only about a third of the market. And the existence of other suppliers as well as consumers and speculators who have incentives to try to "game" OPEC makes precise and predictable application of what controls they do have all but impossible in principle. When all this is taken into account, it is likely that OPEC efforts at stabilization do more to destabilize than to stabilize the market.

The potential for instability is clear from Figure 5 and Figure 7, depicting the market in the very short run (a month or two) and moderately short run (a year or so) respectively. In the moderately short run, any sort of lurch leftward or rightward of either the supply or demand curves will cause a sharp change in equilibrium price. The sensitivity of the price equilibrium is greater in the upward direction, because both demand and supply become less elastic as price increases. The

---

[34] A nation's terms of trade is the ratio between the level of the prices of the goods it has to sell to those it must buy. Obviously, deterioration in terms of trade brings relative impoverishment. Generally, the price levels of non-petroleum commodities have been falling relative to manufactured goods for the past three decades or so, adding to the distress of many poor nations. See [Le Clair 2000].

[35] See [De Santis 2000] for a recent summary of the econometric evidence and references to relevant prior work, as well as interesting simulation results.

supply and demand curves can shift sharply for any number of reasons—weather, natural disasters, wars, recessions, or ill-considered supplier decisions, to name only a few.

Knowing that their demand for fuel is inelastic—meaning simply that they need it very badly—consumers are tempted to stock up in response to news or rumor of supply disruptions. Even if this amounts to no more than being sure to fill the gas tank before it gets down to half full, it brings a marked shift of the very inelastic very short run demand curve. And because supply also is very inelastic in the very short run, this results in a substantial jump in the equilibrium price.

The firms that supply very short run needs for fuel are not organized into a cartel, and in the U.S. are prohibited from even consulting one another about price. But all know quite well that very short run supply and demand are both notably inelastic. When demand is at the very point of swamping available supply, even the actions of a single firm in a competitive market in how it responds to demand may make a substantial difference in price. In such circumstances, supplies can find reasons not to offer as much oil as they might, thus sending the price still higher. And since all suppliers (or at least all who have more than a miniscule market share) face similar incentives, the supplier contemplating an action which will result in supply restriction may feel confident that his competitors are considering similar actions even in the absence of any overt collusion. In technical terms, the suppliers are exerting *market power*—slipping away from the burden of price taking that is forced on them in a purely competitive market and undertaking positive action to raise the prices they can obtain for their goods.[36] In such circumstances, it is possible for prices to jump by hundreds of percent almost instantaneously. The nature of the supply and demand relationships makes prices much slower to fall.

While the market is much less sensitive in the moderately short run depicted in Figure 7, this does not necessarily imply that the greater stability of the moderately short run can be counted up to correct excesses of the very short run. A sharp runup in prices in the very short run could readily create temptations for the firms and nations that produce oil, as well as for others who might wish to speculate in oil. Depending on how the various market participants act and how their actions impinge one on another, it could take considerable time for a shock in the very short run to work itself out and for prices to fall back toward a more economically justifiable level. The history of oil prices in the 1970s and early 1980s provides several object lessons [9].

---

[36] This is not simply a theoretical construct. In the California electric power crisis of recent years, econometric studies have produced rather dramatic evidence of market power exercised by generating firms. See [Borenstein 2001] and [Puller 2001]. The oil market is inherently less susceptible to market power exercise (due largely to the storability of oil products and the existence of stocks) than is that for electric power, but very stressful circumstances would provide opportunities that some would no doubt seize, just as in this case.

Although the oil market has elements of instability, there also are stabilizing influences. While oil prices do fluctuate a good deal, as seen in Figure 1, they don't ordinarily show huge spikes in price, and there is a tendency for prices to move back toward normal competitive (which is to say low) levels after disturbances which do occur. In part this is because there are forces that can mitigate the inelasticity of supply and demand, particularly in the longer run. Faced with unpleasantly high prices, consumers can move their demand curve leftward by improving the efficiency with which fuel is used—what is often (somewhat misleadingly) called *conservation*. Or they may simply find alternative ways of conducting their affairs that do not rely on fuel, or demand much less of it. So too, high prices tend to stimulate the entry of new suppliers who add their supply curves to those of existing producers and thus stretch the composite total supply curve toward the right.[37] These are not quick fixes, however—both involve replacement or installation of capital equipment and so take years. Moreover, significant improvements in efficiency of utilization may require additional engineering development effort, which can take even longer.

Scenarios for the very long run

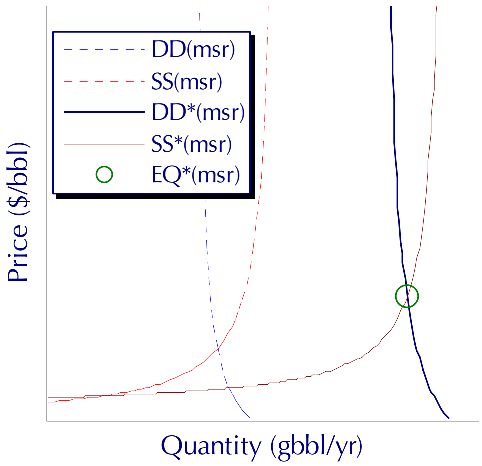
As observed earlier, if the market for oil operated competitively there would be a strong incentive for producers to concentrate their development efforts on the reservoirs that could be produced at lowest cost. But since the lowest-cost reservoirs occur in the territories of major OPEC states, these incentives do not operate. Producers who operate in a competitive environment (which is to say, those outside of OPEC) are left to exploit higher-cost properties. Since OPEC's actions keep prices relatively high (bearing in mind that even $10/bbl is well above production costs for the vast oil reserves of the Persian Gulf) there is plenty of room to make money on more costly reservoirs. Moreover, there is a lively demand from competitive producers for technology to reduce the costs of developing and operating their reservoirs.

Over the long run of several decades it is conceivable that improved technology will make it just as cheap to produce small reservoirs in remote areas as huge ones in the Persian Gulf. It's hard to see this as likely, however. The gap may close somewhat, but there are likely to be enduring economies of large scale operation.

If so, and if the owners of the large, cheaply-producible reservoirs of the Persian Gulf region continue to restrict their output while those who own higher-cost reservoirs are more vigorous then it is likely that eventually the balance between lower-cost and higher-cost oil will shift. More of the higher-cost oil will be used up and it will gradually become increasingly difficult to find more. But there will still be relatively large quantities of low-cost oil waiting to be developed in the Persian Gulf region.

[37] Another way of describing this is to say that elasticities are greater in the long run than in the short. I prefer to avoid this terminology as imprecise and subject to confusion.

Figure 10: A very long-run supply/demand scenario



All this would take place very gradually, of course, but over a period of several decades we might expect to see a shift something like that shown in Figure 10. In this hypothetical scenario, demand has shifted rightward from DD(msr) to DD*(msr) as population and wealth have grown, despite advances in conservation. Supply has moved rightward too, responding to demand, from SS(msr) to SS*(msr). But the supply curve has not moved upward very much, and the proportion of supply provided by high-cost producers has declined.

As the curves have been drawn, the equilibrium price has increased over the decades. Of course if supply had expanded a bit more or demand a bit less, this might not be so. But in any event the actual trajectory of prices will be influenced not only by the competitive market balance sketched here but also by the attempts of OPEC and others to exert market power. If the competitive equilibrium price is in fact rising, it may not be very apparent due to the artificialities of the market.

If the competitive equilibrium price were rising, it would be a signal of increasing relative scarcity of oil. The production from existing pools will always be falling off with time, as portrayed in Figure 8. Producers will continually develop new reservoirs in order to maintain and expand production to meet demand. If new reservoirs are becoming harder to find, this will be reflected in the prices that producers must pay for exploration or to purchase rights to known reserves. They will hold off on committing to these expenses until they can see prospects of covering them through higher prices for their products. Thus scarcity will bring higher equilibrium prices. But if the price level is held up above equilibrium by market power exercise then it may not be apparent that the equilibrium is rising. This is because in reality no one knows very accurately what the supply and demand curves truly are—market participants must “feel” their way to equilibrium by observing price and quantity movements, not hear it announced for them.

At some point the cost of acquiring and developing new resources will climb above a level that can be supported by current oil prices. Development of new production will slow. As old reservoirs are depleted without strong development of new ones, the supply curve will shift leftward, or at least not shift to the right as fast as demand. The equilibrium price then will rise to a level at which producers feel encouraged to develop higher-cost supplies. Of course if Persian Gulf suppliers are still holding back low-cost capacity, perhaps they will also be encouraged to put some of that on line. But past a certain point, even production in the Persian Gulf will begin to become more expensive. The producers there can get more from their reservoirs—there is always more to be gotten from any reservoir, given enough money—but the cost of each increment will rise.

In the hypothetical future illustrated by Figure 10, the cost of each increment of production above EQ*(msr) rises steeply due to thinning out of higher-cost reservoirs in production. What about the cost of extending the supply curve to provide more capacity? There is a lot of low-cost production on line in the case shown, and this can be developed more intensively even if there is little more like it left. This will increase supply quantities while raising the floor of the supply curve. As this occurs, the oil remaining in the great Persian Gulf reservoirs will be depleted with increasing rapidity. There will always be more small reservoirs to be found, albeit at higher cost. But the distribution of oil is very skewed. Only six provinces, out of more than more than 350 known, account for more than 50% of all the oil believed to exist.[38] As the larger reservoirs are drawn down it will become harder and harder to find enough small ones to take up the slack. This increasing difficulty will be ameliorated by improved technology for finding and extracting oil, of course. But the technology will not only have to improve but to do so at an ever-accelerating rate in order to compensate fully for the need to find exponentially more smaller and smaller reservoirs.

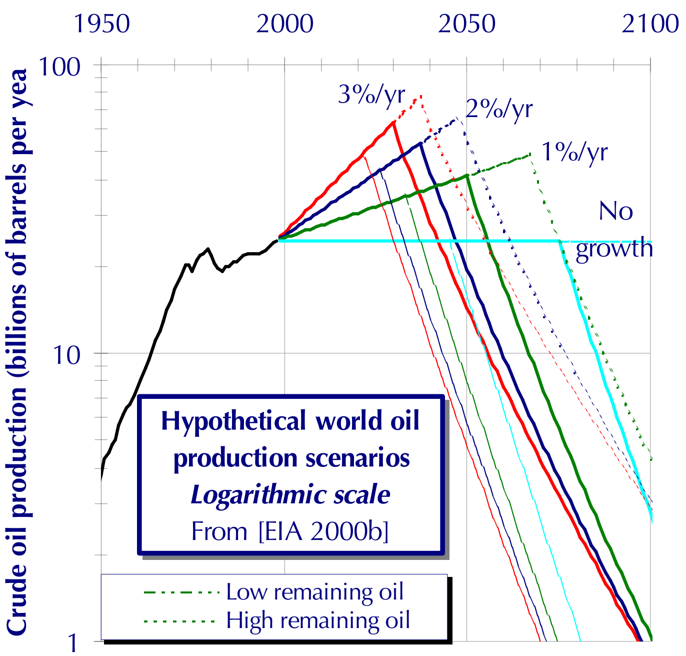
Exponential growth does not continue forever, in technology or anything else. A point will be reached at which even extremely rapid inflation in oil prices will not support continued expansion of supplies. If the world's economy can tolerate increases of 50%/year, say, soon it will be 100%/year—or 200%/year. For the reasons we have explored above, price increases are likely to come not in a smooth swoop but in sharp surges. Over the period from the beginning of 1999 to the end of 2000, as shown in Figure 1, a strong world economy absorbed a 350% jump in oil price without major ill effect. But repeated bouts of ever sharper increases might take a serious toll.

Simplified models of growth and decline

The Energy Information Administration (EIA) of the U. S. Department of Energy has published a study of how long oil production might continue to grow under various simple assumptions [10]. Figure 11 is an adaptation of one of the EIA charts. Figure 2 plots some of the same data, but here I show them using a logarithmic scale for the vertical axis in order to help make the rates of growth and decline easier to see. In essence, the EIA has used an assumption that global oil production would start to decline once supplies have become as tight as they have been in the U.S. for the past two or three decades, and that the pattern of decline would match that seen in the U.S. Because the U.S. is the only major producing nation to have firmly settled in the decline phase, and because its oil industry is

[38] A "province" is a geological concept, implying an compact area in which like geological and climatic processes have given rise to structures that are homogeneous across the province. See Table 1 of [Klett *et al* 1997] for the known oil-bearing provinces.

Figure 11: Some scenarios for 21st century oil production; rise and decline



relatively well studied and documented, it makes sense to use it for a model of production decline.

Once the decline profile is settled, the only remaining questions are how much oil is left and how fast it's pumped from the earth. For the amounts, the EIA took three different values based on the USGS data described in Appendix D. They looked at four different annual growth rates in production: 0%, 1%/year, 2%/year, and 3%/year. Production has grown somewhat less than 2% per year over the past two decades, and the EIA projects that the growth rate could be 1.9%/year for the next two decades [11]. If this rate of growth is borne out over the coming years and if the "mean" estimate of about 3 trillion barrels of oil proves accurate, then this simplified model predicts that production will more than double, to more than 53 billion bbl/yr, by 2038, and then fall off sharply thereafter. Production under this scenario would fall back to the levels of today by about 2045 and to 1950s levels by 2075.

Depending on the rate of production growth and the total amount of oil, the EIA model can produce estimates of the year of peak production ranging all the way from 2021 to 2112. (If one assumes that production will grow by at least 1%/year, however, the upper end of the range pulls in to 2067.) But all of the curves in Figure 11 have a somewhat dramatic appearance— soaring smoothly upward and then falling off a cliff as the production peak is reached and passed.

Will we fall off the cliff?

This "falling-off-the-cliff" behavior is exactly what many incrementalists do not expect to see. They anticipate that signs of tightening in oil production will stimulate price rises, which in turn will stimulate reductions in use, introduction of alternative fuel sources, and improvements in the technology of crude oil production. In this view, the peak will in fact be delayed and gently rounded, and the falloff less steep, while the gap left by the falloff will be filled by fuels from non-oil sources. Moreover, they do not believe that what has happened in the U.S. is necessarily a valid model for the world as a whole.

Will higher prices stimulate more discovery and recovery?

As is explained in Appendix D in the section on "An unequal distribution" at page 75, the sizes of oil reservoirs differ radically. At the level of oil provinces, more than 50% of known world oil is contained in only 1.7% of known oil provinces. Geologists believe that future discoveries of oil will follow similar patterns, in that most of the oil that will be found will lie in only a few reservoirs.

Large reservoirs give better returns on both exploration and production investment than small. The net effect can be seen in Figure 23, which shows estimates of how much more oil can be found and produced in land and immediate offshore waters of the U.S. as a function of cost.[39] Diminishing returns are very apparent.

One implication is that increases in oil prices associated with anticipated shortages will have only a fairly limited effect in increasing oil supplies. There is one aspect of the supply question which this does not address, however: *recovery,* or the percentage of the oil within the reservoir rock that can be recovered. Recovery varies a great deal with the geological conditions as well as the technology used, and yields of 50% or more are obtained in favorable conditions. But the general average recovery is more like 30% to 35%. If we accept the estimate that the world started out with about 3 trillion barrels of recoverable oil, then increasing recovery from 30% on average to 40% would provide an additional 1,000 billion barrels.[40] Thus there might be potential to stretch supplies significantly through investment in production technology.

How much this can be relied upon to significantly change the story told by Figure 11 is another matter. There are three mutually-reinforcing problems:

- This is the kind of technology which, so far, has not moved rapidly—as it would in order to materially cushion the sharp peaks of Figure 11.
- Even once proven and put into practice, new production technology has not tended to result in major increases in production rates. The more usual effect has been to reduce the falloff in production.
- Because of the huge production rates envisioned by the middle of the 21st century, even an added trillion barrels is unlikely to delay a decline by much more than 15 years. This seems surprising until we look at the curves of Figure 11 more closely. The difference in recoverable oil between the "mean" and "high" cases is about 900 million barrels—and the difference in peak year stretches significantly beyond 15 years only if growth rates remain below 1% per year.

---

[39] The U.S. makes a good example since there are good data and the USGS to analyze them. There is every reason to believe that the patterns are typical of the world in general.

[40] That is, the 3 trillion barrels represent the 30% of the total that is assumed to be recoverable, so increasing the recovery yield to 40% increases recoverable oil by 1 trillion barrels to 4 trillion.

We can certainly expect that economics-driven technology advances will have significant effects on discovery and recovery of oil. But it is much less clear that this will bring major changes in the "falling-off-the-cliff" peaks shown in Figure 11. It doesn't seem as if we should count on it.

Will prices respond smoothly and gradually?

It is certainly to be expected that, as oil productive capacity tightens, producers will raise prices. So long as there are many producers, none dominant, economic theory and experience suggest that their ability to raise prices will be disciplined by the free market. That is, prices will reflect oil's real scarcity relative to demand, suggesting that, absent any sudden and sharp changes in demand or supply, oil prices will change in a reasonably smooth and gradual manner as oil demand rises.

The important questions are:

- Will the market conditions be near enough to the ideal of perfect competition to allow this to happen?
- Will the stimulus of price rises be early enough and strong enough to ensure a smooth transition to alternative sources of fuels?

It seems, as we saw above, that the distribution of remaining oil resources will become yet more uneven as the century progresses. Many of today's significant producing nations are likely to enter their production decline phases within a decade or two at most. Some new resources will open up in remote areas of the Arctic, Antarctic, deep ocean, and elsewhere, but these probably will not have a large overall impact. It takes the equivalent of another new Mexico, Nigeria, or UAE to move the peak of production by a year, and it's unlikely that many new reservoirs on this scale will be found.

It could well be that at some time within the next two or three decades well over half of the world's remaining oil production capacity will come to lie in the hands of no more than three or four nations in single region: that around the Persian Gulf.[41] (In 1999, 28.5% of world oil production came from the Persian Gulf [12]. Productive capacity was not an issue, since there were many areas around the world in which it would have possible to raise production relatively quickly by investing in new facilities with prospects of very good return on investment.) This concentration of production in a few hands may very well lead to less-than-perfect competition on the supply side. It would seem to offer the producers an opportunity for a replay of the scenario of the 1970s, but with vastly greater market power.

Indeed, experience suggests that it can take relatively little departure from perfection in markets to lead to significant price shocks in conditions of rapid change. The recent electrical power crisis in California offers a case in point.

[41] See [EIA 2000c], p. 58 *et seq.* and [EIA 2000a], p. 37 *et seq.* for analyses of some of the possibilities over the coming two decades.

On the other hand, there is no prospect of perfect monopoly either. Even if an oil-producers cartel could somehow gain the adherence of every significant source of oil, it would not have utterly free control over prices, for consumers would still have alternatives. The alternatives may be expensive and painful, but there would be no way for producers to gauge consumer willingness to accept these penalties in advance.

The picture this suggests is one of a succession of price shocks, with price rises being followed in some cases by partial retreats. It will be in the interests of the suppliers to convey the impression that each rise is the one needed to attain "stability," since the prospect of continuing rises will tend to give consumers added incentives to seek alternatives.[42]

Will alternatives come forth promptly to fill the gaps?

As is made clear in Appendix E, there are a good many alternatives to dependence on crude oil as a source of fuels. Some of these are economically competitive today, to a limited extent, and it is likely that more economic competitors to crude oil will emerge over the next few decades, even if oil's price does not rise greatly. But the extent of these alternatives truly is very limited. World consumption of crude oil runs to more than 25 billion barrels each year today, while it appears that alternative liquid fuel sources and substitutes for liquid fuels total no more than a small fraction of this. It would take remarkably strong growth in development of alternative sources in order for them to reach even 10% of the fuels market within the next three decades, especially given that the fuels market is itself expected to grow vigorously in that period.[43]

So let us suppose that in the year 2035 (simply to take a concrete example) it comes to be widely believed that crude oil production is likely to begin falling within five years. We'll suppose that the gap between supply and demand is forecast to grow to more than 30 billion bbl/yr by 2050, taking account not only of falling crude oil production but also of continuing (albeit slowing) demand growth. Foreseeing a great opportunity, firms around the world embark on crash programs to bring on line alternatives capacity equivalent to 10 billion bbl/yr in 5 years, another 10 billion bbl/yr in 10 years, and a further 10 billion bbl/yr in 15 years. What's the likely result?

As can be seen from the discussion in Appendix E, the scope for sudden change-over to radical alternatives is very limited. Most of any alternative to crude oil is going to have to involve the production of liquid hydrocarbon fuels from other sources—which might include tar sands, oil shales, coal, natural gas, and

---

[42] Indeed, we have already seen the OPEC nations criticizing consumers for their failure to rein in demand and cite this as a factor that compels them reluctantly to raise prices.

[43] Again, it must be kept in mind that alternative sources will have to compete with an oil-geared system whose technology is constantly being improved.

biomass. Here's a brief summary of what is involved in each, drawn from Appendix E:

- **Tar sands.** The raw material has to be extracted by mining. After the ore is crushed, solvents are used to extract heavy oil or tar for processing. Mining is the controlling expense factor. Where deposits are shallow tar sands are economical to mine in some cases already. In many cases, however, deposits extend to depths of thousands of feet. Strip mining on the scale required for large-scale production raises significant environmental issues. Canada and Venezuela have some of the largest deposits.
- **Oil shales.** Here too, the ore has to be extracted by mining. Processing, involving heating the ore to 500°C or so, tends to be somewhat more expensive than for tar sands, but the issues and problems are otherwise broadly similar. The United States has extensive deposits. It doesn't appear that there is any economically competitive production of oil from shales at this point, but there are experimental plants.
- **Coal.** Again, mining is the first step.[44] Processing is complicated by the low hydrogen content of coal and coal generally is less economic as a liquid fuel source than tar sands or oil shales. Coal is not competitive as a source of oil today, but experimentation continues under government auspices—particularly so in the U.S., where coal reserves are especially great and coal producers have significant political influence.
- **Natural gas.** Liquid hydrocarbons can be produced from natural gas feedstocks via F-T processes. Other, more direct processes also are under investigation. If natural gas is used as the source for liquid fuels, it may be more attractive in some cases to convert consumption to methanol rather than hydrocarbons. There do not appear to be any commercial producers of liquid fuels from natural gas at this time, but the industry expectation is that this could prove economical for certain gas deposits.
- **Biomass.** F-T processes can produce liquid hydrocarbons from biomass, or alcohols can be produced by fermentation and distillation. Under optimal conditions, it takes an acre of land to produce 10 bbl of oil equivalent per year. It seems unlikely that biomass could be economically competitive as a source of liquid fuels under present conditions.[45]

Obviously, each of these alternatives involves investment in facilities to mine or produce the raw material as well as plant for processing. In terms of current prices, it seems likely that investment costs would be somewhere on the order of

---

[44] Some investigations are being conducted of means of producing syngas or liquids from coal *in situ,* rather than mining the coal for conversion in an above-ground plant. The prospects are difficult to assess at this point.

[45] There is subsidized fuels production from biomass.

$100 for each bbl/year of productive capacity added.[46] If so, this would mean spending roughly $1 trillion in five years and another $1 trillion for each of the two succeeding 5 year periods to support the program I've outlined. Given that world economic output is likely to be something on the order of $50 trillion per year at that point, this seems very ambitious, but not entirely out of reason.

Naturally, the risks and uncertainties would be enormous. Investors would have to be convinced not only of the demand but of the economics of the particular route they are being asked to support. Crude oil producers could feel incentives to withhold information that would make the imminence and extent of a falloff apparent, thus increasing investor uncertainties. Bringing expensive alternative capacity on line while crude still remained plentiful at reasonable prices could pave a path to bankruptcy on a massive scale. Even if oil prices had already soared, investors would be bound to reflect on previous episodes of sharp price rises followed by rapid price erosion.

It is important to recognize that the crude oil producers would hold great leverage for a long time, even past the peak of crude production. Crude oil can be produced at marginal costs of well under $5/bbl in the Persian Gulf and other favored regions [13]. If prices climb to $50/bbl or more, producer margins would be 1000% at very least. This would allow them great scope to cut prices for a while in order to put high-cost alternative producers under pressure. It would probably take several decades after the peak in crude production for crude volumes to erode to the point where this was no longer a serious threat to producers of alternatives. This is sure to temper enthusiasm for investment in facilities for alternative production. Investor confidence in the accuracy of engineering forecasts of costs will also play a role, as will expectations regarding public acceptance of environmental impacts. Finally, unforeseen technical or construction problems could have an impact.

In the long run, there is little doubt that alternatives will be brought into production sufficient to meet fuels demands. (Naturally, these demands will be lower if prices are higher.) But there seems to be every reason to anticipate a very turbulent period near the peak of crude oil production, and for a decade or more thereafter. Much will depend on investor evaluations of risks, and their risk-reward calculus. It would not be surprising if supply fell well short at some points. In fact, it would be rather surprising if it did not.

To sum up so far, we can reasonably foresee a course of events somewhat along the following lines:

- An increasing concentration of crude oil production capacity in the hands of a few nations—around the Persian Gulf especially, with Iraq and Iran very prominent. The Persian Gulf might come to hold more than 50% of the

[46] Investment costs to add a bbl/yr of crude oil production capacity are generally less than $30 today. See [EIA 2000a], page 33.

world's remaining accessible oil by 2020 or so, and the proportion could increase further.

- A sharp narrowing of the gap between potential production and consumption. Eventually, the gap will close altogether and it will no longer be feasible to maintain production rates. The production peak might come as early as the 2020s or as late as the 2060s, depending on how much oil there actually is and how fast production grows.
- An increase in prices as the slack in supply is taken up. This could be gradual and smooth, but a series of sharp price shocks seems much more likely.
- Massive investment in facilities to produce alternative sources of fuels as the peak of crude oil production is approached and passed. As these facilities come on line they will cushion the impact of crude oil's decline by providing sources of fuel. But the fuel they produce will be costly and it is unlikely that new production capacity will match demand smoothly.
- Continued dominance of the market by the crude oil producers for decades following the peak in crude production. While their share of fuels production will decline, they will have a large production-cost advantage that will give them great market power.

"Strategic" petroleum reserves

When oil and gasoline began to be important for military operations, early in the 20th century, attention naturally turned to security of supply. The concern was particularly acute in nations lacking domestic or nearby sources of supply. At the time that Japan initiated World War II in the Pacific, for instance, it had accumulated stocks of more than 50 mbbl, thought to be sufficient for nearly two years of wartime operations (although good for no more than a year at the actual rates of expenditure) [14]. This reserve was held in costly above-ground storage tankage. By the end of the conflict, Japan was reduced to sending warships on one-way missions because it lacked fuel to see them home.

In the Cold War era, the U.S. adopted a policy of stockpiling materials thought to be of strategic importance for supporting industrial mobilization in a war emergency. Various proposals were advanced for a strategic petroleum reserve (SPR), but no significant action was taken until the 1970s when, in the wake of the "embargo" scare, several salt caverns near the coast of the Gulf of Mexico were acquired for oil storage. Today, the U.S. has facilities for about 700 million barrels of oil, with about 570 mbbl of oil actually stored [15]. A few other nations also hold SPRs, but the U.S. reserve is the largest. Japan has an SPR containing more than 300 mbbl, Germany one of about 55 mbbl, and all other European nations together have about 10 mbbl, bringing the total to nearly 1 gbbl [16].

Nations belonging to the Organization of Economic Cooperation and Development (OECD)—which includes essentially all industrialized states—have agreed among themselves to keep oil stocks on hand equivalent to at least 90 days of net imports at normal rates. Most meet this commitment through commercial stocks in the hands of refiners and wholesalers. Commercial stocks amount to more than 2,600 mbbl, including about 930 mbbl in the U.S. [17]. Overall, the OECD's International Energy Agency (IEA) estimates that total stocks are adequate to cover more than 110 days of imports at normal rates, with commercial stocks contributing about 75 days of this [18]. It is likely that the substantial majority of commercial oil stocks are simply what is necessary for normal oil refining and supply operations and hence do less than might seem to contribute to price or supply stabilization.[47]

The U.S. policy with regard to the use of the SPR is essentially that crude oil from it will be sold to refiners at market prices when the government determines it to be necessary or desirable.[48] The criteria are broad and sales that have been made have all attracted political controversy. Nevertheless, it is likely that the existence of the reserve, even if imperfectly employed, has had some tendency to dampen price spikes. Use of market-based mechanisms, such as forward option contracts, to automate the determination of when oil is withdrawn would probably make the price-damping function more effective.

So long as oil is traded on worldwide markets, any SPR is inherently a worldwide public good—if oil is released from any SPR in response to price or supply fluctuations, all buyers of oil everywhere receive equal benefit.[49] Because those who do not pay for SPRs enjoy their benefits without cost, it is naturally difficult to persuade anyone to pay for them.[50] There have been recent proposals for a joint

[47] Some nations do have mandatory minimum stock requirements for refiners and wholesalers. There are estimates that in some cases these raise net stock positions in some cases by as much as 50%, but it is difficult to very certain. Of the roughly 1.5 gbbl of commercial stocks in Japan and Europe (the places where mandatory minima are commonly applied) we might guess that perhaps 400 mbbl would represent excess over those held to meet normal operating needs. See [APERC 2000], page 39.

[48] More precisely, under the Energy Policy and Conservation Act (EPCA), as amended in 1992, the President has the authority to order release of the SPR, if it is determined that: (a) an emergency situation exists and there is a significant reduction in supply which is of significant scope and duration; (b) a severe increase in the price of petroleum products has resulted from such emergency situation; and, (c) such price increases are likely to cause a major adverse impact on the national economy.

[49] In extreme circumstances in which markets break down, of course, the owner of the SPR may get special benefit from it. In Japan, part of the SPR is held in the form of products that are less widely traded, which tends to localize benefits somewhat more.

[50] The capital costs for salt-cavern storage are typically of the order of $5/bbl. Operating costs are dominated by those of financing the inventory and thus will be sensitive to the price of oil. At current prices and given the low financing costs of major governments, costs on the order of $1/bbl/yr will be typical. When the oil is sold to counteract price rises, a profit will normally be realized, of course. But if the NPV of such future profits were positive, there would be no need for governments to act, since commercial interests would set up reserves as a profit-making enterprise. See [APERC 2000], pp 47-50.

SPR for the nations of the Asia Pacific Economic Cooperation (APEC) group, but it appears that action is not in immediate prospect [19].

The capital costs for salt-cavern storage are typically of the order of $5/bbl [20]. Operating costs are dominated by those of financing the inventory and thus will be sensitive to the price of oil. At current prices and given the low financing costs of major governments, costs on the order of $1/bbl/yr will be typical—a cost which would rise if oil prices were to increase. When the oil is sold to counteract price rises, a profit will normally be realized, of course. But if the NPV of such future profits were positive, there would be no need for governments to act, since commercial interests would set up reserves as a profit-making enterprise. Calculations are sometimes offered regarding the public benefits to be realized from an SPR, but these generally depend on macroeconomic forecasting models of questionable validity.

In effect, the public-good nature of SPRs means that for economic purposes there is just one worldwide SPR, comprising the publicly-owned SPRs (principally those of the U.S., Japan, and Germany) plus some poorly-known portion of the stocks in commercial hands. At a rough estimate, this amounts today to something like 1.5 gbbl. Because it is a worldwide public good, the meaningful measure of the world SBR is its relationship not to import volumes but to total world consumption, running to about 75 mbbl/dy at present. At this rate, the world SBR is equivalent to about 20 days. Call it the *duration* of the world SBR.

The world SBR is a buffer against shocks, like the suspension of a car running on a rough road. The duration is like the suspension travel. Twenty days of suspension travel will help to smooth a lot of bumps. But it won't help much if our oil supply car runs off a cliff, and even a major Washington-DC type pothole may do a lot of damage with only 20 days of cushion.

Leaving aside the question of who will pay, it does seem as if more than 20 days of duration would be worthwhile. If there is any substance at all to the scenario of mounting price shocks to come that I have sketched above, an SBR with 90 days or more of duration could very well seem a wise investment. Even 90 days would not do much for a cliff, but it could help absorb some pretty big potholes.

Hotelling and the theory of exhaustible resources

When confronted with questions regarding the economics of petroleum, a great many economists think immediately of a theory associated with the name of Harold Hotelling (1895-1973), a very eminent economist and mathematical statistician who taught at Columbia University and was a member of the National Academy of Sciences, and who is remembered for a number of very fundamental contributions.[51]

[51] Hotelling was as much mathematical statistician as economist, and eventually left Columbia's economics department to take up an appointment as professor of mathematical statistics at the

One of Hotelling's papers addressed "the economics of exhaustible resources" [21]. In it he sought to answer questions such as

- "How much of the proceeds of a mine should be reckoned as income, and how much as return of capital?
- "What is the value of a mine when its contents are supposedly fully known, and what is the effect of uncertainty of estimate?
- "Is it more profitable to complete the extraction within a finite time, to extend it indefinitely in such a way that the amount remaining in the mine approaches zero as a limit, or to exploit so slowly that mining operations will not only continue at a diminishing rate forever but leave an amount in the ground which does not approach zero?"

Hotelling addressed these very complex and subtle questions at a time when data were quite sparse and computers nonexistent. He took a theoretical approach, relying heavily on the mathematical apparatus of the calculus of variations. Notwithstanding the power of this technique, he was forced to make radical simplifying assumptions in order to get anywhere. The crucial simplification is that "this paper will be confined in scope to absolutely irreplaceable assets."[52]

In essence, he likened the owner of a completely fixed, irreplaceable, and exhaustible resource to one who had buried a treasure. It would be reasonable to keep it in the ground, Hotelling pointed out, if its value were increasing fast enough to make holding it an attractive investment.

This led Hotelling to posit that, all else equal, the value of a deposit of an exhaustible mineral ought to rise at a rate commensurate with the rate of return on other investments, such as bonds. Otherwise, he argued in effect, the owner would be wise to dig the treasure all up, sell it off, and put the proceeds in a better investment.[53]

This particular part of Hotelling's work was not widely remembered until it was revived in the 1970s by another extremely eminent economist, Robert M. Solow, MIT professor and Nobel laureate [22].

Hotelling's Rule (as it is often called) is taken to imply that the price that producers charge for oil, net of the costs of production, should increase like compound interest—exponentially. If oil is thought to be an especially secure investment, for instance, then perhaps its price might grow by as "little" as 3%/year in

---

University of North Carolina. At the time of his work on exhaustible resources, he taught mathematics at Stanford, specializing in economic applications. See [Darnell 1990] for an appreciation.

[52] [Hotelling 1931]. As reprinted in [Darnell (ed) 1990] it falls on page 66. Anyone consulting the article is advised to do so in the reprint in preference to microfilm copies of the original, which often obscure critical subscripts in the mathematics. For a modern treatment of the theory, going well beyond Hotelling, see [Dasgupta & Heal 1979]. [Heal & Chichilnisky 1991] and [Solow 1974] provide less technical brief summaries.

[53] There is a great deal more to the paper than that, and indeed this is really only the largely-unexamined premise from which Hotelling begins his explorations.

real terms (i.e., over and above any general price movement due to widespread inflation or deflation). At this rate, its price would double in less than 24 years. But if oil seems a bit less secure (perhaps because those who hold it feel insecure in their places, for instance) and the "natural" rate of growth in its price is taken to be 6%/year in real terms then its price would double in 12 years.

The natural corollary of the exponentially increasing price of oil should be rapidly decreasing use, as fewer and fewer users are able to afford it.

The trouble with all this is that it rests on a theoretical simplification that is more limiting than might seem. Recall Hotelling's caution that "this paper will be confined in scope to *absolutely irreplaceable assets*" (my emphasis).

As an economist, Hotelling well knew that there are no absolutely irreplaceable non-monetary assets.[54] At some level, each good is of course unique and irreplaceable. But from an economic standpoint, all goods are to some extent substitutes for one another. No two oil reservoirs produce oil that is exactly the same, but with some adjustments in refining equipment and technique, refiners have found they can deal with a lot of variation. High-sulfur "sour" oil, once thought to be all but worthless due to refining problems, now is nearly as valuable as "sweet" grades. The bitumen from tar sands is different from crude oil, but with some treatment can serve adequately as a substitute. Coal doesn't seem much like oil, but a serviceable oil can be made from it. Hydrogen gas is only distantly related to oil, but may serve even better as a fuel when married to a fuel cell. Even photons of sunlight or thermal neutrons from the fission of uranium can be used to provide replacements for oil—and so can muscular energy for walking, or electronic transmission instead of physical transportation.

While the principle of substitution had earlier been clearly enunciated, its ramifications were much less apparent in the time of the Hoover administration than they are today. Subsequent research in the economics of growth and technical change has made it clear that a great deal of technological progress has to do with efforts to make goods more substitutable one for another. If A is expensive and B is cheap, one can make a great deal of money by finding ways to substitute B for A. In the race between exhaustion and the technology of substitutability, substitution has been winning. Not in the sense of substituting other things for oil (not yet) but in discovering and developing new sources, including making "high-cost" or "uneconomic" oil into a commercial proposition.

In this paper, of course, I argue that technological efforts to improve substitutability for oil have certain limits and cannot be relied upon to smooth all paths perfectly. But this is a far cry from assuming that they do not exist or will never yield any worthwhile results.

---

[54] Money is an exception because it is the universal asset, subsuming all others, and thus occupies a class of one. This is the point behind my description of Hotelling's theory as the economics of buried treasure. Strictly, however, even this applies only to perfect or ideal money, of which actual monies are only approximations.

Oil is a business not of absolute irreplaceability but of a competition between exhaustion and substitution. So far, the progress of substitution has outweighed that of exhaustion. What is remarkable is not that this was somewhat obscure to Hotelling, seven decades ago, but that it seems obscure to so many of his colleagues of today.[55]

The difficulties of the Hotelling theory can perhaps be better appreciated in the context of another "irreplaceable" mineral—copper. Copper has been used continuously by humans for more than 8,000 years, and has been a major basis for material civilization for more than 5,000; copper mining has been a major industry for more then five millennia. If the average rate of interest over that period had been as low as 0.5% then the value of a ton of copper-bearing ore of a certain grade ought to be higher than that in 3,000BC by a factor of about 68 billion. That is to say that if a ton of ore had been worth $0.001 5,000 years ago it would be worth $68 million today. In fact it is clear that interest rates have mostly been well above 1% throughout this period, and copper prices are probably lower than at any point in history. The only way to square these facts with the theory is to change radically what one means by "interest rate".

It is also surprising that the only aspect of Hotelling's work in this area that is usually referred to is his opening premise regarding mineral values. The question he addressed was not primarily that of the value over time of mineral deposits but the behavior of their sellers. Even with very sophisticated techniques, he had to make strong assumptions in order to render the problem mathematically tractable. We can see now that the assumption of absolute irreplaceability was a bit too

---

[55] Some authors argue that oil's widespread economic importance makes it necessary to look beyond the oil market itself and study its interactions with other economic systems. In economic terms, they seek a *general equilibrium model* rather than a *partial equilibrium model.* In so doing, it is very tempting to accept, as Hotelling did, the "Hotelling Rule" in order to make exact analysis tractable. As the discussion of this section suggests, this is a very dangerous temptation, which should be accepted only knowingly and with due cautionary warnings to the reader. Existing treatments do not pass this test.

Various efforts have been made to subject Hotelling-like models to empirical tests. Even when relying only on very brief segments of oil's 142-year price history, these efforts have generally yielded positive results only in the case of model variants with enough free parameters as to cast serious doubt on their significance.

strong—it drew his model too far away from the facts of the real market. But the questions he raised remain very relevant, and can now be addressed with more powerful tools and better data.

Appendix B
Doomsters, cornucopians, and incrementalists

I'm going to sketch three positions, which I call the doomster, cornucopian, and incrementalist viewpoints.[56] I start with the doomsters, because it's easier to explain the others in contrast to this position.

Position 1: *doomster*

Those who I call the *doomsters* believe that the end is in sight, that oil supply is destined to get tighter rapidly, starting very soon. We could equally well have called this the *oleo-Malthusian* view.[57]

Hubbert and doom

Some people know it as the *Hubbertist* view. M. King Hubbert (1903-1989) was a pioneering geophysicist who taught at Columbia and elsewhere, and worked for the oil industry and the U.S. Geological Survey (USGS). He made important contributions to geophysics and received many honors, including election to the National Academy of Sciences. He was a founder of the "technocracy" movement and expressed disdain for academic economics—not uncommon among "hard" scientists and technologists of his generation, who had experienced first-hand the economic turmoil of the Great Depression.

In the 1940s, Hubbert began to warn that oil resources were finite and that production must inevitably peak and decline [23]. Other geologists had been saying similar things at intervals over the preceding 80 years; their predictions had proven wrong time and again, and people turned to this record of failure in dismissing Hubbert's warnings. But Hubbert introduced a new device—he analyzed oil production using the logistic curve. A logistic curve is simply an S-shaped curve of a certain mathematical form, with free parameters allowing it to assume a variety of particular shapes. It is often used to fit data representing product life cycles or the growth of animal or plant populations. There's no real theory of the logistic curve—it's simply a convenient way to fit data concerning things that grow slowly

---

[56] I mean these labels to be convenient and evocative, but not prejudicial. None of these views is altogether without merit or reason, as I will show.

[57] Many oil doomsters are not doom-sayers in any larger sense—they think that oil will run out but expect that civilization will find other ways to meet its energy needs. Thus their differences with cornucopians often are more of degree and emphasis than of kind. There are, to be sure, some others who foresee much more dire results as oil is exhausted.

at first, then increasingly fast, and then slow down again and finally stop growing as some natural or imposed limit is reached.

In the right circumstances, logistic curves can be useful for predicting processes of these sorts, and so it proved for U.S. oil production. In 1956, Hubbert read a paper containing a prediction that U.S. crude oil production would peak out between 1965 and 1970; in fact 1970 did turn out to be the peak year [24]. Doomsters generally cite Hubbert's prediction as an example and adopt at least some of his methods.

Hotelling and doom

A rather different version of doomsterism is associated with the name of Harold Hotelling (1895-1973), a very eminent economist and mathematical statistician who also taught at Columbia and also was a member of the National Academy of Sciences. According to the theory that is associated (a bit misleadingly) with his name, we are doomed to steep and perpetual rise in oil prices.

Because these views still command wide currency among economists, I have addressed Hotelling's work in a section of Appendix A, at page 47.

Position 2: *cornucopian*

Cornucopians are impressed with nature's abundance and humankind's ingenuity and resourcefulness in exploiting it. They don't believe that we will ever truly "run out" of oil, and think that any problems arising from exhaustion of the Earth's supplies of conventional liquid petroleum will be minor, transitory, and far in the future.

It may be best to distinguish two somewhat different flavors of cornucopianism: *rational cornucopians* and *empirical cornucopians.* The empirical cornucopian says, "People have been warning about running out of oil for well over a century, and we've always found more. There's no need to worry."

The rational cornucopian acknowledges that oil resources must indeed be finite, and that we could conceivably exhaust them at some point well in the future. But he argues that there are a great many potential substitutes, and that if liquid petroleum ever should come into short supply, we'll find ample alternatives.

Naturally, the empirical cornucopians don't cite any particular theorist to support their position, preferring to rely on their own "common sense" (although they clearly don't hold it in common with, say, the doomsters). A name sometimes heard from rational cornucopians is that of Julian Simon (1932-1998), a business economics professor at University of Maryland who devoted much attention to the economics of population growth.[58]

[58] Simon's views on oil are summarized as part of a much broader cornucopian manifesto in [Simon 1996].

Abiogenesis and cornucopianism

Another variant of cornucopianism merits mention: A few (very few) earth scientists have argued for a variant theory of petroleum formation that could imply that there is a great deal more of it than usually allowed. We'll look at this idea in the course of examining what is known about petroleum formation in general in Appendix C at page 61.

Position 3: incrementalist

Incrementalists think we may run short of oil, but not suddenly. They expect that any eventual tightening of supplies will prompt higher prices, which in turn will lead to incremental and orderly development and substitution of other energy sources. They see little reason to believe that this will take place soon—in a few decades, perhaps. Or perhaps later.

In the meantime, unlike Hotelling doomsters, the incrementalists believe that oil should remain easily available at low prices.

Sorting it out

The divisions among the various species of doomster, cornucopian, and incrementalist are not clear or neat. They don't all address the same issues or look at the same facts. Where they share facts, they may differ in how they look at them. At the same time, there are shadings and overlaps.

But in brief, however, here are the traps for the unwary in all these views:

Hubbert doomsterism

Hubbert, for all his intelligence and foresight, got it wrong on two counts:

- There is a lot more oil than he knew. See Appendix D, page 71, for much better recent data.
- There's no particular reason to expect oil production to follow a logistic curve. Indeed, there is plenty of reason to doubt that it should. See the section on "Simplified models of growth and decline" in Appendix A (page 38) for a summary of a better informed and more sophisticated analysis.

It's a bit of a mystery why people keep quoting Hubbert or insist on repeating mistakes that were probably unavoidable 40 years ago but should be very avoidable today.

Hotelling doomsterism

Hotelling, another brilliant researcher of an even earlier era, constructed an elegant abstract theory that simply doesn't apply at all well to oil as it actually is. He did know that oil was not the "absolutely irreplaceable asset" of his theoretical construct, but did not adequately account for this in his theory. (Perhaps could not have, with the tools he had then.) Again, the mystery is why people today, with vastly better information and more powerful analytical tools, do not re-examine the issue more fully and carefully rather than relying altogether on Hotelling's work of 70 years past.

Cornucopianism

Cornucopians are extrapolating from the past, relying on some species of principle (usually unstated) of regularity and continuity in historical process. This can involve them in two major defects:

- As more and more matters involving historical processes come under serious scientific scrutiny (especially in the earth sciences and evolutionary biology) it becomes more an more clear that while regularity and continuity are indeed the rule, there are occasional but important departures from this rule.
- Where two or more evolutionary processes with different dynamics interact, the results may be quite different from what would be expected on the basis of regularity and continuity at a composite level.

Abiogenic cornucopianism

Abiogenic cornucopians are relying on a very weakly supported and suspect theory of petroleum's origins. Additionally, as outlined in Appendix D, at page 79, even validation of much of the theory (a very remote prospect at present) would not of itself dictate cornucopian conclusions.

Techno-cornucopianism

Many cornucopians say, in effect, "Good riddance to oil, for *X* will take its place and leave us the better off for it"—where *X* may be anything from biomass to nuclear power. Appendix E (page 83) is devoted to sober consideration of a broad range of possible *X*s, and shows that few of them measure up well to cornucopian enthusiasms.

Incrementalism

Problems often besetting incrementalist views include:

- While incrementalist skepticism about efforts to foretell the future makes a very important point, there is more good and solid basis for prediction than many would admit, particularly in the sense of drawing bounds on the possibilities.
- Incrementalists rightly stress the responsiveness of technological development to economic incentives but often gloss over
  - The time dimension of engineering development

    - The complexity and uncertainty of the incentives in reality, and the resultant cross-currents in development of technologies

- Incrementalist expectations of orderly and relatively smooth change are founded in economic theories which assume perfect competition. The oil market of course departs notably from perfect competition today, and I suggest that it may well become even less competitive in the future.

Appendix C
Oil
From formation to product

Nature and origins

It is important to understand what oil is and how it is formed in order to understand its supply.

Constituents

The principal part of oil is a mixture of a great many hydrocarbon compounds. There are other components, but for the most part they are undesirable, or at least less valuable than the hydrocarbons.

Oil generally is a mixture of hundreds of distinct hydrocarbon compounds, whose proportions largely determine the oil's characteristics. Overall, commercial crude oils typically contain 82 to 87 percent carbon by weight and 12 to 15 percent hydrogen. The rest comprises non-hydrocarbon components consisting largely of oxygen and sulfur, with smaller amounts of nitrogen and traces of other elements. Oils in which hydrocarbons are more greatly diluted with other substances usually are not regarded as attractive for commercial use due to the waste involved in separating the undesired components.

As their name suggests, hydrocarbons consist of hydrogen and carbon—and nothing else. Hydrogen and carbon (symbolized H and C, respectively, by chemists) are unusual among chemical elements in the wide variety of ways that they will combine. Hydrocarbons which contain small numbers of H and C atoms per molecule are generally gasses at ordinary temperatures and pressures. Methane (CH_4) and ethane (C_2H_6) are the principal constituents of natural gas. Propane (C_3H_8) and butane (C_4H_{10}), often found in combination with oil, also are gaseous at room temperature and pressure.

The hydrocarbons which make up the bulk of most crude oils have anywhere from 4 to 36 carbon atoms per molecule, arranged in chains or rings, with varying numbers of hydrogens (but usually roughly twice as many as carbons). Generally, the hydrocarbons with smaller numbers of carbon atoms tend to have lower boiling and melting points and to flow more freely at normal temperatures.

Petroleum formation

Oil and gas (and also coal and other forms of fossil hydrocarbons) are formed from "organic residues"—dead material left by plants, animals, or (especially, in the case of oil) algae. Scientists have traced the processes of petroleum formation by examining petroleum deposits and their precursors and remains at various stages of development and by simulating portions of the processes in the laboratory [25].

There is no one single way in which petroleum is formed. A number of different routes can lead to oil and/or gas. But all involve a sequence of biochemical, geochemical, and physical transformations of the original organic residues. In broad terms, these include:

- The organic residues are mixed in a mud, usually at the bottom of a body of water, or perhaps in a marsh or swamp, that seals them from contact with the atmosphere or oxygen in the water. The mud has enough clay to provide a seal but not so much that the organic material becomes too dispersed.
- The mud (like everywhere else on Earth, and to a depth of several kilometers within its rocks) is host to a great many bacteria. They feed on the organic residues, multiplying in this nutritive environment. When they die, their remains combine with what they were not able to consume to form *kerogen,* an insoluble waxy substance rich in precursors to hydrocarbons [26].
- The area in which the mud is deposited subsides or is rifted, so that it does not get eroded. As the mud is buried ever more deeply, it is compacted into rock, usually a shale. The organic residues, now transformed into kerogen, remain dispersed in small pores throughout the rock.
- As the *source rock* containing the kerogen is buried or folded deeper in the Earth, the pressure and temperature increase. Temperature is most important in oil formation, although pressure plays a part as well. At a depth which may vary from a few hundred meters to 2,500m, depending on the temperature profile or *geotherm* in the area, the source rock enters the *oil window,* at a temperature of about 50°C (122°F). How readily oil is formed in this window depends on the nature of the source organic residues as well as their biochemical history and the chemistry of the rock. If the residues contained a great deal of lipids (for instance from algae), oil forms readily. If they consisted primarily of woody material, oil formation is less likely. Oil formation peaks at temperatures around 100°C (212°F).
- As the source rocks sink deeper and come under greater pressure and heat, gas is more likely to be formed. If the temperature increases beyond about 140°C, oil will be broken down to gas. At still higher temperatures, 200°C or more, solid carbon (graphite) and methane gas will be all that remain.
- Under certain circumstances, some of the oil may be entrained in water seeping through the pores of the rock and carried to other rocks before the source rock comes under too great a pressure and temperature. If it reaches porous rock, such as sandstone, the oil will move relatively freely and tend to float to the top of the water. If the porous rock lies under an impermeable layer of *cap*

rock and if the geometry of the impermeable cap rock is right, a *trap* is formed under which the oil is captured within the porous *reservoir rock*.

- If the oil is not effectively trapped it may reach the surface in a *seep,* where it will evaporate and/or be broken down by biological processes. It may also be destroyed or degraded within the Earth, particularly if rock fracturing or other processes allow it to come into contact with air.
- Over long periods of time, hydrocarbons will diffuse through even relatively impermeable cap rocks, so that there is a limit to how long oil and gas can remain trapped.[59]

Clearly, there is a long chain of circumstance leading from the deposition of organic residues to oil in trapped reservoirs. Many things could interrupt or deflect the process. Overall, it is estimated that less than 0.1% of the organic residues originally laid down in muds ever form trapped oil or gas.

Because oil is broken down to gas at high temperatures, there is little point in looking for it in any rocks which are hotter than about 175°C, or have experienced such a temperature in the period during which oil was in them. As a result, the vast majority of oil deposits lie at depths of no more than 5km. Petroleum geologists speak of the *oil deadline,* or level below which the temperature is too great to permit the survival of liquid petroleum.[60]

Some of today's petroleum deposits were formed from organic residues laid down more than half a billion years ago, when life was still very primitive. More than half, however, come from the past 150 million years. The rate of formation has been very irregular, with more than 70% of all petroleum coming from three intervals spanning only about 100 million years [27].

Other origins for petroleum?

When scientists first considered the question of petroleum formation in the 19th century there were some who thought it likely that hydrocarbons were formed not from organic residues but from inorganic reservoirs of carbon and hydrogen deep within the Earth. Of course it is impossible to know with certainty what has occurred deep within the earth over the millions of years that it has taken for petroleum to develop. But the *biogenic* theory of petroleum origins has come to be very widely accepted on the basis of a variety of strong evidence:

- Crude oils have consistently been found to contain a variety of substances known to be more or less closely associated with living organisms.

---

[59] Recent evidence, however, seems to suggest that this diffusion process can be a good deal slower than has been supposed, leading to speculation that it may be productive to look for petroleum in much older formations. See [Ballentine et al 2001] and [Marty 2001].

[60] This discussion has been simplified: rock composition, pressure and time spent at temperature also play a part in determining the oil window and deadline, and the values of the parameters are not known with precision. See [Dahl *et al* 1999] and [Rowe & Muehlenbachs 1999].

- Drilling into the Earth has yielded samples of all of the intermediate products thought to have occurred in the formation of petroleum, some of which retain strong connections to organic residues.
- It has been possible in the laboratory to model most of the critical steps in biogenic petroleum formation.
- All petroleum deposits discovered to date lie in places that are consistent with present geological models of how petroleum might have been formed.
- The estimated rates of biological activity in past eras of Earth's history are sufficient to have provided ample raw material for petroleum formation.

Nevertheless, there continues to be interest in *inorganic* or *abiogenic* theories of petroleum formation on the part of a few scientists. Much of this interest is in Russia, where prominent scientists have held to abiogenic views since the 19^{th} century. The only notable proponent of abiogenesis in the West seems to be geophysicist Thomas Gold, emeritus professor of astronomy at Cornell and a fellow of the Royal Society as well as member of the National Academy of Sciences [28].[61]

The entry of an astronomy professor into this issue is not so strange as at first it might seem. Once thought to be exclusively of terrestrial and biological origin, hydrocarbons have now been found in many places in the Solar system. Thus it is clear that they can be produced by non-biological processes, as well as by biological action. Building on this fact, Gold and a few others argue that all the phenomena of petroleum can be explained on the basis that it comes not from transformed organic residues but *entirely* from sources and processes deep within the Earth—and explain them better than theories of biological origin [29]. While most scientists outside Russia think this most unlikely, the available evidence does not appear to be sufficient to resolve the issue with absolute conclusiveness.

One problem faced by abiogenic theorists is that continuing investigation of petroleum samples brings forth new markers of biological origins which seem difficult to explain in terms of the non-biological models so far proposed.[62] One crucial point of Gold's theory is that biological activity within the Earth is responsible for the biological markers that can be seen within petroleum. Indeed, his recent book is entitled *The Deep Hot Biosphere,* referring to this part of his thesis [30]. Remarkably, however, the book does not refer to or cite much of the work that has recently been done by microbiologists in recovering and studying microorganisms from deep within the Earth [31]. The picture that emerges from these efforts (still in a relatively early stage, to be sure) seems on the whole much more consistent with a gradient of life that runs from the surface of the Earth down toward its depths than the other way. Gold's theory seems to demand that microorganisms must exist at depths greater than those of any petroleum deposits, or at least

[61] I classify Gold as a geophysicist on the basis of his National Academy member listing.

[62] See [Dahl *et al* 1999], [Schoell & Carlson 1999] and [Fehn, Snyder & Egeberg 2000] for some recent examples.

greater than those of any oil. None have been found at depths greater than 2.8km, however, which is not deep enough for Gold's purposes [32].

While the assertion of *exclusively* or even predominantly non-biological origin of hydrocarbons meets with widespread skepticism, and notwithstanding the arguments made by Gold and others that all hydrocarbon deposits must have similar origins, many scientists would agree that *some* natural gas deposits may possibly be abiogenic. Some so-called *dry gas* deposits consist almost exclusively of methane and ethane, both known to have been produced in large quantities abiogenically in the Solar system and both too simple to carry unambiguous links to their origin, whether biological or non-biological. There is evidence that methane is brought up from the interior of the Earth in connection with volcanic flows, and it seems possible that there may also be cases in which dry gas from within the Earth forms concentrated deposits.[63]

Exploration

The science of geology has progressed greatly in the past few decades, both in its understanding of the processes molding the Earth and in its accumulation of data about the Earth. Geologists now have a reasonably comprehensive understanding of where the formations most likely to contain oil and gas lie [33]. Prospecting for oil, once largely a matter of "feel", now is almost entirely in the hands of those with professional training in geology and related scientific fields. This is not to say that finding oil is itself a "science" in any strict sense, but that scientific knowledge and methods play a very large part in the search.

According to the model of oil formation outlined above, there are several essentials for oil:

- ***Source.*** There must be sedimentary rocks that could have been formed from muds rich in organic residues.
- ***Reservoir.*** Some rock of the right permeability must be available that could have received and captured the oil from the source rocks. Because oil can migrate over distances of tens of kilometers or more over geological time, the reservoir need not be particularly close to the source.
- ***Geotherm.*** The temperature at the depth of the source must have been in the *oil window* at some point in its geologic history, and that of the reservoir must not exceed the *oil deadline*.

[63] Terminology can be confusing. Methane is formed directly by many biological processes, so that methane deposits can in some instances be *biogenic* in an immediate and present sense: having been made very recently by *methanogenic* organisms which metabolize organics and excrete methane as waste. So people sometimes speak of gas produced from fossil organic residues as *abiogenic* (or *thermogenic*) in the sense that they are not being manufactured by contemporary organisms and their formation depends on geochemical as well as biochemical processes. This is different from the sense in which Gold and like-minded individuals use the word *abiogenic*.

- ***Trap.*** There has to be an overlying impermeable geological trap that will have prevented the escape of the oil from the reservoir.

Even if there were oil of abiogenic origin, there would still have to be a reservoir overlaid with a trap, which would have to lie above the oil deadline.[64]

Prospectors probe the earth in regions of interest using seismic sounding techniques akin to those of sonar.[65] As likely formations are identified, they can be probed in increasing density, until finally a three-dimensional picture is built up, with resolution to a fraction of a kilometer.

Notwithstanding the effectiveness of these remote sensing techniques, it is an axiom of the industry that you can never count on oil until an exploratory or *wildcat* well has brought up samples for analysis. Disagreeable surprises are much less frequent than they once were, but science has by no means banished them. Each well is an elaborate engineering project, and especially so when drilled in areas where access is very complex. Exploratory wells are different from production wells, although in suitable circumstances a successful wildcat may be *completed* as a production well.

Production

A producing well taps a *reservoir* or *pool* of oil. At one time people thought that oil lay in literal pools, within rock caverns. It's been known for 75 years that this is inaccurate, but the terminology lingers. How big a pool one well can tap depends on the porosity of the reservoir rock, the location and frequency of faults or other discontinuities in the rock, the viscosity of the oil, and the *drive* or source of pressure.

Usually there is a *field*—meaning that there's more oil than can reach a single well bore. Additional wells need to be sunk at intervals to tap all of the oil.[66]

The pressure that is driving the oil into the well bore may come from a variety of sources. As more and more oil is *produced* or *lifted,* the drive will fall off (except in certain cases where it is very great compared to the amount of oil in the reservoir). The rate of production needs to be adjusted by the petroleum engineers to make most efficient use of the drive. This means that for any given well, the rate of production will fall off progressively over time.

---

[64] The theory of abiogenesis has significant implications in the case of exploration for gas, where it would predict deeper gas deposits than are usually thought likely. It also predicts that oil and gas might be found far from any potential "source rocks" (and indeed denies that there are any proximate source rocks). It is claimed that some oil prospectors have taken up abiogenic theories to guide their explorations, but it is not clear what the implications of this might be.

[65] In fact, a great deal of oil exploration technology has found its way into use in sonar.

[66] It may be possible and economic to branch off additional bores from a single well rather than drill more near it. But most fields will still require more than one wellhead.

Eventually, the oil entering the well bore will slow to a trickle, usually long before anything like all of the oil in the reservoir has been lifted. If it is economical to do so (which depends on the circumstances) the engineers will set up means for *secondary recovery.* In effect, this means supplementing the natural drive with artificial means, such as injecting gas under pressure in some wells to drive the oil to others.

When secondary recovery trails off, it may pay to go to *enhanced oil recovery (EOR)* or *tertiary recovery,* using more drastic steps to promote flow into the well bore.

In addition to the constant effort of pumping and periodic normal routine equipment maintenance, it usually is necessary to conduct occasional *workover* drilling to keep a field producing optimally. This may be to repair the ravages of time on well bores or to adjust well configuration to meet changes in conditions as the reservoir is drawn down.

Sooner or later, the pool no longer produces enough oil to pay for the well operations. At this point the well is finally *abandoned,* with a concrete *cap* to ensure against leakage.[67] This may be a long time in coming—some wells continue to produce for a century or more, albeit at declining rates.

The initial rate of production from a pool will depend on its natural characteristics (especially rock permeability, reservoir drive, and oil viscosity) and also on the facilities installed by the producer. Generally, production rates will be higher if well bores are bigger and more numerous, up to limits set by reservoir characteristics. Of course it costs more money to put in larger facilities and more of them. Thus there are economic tradeoffs, discussed in Appendix A at page 27.

The tradeoffs often favor limiting production in the first portion of a pool's life in order to economize on drilling and outfitting, thus resulting in "flat" production rates for a year or two before production starts to decline. Sometimes, nature helps. In some cases, the nature of the drive is such that there is no appreciable production falloff even at high production rates. For instance, when the drive is provided by water under the oil, and the volume of this groundwater is much, much greater than that of the oil, production may continue at high rates for much of the total life of the reservoir. (Water intrusion into the oil-bearing strata is usually the limiting factor in these cases.) Complete water drive also typically leads to very high rates of recovery—as much as 85% or 90% of all oil in place in favorable cases. Unfortunately, circumstances this good are relatively uncommon.

In most cases the drive gives out long before all the oil has been lifted. Even with use of secondary and tertiary recovery, in cases where they are economically warranted, only about a third of original oil in place can be lifted, on overall average. Of course a higher price for oil would justify more aggressive use of recovery

---

[67] Of course the well may also be converted to other uses to support the field operation, such as injection of water or gas to improve the drive to adjacent wells.

technology (as well as intensified search for improved technology). But cases vary so much that it is difficult to be sure how greatly recovery might be improved overall as a function of cost.

Because of the many factors involved, the production curve for a pool operated in an economically optimal way may not be very simple or smooth. But for overall planning purposes, it is usually satisfactory to approximate the production curve as having a constant rate of decline, following an initial flat period.[68] The decline may vary a great deal from case to case depending on nature, economics, and circumstances. A rate of about 7%/year is broadly typical, but it can be much lower or higher. And of course it can be effectively 0 for long periods in some cases, as described above.

Liquid products

As mentioned above, crude oil consists largely of a mixture of a great many different hydrocarbons. The process of *refining* turns crude into *products* by separating various hydrocarbon *fractions* and transforming them by chemical means. Before refining it may be necessary to reduce the concentration of undesirable constituents such as sulfur, salts, or metals in order to improve the efficiency of the refining process, reduce corrosion of the refinery apparatus, and avoid poisoning catalysts.

The first step in refining proper is *fractional distillation,* in which the crude is heated to progressively higher temperatures. This vaporizes hydrocarbons, which are driven off from the liquid and collected for condensation. The fraction which vaporizes at the lowest temperature is straight-run gasoline, followed by naphtha, and light and middle distillates. Further heating in a partial vacuum produces heavy gas oil. The remainder may be a tarry residual oil or a near-solid asphalt.

Since gasoline demand is high relative to that for other products, refiners help nature along by *cracking* heavier fractions to make more of the lighter gasoline. Emulating nature, they heat these fractions under pressure, in the presence of catalysts, breaking down or cracking the larger hydrocarbon molecules to the smaller molecules that make up gasoline. It will be necessary to supply additional hydrogen as well, usually obtained by dissociation of methane from natural gas. By modifying the processing parameters they are able to select preferentially for molecular species that will give the product desired characteristics, such as anti-knock performance. Similar approaches are applied to produce other special products, such as jet fuels of various compositions.

---

[68] In mathematical terms this means that production rate, after the flat period, is represented by a *negative exponential* function: $q = q_0 e^{-at}$, where q_0 is the initial production rate, a is the rate of decline, and t is the number of years since the time of initial production. The constant e, which is the base of the natural logarithms, is the limit as n tends to infinity of the quantity $(1 + 1/n)^n$ and has a value of approximately $e \approx 2.71828\ldots$ The rate of decline, a, is related to the annual decrease, r, by $r = e^a - 1$, or $a = \ln(1 + r)$, "ln" being the symbol for the natural logarithm function.

Figure 12: Trends for major oil-production outside Persian Gulf

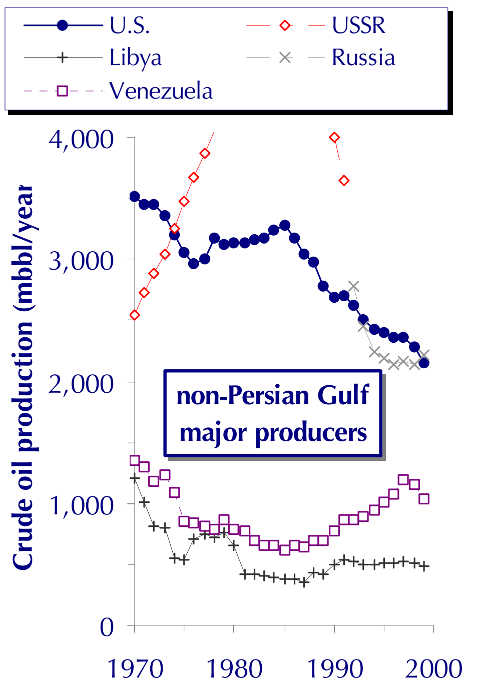
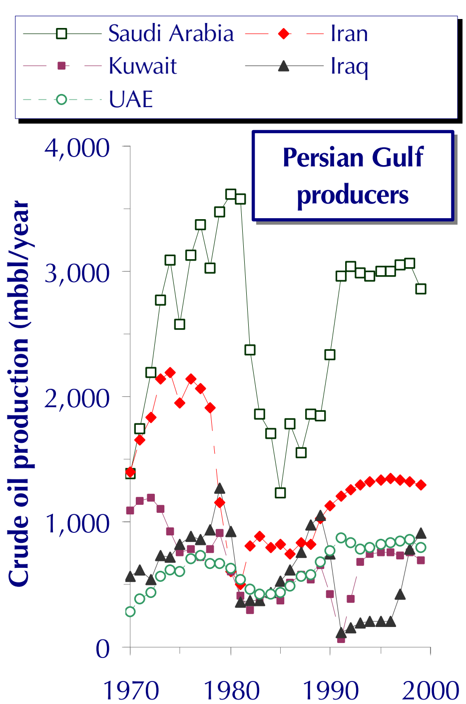


Figure 13: Production trends for Persian Gulf oil-producing nations



Some of the output of the refinery may be used as raw material for plastics and industrial chemicals, but the great majority will be burnt for fuel.

How much and where

Figure 12 through Figure 15 show trends of production by major nations over the past three decades. I want to call attention to the following aspects of this experience:

- **Oil production in the U.S. is on a downward trend.** We're the only major producer that has already produced more than half of our original endowment, and notwithstanding a number of practical advantages and governmental incentives to domestic production, falling production is inevitable. Still, the U.S. remains one of the great producers.
- In many nations, oil production has fluctuated greatly. This stems from a variety of causes:
  - *OPEC-induced instability*. In an attempt to capture monopoly pricing, OPEC has cut back on supply on more than one occasion. But since its control over production by its own members and collaborators is marginal and over that from other sources nonexistent, it has been necessary for some of the major OPEC states to cut back production very sharply—especially Saudi Arabia. Whether OPEC as a whole and Saudi Arabia in particular have benefited in net from the attempt to increase prices is questionable. It should be noted that the exports of OPEC states have fluctuated even more than might seem, since these production on these charts includes that for domestic use as well as export.
  - *OPEC-stimulated increases*. As can be seen

Figure 14: Trends for 2nd-tier producers; N America & Europe

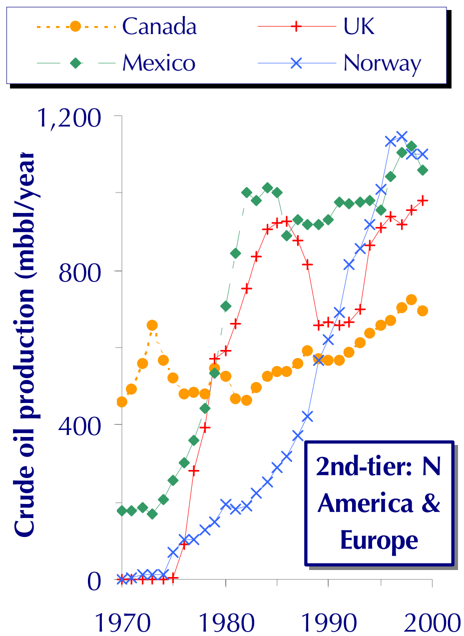
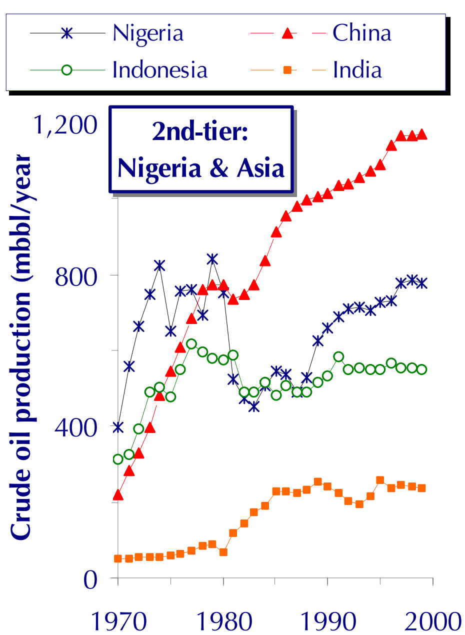


Figure 15: Production trends for Nigeria and Asia



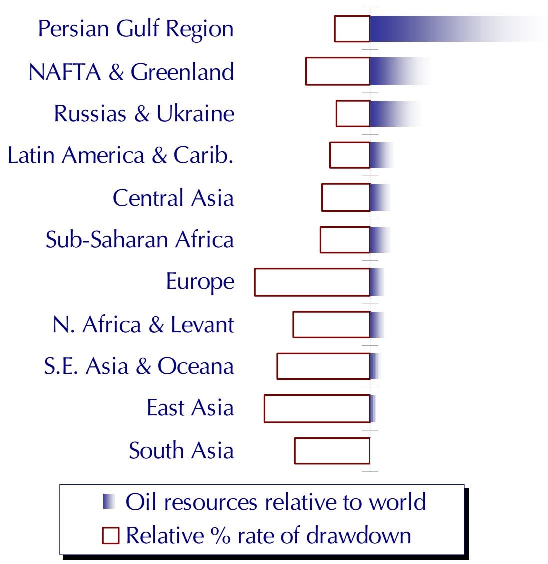
from the charts, the high prices of the late 1970s helped prompt several non-OPEC nations to increase production sharply. Once the production infrastructure had been built, it made sense for them to keep on producing even after oil prices dropped.

- *War and turmoil take their toll.* Many of the dips can be at least partly explained by political factors and the destruction and disruption of war. This is particularly notable for Iraq and Iran during their prolonged war, as well as for Kuwait in 1990-1991 and Iraq thereafter.
- *Technical factors play a part.* Some of the dips and jumps reflect technical factors—timing of new discoveries and new facilities. For instance, Western Europe, never previously regarded as an oil producer, became a significant one due to oil (and gas) discoveries in the North Sea area.
- *Some "unknown" majors, and a minor.* China, Norway, and the UK are among the nations that have become genuine major oil producers without a lot of public attention. All now substantially exceed Indonesia, Canada, or Nigeria. But while India has increased its production greatly in relative terms, it remains a rather minor producer.

Figure 16 and Figure 17 show data on remaining oil resources in various regions and territories, and on the relative rates at which these resources are being pumped from the ground.[69] The blue bars show how much each area has left, and the open red-bordered bars show how rapidly each area's oil is being depleted by pumping from the ground. **(It is important to recognize that the data on remain-**

[69] Resources are from the sources noted and discussed on Appendix B, while production is from [EIA Table G1].

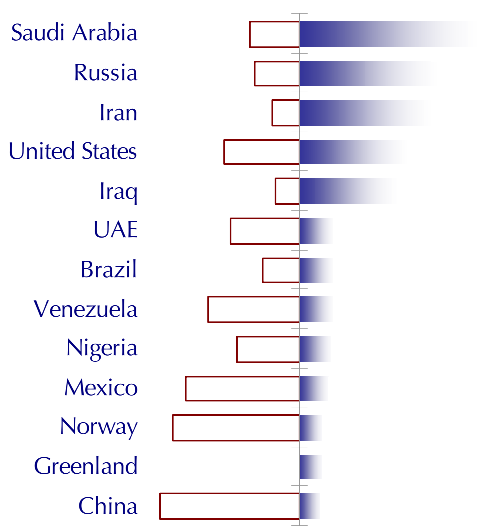
Figure 16: Resources and production-rate trends by world region



ing resources are *far* more uncertain than can be indicated on the chart, even in a relative sense. They should be taken solely as a general indication of trends and not as a basis for any sort of specific planning. Those in need of more precise and comprehensive data should consult the original sources identified in Appendix D.**)** The production data reflect 1998-1999 rates—and as Figure 12 through Figure 15 make clear, these rates could change a great deal in the future.

But to the extent that relative relationships among rates remain reasonably constant, these charts give a general idea of what the geographic distribution of oil may look like in the future: the longer an area's production bar is, the faster its resources bar is shrinking. If A has twice as much as oil as B and if their relative production rates are the same then A will continue to have twice as much. But if X and Y have the same resources but X is producing twice as fast then its resources will go down twice as fast.

Figure 17: Resources and production-rate trends for major oil nations



Assuming that the production rates remain stable (in the sense not necessarily of remaining constant but of retaining the same relationships among themselves) then we can make the following observations:

- **The oil-rich are very rich, and getting relatively richer.** The region around the Persian Gulf not only has an exceptionally large fraction of the world's remaining oil (more than 40%) but actually is producing oil a bit more slowly, in relative terms, than other regions. Thus it could well have a somewhat greater proportion of the world's then-remaining oil in a decade or two than it has now.
- **The least richly-endowed regions are draining their resources relatively rapidly.** Europe and East Asia are pumping fast, and North Africa, Southeast Asia, and South Asia are not far behind in the race to become "oil-free" zones.
- **The North American region still has a lot of oil, but is eating into it.** While the NAFTA-Greenland region isn't producing at quite the relative rate of some of

the less-endowed regions, oil in our neighborhood is being depleted comparatively rapidly. It would look worse without the untapped resources estimated to lie beneath the ice-choked waters off the northeast coast of Greenland, where factors of difficulty and expense have so far inhibited production.

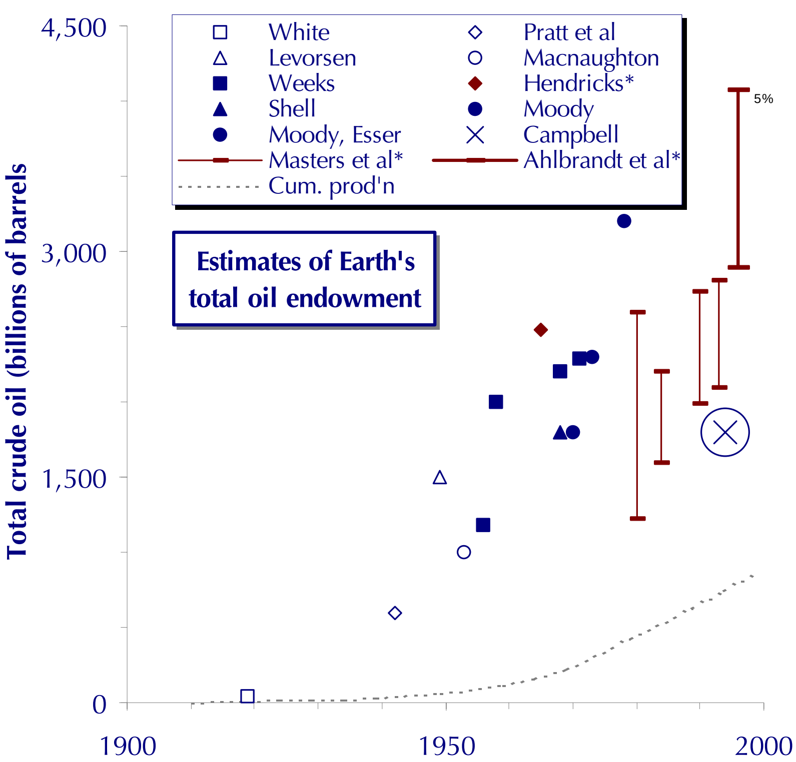
- **The great "underproducers": Iraq and Iran.** Iran and particularly Iraq are producing slowly relative to their very large resources. If these trends were to continue, they would eventually come to have much the greatest concentrations of oil resources remaining on our planet. Because there are significant regions of these nations which have not been extensively developed, uncertainties about their resources are especially great. But there is no question that they are very large.[70]

[70] There is speculation that a combination of the ravages of Iraq's aggressive adventures have combined with mismanagement to damage Iraq's reservoirs. If so, this would increase the cost of producing oil from them in the future, and perhaps reduce the percentage of their oil that ultimately can be recovered.

Appendix D
How much oil is there? Where is it? How fast are we using it?

Most of the discussion here will take as given the standard biogenic theory of oil formation, as outlined in Appendix A. The implications of the abiogenic theory, should it be found to have any validity, will be addressed in a section near the end of this appendix, at page 79.

Figure 18: Evolving estimates of world oil endowment



Serious scientific study of geology began not long before the opening of the oil age in the middle of the 19th century. Several early geologists ventured predictions about how much oil there was and how long it would last. Not surprisingly, given their very limited knowledge and understanding, these often were ludicrously in error. Predictions of imminent exhaustion of resources became something of a standing joke among oil men. So did authoritative statements about where oil could not be found, as intuitive wildcatters discovered it in formations not previously thought to be potential sources. In the U.S. (excluding offshore and Alaska) almost all the major fields were first discovered by "unscientific" methods.[71]

Over the past 75 years, however, geology and geophysics have grown steadily in knowledge and importance. Today, the old "seat-of-the-pants" style of oil explora-

[71] In the lower 48 states, the peak year for discovery was 1930, and the decade of the 1930s was the most productive for new field discovery. Geology and geophysics played a role in this period, but much exploration remained largely empirical until the 1950s.

tion is virtually dead. Those who provide financing for exploration retain their own geological experts and want to see scientific evidence before advancing tens to hundreds of millions of dollars for a campaign. Most of the world has now been mapped thoroughly enough to give a reasonably good basis for predictions about the chances of oil discoveries. Prospects for unexpected major oil finds—or major disappointments—have all but entirely evaporated.

Naturally, this progress has had an effect on estimates of the Earth's total crude *oil endowment*—the amount of oil estimated to have lain within the Earth at the time that humankind first began large-scale commercial exploitation of the resource in the 1850s. It might be supposed that the effect would be to reduce the scatter in estimates and bring convergence toward some value intermediate between the most and least optimistic. In fact, however, the results have been somewhat different, as shown in Figure 18—the latest major estimate is more optimistic than any made in the past [34]. We will come back to this estimate shortly and explore why it is as it is.

Figure 19: Trends in estimates

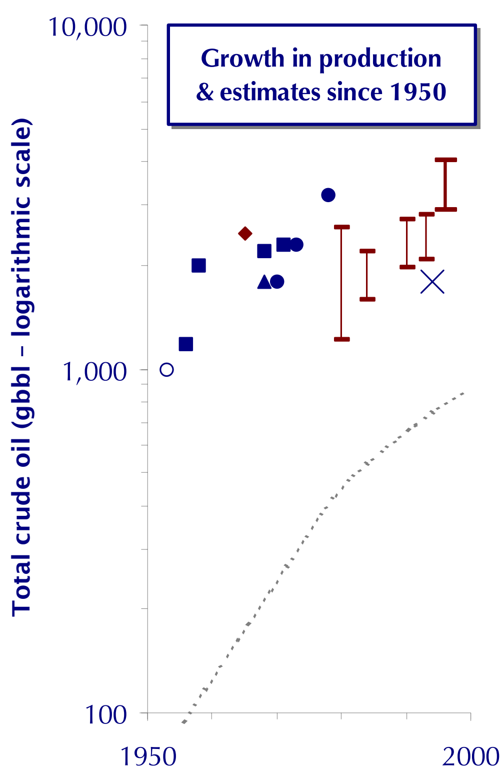


Figure 18 also shows total world cumulative crude oil production data. The vertical distance between an estimate of total endowment and the production curve of course represents the estimated remaining resource. Roughly speaking, the increase in estimated endowment has grown even more than production, so that the estimate of remaining resource today is as great as or greater than the corresponding estimate of four or five decades ago.

Figure 19 shows the same data but with a logarithmic scale of oil volume, to clarify rates of growth (and a shorter time history).[72] This chart makes clear the decreased rate of growth in oil production since about 1980. The overall trend of increase in endowment estimates is evident on this chart too, but whether the slope is as great as that of the increase in production must depend on one's choice of estimates to measure.

In the past, most estimates of world endowment were made by individual geologists

[72] Recall that on a logarithmic chart, curves of exponential (i.e., constant-percentage) growth plot as straight lines due to the distorted vertical scale. Parallel lines have the same rate of growth (in percent per year), and a line's slope or inclination to the horizontal directly measures its rate of growth.

Figure 20: Current USGS estimates

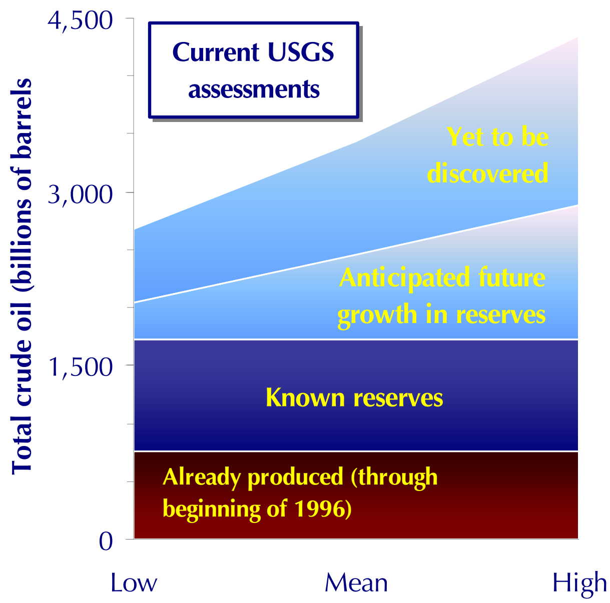
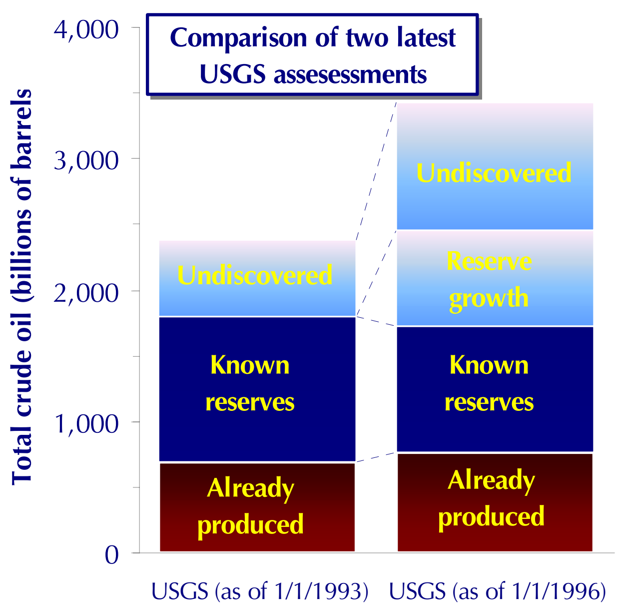


Figure 21: Comparison of estimates



combing through published reports, perhaps with the help of a few colleagues or graduate students. In recent years, however, government interest has prompted much more formalized data-driven efforts, particularly by the U.S. Geological Survey (USGS). The most recent and notable of these is reported in [Ahlbrandt *et al* 2000].

All involved will agree that the accuracy of an estimate is by no means directly proportional to the effort expended on it. The great majority of oil is contained within a few very large fields, so an effort which concentrates on these and treats lesser sources in a more summary fashion may produce results that are not vastly less accurate than those of a more comprehensive effort. Nevertheless, given equivalent levels of competence, it is reasonable to expect that the larger teams working over extended periods will produce results better than those of a lone individual, and this is a field in which an answer correct to the nearest factor of 2—or even 1.5—is inadequate for many purposes.

Current USGS assessments

Figure 20 illustrates the latest assessments by the USGS.[73] A comparison (mean values only) with the

[73] [Ahlbrandt *et al* 2000], [USGS 1995]—and also [MMS 2000], a report by the Minerals Management Service. This is a summary that the authors of these reports would certainly not entirely approve of. Their probabilistic conceptual framework is not really consistent with this simplified mode of presentation, and in particular the neat line between reserves growth and undiscovered oil distorts their views. Nevertheless, provided that the large uncertainties are kept in mind, this is a useful way to look at the assessments.

preceding USGS estimate[74] is shown in Figure 21. As can be seen, a major difference between the two estimates is that the more recent ones include a category reflecting anticipated future growth in reserves.

Reserves and reserve growth

Almost everyone has heard of *reserves* in the context of oil and other minerals and has an idea of what the term means. In making assessments of oil's future, however, precision and accuracy in dealing with reserves becomes very important—and very difficult.

Any oil-lord wants to have an idea of how much oil lies within his domains, and so do those who finance and operate his production and who do business with him.[75] These reserve estimates tend to be particularly important for capital investment: if there is a lot of oil which can be exploited profitably at current oil price levels then the oil-lord is likely to be especially interested in investing in new development and production, and financers are likely to be interested in funding the capital to do so.

To gain an accurate idea of reserves costs money. One must conduct geological reconnaissance, geophysical survey, and ultimately exploratory drilling. The amounts can be considerable—millions to tens of millions of dollars. So reserves definition is an activity that competes for capital with development and production. The prudent oil-lord is going to try to strike a balance that reflects his cost of capital and assessments of geological and market prospects. He certainly will not be motivated to spend large sums (relative to his capital base) in expanding reserves that he doesn't expect to exploit within the next few years.[76]

In light of this it is scarcely surprising that the reserves for any given field tend to grow over time. This is not an invariable rule of course—sometimes it is found that reserves have been overestimated. But it is the more general case. It might seem that this would not be too significant in the grand scheme of things—that undiscovered oil in entirely new areas would be much more important. But it has gradually become clear that in fact prospective *reserves growth* in existing fields represents a major portion of the world's oil endowment [35]. Of course this is in line with the long-standing oilman's rule of thumb that the best place to look for oil is near where it is already known to lie.

---

[74] [Masters, Attanasi & Root 1994]

[75] As explained in the main body of the report, *oil-lord* is a term I have invented to denote a person, corporation, or state exercising proprietorial rights with respect to oil deposits—after *landlord*.

[76] Because reserves are treated as assets in financial matters, they are subject to regulation and scrutiny. In the U.S., financial authorities have imposed relatively tight limitations on reserves reporting. Moreover, U.S. legal requirements for annual reports by operators to the Department of Energy on petroleum production and reserves probably tend to encourage a systematic approach. Elsewhere, regulations are different, and in some cases more lax or altogether absent. Moreover, some oil-lords and producers are much more conservative than others, either because it suits their economic or political situation or for idiosyncratic reasons.

Estimating the unknowable

Both reserves growth and yet-undiscovered oil volumes involve a seemingly paradoxical effort to account for the unknown. The USGS assessors have tackled this problem by statistical methods, developing elaborate and complex models to project these quantities on the basis of prior experience in similar cases [36].

Ultimately, the reliability of these estimates depends a great deal on how similar the cases truly are. It is arguably in this that the large USGS assessment teams, drawing in expertise specific to a great many fields of knowledge as well as to oil-producing regions, show to greatest advantage. These efforts also benefit from having the resources to do extensive statistical calculations carefully.

Within the U.S., there are good data regarding reserves growth, allowing predictions with considerable confidence. In many other parts of the world, data are scanty and inconsistent, making growth predictions considerably less sure. In the latest USGS assessment, trends based on U.S. experience are applied world-wide. The assessors argue that this is better than ignoring reserves growth outside the U.S. altogether, but acknowledge that their predictions could be subject to substantial error—in either direction [37].

Secret knowledge

Those who know best about where specific pools of oil lie and how much is in them have spent a great deal of money to acquire this information and see considerable commercial advantage in concealing it from their competitors. Even if oil producers and oil-lords might be disposed to share their knowledge with the USGS, the logistical obstacles to gathering all this information would appear formidable.[77]

Fortunately, to some extent the incentives to secrecy are counterbalanced by the gains that all producers and oil-lords can gain if their information is pooled. Some consultancies have established profitable niches on the basis of aggregate analysis of data received in confidence from many producers and owners. The USGS assessors report having benefited from the cooperation of some of the most prominent of these [38]. Of course this cannot guarantee that they have full access to all potentially-relevant information, but it is hard to see any major stones unturned in their efforts.

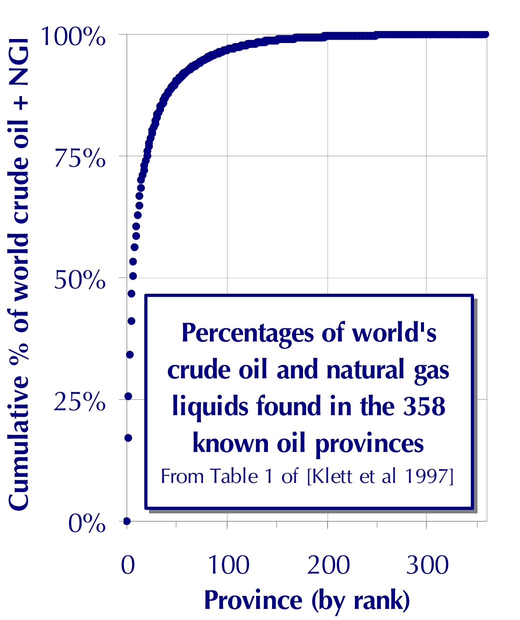
An unequal distribution

To begin with, the world's oil lay in many reservoirs of widely varying size. At the level of geologic provinces, more than 350 are known to contain crude oil and/or natural gas liquids. Of these, six account for more than 50% of known oil,

[77] This is much more so for foreign data of course. In the U.S., legal requirements for data reporting combine with inculcated habits of openness to provide reasonably good data.

20 for more than 75%, 49 for more than 90%, and 125 for more than 98%.[78] Figure 22 summarizes these data.

Figure 22: World oil province sizes; very unequally distributed



This pattern of very unequal amounts is repeated regardless of the level and extent of analysis. It is of course exactly what we should anticipate from the ideas on how oil is formed that are set out in Appendix C: since it takes special and unusual conditions to form oil, we expect to find most of it in a relatively few places where these conditions happened to prevail. Geologists believe that future discoveries of oil will follow similar patterns, in that most of the oil that will be found will lie in only a few reservoirs.

One implication is that the returns on exploration effort, in terms of amounts of oil found, diminish sharply with added effort. That is exactly the pattern that has been observed in the U.S., for instance, where the greatest concentrations were found in the 1930s. Returns on exploration effort have diminished ever since, notwithstanding greatly improved exploration technology and methods. So while impending shortages of oil can be expected to spur greater effort in exploration, we should not expect this to result in even a proportionate increase in oil discoveries. It is important to recognize that this is not a matter that can be changed in any fundamental way through improvement in technology: technology can make it easier to find the oil that exists, but cannot alter the amount or distribution of that which does exist.

The heterogeneity of reservoir sizes is one reason for heterogeneity of production costs. Other things equal, the cost of putting in a well is largely independent of the size of reservoir it taps, so that large reservoirs yield more oil per unit of investment. The other major factor in production costs is accessibility, with costs increasing in offshore and remote environments. The net effect can be seen in Figure 23, which shows estimates of how much more oil can be found and produced in land and immediate offshore waters of the U.S. as a function of cost.[79] Here too, diminishing returns are very apparent.

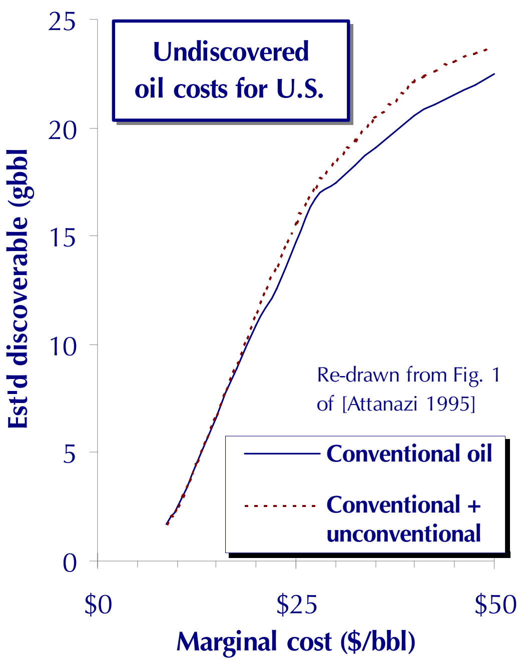
---

[78] Again, from [Klett *et al* 1997], Table 1. The six largest are the Mesopotamian Foredeep Basin (17.1% of total known crude oil + NGL), Greater Ghawar Uplift (8.7%), West Siberian Basin (8.3%), Zagros Fold Belt (7.1%), Rub Al Khali Basin (5.4%), and Volga-Ural Region (3.8%).

[79] The U.S. makes a good example since there are good data and the USGS to analyze them. There is every reason to believe that the patterns are typical of the world in general.

The net implication is that increases in oil prices associated with anticipated shortages will have only a fairly limited effect in increasing oil supplies. There is one aspect of the supply question which this does not address, however: *recovery,* or the percentage of the oil within the reservoir rock that can be recovered. Recovery varies a great deal with the geological conditions as well as the technology used, and yields of 50% or more are obtained in favorable conditions. But the general average recovery is more like 30%. If we accept the estimate that the world started out with about 3 trillion barrels of recoverable oil, then increasing recovery from 30% on average to 40% would provide an additional 1,000 billion barrels.[80] Thus there might be potential to stretch supplies significantly through investment in production technology.

Figure 23: Estimated production costs for oil yet to be discovered in U.S.



How much this can be relied upon to significantly change the story told by Chart 7 is another matter. There are three mutually-reinforcing problems:

- This is the kind of technology which, so far, has not moved rapidly—as it would in order to materially cushion the sharp peaks of Chart 7.
- Even once proven and put into practice, new production technology has not tended to result in major increases in production rates. The more usual effect has been to reduce the falloff in production.
- Because of the huge production rates envisioned by the middle of the 21st century, even an added trillion barrels is unlikely to delay a decline by much more than 15 years. This seems surprising until we look at the curves of Chart 7 more closely. The difference in recoverable oil between the "mean" and "high" cases is about 900 million barrels—and the difference in peak year stretches significantly beyond 15 years only if growth rates remain below 1% per year.

We can certainly expect that economics-driven technology advances will have significant effects on discovery and recovery of oil. But it is much less clear that this will bring major changes in the "falling-off-the-cliff" peaks shown in Chart 7. It doesn't seem as if we should count on it.

[80] That is, the 3 trillion barrels represent the 30% of the total that is assumed to be recoverable, so increasing the recovery yield to 40% increases recoverable oil by 1 trillion barrels to 4 trillion.

Onward and upward?

Chart B1 makes it very clear that the USGS assessments have tended to report more and more oil as time goes on. Reviewing the assessments makes it clear that this growth reflects increases in both scope and quality of data [39]. The jump between two assessments shown in Chart B4 is particularly large because of the decision to include non-U.S. reserve growth.

The current USGS assessment is not seen by its authors as any sort of final word. It is, they stress, not an assessment of "ultimate recoverable resources." Instead, mindful of the technical and economic changes likely to come in the future and the uncertainties attending them, they elected to restrict themselves to forecasting the resources which might be expected to be added over three decades, through 2025 [40].

Whether this means that future USGS assessments will estimate yet higher levels of resources seems quite unknowable.

The skeptics

Naturally, not everyone accepts the USGS assessments without reservation. In particular, of course, anyone with strongly-held doomster views will naturally be disposed toward skepticism about assessments that keep showing more resources.

A prominent and very experienced French petroleum geologist, Jean H. Laherrère, has published a critique of the most recent USGS assessment [41]. His paper was based on incomplete early information, however, and a good deal of what he says can be seen to be inapplicable on the basis of the full report. Other differences seem to reflect mostly a consistent preference on his part for quite conservative readings of most issues.

Laherrère and another prominent European petroleum geologist, Colin J. Campbell, have jointly published an article in which they subscribe to estimates, previously published by Campbell, that the Earth's original endowment of oil was no more than about 1,800 billion barrels—substantially less than that projected by the USGS [42].[81] As can be seen from examining Chart B3, this would imply that there is essentially no oil to be found beyond today's reported reserves, either through exploration or field growth. Campbell bases this projection largely on a belief that some of the largest reserve reports—those of Persian Gulf states—are mendacious, having been manipulated for political purposes. Thus he expects future exploration and reserves growth to do no more than compensate for "hot air" now being reported as reserves.

[81] While the article antedates the most recent USGS assessment report, Laherrère's published views seem to make it clear that he at least would not modify his predictions in the light of any subsequent knowledge.

Campbell and Laherrère are joined, to one extent or another, by a number of other respected geologists and other scientists in expressing doomsterist views [43]. For the most part, their pessimistic projections reflect data not unlike those used by the USGS. But in addition to viewing it in a more skeptical light, the critics also have (out of necessity, for want of resources) subjected it to much less searching inquiry.

Additionally, of course, there are those who accuse the USGS of deliberate fudging for "political" reasons, or gross bureaucratic incompetence. While the long history of the Geological Survey may have a few disreputable chapters, it is on the whole well regarded for the scientific objectivity and quality of its work. Like any organization (or individual) it may have reasons to find some truths harder to see than others, but it is not clear where the Survey would find a strong motivation for upward bias in its petroleum assessments.

Abiogenic oil—what would it mean?

As discussed in Appendix A, the standard theory of oil formation involves biological and geochemical transformation of the residues of ancient aquatic plant and animal life, principally single-cell organisms. But there is also an alternative theory, also outlined in Appendix A, that oil is formed from hydrocarbon compounds that bubble up from deep within the Earth—known as the *abiogenic* theory of oil origin.

The abiogenic theory is quite interesting and is not without its attractions, but at the moment there is very little direct evidence to support it—and a great deal of evidence to support the standard biogenic theory. But suppose that the abiogenic theory were to be proven true; how much difference would it make?

For oil, it would seem unlikely to make very much difference.[82] First, recall that to be producible, oil must lie in reservoirs contained in traps beneath impermeable cap rock. No trap, no oil—because it will rise to the surface and be lost in seeps. But the search for formations that could serve as traps is already a key component of the search for oil.

It is true that petroleum explorers look for traps that form a part of a geological system thought to be associated with biogenic petroleum. In particular, they look for potential biogenic source rocks that are associated with traps. But they know that oil can migrate over considerable distances from source to trap, and thus are not too strict in insisting that traps have very nearby sources. Because of this, a very substantial portion of the places where any abiogenic oil might be discovered are already on the USGS list of likely prospects.

Some see abiogenic theory as exciting because they believe it would imply that oil resources are continually renewed by hydrocarbons streaming up from deep

[82] It might make a greater difference for gas.

within the Earth's crust and upper mantle. They contrast this with biogenic oil which they believe must be non-renewable.

This difference is an illusion which evaporates with clearer thinking. Biogenic oil would be renewed, too—organic residues are being deposited in mud at the bottom of bodies of water today that would eventually be transformed to oil. The question is not *whether* the oil is renewed, but *how fast*. The problem with biogenic renewal is that it is thought that oil is generated at a rate that is at least 1,000 times slower than the rate at which we are using it.

Because the abiogenic theory is so speculative at this point, it is impossible to draw any credible quantitative estimates of renewal rates from it. But there are clear reasons for supposing that there cannot be a great deal of abiogenic renewal going on.

Imagine that we have an oil trap that is being replenished with a continuing stream of hydrocarbons rising from deep within our planet. The situation is like that of a bowl inverted above an open flame. At first the smoke from the flame collects at the high point in the bowl and is trapped. But as more smoke enters, it fills the bowl and eventually overflows from beneath the edges, rising up around the outside of the bowl.

In the same way, if oil were streaming upward into the trap at a significant rate, it would eventually overflow and begin rising around the trap's margins. Since the abiogenic theory envisions that hydrocarbon streams have been rising from the Earth's mantle and crust for billions of years, by now all but the most newly formed of traps would long since have overflowed. We would see evidence of these overflows in the form of surface seeps. Seeps are certainly associated with some oil traps, but not too often. (Oil prospecting would be a great deal easier if oil reservoirs were almost always signaled by nearby seeps!)

From this we can be sure that if there is indeed any abiogenic formation of oil, it must usually be so slow that traps are not filled to overflowing even over periods of hundreds of millions of years.[83] Or perhaps so slow that seepage from overflowing traps is too slight to be noticed. This would seem to suggest that any renewal of abiogenic oil would be no faster than that thought to be taking place biogenically—perhaps even slower.

Thus we can say that:

- Abiogenesis of oil may be conceivable, but is by no means well supported by evidence at this time.
- If there is abiogenic oil, the great majority of it will be found in the same places one would look for biogenic oil.

---

[83] Because of the movement and working of the crust, traps will not often remain stable for billions of years. But many traps are known to have been stable for hundreds of millions of years.

- If there is abiogenic oil, its renewal will generally take place at rates which are exceedingly small relative to the rate at which oil is being consumed.

Appendix E
Hydrocarbon fuels and alternatives

It is often remarked that the past 150 years have seen a dramatic and progressive transformation in the sources of energy and the amounts of energy utilized by human activities. Although there are many in our civilization who decry its energy-intensiveness, the great majority even of them do not omit to travel about in motorized vehicles or to live in homes with domestic heat and electric light. Even more fundamentally, few fail to work in industries which depend on energy for processing and transportation—for to do so would be to eschew employment other than subsistence agriculture.

The vast majority of the energy we use comes ultimately from our Sun, which is a great thermonuclear furnace fuelled by an enormous quantity of hydrogen—about 2×10^{27}tons of it, a mass about 330,000 times that of the entire Earth. In many respects it would be desirable to provide for human energy needs by direct conversion of solar energy. While considerable technical effort has been devoted to various aspects of direct conversion, technically and economically viable solutions are not yet available for most needs.

Fuels[84]

Hydrocarbon oil fuels

As described in Appendix A, petroleum is a product of ancient life, preserved and transformed by biological and geological processes. It is ultimately a product of solar energy in that it was energy from the Sun that nourished the life forms which provided the original organic residues. Of course, the oil we extract today contains only a tiny fraction of the energy that fell on the earth in the past. Nevertheless, it provides a particularly convenient and concentrated form of fossilized energy.

Petroleum-based fuels are composed almost entirely of hydrogen (H) and carbon (C). Both combine readily with oxygen, which of course is freely available in the atmosphere, and liberate considerable energy in so doing. Complete oxidation of hydrocarbons yields water (H_2O) and carbon dioxide (CO_2).

The lighter hydrocarbons have the greatest yield of energy per mass burnt. That's because they have the greatest ratio of H to C in their composition, and H yields about 3.7 times as much energy per unit of mass as C. However, the very

---

[84] [Weiss *et al* 2000] provides considerable information regarding fuels and their prospects in the context of the future of automobiles. It's important to bear in mind, however, that what will work for a car may be quite ill-suited to aircraft, ships, or military vehicles—and conversely.

lightest of hydrocarbon species (methane through butane) are gases at normal temperature and pressure, which makes them difficult to store compactly aboard ships, aircraft, and other vehicles. So it is gasoline—a mixture of the lightest of liquid hydrocarbons—that is used for most cars.

For aircraft and ships, kerosene and similar weight hydrocarbon products—heavier than gasoline—are preferred. One reason is that gasoline gives off large quantities of very flammable vapors, making it unsafe to carry in bulk unless special precautions are taken. But the distillates used for aviation and marine gas turbine fuels also benefit from being denser than gasoline, so that they yield more energy per volume even though a bit less per mass. And they are also somewhat less expensive.[85]

For home heating and industrial use, heavier products are preferred because they are even safer and less expensive, and getting the greatest possible heat energy per mass or volume tends to be less important in these applications. The heaviest liquid fractions generally go into making lubricants. And the tarry and semi-solid residues may be used either for industrial fuels or for products like paving asphalt.

Gaseous hydrocarbon fuels

The petroleum gases find major use both as fuels for domestic and industrial use and as feedstocks for conversion into a wide variety of industrial chemicals. The great majority of commercial production of hydrogen, ammonia, methanol, and plastics starts with natural gas, and that's only skimming the surface of the uses of gaseous hydrocarbons.

Some vehicles are fuelled by propane (C_3H_8), which is a gas under ordinary conditions.[86] It turns to liquid at a temperature of –44°F at ordinary pressure and can be kept liquid at moderate pressure at ordinary temperatures, so it can be stored in pressure containers. It's a desirable fuel in many respects, but the weight of the pressure vessels eats into its *energy density*.[87] Because of the penalty in energy density, propane or LPG is only practical for vehicles where fuel weight is not crucial.

Liquefied natural gas (LNG) is used to fuel certain vehicles as well—principally buses, local delivery vehicles, and others whose missions do not make heavy de-

[85] Of course gasoline is especially attractive for cars and recreational trucks because it is well suited to spark-ignition piston engines, which provide an economical light-duty power source.

[86] Liquid petroleum gas (LPG) also is used. It's largely propane, with a little butane (C_4H_{10}) and traces of other gaseous petroleum fractions, and has properties that are very similar to those of pure propane.

[87] Energy density is a measure of the amount of energy that can be stored in a given weight (or a given volume, which may be more important for some applications). Various units are used, depending on the purpose, and it's important to be clear about what is and is not included in the definitions of weight and available energy. The term *specific energy* also is used.

mands on energy density and do require low emissions. It is principally methane (CH_4), which can not be kept liquid above –100°F. LNG has to be stored in insulated tankage, which further cuts into its energy density and creates a variety of practical problems. In most cases, natural gas fuelled vehicles use compressed natural gas (CNG), stored in tanks at a pressure typically about 3,000 lb/in^2. This too results in poor energy density, but with fewer practical problems.[88]

Alcohols and ethers

Many other substances are liquids under ordinary conditions and can be oxidized to release energy. The most common are alcohols, of which only *methanol* and *ethanol* have much importance as fuels.[89] A related compound, *dimethyl ether,* is gaining attention as a potential fuel as well.

Methanol can be thought of as methane which has been partly oxidized in a certain way to make a liquid. In fact, methanol is usually produced from methane from natural gas. It is also derived from breakdown and distillation of woody plant material, but this tends to be somewhat more costly. Its chemical formula is written CH_3OH, emphasizing that the oxygen occurs in a *radical* with hydrogen and is not bonded directly to the carbon. The principal problem with methanol as a fuel is that its energy density is poor.[90] The addition of the oxygen atom to the methane molecule doubles its mass while adding no energy. Thus methanol delivers only about half as much energy per pound as methane. But in practical applications the energy density of methanol is generally better than that of liquefied methane because it can be stored in relatively simple uninsulated and unpressurized tanks. Still, its energy density is not much more than half that of gasoline or kerosene.[91]

Adding an oxygen atom to ethane results in ethanol, C_2H_5OH. It is most familiar as the active ingredient of beer, wine, and distilled spirits. In addition to grain fermentation and distillation, ethanol can also be produced from natural gas or other hydrocarbon sources. It's a better fuel than methanol in terms of energy density, since oxygen constitutes only about a third of its mass. But it's also more expensive, and it still falls far short of liquid hydrocarbons in energy density.

---

[88] Compressed gaseous storage tends to be more attractive for small masses of fuel, cryogenic liquid storage for larger masses. But practical issues of supply often play a dominant role in the choice, tending to favor CNG.

[89] Methanol is also called methyl alcohol or wood alcohol, while ethanol is better known as ethyl alcohol or grain alcohol.

[90] There are also problems of toxicity and corrosion. Most fuels have practical problems of one sort or another which system engineers must work around. Such problems and the associated costs often are a factor in selecting one fuel over another.

[91] As a fuel for spark-ignition engines, methanol can be more attractive than this would suggest due to its very high resistance to knocking. It is difficult to employ in compression-ignition (Diesel) engines.

If two methane molecules are each stripped of one hydrogen and joined by an oxygen, the result is *dimethyl ether,* CH_3OCH_3.[92] *DME* (as it is usually referred to) is normally a gas but, like propane, can easily be liquefied under moderate pressure. It is becoming widely employed as a propellant for aerosols and is receiving attention as a potential fuel. Unlike the alcohols, its characteristics suit it well for use as a Diesel fuel (but not for a fuel for spark-ignition engines).

Agricultural and timber interests have promoted alcohol fuels as a means of expanding their markets. But in most cases the most economical source of alcohols (as of DME) is conversion from natural gas. Whether alcohols or DME are economically attractive as fuels is largely a function of the relative prices of oil and natural gas.[93] But even where they are economically competitive with petroleum liquids on the basis of cost per unit of energy, factors of energy density and lack of infrastructure will work against their widespread use.

Hydrogen

In many ways, pure hydrogen makes a highly desirable fuel. Complete oxidation of hydrogen produces about 2.8 times as much energy per unit of mass as hydrocarbon fuels. And it's the ultimate in clean fuels, with only water for a product of combustion.

The problem of course is that hydrogen is (a) a gas and (b) expensive. It can be stored in liquid form, but only at temperatures below –400°F. The heavily insulated tankage required for this is expensive, heavy, and bulky.[94] Compressed gaseous storage also is possible, but even storage at pressures of 5,000 lb/in^2 is bulky relative to cryogenic liquid storage, and tends to be heavier except for small masses.[95] One practical problem of all hydrogen systems is that the small size and mass of the H_2 molecule results in high leakage rates through available seals and tank wall materials. This is exacerbated by the fact that liquid hydrogen will constantly boil off some gaseous hydrogen unless actively refrigerated.

Most hydrogen is evolved by decomposition of hydrocarbons. This tends to make it considerably more expensive than the hydrocarbons from which it is pro-

[92] It will be noted that ethanol and dimethyl ether have exactly the same numbers of carbon, hydrogen, and oxygen atoms in each molecule—2, 6, and 1, respectively. But the different structural ways in which the atoms are joined give the two compounds significantly different characteristics.

[93] *Stranded* or *remote* gas—gas too far from markets to be economic for pipeline transport—may be attractive as feedstock for conversion to alcohols or DME in an on-site plant if the costs of producing the gas itself are low, since the long-distance transportation costs per unit mass of liquid are much lower than for compressed or liquefied gases. Many gas deposits are known to exist in such remote areas.

[94] Even in liquid form, hydrogen occupies roughly ten times as much volume as a comparable mass of hydrocarbon fuel.

[95] Hydrogen can also be stored at moderate pressure and temperature in solid metal hydride compounds, but this generally is not attractive relative to the other two choices.

duced. Hydrogen can be made by decomposition of water, but this is more expensive still, except in cases where electricity is unusually cheap.

Hydrogen is often viewed as especially liable to present a risk of explosion, but this does not stand up either to rational engineering analysis or review of the extensive experience with hydrogen in industrial and other applications. Hydrogen's inherent leakage problems do require care in design and operation of hydrogen systems, however, to avoid dangerous collections of gas.

Summing up on fuels

It is very difficult to improve on liquid hydrocarbons as fuels. The first thing that makes a good fuel is a fairly stable liquid form and storability, which many hydrocarbon products provide. Then it is very desirable to have as much hydrogen as we can get, and hydrocarbons go about as far in this direction as is possible with liquids. It's important that the other constituents be combustible with good energy release and acceptable reaction products, a role that carbon fills pretty well. Finally, a practical fuel needs to have tolerable levels of toxicity, corrosiveness, and explosion hazard—also satisfied by many petroleum-based hydrocarbons.

Alcohols burn well but fall short because a third to a half of their mass is tied up in oxygen which provides little or no benefit for use as a fuel. Hydrogen is very desirable in many ways as a fuel, but there is no good and economical solution at this point to the engineering problems of hydrogen storage.

It is difficult to be precise about energy densities, due to many variations among systems, but even approximate figures are revealing. As a broad generalization, vehicles fueled with liquid hydrocarbons (or alcohols) generally have fuel systems that weigh between 5% and 20% as much as the full load of fuel they handle. For compressed natural gas or liquid hydrogen, this typically becomes 500% or so. This implies that alcohol-fueled vehicles will have energy weight densities that are worse than those of vehicles running on liquid hydrocarbons by at least one-third.[96] For CNG vehicles, the handicap is something like three-quarters—prohibitive for many vehicles. With careful engineering, vehicles fueled with liquid hydrogen may have energy weight densities approaching those of hydrocarbon-fueled vehicles, due to the high energy content per pound of hydrogen. But their energy density on a volume basis is significantly worse, which is a problem for many vehicle types that tend to have volume problems in any event.

[96] This might not be especially serious in some cases of vehicles with piston internal combustion engines, as such engines can be made to perform especially well on alcohols, which are very resistant to pre-ignition knocking. It is prohibitive, however, for high-performance gas-turbine vehicles such as aircraft.

Non-petroleum solutions

All of the fuels discussed in the preceding section are generally made from petroleum. Where they can be made from non-petroleum feedstocks, the price is usually increased significantly.

One thing that almost everyone agreed on is that should petroleum ever begin to run short, other sources of energy will be developed to take their place. Only the very darkest of doomsters generally dispute this. Where there is difference is on how much cost and disruption this will involve, and the path it will take.

This section will briefly examine a fairly lengthy list of alternative energy sources that have been proposed at one time or another:

- Hydrocarbon fuels manufactured from:
  - Natural gas
  - Coal
  - Shale
  - Tar sands
  - Biomass
- Alcohol fuels manufactured from:
  - Biomass
  - Grain
- Gas hydrates
- Solar energy:
  - Direct use
  - To decompose water for hydrogen
- Electrical energy from batteries
- Fuel cells
- Nuclear fission
- Thermonuclear fusion
- Highly-speculative concepts:
  - Zero-point energy
  - “Cold fusion”

These are very much comparisons of apples and oranges—and bricks as well.

Important preliminaries

Everyone knows that substances can be combined or decomposed in chemical reactions to make new substances. If one mixes hydrogen and oxygen in the right quantities and gives the reaction a little nudge (say with a spark), they will combine to form water:

$$2H + O \rightarrow H_2O + \text{energy}$$

We write "+ energy" because this is an *exothermic reaction* that liberates energy—indeed, hydrogen and oxygen will detonate when combined.[97] With somewhat more trouble, the reaction can be made to run the other way:

$$H_2O + \text{energy} \rightarrow 2H + O$$

That is, water can be decomposed (usually by *electrolysis,* which is to say by passing an electrical current through it) *endothermically* to yield oxygen and hydrogen. When doing this, it is necessary to take care to remove the products—the oxygen and hydrogen—from the reaction as they are formed, as otherwise they will simply recombine to form water. The efficiency with which this separation of the reaction products is achieved will contribute to the *yield* of the process, meaning the proportion of the oxygen and hydrogen that are actually recovered (as opposed to recombining and so being lost to us). Often, getting higher yields means increasing the complexity of the process and the equipment necessary for it.

Can we get there from here?

Thus combining oxygen and hydrogen to form water proceeds very easily (too easily for safety!) but separating oxygen and hydrogen *from* water is much more difficult and complex. The natural consequence of this is that we don't find free hydrogen and oxygen in nature, waiting to be combined to form water and give up energy—such reactions have already taken place on their own. This simple case illustrates a general truth about chemical reactions: some all but manage themselves, while others require very substantial intervention. The ones we want to accomplish will usually be the difficult ones, because the easy ones will normally already have taken place in nature, leaving the desired products lying about for our use.

In principle, it is possible to synthesize any given hydrocarbon species from elemental hydrogen and carbon, or from any convenient source thereof. For instance, suppose we wanted octane. We could write down a chemical equation for its synthesis from water (from the sea, say) and carbon dioxide (from the air, or underground deposits):

$$8CO_2 + 9H_2O + \text{energy} \rightarrow C_8H_{18} + 25O$$

[97] It would be more correct to write the equation as $2H_2 + O_2 \rightarrow 2H_2O + energy$, since both oxygen and hydrogen occur in two-atom molecules and not as single atoms. But we will use the simpler atomic form for clarity.

This looks like the earlier equations, but in reality it would probably take a very complex multi-stage process to accomplish this, with many intermediary products. At each stage the yield would be less than 100%, and losses can mount up. For instance, if a five-stage process has a 50% yield at each intermediate stage the overall yield will be $(0.5)^5 = 3\%$. This would probably be pretty uneconomical and lead to a search for ways to increase stage yields. If they could be raised to 80% per stage then the overall yield goes up to $(0.8)^5 = 33\%$. But this might involve very complex and costly equipment.

Making it all add up

Even though the feedstocks of water and carbon dioxide may be available at little cost, synthesis of hydrocarbon fuels in this way would involve great expense because of the complexity of the plant, as well as the large energy inputs. In general, it is helpful to keep in mind the accounting equation:

Feedstock cost + Plant capital cost + Plant operating cost – Subsidy = Fuel cost

If we assume no subsidy (or comparable subsidies for all alternatives) then the problem is to find a process which will minimize the sum of the feedstock, capital, and operating costs. In many cases it will be valid to assume that energy input is the dominant operating cost. Even with this simplification, there are many variables to be taken into account, making the problem very complex.

An additional complication is that many processes produce two or more product streams, for two or more different markets. For instance, some processes produce both methanol and ammonia (NH_3). In such a multi-product process, the economics depend on the dynamics of all the markets into which products are sold. A process which produces fuels in volumes that are great enough to have a significant market share will typically also be producing its other products in volumes that are large for their markets, thus making prediction of market prices very complex and uncertain.

Add time, money, knowledge—and luck

It is also important to recognize that large-scale production of fuels is a problem of chemical engineering. There has been enough experience in chemical engineering to provide some useful perspective.[98] Chemical engineering starts with chemistry, with a reaction or series of reactions that has the potential to yield the desired products. A sequence of process steps is designed to carry out the reactions at high rates in large quantity. The process design involves considerations not only of chemistry but also of the physical handling of reactants and products. Then a plant is designed to implement the process.

[98] Large-scale chemical production began in the middle of the 19th century. The petroleum industry was a great stimulus to the development of chemical engineering as a discipline.

Elaborate computer calculations can give a great deal of information about the operation of a plant before it is built. But neither the scientific knowledge of the processes nor the capacity of the most powerful computers is adequate to permit a completely faithful "virtual plant" to be built.[99] Thus, one or more pilot plants are generally built to gain data and experience with the process before full-scale production plants are constructed. Even so, the full-scale plant may reveal phenomena not apparent at pilot scale.

One aspect of process design that is particularly crucial is that of catalysis. Catalysts are substances which enter into a chemical reaction and increase its rate and/or specificity without themselves being transformed in it. Catalysts very often make the difference between a practical, economic process and one which is entirely infeasible. Their operation can be extremely complex and is by no means fully understood. Finding effective and affordable catalysts for a given process generally involves considerable trial and error, even with the best of theoretical models.[100] But finding and developing catalysts is frequently the key to successful chemical engineering.[101] It is conceivable that a catalyst might someday be found to enable the direct and selective synthesis of liquid hydrocarbons from water and carbon dioxide.

Another mechanism that is coming to have increasing importance in processes is molecular membranes or sieves for filtering. These are made to pass molecules of one species and not others, and hence can be used for low-energy separation of substances that are in solution.[102]

A process will not be brought on line for production until it can be operated economically.[103] But further study and experimentation often leads to considerable improvements and refinements, which may greatly improve process economics. Thus a process may start out filling a specialty or niche market (or one in which there is a subsidy, for one reason or another) and then later be refined to form the basis for a mass market.

---

[99] The comment about limitations of computer capacity may surprise those accustomed to thinking of this as a time of "computational plenty". It is true, however, that there are processes whose dynamical equations can not be solved in practical lengths of time by any existing computer. An example is that of fluid flow, a process important in almost everything involving chemical engineering. The governing equations, the Navier-Stokes equations, have been known for nearly two centuries, but computers something like a billion times more powerful than today's best will be needed to provide good solutions for cases of realistic complexity. And some processes involve phenomena that are orders of magnitude more complex.

[100] Moreover, for many important categories of catalysts, virtually no theoretical models are available at all.

[101] "Developing" comes in because details of physical and chemical form can make a large difference in the effectiveness and economy of a catalyst.

[102] There are a great many such membranes in nature and many biological processes depend on them. Observation of natural membranes did much to stimulate research in the area

[103] Unless there has been a mistake, which sometimes happens even now…

The point of all this is that large-scale chemical engineering requires time and resources as well as skill and knowledge—and a certain amount of good fortune. To go from laboratory demonstration to economical mass operation on the scales necessary for fuels will generally take not less then a decade and billions of dollars. It can easily take a great deal more.

How much does it really cost?

It is extremely important to know how much it will cost to produce fuels (or other forms of energy) by various processes—and extremely difficult to find out. There are two largely separate classes of reasons:

- Until a process is online and in full production, its costs are always subject to real uncertainty. That should be obvious from the preceding discussion of the facts of life in chemical engineering. While improved scientific knowledge has reduced uncertainties, they remain considerable. In most cases surprises will be unpleasant ones, leading to higher costs, not lower.
- Those who have the greatest knowledge of a process usually have a commercial or bureaucratic interest in its success, and are naturally ill-disposed to share information which might damage their interests.

The general rule is that it is best to be piercingly skeptical of cost estimates until they have been very thoroughly examined in light of full technical and economic information—and at least moderately skeptical thereafter. The cost estimates often behave in ways that will be familiar to those with experience in other areas of engineering. A typical scenario might involve a newly-designed process which is estimated to be able to produce the product at a cost of, say, $150/ton. As work progresses and more is learned (or revealed), the cost climbs to, say, $300/ton. If the project nevertheless proceeds to production and if production is successful and economic, then improvements are developed which may enable the process to fulfill or even exceed its initial expectations. The cost may eventually come down to, say, $125/ton. But this typically takes decades, during much of which the process has been far from meeting its original goals. Knowing all this, and recognizing the very high initial investments typically required, commercial interests tend to be quite cautious about investing in untried processes.[104]

Manufacture of hydrocarbon fuels[105]

Because liquid hydrocarbon fuels have many desirable properties and can be used with existing engines and fuel infrastructure, their manufacture from other sources may be the most attractive substitute for their extraction/transformation from crude oil. There are a number of processes for doing this, starting with a va-

---

[104] For a thought-provoking economic perspective on the chemical industry and chemical engineering see [Landau & Rosenberg 1991].

[105] For a much deeper treatment of most of the issues of this section see [NRC 1990]. Another valuable overview of all hydrocarbon resources is [Rogner 1997].

riety of feedstocks. They can be divided into two general classes: direct processes and *F-T* processes. None offers attractive economics under present circumstances, but some show promise.

F-T processes

If we begin with a carbon-rich feedstock, we can add oxygen and steam and oxidize the carbon partly, under pressure, generating heat and carbon monoxide (CO) plus hydrogen. This CO + H_2 mixture (which will also generally contain a variety of other substances in lesser concentration) is called *synthesis gas,* or *syngas.* Syngas has been used for many decades as a starting point for synthesis of a variety of carbon-hydrogen compounds, including hydrocarbons.

The processes used to produce hydrocarbons (and related substances) from syngas are known generically as *Fischer-Tropsch* (or *F-T*) processes, after the men who invented the first such process in 1923. This involves reacting the CO and H_2 over a catalyst.[106] Depending on the specific catalyst and the reaction conditions, an F-T process can synthesize various hydrocarbons, with water and/or carbon dioxide and considerable heat as byproducts. The syngas input must be of high purity (to avoid poisoning the catalysts) and comprised of hydrogen and carbon monoxide in the right proportions.

The hydrocarbon output will be a synthetic crude oil or *syncrude* which must be refined and reformed to produce the desired fuel products. Because the syncrude is made from a highly purified syngas, it contains few undesirable contaminants such as sulfur and thus is easy and economical to refine. F-T syncrudes are particularly desirable as feedstocks for Diesel fuels.

The raw input for the syngas step can, in principle, come from virtually anything that contains carbon—natural gas, coal, wood byproducts, etc. The more hydrogen and the fewer contaminants the easier and simpler the process. Even if the raw input is inexpensive and high in quality, the cost of F-T based processes tends to be fairly high, driven by the cost to produce oxygen and build the complex, multi-stage plant. The most economical variants of the F-T process tend to produce quite a lot of carbon dioxide, an undesirable greenhouse gas. Reliance on wood byproducts or other biomass as a source of syngas or of hydrogen to enrich the syngas from other sources can reduce or even eliminate net additions of CO_2 to the atmosphere, but at present this increases the complexity and cost of the overall process.

Direct processes

Direct processes depend on sophisticated catalyst systems to go from the input carbon source (plus sources of hydrogen) to hydrocarbons in a single process step [44]. These processes are still quite experimental and so far are restricted to high

[106] These are relatively simply catalyst systems, usually cobalt, iron, or nickel in various forms.

quality feedstocks with good hydrogen content (which is to say, natural gas), but the potential they offer for simplification is attractive and could lead to low costs.

Coal

Coal can yield liquid hydrocarbons via F-T processes, but there are other routes to liquefaction as well [45]. All require considerable extra hydrogen, since coal is generally low in hydrogen, and this tends to make them relatively expensive. The large reserves of coal in the U.S. and the economic importance of the coal industry have stimulated a good deal of government-funded research in this area.

It is common to find methane trapped in coal-bearing formations. (This is the source of the disastrous explosions that sometimes wrack coalmines, and a danger that miners work to recognize and avoid.) In the United States, coalbed methane is often drawn off and exploited as natural gas, accounting for about 4% of domestic natural gas. There is interest in extending this to other coal regions. The process of producing coalbed gas usually requires breaking up the coal to release it [46].

Oil shales

So-called "oil shales" are something of a special case. Essentially, these are kerogen-containing source rocks whose geologic history has never carried them to the depth/temperature regime at which the kerogen would be converted to oil. They are of special interest to the U.S., since we have vast quantities of oil shale rich in kerogen lying at relatively shallow depths in the West.

The kerogen in these shales can be made to yield crude oil by simulating the natural processes—heating the kerogen. But kerogen is an insoluble waxy solid that will not flow through the pore spaces of the rock. Thus it is necessary to excavate and crush the rock to obtain the kerogen. The crushed rock is sized and heated to about 500°C in a retort, producing oil, gas, and coal-like char (which is burned to provide the process heat). Further processing is needed to make the oil flow freely enough for pipeline transport to a refinery.

To produce significant quantities of fuels, oil shales would have to be mined on vast scales—typically, a ton of ore is needed to produce one-half to two-thirds of a barrel of oil. Disposal of ore fines, excess tailings, and retort wastes, restoration of the mine pits, and cleanup of stack emissions present significant problems that add to the expense of oil shale exploitation.

While oil has been produced from shales in the past, there does not appear to be any genuine economic (as opposed to experimental or demonstration) production at this time. There may be a few cases where unusually shallow shale deposits of unusual richness can be exploited at competitive costs, but this is distinctly not the rule.

Tar sands

These are unconsolidated sediments that contain bitumen, a tarry substance rich in hydrocarbons, thought to have been created by biodegradation of oil. The bitumen won't flow through the sediments and so cannot be tapped by drilling as conventional crude can. But the tar sands can be mined like oil shales. Extraction of the bitumen from crushed ore is simplified by its solubility; it is dissolved in hot water or oil (depending on the composition of the bitumen and ore) before thermal processing [47]. In western Canada, where there are very large tar sands deposits at accessible depths, there are several commercial operations.[107] While the solvent extraction process is better developed and somewhat more economical than the retorting processes used for oil shales, the challenges and costs of tar sands exploitation tend to be similar in other respects. There is economic production of oil from tar sands on a limited scale in Canada.

There are also borderline deposits of *heavy oils* which may be produced from wells if the oil is made to flow through injection of steam or like means. And there are proposals to treat tar sands *in situ* so as to form products capable of being lifted by wells. Heavy oils frequently have heavy concentrations of undesirable contaminants such as sulfur and heavy metals, adding further to the complication and expense of exploiting them.

Manufacture of alcohol fuels

For the most part, the alcohol story is much like the hydrocarbon story. While alcohols traditionally were produced by fermentation and distillation, or as by-products of charcoal production in the case of methanol, most alcohol is now produced from petroleum feedstocks—principally natural gas.

A partial exception is ethanol (grain alcohol), where all production for human consumption and a considerable proportion of that for industrial purposes is still from fermentation and distillation of grains. Many people would like to see greater use of biologically-produced alcohols as fuels, believing that this represents a "clean" and "natural" source of fuel that would avoid emissions of greenhouse gases.[108] (Many others, of course, would like to see it because this would benefit their particular economic interests.) We will take up the question of biomass fuels below.

---

[107] Two of them provide informative Web sites with illustrated explanations of their operations: http://www.suncor.com/ and http://www.syncrude.com/.

[108] Burning alcohol emits carbon dioxide just as burning hydrocarbons do, of course. But growing more crops and trees to make more alcohol takes carbon dioxide out of the atmosphere, since plants intake CO_2 and break it down to carbon and oxygen, incorporating the carbon in their own structure. Thus, in principle plants provide a "renewable" source of fuel that does not contribute to climate change.

Gas hydrates

It has relatively recently been discovered that large quantities of methane exist in a form previously unsuspected—oceanic *gas hydrates*. If economical ways can be found to extract them, this would substantially increase the world's estimated natural gas resources. At the moment, this appears to be a rather remote prospect, but our knowledge is scanty enough to make a pleasant surprise conceivable. There are also some darker possibilities, including serious environmental problems.[109]

In a gas hydrate (or *clathrate* hydrate, a somewhat more inclusive term), gas molecules are incorporated within a crystalline "cage" structure of water molecules somewhat like ordinary ice. Several different structures are known, some of which can accommodate relatively large molecules. The most common natural clathrate hydrates contain light gases, however, including hydrogen, helium, carbon dioxide, and (especially) methane. When a quantity of gas hydrate breaks down (due to some combination of heat and low pressure) it releases water and the previously-trapped gas.

The typical natural history of methane hydrates appears to start with bits of organic residues buried in sediments that have not yet consolidated into rock. They are metabolized by bacteria living in the sediments, who produce methane as a metabolic waste. Light methane molecules bubble up through the water-filled pores of the sediment. Much methane is consumed by other bacteria which, in a complicated process, oxidize it to produce CO_2 and water. Most of the remaining methane eventually reaches the surface and is lost to the atmosphere or sea. But as the remaining methane rises it encounters decreasing temperatures, particularly in high latitude areas, or in sea bottom. Eventually, some of it reaches a level at which the temperature is relatively low while the pressure remains moderately high—conditions favorable for hydrate formation. For instance, methane hydrate will form at a depth of 1km below the surface if the temperature falls below about 15°C, while at 100m depth a temperature of about –15°C will trigger hydrate formation.

Naturally, as hydrate crystals form, they are trapped within the pore space of the sediment and do not rise as free methane will. As more hydrate accumulates, it can come to form an essentially continuous layer in which virtually all of the pore space is occupied by hydrate crystals. Thereafter, methane rising beneath this layer is trapped under it. Thus a considerable layer can form in which much of the sediment's pore space is occupied by trapped free methane.

All this happens most frequently beneath the sea, especially below the slopes of the continental shelves. Methane hydrate layers can also be found in some cases at

---

[109] As yet, standard reference sources provide little on gas hydrates. For accessible overviews see [Haq 1998], [Simpson 1999] and [Kleinberg & Brewer 2001].

high latitudes on land, generally beneath permafrost, where the low temperatures allow hydrates to form at relatively low pressures.

It is obvious that it is difficult to extract hydrates buried beneath the sea floor or permafrost. In fact, it has been difficult even to recover very much of this material for scientific study. Estimates have been made of how much gas hydrate lies buried based on seismic sounding in a few areas, extrapolated to a worldwide basis. Of course these estimates are highly uncertain, but there is not much doubt that the total amount of methane in hydrates and in free form trapped beneath hydrate layers is very large—probably amounting to more than half of all known hydrocarbons. However, the inaccessible locations, combined with the fact that most hydrate methane is thinly distributed, make it very difficult to see how it can be extracted at affordable cost.

There may be some areas in which hydrate concentrations are high enough to make exploitation economically feasible. This seems particularly likely in cases where the hydrates form the seal over an economic reservoir of free natural gas. In such cases it is possible that spontaneous decomposition of hydrates as the underlying free gas is produced (thus lowering pressure beneath the hydrate layer and allowing decomposition) will increase gas recovery. It is thought by some that this has already occurred in the Messoyakha gas field, in the Russian arctic, on the shores of the Kara Sea, where the gas is overlain by hydrates. However, few hydrate deposits are located in places that would be economical for gas production at present, even if there were quite rich reservoirs beneath them.

Commercial energy companies have been exploring the potentials for hydrates but have yet to make major investments.[110]

Energy from the Sun—electrical and thermal [111]

In principle, the great majority of the energy we use is solar in origin. But most of this is fossilized solar energy. We continue, however, to receive vast quantities of energy from the Sun, falling on Earth every day in the form of light and heat radiation. Of course some of this goes to making our world warm enough to support life, providing energy for plant photosynthesis, and powering the circulation of the atmosphere and oceans. But what is left over would be ample to meet all of humankind's energy needs, if we could harness a fraction of it.

[110] The environmental concern about hydrates stems from methane's role as a greenhouse gas. What if some catastrophic event were to result in decomposition of large quantities of hydrates and the release of massive amounts of methane? There is pretty strong evidence that this has actually occurred in the Earth's past, contributing to some of the instances of drastic climate change that can be discerned in the geological record. See [Bains *et al* 2000] and [Hesselbro *et al* 2000]. Such unpleasant possibilities should logically have no effect on schemes to exploit hydrates unless these somehow involve some mechanism that could trigger massive release. But it is easy to imagine a less logical public response.

[111] In addition to standard reference sources, this section relies on [Stone 1993], and also draws from [Dostrovsky 1991] and [Service 1998a].

A spacecraft near the orbit of Earth can rely on receiving 1.37kW per square meter of surface that is turned directly toward the Sun. But at the Earth's surface, the energy received from the Sun is diminished because of attenuation by the atmosphere and also because the planet's curvature and rotation mean that surfaces are mostly either oblique to the Sun's rays or entirely shielded from them. On average, the solar energy received at sea will vary from as much as $250W/m^2$ in the sunniest Equatorial regions to less than $100W/m^2$ in the cloudy parts of seas at latitudes more than 40° from the Equator, averaged over the day and year. With reasonable conversion efficiencies, it would take a collecting area of more than an acre to provide the 100kW needed by a modest-sized ship or tactical aircraft. This is clearly out of the question, so we can immediately rule out any notion of direct solar power for such purposes.[112]

In fixed sites, solar electrical power is a commercial reality in many applications. This is not based on direct cost competition with conventional hydrocarbon-fueled generating plants, which can produce power for a fraction of what solar power costs. It is the flexibility and modularity of solar systems that makes them competitive. In many circumstances, a solar power source will be a sensible alternative if wires must be otherwise be run for only a few hundred yards from existing power lines. But where large amounts of electricity are used in a concentrated area, solar power is not competitive at this time.[113]

It has been suggested that using sunlight to split water in order to produce hydrogen would be a very attractive source of fuel, since it would seemingly involve no harmful environmental effects.[114] At present, however, the costs of this are vastly greater than those of hydrocarbon fuels. Technological progress has been made in laboratory demonstrations, but such schemes are a very long way from economic feasibility [48].

Energy from the Sun—photosynthesis and biomass[115]

Since before history began, humans have been fermenting sugars from plants to obtain ethanol. Distillation has been used for more than a millennium to concentrate and purify ethanol from grain fermentation products and methanol from charcoal residues. As noted above, ethanol and methanol can be used as transportation fuels in themselves, or as feedstocks for synthesis of hydrocarbons.

---

[112] This is to say nothing of the other problems that would be involved, such as storage of energy to see the vehicle through the night or periods of heavy cloud cover.

[113] Improvements in both efficiency and cost continue to be made and solar cells—*photovoltaic cells*—may well become an economically attractive alternative to conventional central station electrical generating plants in the future.

[114] This neglects the environmental effects of manufacture of the apparatus for water splitting, which can be significant.

[115] This section is based on the comprehensive review [Kheshgi, Prince & Marland 2000].

Another ancient fuel product of plant origin is oil pressed from seeds, which can be refined to produce light and middle distillates for Diesel fuels and like uses.

Plants use pigments (especially chlorophylls) and enzymes (proteins which serve as catalysts) to synthesize sugars out of carbon dioxide from the atmosphere and water from the ground and atmosphere in a process called photosynthesis.[116] These sugars serve as fuel and raw material for other enzymes to synthesize the proteins, carbohydrates, oils, cellulose, and other substances needed by the plant.

Energy for photosynthesis of sugars comes from the sun. Ideally, the most efficient of land plants convert solar energy falling on their leaves into the chemical energy of sugar with an efficiency of 6.7%. Averaged over the acreage of the fields, the best results obtained in agriculture translate to effective efficiencies of less than 1%. This low efficiency in converting sunlight to chemical energy means that the yield of fuel per acre is low. The best results obtained to date amount to less than 15bbl/acre/year of ethanol—the energy equivalent of less than 10bbl of oil.[117]

This low density of production has two important implications:

- A great deal of land would be required to produce large quantities of biomass fuels
- Production of biomass fuels itself takes a lot of energy to sow, cultivate, harvest and bring in the crop over a broad area

The land required to grow enough biomass to replace a significant fraction of petroleum would impinge seriously on food production. In the U.S., for instance, it has been estimated that less than 10% of gasoline consumption could be substituted with corn-based ethanol by using arable land not needed for food and other commercial crops.

The large inputs of land and energy needed to produce biomass fuels makes them expensive. Moreover, because energy is so large an input, the production cost rises significantly as energy prices increase.

Because oils are a secondary product of plant biosynthesis, the economics of oil production by plants tend to be even more discouraging.

Aquatic plants may provide a more economic source in certain circumstances. Microalgae can be highly productive, particularly in an environment that is very rich in carbon dioxide. In shallow tanks they might serve as CO_2 scrubbers for power plants while producing biomass sufficient for perhaps 100bbl/acre/year of oil. But this is far from large-scale commercialization, and the capital cost of tanks and CO_2 supply is an obvious constraint on the economics of biomass fuel production by such means.

---

[116] The "waste products" of this synthesis include oxygen, which makes animal life possible.

[117] This from sugarcane in Brazil.

Electricity and batteries

A century ago, electric powered cars and boats were relatively common. They depended on power from storage batteries carried aboard the vehicle and recharged when it was not in use. The smoothness, silence, and cleanliness were attractive, but the low performance, high weight, and cost were not.

One major class of vehicles powered by storage batteries has persisted to this day: Diesel-electric submarines (which run on storage batteries when submerged too deeply to obtain air for their Diesel engines). There have been improvements in technology and design of batteries for these submarines over the years, but battery propulsion remains severely limiting for them. It is notable that those navies which depend on submarines for overseas duties have all gone to nuclear propulsion, notwithstanding its much greater expense.

Environmental concerns prompted a revival of electric automobiles in the 1980s and 1990s. Hopes were raised that improved technologies for batteries would significantly improve the practicability and cost of these cars, but these expectations have not been met and it is now generally conceded that pure electric cars are not likely to see wide use.

The fundamental problem with batteries is that they store very little energy relative to their weight and volume, and release it slowly. At very best, a battery will store considerably less than 5% as much energy as an equal mass devoted to a tank full of hydrocarbon fuel [49]. Even though electric motors make much more efficient use of electricity than Diesel or gas turbine engines do of fuel, this results in a prohibitive penalty on battery power systems. A further drawback, if one were needed, is the slowness of the recharging process.

Fuel cells

Fuel cells are an alternative means of using fuels, not a substitute for fuels. But they merit attention.[118]

It was remarked above that water can be split into hydrogen and oxygen by passing an electric current through it, in a process known as electrolysis. An early electrolysis experimenter, William Grove, noted that when he allowed the hydrogen and oxygen to recombine in his apparatus, a current was generated—and the fuel cell was born. In essence, a fuel cell takes the energy out of oxidation reactions in the form of a flow of electrons (that is, electric current) rather than the heat that is the yield of combustion in a Diesel or gas turbine engine. It physically

[118] Fuel cells are a hot topic and there are many useful sources. For a very brief but informative overview of current efforts see [Service 1999]. A more extensive survey is [Srinivasan *et al* 1999]. An accessible introduction to the physical fundamentals is provided by [Kartha & Grimes 1994]. [Appleby 1999] provides a good summary of the engineering aspects of fuel cells for road vehicles, many of which apply to other vehicle applications as well. Basic but useful treatments include [Thomas & Zalbowitz] and [*Economist* 1997a]. Standard references provide useful summaries, but are not always up to date in this fast-moving field.

separates the stages of the reaction—stages that take place nearly instantaneously in ordinary combustion—and makes the partial products follow different routes to complete the reaction. Electrons are one of these partial products and they are made to do work by their flow on the way to helping to form the water that is the final product. The means and routes for doing this vary quite a bit between various fuel cell types, but they all work on this fundamental principle.[119]

Grove published his results in 1839. The attractions of fuel cells were clearly recognized and a number of 19th century scientists and inventors built experimental units. It wasn't until the 1930s, however, that fuel cells were made that could operate more than briefly, and not until the 1960s that they found practical application, when cells operating on hydrogen and oxygen went into space as electricity generators for U.S. manned spacecraft. Fuel cells also found uses in deep submergence vehicles. These cells worked very well and produced good output for their size—but cost more than 1,000 times as much as an ordinary Diesel generator of comparable output.

Fuel cells are seemingly very simple, with few of the complex mechanisms of combustion engines. But this is deceptive, for the electro-chemistry that underlies their operation is extremely complex, and not at all thoroughly understood. Finding catalysts, materials and configurations that work well (at affordable cost) has been a slow process involving much trial and error—160 years of it. Now, however, fuel cells are beginning to find niches in which they are commercially attractive, thus providing additional impetus to development.

To date, practical fuel cells have generally consumed pure hydrogen for fuel. The hydrogen may either be supplied as such or formed from a hydrogen-containing fuel in a *reformer* just prior to being fed to the fuel cell. There's no reason in principle why other fuels cannot be used directly in the cell, but direct use of fuels with more complex compositions introduces complexities of chemistry that have so far been insurmountable, exacerbating fouling and poisoning of the cell. Encouraging progress has recently been reported in direct oxidation of hydrocarbons in an experimental fuel cell, but practical application is likely to take some time [50].

It now seems certain that fuel cells suited to powering buses and trucks will become a reality, although it is naturally less sure whether they will meet the test of the market in terms of cost and practicality [51]. It appears very likely that fuel cells will also go to sea as submerged power sources for non-nuclear submarines.[120]

---

[119] So do batteries, which differ little in overall principle from fuel cells. But the fact that the battery has only a fixed and very limited amount of "fuel" makes a vast practical difference.

[120] Experimental submarine fuel cell installations have gained a fair amount of experience and Germany has now committed to a new class of submarines, the Type 212, with fuel cells. In this first generation of fuel-cell subs, the fuel cells are really add-ons, additional to the Diesel and battery. If they prove successful enough, it is likely that eventually fuel cells will supplant the Diesels, although a battery probably will be retained for backup and sprint loads. See [Windolph 1998], [Foxwell & Scott 1999] and [*Maritime Defence* 1995].

Broader applications in road vehicles seems quite likely, and fuel cells could very well become a standard technology for ship propulsion. The trend toward integrated electrical systems to supply all shipboard energy needs naturally tends to favor a power system that, like a fuel cell, produces electricity directly. Whether fuel cells will ever be attractive as aircraft propulsion plants is much less certain at this point.

Interest in fuel cells has mounted in the past decade. Business-oriented as well as technically-oriented publications often feature breathless articles assuring us that they are certain soon to be a great success.[121] But substantial technical problems remain to be resolved, and fuel cells compete against alternatives which are themselves being improved. Their success is a pretty good bet, but by no means a sure one.

One problem to note is that fuel cell economics are sensitive to the price of platinum. The reactions that drive the fuel cell must be catalyzed, and so far platinum is the only catalyst found to work well. Unfortunately, the price of platinum is subject to wide fluctuations—it's increased more than 70% over the past 18 months [52]. Even though the amount of platinum in each cell is conserved by dividing it very finely, the price of $600/oz is so great that it is a substantial factor in fuel cell cost—enough so that fuel cell development has been driven significantly by considerations of how much platinum (and other expensive rare metals) are needed for a given approach. Moreover, if fuel cells are ever to be large scale substitutes for internal combustion engines, their demand for platinum will greatly exceed total current world production, which of course would tend to put further upward pressure on the metal's price.[122] Success in finding other catalysts could be a key factor in determining the fuel cell's ultimate future [53].

The factor that ultimately makes fuel cells so worth their (quite considerable) trouble is the efficiency with which they operate. A fuel cell plant should be able to produce at least twice as much electricity from a given quantity of fuel as most combustion plants.[123] It's an advantage of immense value and may very well put fuel cells in a place of dominance in power generation for a wide range of applications. If so, this could have a large impact on the demands for fuels. It may be that fuel cells will be the stimulus to bring the commercialization of hydrogen as a fuel. Alternatively (or additionally), fuel cells could bring methanol to the fore, since it is particularly easy to reform it to provide hydrogen—and is attractive from an en-

[121] For examples of some of better-informed of these sorts of articles see [*Economist* 1997a], [*Economist* 1999], [*Economist* 2000b], [*Economist* 2001a].

[122] Worn-out and obsolete fuel cells will normally be scavenged for their catalysts, which will help to balance supply and demand over the long run, but only added production from mining can supply catalysts during a period of buildup in fuel cell use.

[123] Fuel cells also are advocated on the grounds of lower maintenance costs and reduced wear, stemming from their lack of moving parts. It remains to be seen whether catalytic poisoning, corrosion and fouling will offset these advantages under service conditions.

ergy and voltage standpoint for direct reaction, should that prove practical.[124] It is also possible that the economic advantages of sticking with existing kinds of fuels, with an established infrastructure for storage and distribution, will outweigh those of hydrogen or methanol and lead to finding ways to accommodate them in fuel cells—and/or constrain fuel cell acceptance.

Nuclear fission[125]

Half a century ago, nuclear fission was widely foreseen as an all-but limitless source of clean, cheap energy—humankind's first major energy source not ultimately of solar origin. Today, few people have a good word to say for nuclear power, especially in the United States.[126] Fission reactors are generally regarded by the public as highly dangerous sources of serious health risks and environmental pollution.[127] Some public utility reactors have been abandoned before the end of their economic life (or even before its start), while those reaching the end of their service lives are not replaced with new reactors. Naval nuclear power is in less parlous state, but the number of nuclear ships has been shrinking due to cost factors.

Nuclear power makes a very interesting and important case study in the interaction of engineering and economics, but this is not the place to pursue it. It is valuable to reflect, however, that if the economic benefits of nuclear power were more compelling then there would be both more reason for people to accept its side effects and more impetus toward ameliorating them through engineering. Some prophesy that rising fuel prices in the future will lead to a great revival of interest in and acceptance of nuclear power, and this could very well come to pass.

From the perspective of this paper there are two significant possible applications of nuclear power:

- As a source of power for synthesis of fuels, especially for splitting water to form hydrogen, or
- As a source of power for ship propulsion, thus substituting for chemical-fuel plants.

We can dismiss the first of these pretty summarily: as observed above, formation of hydrogen from water for fuel is distinctly uneconomical today even with

---

[124] Hydrazine (H_2NNH_2) and formic acid (HCOOH) also are theoretically desirable, but are unlikely to be economical as fuels—and formic acid is in any case much too difficult and dangerous to handle.

[125] [*Spectrum* 1997] provides an overview of fission's state of commercial development.

[126] Public acceptance is much greater in some other places, such as France, where the economics of nuclear power are relatively more attractive and its application has not brought widely-publicized hazards.

[127] These perceptions do not match the history of fission power, which has been quite benign relative to other power sources, but this is what the public in general seems to believe.

the cheapest of electricity sources, and nuclear power is far from the cheapest of such sources.

For ship propulsion, nuclear power's economic disadvantage is even more marked than in power production, due largely to smaller plant size and special environmental demands. Where the U.S. Navy buys nuclear power (for aircraft carriers and submarines) it is for its strategic advantages, counting them as worth the extra cost. Over the past four decades a considerable number of proposals have been advanced for design or technology alternatives claimed to lend themselves to more economical nuclear propulsion plants. Development costs and risks would be high for any of these, and the benefits have never seemed great enough, sure enough, or near enough to command widespread support. Of course a large permanent increase in the price of fossil fuels would make nuclear ship propulsion relatively more attractive and could revive interest both in building more ships with nuclear plants and in developing better plants.

Thermonuclear fusion

If nuclear fusion is a candle that flared and then guttered, thermonuclear fusion is one that never took light in the first place. At least not so far. There's no doubt that the phenomenon exists—it's what lights the Sun and makes hydrogen bombs go off—but harnessing it for power production has proven to be very difficult.

Fission and fusion both tap the *binding energy* of the atomic nucleus. Nuclei are composed of multiple positively-charged protons and electrically-neutral neutrons.[128] Since the protons tend to repel one another, energy is required to hold the nucleus together. In fission an extra neutron is injected into a large nucleus in such a way that it becomes unstable and splits apart into pieces whose total binding energy is less than that that of the original nucleus. The extra binding energy appears as radiation of heat, light, X-rays, and gamma rays, as well as the kinetic energy imparted to the fragments.

In fusion, two or more light nuclei are induced to come so close that they fuse together in a way that results in a larger nucleus whose binding energy is less than the sum of that of the original nuclei. The energy release is enormous: millions of times as much per unit mass of fuel as is released in combustion of hydrogen and oxygen (and several times as much as in fission). But first the nuclei must be made to overcome their mutual electrical repulsion (caused by the presence of positively-charged protons). In the Sun this can happen because its hydrogen is compressed and heated so greatly by gravitational forces that nuclei hurtle into one another at huge velocities. In an H-bomb, comparable conditions are achieved by using a nuclear fission device to compress and heat the fusion fuel to ignition, requiring a temperature in excess of 50 million degrees Fahrenheit.

[128] Except for the ordinary hydrogen atom, whose nucleus contains only a single proton.

It is one thing to produce the conditions of the interior of a star on Earth for an instant with an atomic explosion, quite another to do so in some continuing way. That is the challenge of controlled nuclear fusion for power production, a goal which has now been pursued for half a century. The principal problem is one of keeping the hydrogen gas confined in a reactor while heating it to solar temperatures. Two principal avenues of approach have been pursued:

- *Magnetic confinement* in which magnetic fields are used to contain a cloud of ionized (charged) hydrogen while it is heated
- *Inertial confinement* in which hydrogen nuclei are "shot" into one another and confined with laser or particle beams playing against them from many angles

In both cases, the reactions involve fusion of heavy isotopes of hydrogen—deuterium (having a neutron in its nucleus in addition to the proton) and tritium (with two neutrons). In nature, deuterium constitutes about 0.015% of the hydrogen atoms in seawater, natural gas, etc., and it is usually obtained by separation (normally of water). Tritium, which decays radioactively with a half-life of 12.3 years, is extremely rare in nature and is obtained artificially by nuclear transformation from other atomic species (normally lithium). Naturally, deuterium and tritium are much more expensive than ordinary hydrogen (which is what the Sun consumes for fusion fuel). However, they fuse quite a bit more readily than normal hydrogen and yield somewhat more energy. More advanced reactors with hotter temperatures may be able to dispense with the tritium and consume only deuterium, which would reduce costs and also minimize harmful radiation.

Both magnetic and inertial confinement have produced fusion in laboratory models, but neither has even closely approached the conditions for sustaining a continuing, energy-producing reaction. Both approaches require machines that are huge and enormously expensive to build. Enthusiasm for very expensive research in fusion has cooled as a result of slow progress, technical/costs problems, and lack of perceived urgency. Few expect fusion to become a significant source of energy in the first half of the 21st century.

Half a century ago, fusion was seen as a very cheap, clean, almost limitless source of energy that needed only a relatively brief period of major R&D effort to reach fruition. People talked confidently of widespread use of fusion to generate electricity by 2000. These hopes long since have faded.

It does seem likely that ways will be found to sustain and control thermonuclear fusion reactions, but it could well take decades to do so. It seems quite unlikely that early model fusion reactors, when they do become technically feasible, will be able to compete economically with conventional electric plants fired by coal or natural gas, or with nuclear plants.

Highly-speculative concepts

Energy production generally relies on very complex physical and chemical mechanisms that most people know little about—combustion, oxidation-reduction reactions, fission, fusion, etc. In many cases, the mechanisms are not thoroughly understood scientifically even though they have been employed for decades or centuries in production of energy. Thus it is natural to wonder whether there are unfamiliar mechanisms that might offer even greater promise as energy sources. This section reviews two that have received fairly widespread attention.

Fleischmann-Pons cells ("cold fusion")

In the 1920s, when the mechanism of thermonuclear fusion was first understood, scientists wondered whether fusion could proceed at ordinary temperatures and pressures if hydrogen or deuterium atoms could be brought close enough to one another. Experiments along these lines showed no evidence of fusion. But 60 years later, electrochemists Martin Fleischmann and Stanley Pons of the University of Utah decided to try again. They built cells with platinum and palladium electrodes in an electrolyte based on heavy water (i.e., water in which the hydrogen atoms are replaced by atoms of deuterium). They passed electrical current through the cell to "charge" the palladium with deuterium to such a concentration that the deuterium atoms were brought into close contact, in hopes that this would promote fusion.

If fusion were actually to occur in the cell then it should produce heat—more heat than that produced simply by electrical resistance. After several years of experiments, Fleischmann and Pons believed they had exciting results. Foreseeing great commercial potential, they announced their work at a large press conference in March 1989.

As soon as details became available, many experimenters around the world raced to reproduce the results. Their results were very disappointing, however: most could not find any excess heat, and none could see it reliably. Moreover, there were no detections of the particles or radiation that should have been among the products of fusion. With no reliably repeatable experimental data and no sensible theoretical basis for the Fleischmann and Pons claims, most scientists soon wrote them down to faulty experiments fueled by hope, not facts.

Fleischmann, Pons and others, however, have persevered. They lay failure to reproduce the excess heat to sample variability of the palladium, contamination of the electrolyte, and other subtle problems. They claim to have found traces of tritium and other radionuclides in cells following experimental runs. There is a conspiracy to suppress them and their results, they claim, backed by shadowy powerful interests [54]. In the meantime, sources of funding for "cold fusion" research have all but dried up [55].

Fusion at low temperatures is not impossible. Even at low temperatures, some atoms in a gas travel at very high velocities, and it may be that two of them will collide and fuse. But at ordinary temperatures the number of atoms with sufficient energy is exceedingly small, and the probability that two of them will collide is much smaller still. The work with Fleischmann-Pons cells and variants has produced no evidence that the very low rate of fusion events at ordinary temperatures can be appreciably increased by such means. In the absence of any of the physical signs that must accompany fusion, to call these experiments "cold fusion" is simply a misnomer.[129]

But reports continue to trickle out of experiments in which there is excess energy production. Don't these indicate that there is *something* significant going on? No, not in the absence of any reliable, reproducible results. There are many possible sources of error in these experiments, which involve measurements of small differences between inputs and outputs in different forms. It has been shown many times that there is a certain definite tendency for even the most scrupulous of experimenters to get the results that they expect or hope for. Unless and until there are results that can be repeated by competent experimenters under controlled conditions it would be foolish to put any faith in an energy-producing mechanism.

Finally, let us imagine something which we have no reason to believe will ever come about: that someday there might be a demonstration of an energy-production mechanism of some sort from Fleischmann-Pons cells. Wouldn't this constitute a source of limitless free energy that would transform the world? The answer is clear: it would be no such thing. In fact, at least in the form suggested by the Fleischmann-Pons work, it would probably never be anything beyond a laboratory curiosity. Consider that this is an apparatus constructed from rare and costly materials which must be operated with extreme care (suggesting the need for elaborate controls and systems as well as high levels of skill). It consumes energy in the high-level, concentrated form of electricity and produces it (again on the supposition that it will ever be shown to produce any at all) in the low-level, diffuse form of heat at low temperature. In order to close the cycle of operation and make the cell's reaction self-sustaining, this low-temperature heat must be converted to electricity, a process subject to severe inefficiencies. Unless the heat energy output were at least four times the electrical energy input, it is very unlikely that the cell could be kept operating. And the apparatus for converting the heat to electricity would be elaborate and expensive. Thus, even by the very most optimistic account, Fleischmann-Pons cells could scarcely be more than a severely limited and vastly expensive energy source.

Zero-point vacuum energy

The fundamental idea of *vacuum* is absolute emptiness: no matter or energy of any kind. Of course we would never expect to find a perfect vacuum in nature, but

[129] This is the reason for the quotation marks in the title of this section: whatever may be going on here, it isn't cold fusion.

surely we can hold the perfect vacuum as an idealized concept, can't we? As it turns out, however, the notion of space empty of all energy does not seem compatible with the nature of our universe. Both quantum theory and classical relativistic physics lead to the conclusion that space must be suffused with energy that does not vanish even when all thermal energy is removed (by reducing the temperature to absolute zero)—the *zero-point energy* or *vacuum energy* [56]. At least one phenomenon thought to arise from vacuum energy—the Casimir effect—has been observed and measured in experiments [57].

Zero-point energy lies at one of the seams of current physical theory. Both quantum and classical theories predict that its density is infinite: every volume of space, no matter how small, contains limitless zero-point energy. However, other theories show that the sum total of zero-point energy in the whole universe must be extremely small. If zero-point energy truly were very large, its effective mass would warp space so severely that the effects would be easily noticeable. Something must be missing in the theories as they presently exist.

Taking the theory of infinite zero-point energy at face value, some have embraced it as a limitless source of "free energy" with enormous implications [58]. Unfortunately, there is very little foundation for this. In order to do work, energy must flow from one place or state to another, and no plausible mechanism for accomplishing this with zero-point energy has been suggested. It's a bit like the gravitational field of the Sun—it represents immense potential energy, but we have no way to tap it.[130]

Summing up on non-petroleum solutions

As said before, it's very difficult to improve on hydrocarbons for fuels. It's not as difficult to improve on conventional petroleum as the source for hydrocarbons, but it's not easy or attractive either. Natural gas, tar sands and oil shales are all candidates. Coal can also be made into liquid hydrocarbons, but with significantly greater complications. Cost estimates are very slippery, for the reasons discussed at the head of the section, but on the whole there seems little prospect that these alternative hydrocarbon fuel sources could be fully and widely competitive with crude oil at prices below about $60 per barrel. That is, there may be some particularly economical resources that could be exploited competitively at lower cost, but not enough to substitute for a great deal of petroleum production. Because of the large capital expenditures and major engineering efforts that would be involved, it is likely that it would take a number of years at these price levels before large volumes of alternative production could come on line. All of these alternatives have the same environmental problems that petroleum does—plus some added ones of their own in most cases.

[130] Some have pointed to the Casimir effect as a way to utilize zero-point energy, but this is entirely unrealistic. It acts as a force of attraction, so minute that it was regarded as a substantial experimental feat to observe and measure it.

Natural gas hydrates are unlikely to provide an economical source of energy in the foreseeable future. The dispersed deposits in inaccessible locations present significant obstacles with no clear solutions yet in sight. And they too would present substantial environmental costs.

Concerns about greenhouse gas emissions and their effects on climate may prompt serious governmental action to foster "greener" energy sources, including biomass-derived fuels or hydrogen fuel produced using solar or nuclear energy. Biomass fuels are bound to be expensive, and their demands for land will prevent them from being a dominant fuel source at any price.[131] Hydrogen itself is expensive, it imposes costs on vehicles that use it because its volumetric energy density is quite low, and its widespread use would require vast investments in infrastructure for storage and distribution.[132] It seems very unlikely that hydrogen will see widespread use as a vehicle fuel in the first half of the 21st century.

There is no prospect that pure battery propulsion will see significantly wider vehicular use.[133] But fuel cells are at last poised on the brink of practical application for vehicle power systems. The fate of the fuel cell and the fate of fuels are intertwined in ways that don't lend themselves to facile prediction. It may be that hydrogen-oxygen fuel cells will offer advantages great enough to lend stimulus to the development of hydrogen as a fuel. It's important to bear in mind that hydrogen can also be generated onboard the vehicle from alcohols or hydrocarbons by using a reformer, and that some fuel cell types can use methanol directly. But the costs and complications of the reformer could combine with concerns about greenhouse gases to increase the relative attractiveness of pure hydrogen. It all depends on balances among costs that are impossible to predict with any precision.

Thermonuclear fusion may eventually become an important or even dominant source of energy.[134] But this won't come in the first half of this century, and there is no present prospect that fusion will ever become an energy source for vehicle propulsion.

There is a great deal of woolly thinking about energy alternatives, usually signaled by the phrase "free energy". All energy is free—nature levies no charges. The expense comes in collecting, concentrating, transforming, and supplying the energy in a usable form. All of the putatively "free" energy sources are either

---

[131] This could change in the long term as a result of new discoveries, genetic engineering, etc., but not in the first half of this century.

[132] Much could change if engineering solutions could be found to hydrogen's energy density problems, but there is nothing promising in sight.

[133] Batteries may well find increasing application for carrying short-duration peak demands, as during spurts of acceleration, thus allowing a smaller base-load main propulsion system—such hybrid systems are now starting to come into automotive use (although their economic justification remains unclear).

[134] Earthly thermonuclear fusion, that is, not the solar fusion that today supplies nearly all our energy in various indirect ways.

wholly infeasible (like Fleischmann-Pons "cold fusion" or zero-point vacuum energy) or costly to exploit. We can't afford "free energy", and we certainly can't afford to depend on it.

Appendix F
Strategic and policy issues

Security issues in the Persian Gulf

We've all become accustomed to the notion that strategic issues often have economic roots, and equally to the idea that economic issues are best left to the free market. These are good guidelines on the whole, of course. But it can be a bit too easy to generalize them too far.

Economics is the science of the allocation of goods and services, but it generally does not consider all means of deciding on allocations. It tends to focus on market-based allocation through a price mechanism, and on the whole tends to ignore the older and more primitive mode of allocation by forcible seizure. For the most part, economists argue that market allocations work better for everyone in the end than force, and they make a good case. But they have yet to convince all individuals, groups, or even nations of this.

Temptations to force are strengthened by perceptions that markets are imperfect or unfair. Such perceptions often are widespread even in the freest and best conducted of markets. It is no secret that suppliers have manipulated oil markets to their advantage since their very earliest days, and the events surrounding the development of genuine shortage might well tend to increase suspicions.

In an important sense, the phrase "free market" is an oxymoron. And the vulgar notion that free markets are somehow natural is patently absurd. Free exchanges of goods can take place only within a framework of rules that all market participants can depend on those they trade with to observe. Ultimately, it requires governmental powers to make a good market, and the enforcement and regulation of market freedom should be recognized as one of the highest functions of modern governments. A desire for international free markets has been a major stimulus to international cooperation and has led to a number of conventions intended to assure the integrity of various markets. Nations have surrendered a great deal of sovereignty in pursuit of international market efficiency, but have gained greatly in wealth and real power in so doing.

The nations we designate as "developed" or "industrialized" might equally well be labeled as "marketized", for it is they who are the chief proponents, proprietors, and beneficiaries of markets, and markets have a great deal to do with the enormous prosperity for which they are noted and envied. The "undeveloped" nations are seen by many of their leaders as severely disadvantaged in world markets and deriving relatively little benefit from free trade.

Nature might very well have arranged that the bulk of the world's oil should lie in the territory of developed market-oriented states, but in fact placed the greater share in Arabia and Iran. Many centuries ago, Iran was the seat of a vast and wealthy empire with far-flung trade relations, and Arabia was a key link in the trade in luxury goods between East and West. But for centuries before the discovery of oil in their territories, world trade had passed these areas by and they had scarcely any economic activity beyond the most basic subsistence agriculture and nomadic husbandry. Sporadic efforts to employ oil wealth to develop other forms of economic activity have availed them little. Without oil they would count for virtually nothing in the world in economic terms.

Their political development matches and reflects their economic development: it is primitive. Iran, alone of the major oil nations in the region, has some of the structures that lend legitimacy, power, and flexibility to modern states. But in Iran, modernism exists in a tenuous competitive balance with medieval absolutism, and the outcome remains very uncertain. All the other states are governed either by modern despotisms of the crudest sort or medieval relics. Who can foresee the future course of states whose governments so lack for broad legitimacy or mechanisms of adaptation? What ruler of such a state can afford to take a long view?

None of these states has a deeply-rooted commitment to international order or market solutions. They have neither the political culture nor the perceived economic interest to support these things. It may very well be that they would in fact all be better off if they did, but they do not.

At present, this is most manifest in their enthusiasm for oil price fixing, via OPEC. They did not invent OPEC or establish it in power, but they have embraced it and made it their own. In reality, the cartel has brought them serious problems—arguably more serious than any it has solved—but their enthusiasm shows no dimming.

One of the worst of the problems of cartelization has been the conflicts over adherence to assigned market shares and prices. The temptation to produce and sell a bit extra "on the side" has frequently proven to be too much for most members.

The temptations of force

In economic terms, Saudi Arabia is the cartel's natural leader and enforcer, as the largest producer. But its weaknesses in other respects have limited its ability to play this role. This has been a contributing factor in two wars in the region, Iraq's sanguinary assault on Iran and its serio-comedic one on Kuwait.

At present relative rates of exhaustion, Saudi Arabia will eventually lose its clear superiority in production, leaving the question of leadership even less clear. Iraq is about equal to Saudi Arabia in population and Iran is larger than both combined. Saudi Arabia's per capita income is highest of the three, but that simply reflects its more fully-developed oil production. The potential for conflict among these three for dominance in cartel decisionmaking seems clear. If the stakes rise, as they certainly would under the scenario I have sketched, the potential for conflict can only increase.

External threats

Iraq's wars are by no means the only ones in which oil has figured largely. For both Nazi Germany and Imperial Japan, control over oil resources was a major war aim in World War II. Indeed, Japan's attack on the United States, Britain, and the Netherlands was motivated almost entirely by a desire to seize oil producing areas in what were then the Netherlands East Indies (modern Indonesia) and British colonial territories.

In 1941, Japan was much less wealthy and powerful than its principal adversary, the United States. According to the best modern estimates, in 1941 Japan had a population that was 55% as large as that of the U.S., and an economy 18.6% as large.[135] Almost to the brink of war, U.S. policy makers, aware of these differences, cited them as reason to discount the threat of conflict. Surely, they reasoned, Japan would not pursue a struggle in which it would be at so great a disadvantage. Japanese leaders, though certainly anything but sanguine about the prospect of war with the transpacific giant, thought that the gains outweighed the risks. In effect, Japan had entered a dangerous window: poor enough to imagine gains from aggression, rich enough to undertake it. And the gains it sought had mostly to do with oil supplies.

There is no nation which today seems to pose the same kind of threat of external aggression to gain control of oil. But there are a number of states with reasonably great economic and military potential, access in one degree or another to the Persian Gulf region, and governments whose long-term stability seems more or less seriously in question. If one or more of them were to evolve in unfavorable directions over the coming decades then it is surely possible to imagine efforts to seize control over some or all of the Persian Gulf region as the oil stakes rose.

Hybrid external-internal threats

For a while in World War II, Germany entertained notions of extending its empire to Arabia and Iran. In the event, the ability of the British to hold Eastern Egypt and the uncooperativeness of Turkey rendered these plans moot. But the Germans received indications from some of the governments in the region of willingness to cooperate in the scheme.

With the Persian Gulf states now relatively stronger, the possibility of such hybrid outside-inside aggression grows. In particular, if there were to be a two- or three-way power struggle among the major oil nations of the region that boiled

[135] Derived from data in [Maddison 1995], Tables A-3(a) and C-16(a).

over, it seems easy to imagine one or more sides shopping for allies outside the region.

The implications of geography

The great majority of the Persian Gulf region's trade in oil is carried by tankships. For the most part these load in the Gulf itself and transit the Strait of Hormuz to reach the Arabian Sea. There is also some oil trade from ports on the Red Sea, and from ports seaward of the Strait, but any stoppage of Strait transit would severely restrict shipments.

A glance at a small-scale map can give an exaggerated impression of the constriction of the Strait of Hormuz, but there is no doubt that it is rightly thought of as a “choke point”. At narrowest, its width is about 30 nmi, and batteries on either the Omani or Iranian side could endanger all traffic through it.

From the Strait to the head of the Gulf is about 500 nmi and the average width is roughly 100 nmi. Although oil fields are clustered around the shores of the Gulf, principally near its head, they extend for a considerable distance inland as well.

The climate of the region is notably insalubrious and vegetation is very sparse except in marshes and areas under irrigation. The coastal plains generally lend themselves reasonably well to large-scale mobile warfare. On the Iranian side, the plain is quite narrow and is backed by the 250km wide belt of the Zagros Mountains. The Zagros mostly lie above 2,000m in elevation and have a great many peaks above 3,500m. Their ruggedness, combined with the arid climate, make them a formidable military barrier. Further to the east lie deserts that are sparsely populated and all but impassible. On the Arabian side, there is generally more than 1,200km of arid, trackless, harsh terrain between Gulf and the nearest major centers outside the region.

Thus the Persian Gulf region is somewhat cut off from both Asia and the Levant by geography. Invasion over land is not impossible, as history shows, but it presents significant difficulties. Military operations within the region also confront difficulties of distance, terrain, and climate, but are relatively more feasible.

The problems of Western military presence

All of the countries of the Persian Gulf region have large Muslim majorities, and Islam is the state religion in most. As elsewhere in the Islamic world, the confrontation with modernity is a source of ongoing trauma. Scarcely anyone in the region would or even could return to the conditions of life that prevailed there before the 20th century, but most feel intensely repelled by many aspects of modernity even as they eagerly embrace others.

Because the West preceded them into the modern age, they identify its “evils” with the West and project their hostility toward it onto the West. The conflict is sharpened on both sides by ancient religious divisions, now revived, reinterpreted, and given new energy. The resulting tensions significantly constrain options for both local and Western governments in dealing with security issues.

One result has been to make it very difficult to garrison Western troops in the region. Even in cases where local governments might see hosting foreign troops as otherwise advantageous, fear of public reaction counsels caution.

For most of these governments, religion is a major factor in legitimacy. Although all seek to manipulate and direct religious sentiment, all face currents that are beyond their control. Their situation is a bit like that of the English Crown in the 17th century; if they permit a convergence of religious, economic, and social discontents against them, none can stand.

To call upon these governments to embrace Western military presence on a large scale is absurd and potentially harmful. Even if their leaders could free themselves altogether from their own culturally-induced hostilities, and even if they were convinced of a genuine convergence of interest, they cannot embrace the West more than very lightly without undermining their own legitimacy.

Far, far away

Table 1: Flight distances and times to the Persian Gulf region

From	Most direct		Zero overflight	
	nmi	hours	nmi	hours
U.S. East Coast	6,150	13	12,000	26
U.S. West Coast	7,100	15	11,500	25
Guam	5,200	11	6,000	13
Diego Garcia	2,350	5	2,600	6

The Persian Gulf's location and geographic isolation present significant obstacles of time and distance to Western military presence and intervention. Table 1 summarizes the distances and time of flight for movement of forces by air from major base areas in the U.S., from the U.S. island territory of Guam in the Pacific Ocean, and from the U.S. base on the British island of Diego Garcia in the Southern Indian Ocean. The destination is point near the middle of the region. Flight at a steady speed of 460 knots (equivalent to Mach 0.8 at high altitudes) is assumed. Two distances are shown, the most direct great circle route and a route that avoids overflying any non-U.S. sovereign territory. In general, the distances greatly exceed the useful unrefueled capabilities of current aircraft, so these missions would require air or ground refueling en route. Diego Garcia is an exception; heavy aircraft can cover this leg with a good payload without refueling.

Heavy equipment, logistic support, and the main stocks of weapons and consumables must come by sea. Table 2 summarizes maritime distances and times. It includes a number of U.S. bases as origins as well as three points that serve as convenient reference markers: London, Malta (mid-Mediterranean), and Singapore (at the mouth of the Malacca Strait). Here the destination is the Strait of Hormuz, at the mouth of the Persian Gulf. It can take another day or more to steam to destinations within the Gulf, depending on how far up the Gulf they lie. However,

Table 2: Maritime distances and steaming days to the Strait of Hormuz

From	Distance (nmi)	Days of steaming At 14 kts	At 24 kts	At 28 kts
Norfolk, Virginia (via Suez Canal)	8,120	24.5	14.6	12.6
Norfolk, Virginia (via C. of Good Hope)	11,545	34.4	20.0	17.2
San Diego, California	11,117	33.1	19.3	16.5
Pearl Harbor, Hawaii	9,255	27.5	16.1	13.8
Yokosuka, Japan	6,264	18.6	10.9	9.3
Guam	5,966	17.8	10.4	8.9
Diego Garcia	2,263	6.7	3.9	3.4
Singapore	3,381	10.1	5.9	5.0
Malta	3,788	11.6	7.1	6.1
London, England	6,167	18.7	11.2	9.7

warships approaching the Strait of Hormuz may be able to strike at targets within the region as much as several days before reaching it, particularly if approaching from the Suez Canal. All routes from Europe and the U.S. East Coast are assumed to pass through the Canal except in the one case noted. The three speeds used for time calculations correspond to a normal speed for routine transit by warships in peacetime (14 kt), the best speed of fast logistics ships (24 kt), and the best sustained speed of warships rushing to a crisis (28 kt).[136]

Force at a distance

The two tables help to clarify the problems the U.S. and our allies face in any effort to exert military power in the Persian Gulf region in the absence of any substantial in-region garrisons.

For more than eight decades, the U.S. has striven to develop very long-range precision strike systems as a more-or-less comprehensive solution to demands to exercise military power at great distance. Despite very impressive technical and operational accomplishments, strategic effectiveness remains unclear and subject to scholarly dispute. [59] Not withstanding the urgings of a substantial corps of enthusiasts, no American administration has yet felt sufficiently confident of long-distance air power's puissance to rely upon exclusively for non-nuclear deterrence or compellence.

[136] For air distances I have calculated great circle routes from the major military base areas on the U.S. eastern and western coasts, as well as the other points shown, to Bahrain. The non-overflight routes are modified from maritime routes. Sea distances are calculated from data in [NIMA 1999]. Routes from Pacific origins all transit the Strait of Malacca and the channel between India and the Laccadive Islands. Transit via the Eight Degree Channel would add little to the distances but use of straits more southerly than the Malacca or more circuitous routes through or around the barrier of the Maldive Ridge would extend distances from Pacific ports. For routes involving Suez Canal transit, an allowance of 16 hours has been used for preparation and transit.

This is not to say that long range air power plays a small role in the U.S. posture with respect to the Persian Gulf. Bombers staging from a base on Guam have struck targets in Iraq several times since the Gulf War, and bombers based temporarily in Diego Garcia and Egypt were prominent in Gulf War operations. The operations of U.S.-based B-2A bombers against targets in Serbia during Operation Allied Force could well presage yet longer-ranged sorties against targets in the Persian Gulf region. But few outside the ranks of the U.S. Air Force appear ready to reckon such forces as sufficient, in themselves, to bear all or most of the burden of deterring and fighting wars in the Persian Gulf region or elsewhere.

The use of other kinds of force for deterrence and compellence in the Persian Gulf region depends on bringing heavy matériel into or close to the region. Present U.S. airlift resources are not nearly sufficient for this and there is no plan at this time to expand them greatly. As can be seen in Table 2, heavy forces that must be sealifted from the United States mainland will take more than two weeks to begin to arrive—four weeks is a likely minimum when the times for loading, offloading, and marshalling are taken into account.

The U.S. has ameliorated this problem by propositioning much matériel within or close to the region. Several brigade sets of ground forces equipment are stored in land depots or on nearby ships. They could equip troops flown in from the U.S., who could be ready to fight within days.[137] Tactical air units can of course fly to the theater in timeframes suggested by Table 1, and there are prepositioned stocks of ammunition and other logistics to support them.

Nevertheless, U.S. administrations have shown a strong disposition to keep naval forces afloat in or very near the Persian Gulf more or less continuously. Since normal deployments are limited strictly to 180 days out of concern for the burdens of long deployments on sailors and Marines, and since (as can be seen in Table 2) normal transit times can take up half or more of this period, it generally takes about two ships "on deployment" to keep one in the Persian Gulf. Maintenance and training requirements generally prevent ships from deploying more often than 6 months out of 18, so on average the Navy must have 6 ships or more for every one it keeps on station there. (Of course most of the ships that are in training or maintenance are available for more or less immediate dispatch in case of a serious emergency and so contribute to surge capabilities. Indeed, studies suggest that the practice of rotating deployments adds little to the costs of owning naval forces and subtracts little from their availability to meet surge requirements.)

[137] The prepositioning ships can be based as far away as Diego Garcia without adding appreciable delay over that involved in airlifting troops.

What is the U.S. interest?

Having seen something of the burdens involved in exerting military power in a theater so distant, it seems reasonable to ask whether and to what extent it is in American interest to do so.

The problem

I have argued to the following effect:

- International oil markets cannot be depended upon to provide a competitive and orderly vehicle for exchange except to the extent that outside authority assures it; there is no in-built automatic mechanism to assure competitiveness or order.
- States which are very rich in oil resources and strong in oil production—most of them lying in the Persian Gulf region—have combined to restrict output and undermine competition in an effort to capture additional profits.
- The cartel's success depends on concerted action by enough suppliers to constitute a substantial majority of potential supply. Yet this demands that each member sacrifice some potential sales for the good of all producers (whether members or not). Cartel participants are bound to squabble over shares, and each stands to gain if he can produce more than allowed and sell it at inflated prices. Thus there is an in-built source of tension and even conflict among participants. That is, the existence of a cartel tends (in this situation) not only to impair competition but to undermine market order at the same time.
- Three possible future trends could tend to make the cartel less stable and more contentious:
    - At present, Saudi Arabia is substantially the largest producer and largest holder of oil resources. But if recent trends continue, Iran and Iraq are likely eventually to draw closer to parity with the Saudis. Thus there will be no single natural leader or dominant force in the cartel.
    - The proportion of the world's potential oil production controlled by the cartel, and in particular that lying within the Persian Gulf region, could well climb considerably over the coming decades—perhaps to significantly more than 50%. If so, of course, the cartel will have better prospects for exerting market power. But at the same time, the stakes for individual cartel members will increase.
    - If diminishing resources of oil begin to drive the costs of finding and developing productive capacity up sharply, the profit potential of the Persian Gulf producers could increase, as the holders of the last remaining major reserves of low-cost oil. But of course this would also work to raise the benefits others might hope to reap if they could gain control over them.

All of this, as I see it, makes it very possible that someone might attempt to gain market power through non-market means: the *ultima ratio regum.* Every effort should be made, obviously, to minimize this risk through economic and diplomatic measures. Yet with so much at stake, I assert that the risk of violence cannot be avoided altogether, and that to minimize it will require credible deterrent force.

Why the United States?

Any success in improving the competitiveness and orderliness of oil markets represents a widespread public good, benefiting all consumers and arguably all producers as well. This being so, why should the responsibility fall disproportionately upon the United States? Of course this is simply an instance of a very broad class of such questions.

It must always fall to the greatest beneficiary to take the lead in pursuing any public good. The great beneficiary need not be a single nation, firm or individual, of course. Entities often form coalitions to pursue public goods, and the history of American domestic politics provides many examples.[138] As the world's largest economy (by a very wide margin)—and one of the faster growing economies—the U.S. generally has most to gain from economic order and competition.

The U.S. has occupied a comparable position for more than a century. In 1900 the U.S. produced 16% of world output; the second-largest economy (that of the UK) was 56% of the size of America's. By 1992, the U.S. share of world output was 20% and number two (Japan) was 44% as large.[139] This could change in the future, but there is not much present reason to expect that it will.

Up until 1917, the U.S. had remained generally aloof from world affairs, reflecting both its relative geographic isolation and its absorption in issues of domestic growth and development. The results of participation in World War I seemed quite unsatisfactory to many Americans, leading to a reversion largely to the traditional policy in the 1920s, and particularly during the searing era of the Great Depression in the 1930s. Thus the U.S. responded only mildly to Japanese expansionism in the 1930s, and scarcely at all to Germany's. The experiences of World War II made this seem like a grave error. U.S. policymakers took up the fallen torch of

---

[138] Doubt about the possibility of forming broad coalitions in support of public goods was at the heart of the traditional skepticism about the potential for democratic self-government. It was the genius of America in forging political conditions and institutions to make such coalitions feasible that finally broke down millennia of conventional wisdom that humans could not govern themselves.

[139] Derived from [Maddison 1995], Tables C-16(a) and G-2. These data are on purchasing-power parity (PPP) basis and will differ from those figured on market or official exchange rates. While more recent data are of course available, I have stayed with Maddison's (which extend only to 1992) to assure consistency. America's output had overtaken Britain's by 1870, and considerably surpassed it by 1890. On a per-capita basis it was only in the 1920s that the U.S. began greatly to outpace the other major industrial nations.

international organization for stabilization and security cooperation—most major institutions of this sort owe their founding largely to U.S. support. But they also concluded that such organizations were not likely to be effective unless led by a United States whose economic strength and diplomatic resolve were backed by great military force.

This is not the place to go into an extended analysis of the arguments and evidence regarding this proposition. I would suggest, however, that nothing since would seem fundamentally to invalidate the conclusions of the statesmen of the 1940s and 1950s. That is, the U.S. can best assure effective international cooperation toward shared goals to the extent that it displays a capacity and willingness to act on its own should that be necessary.[140]

Obviously, this cannot be the entire answer, for if the U.S. can be counted upon to provide public goods, there is little incentive for others to participate. Here, the U.S. is served by a policy of linkages. It stands at the center of a great network of international public projects. Many are not *pure* public goods—the benefits may be widely shared, but not necessarily universally or uniformly so. Thus the U.S. is in a position to make cooperation broadly rewarding, and to limit the extent to which nations may pick and choose areas of cooperation while still reaping maximum benefit in the large.

Americans generally have felt frustration over the imperfectness with which the burdens of creating international public goods have been shared. To some extent, of course, it is always easy for everyone to underestimate how heavily the burdens carried by others truly weigh upon them. Even allowing that some may have borne more than their share and others less, however, the amazing thing is that the burdens of international public good have been shared at all.

There is no demonstrated or plausible substitute for United States leadership in such matters. And there can be no leadership in matters in which force may be necessary without the possession of great force.

Issues and implications for U.S. policy

Many implications can be drawn and many issues identified in all that has been said here. I list those that seem primary to me.

Improve force posture for Persian Gulf action

While the U.S. has very good capabilities for exerting military presence and force in and around the Persian Gulf, they could be better. I do not want to address the quantity of resources devoted to this role here, for to do so intelligently

[140] Of course this must be allied with a readiness to respect and accommodate the views of others who show resolve and capacity to contribute to the common good. It is not an argument for leadership by heedless unilateralism.

requires a survey of other resource demands that is beyond the scope of this paper. Nor is this the place for technical specifics. But a few general implications stand out:

Improve lift technology

For many decades, Defense took the lead in development of technology for lift vehicles—ships and aircraft for carrying matériel to distant places. In recent decades, the tendency has been to take and adapt whatever technology may be developed for commercial purposes, with very limited government funding for fundamental improvements. Because commercial needs are quite different, this has meant stagnation in lift technology. The demands of exercising military power in the far-distant Persian Gulf suggest that it would be worthwhile to seek improvements in lift technology. Since such improvements generally take many years to reach fruition, it is not feasible to wait until the need is acute.

Lighten the loads

Another way to improve lift capabilities is to reduce the burdens to be lifted. This involves two thrusts:

- Substitute forms of force requiring less matériel for those requiring more
- Reduce the mass and volume of matériel relative to military capability through improvement in design and/or technology

Again, for the most part measures like this take many years to mature.

Get closer

I sketched above how prepositioned matériel aids in force responsiveness, and Table 2 makes it clear how helpful forward bases are in reducing time for response in a crisis as well as trimming the overhead of transit time for seaborne deployment. More effort should be made to find and develop suitable bases that would reduce the burdens of routine and emergency deployments. This should not be read as a call for attempts to secure garrisons within the Persian Gulf region; as I have suggested, that is a notion fraught with peril.

In general, it will be easier to find logistical and maintenance basing than places for large garrisons or for mounting warlike operations. Adaptation in operating practices and patterns may be necessary to make use of the facilities that can reasonably be obtained.

Keep linking

Linking Persian Gulf states into the international system has been difficult. Oil contributes so great a portion of their wealth as to dominate other interests, and suspicions and hostilities with cultural and religious roots have inhibited clear dialog. And of course the very tenuous legitimacy of regional governments and their lack of strong and resilient institutions have brought many efforts to ruin. Many of the claims made for the results of linkage-based diplomacy in the region in the past do not stand up very well to critical scrutiny [60]. Even at best, it is very difficult to be sure how effective diplomacy has been in the past or how well it can serve in the future.

Nevertheless, diplomacy makes too much sense and costs too little to be dismissed. In effect, diplomacy endeavors to re-create on an international scale the kinds of networks of relationships that tie societies together and stimulate and constrain the actions of individuals and social groups. This analogy of course also suggests some of the inherent limitations of diplomacy in dealing with states that reject the international order and insist on remaining aloof from it. The more attractive we can make our linkages seem, the more effective our diplomacy.

Strengthen oil markets

The better oil markets operate—the greater their efficiency, transparency, and order—the better off we shall all be. In particular, good markets will improve the timeliness and quality of economic responses to diminishing oil resources or any other disturbing factors.

Align costs and benefits

Markets can never be entirely "free", for ultimately they can only be regulated and guaranteed by governmental power. They can function to allocate resources efficiently only to the extent that costs and benefits are directly aligned. Those who regulate markets must be very careful to avoid situations in which A must pay for what B gets. To do this is far from easy, trivial, or "natural". The vulgar notion that it is only "government interference" that imbalances markets in the first place and that all imbalances can be righted by "deregulation" is both absurd and dangerous. Markets are creations of society, not nature, and this makes societal regulation inherently unavoidable; the question is only that of the knowledge, intelligence, and honesty that informs it.

Tax wisely

Because trade in oil is a major sector of economic activity, it is a natural subject for government revenue raising through collection of taxes and fees. As always, it is important to apply these in ways that do not distort market incentives, or at least not to do so without very serious and careful consideration of the implications. Taxation of oil is made more complex because governments own the property rights to so much of it.[141] Taxes that take a portion of profits (over and above costs of acquiring and developing deposits) do not distort incentives, but those which

[141] The U.S. is all but unique in assigning subsurface property rights to land owners. But even in this country, a great portion of the oil resources are government owned because they lie beneath government lands or bodies of water.

take a fixed fraction of selling price act to tilt the scales against of smaller reservoirs, which have higher costs [61]. The U.S. has made some progress toward profit-based taxation, but more remains to be done. And many foreign nations are far behind the U.S. in this. Such sources of inefficiencies should be eliminated—the need is not to tax less but to tax in ways that do not distort incentives and make production less efficient.

Consumption of oil and its products also is taxed—heavily in many places, very lightly in the U.S. This is less likely to distort market incentives, but some care must be taken to ensure against unintended consequences of consumption taxation.

Deal wisely with climate change and other public issues

The evidence that human activities are warming the lower atmosphere of our planet is strong and growing rapidly. The imminence, severity, and exact nature of the consequences is still subject to considerable uncertainty, and it may in fact be inherently impossible to resolve it short of trying the experiment. Nevertheless, it seems likely that something must be done in order to avoid serious problems, and at least conceivable that something will be. Limiting carbon dioxide emissions seems bound to be a major aspect of any program, and it is hard to see how this can be done without limiting the burning of oil and other carbonaceous fuels.[142]

The best way to allocate the burdens associated with any controls is almost sure to lie through market mechanisms. Ideally, these will take the form of taxes levied directly upon emissions and borne by those who control and benefit from the activities that produce them. This will not be feasible in all cases, and less direct taxation or perhaps (least desirable) outright controls will be needed. Such measures must be crafted carefully to avoid distortions and perverse incentives that lead to inefficient allocations of resources. Naturally, increased taxation of emissions or fuels must be offset by reductions in general taxation to avoid a drag on the economy as a whole. It will undoubtedly be necessary to experiment with tax rates somewhat in order to determine the price elasticity of emission levels.

Shed more light

Good markets promote economic efficiency by providing participants with reliable and timely information about current prices and trading volumes for a variety of goods. Unfortunately, cartelization and governmental involvement in the oil market have worked greatly to obscure market information by decoupling price and quantity from economic forces.

The U.S. government maintains several research and statistical activities that provide reliable information which to some extent compensates for the lack of

[142] CO_2 is by no means the sole nor even the most potent (per unit volume) of greenhouse gases, but it is produced in such great and growing volume through burning that little can be done to control warming without limiting its production.

good market information.[143] Care needs to be taken not to cripple these critical functions in efforts to economize in government. Indeed, every effort should be bent toward strengthening information so as to counterbalance the effect of cartelization in obscuring market information.

Prepare for the future

Look ahead

This paper presents and summarizes some efforts to see what may be coming in oil markets for the future, as affected by economic, natural, and political forces. A great deal more can be done along these lines, and should be. In particular, well thought-out and structured gaming activities, coupled with and informing computerized mathematical simulations, can do much to illuminate possible modes of market and even political evolution in response to market, political, and natural events. Given the economic and political importance of oil and the uncertainties surrounding it, it is truly remarkable how little support there is for serious research into these possibilities.

Re-examine strategic petroleum reserves (SPR)

An SPR of the right size, managed in the right manner, can help much to cushion the impacts of shocks and upsets to oil supply. Present SPRs of approximately 1.5 gbbl may be adequate for present circumstances. (See Appendix A section on "Strategic" petroleum reserves at page 45.) But the possibility of much greater disturbances in the future suggests that much larger SPRs may be worthwhile. This should be studied using the simulation tools I recommend above. Since SPRs are international public goods, efforts should be made to secure broader international support for their costs.

Learn more about alternatives

In the past, the U.S. government has spent substantial sums on research into alternative energy technologies intended for commercial application. Common belief notwithstanding, there is little evidence that the government is worse at making commercial technology choices than is private industry. But there is equally little to suggest that it is superior. The impediments to transferring technology suggest that it would be wiser to leave its development to those who stand most to benefit from it.

Where the government can and should play a stronger role is in sponsoring the scientific research that will hopefully provide the basis for future technology. It

---

[143] Particularly notable in this connection are the efforts of the Energy Information Administration (EIA) of the Department of Energy and the U.S. Geological Survey (USGS) of the Department of the Interior. It will be noted that EIA and USGS publications occupy a prominent place in the bibliography of this paper. The U.S. is all but unique in the excellence and comprehensiveness of its public economic data and research, and derives great benefits from it.

is well established that scientific research has high economic returns. But because it is difficult for those who sponsor research to capture the returns, incentives to private sponsorship are weak. The U.S. government has a good record in sponsoring important and productive research. It needs to put more effort into research areas that will affect alternatives to oil and for oil. Appendix E (page 83) gives some idea of the scope of the possibilities.

Learn more about problems

The U.S. government has a reasonably good record in sponsoring scientific research relating to climate change and the other environmental effects (known or hypothesized) of oil production and consumption. As public controversy develops regarding these issues, there can be a temptation to cut back on research support (or to attempt to force research in certain directions) to gain short-term political objectives. This is a grave error which can have serious long-term consequences, and should be avoided at all cost.

Appendix G
Glossary of terms and abbreviations

An asterisk (*) next to a term indicates that it is non-standard, or employed in a non-standard manner in this paper.

Abandon (a well)	Cease production permanently. Implies that well has been capped and all production equipment removed for re-use or salvage.
Abiogenic	Not involving biological processes. In the case of so-called *abiogenic petroleum,* however, the theory involves some biological activity.
Abiogenic methane	Used in two different senses by various authors (and hence subject to confusion): 1. Methane not produced by *contemporary* biogenesis; ancient biogenesis it not ruled out. (This is the more standard and widespread usage.) 2. Gaseous *abiogenic petroleum* (q.v.)
Abiogenic petroleum	Supposed petroleum of ultimately extraterrestrial origin. According to a theory by Prof. Thomas Gold (see [Gold 1999]), *all* terrestrial petroleum originates in hydrocarbons from space which accreted to Earth in the process of its formation. Non-standard theory.
Alcohol	Any of a wide class of chemical compounds composed of hydrogen and carbon atoms, with a single oxygen. In essence, a molecule of an alcohol is a water molecule in which one of the two hydrogens has been replaced with a hydrocarbon chain. See also *ether.*
Algae	Any of a wide variety of single-celled organisms, mostly living in water, that function like plants.
Barrel (oil)	A unit of measure for oil equal to 42 U.S. gallons, equivalent to about 159 liters. The density of oil varies, but on average a barrel of crude oil weighs about 300 lbs or 136 kg.
bbl	*Barrel,* abbrev.

Biogenic	Produced through biological action.
Biogenic methane	Often used to distinguish methane produced by immediate, contemporary biogenesis from methane produced in the past (whether biogenically or otherwise) and held in the Earth by geologic traps.
Biomass	Any organic matter (especially of plant origin) that can be converted to fuel.
Butane	A hydrocarbon often found in natural gas, chemical formula C_4H_{10}
C	Chemical symbol for *carbon*.
Cap (a well)	A seal, usually concrete, in the bore of an abandoned well.
Cap rock	An impermeable geologic structure lying above a petroleum *reservoir* and forming a *trap*.
Carbon	A chemical element, symbol *C*.
Carbon dioxide	A compound, gaseous under normal conditions, each molecule of which contains one carbon atom and two oxygens, having chemical formula CO_2
Catalyst	A chemical substance which enters into and facilitates a chemical reaction but emerges from the reaction in its original state.
Clathrate	A chemical substance in which a molecule of one substance fills a place within the crystal lattice of another substance. *Gas hydrates* are clathrates.
CNG	Compressed natural gas.
CO_2	Carbon dioxide.
Cold fusion	Thermonuclear fusion taking place at low (average) temperatures. Often (incorrectly) associated with *Fleischmann-Pons cells* (q.v.).
Cornucopian*	One who expects that the advance of technology or other processes will continue to provide resources in abundance, notwithstanding population growth and the exhaustion of certain forms of resources.
Crack, cracking	Decomposition of hydrocarbons through application of heat and/or pressure, in the presence of catalysts.
Crude oil	*Petroleum* in liquid form. Because petroleum is so complex and varied, and because petroleum liquids often are intermixed with solids and gases, definitions of crude oil often incorporate specifications of viscosity, vapor pressure, etc.

	This differ, and can result in differing classifications of some samples.
Diesel	A heat engine cycle invented by Rudolph Diesel, distinguished by compression ignition and fuel burning at essentially constant pressure.
Diesel fuel	Fuel adapted for Diesel engines. The fuel must ignite readily —but not too readily—in a fuel-air mixture in response to compression. Diesel fuels generally are unsuitable for spark-ignition engines, and conversely.
Dimethyl ether	A compound comprising two methyl radicals joined to an oxygen: CH_3OCH_3. The simplest *ether.* A gas at ordinary temperatures and pressures, but can be liquefied at modest pressures. A potential Diesel fuel.
DME	*Dimethyl ether,* abbrev.
Doomster*	One who expects that oil supplies will run out in the relatively near future.
Drive	The force that drives petroleum through reservoir pores to the well bore. Drive derives ultimately from gravitational force, stored and transmitted by fluids within the earth. In most cases, the drive in a reservoir or field will fall off over time as it is produced.
Dry gas	Natural gas that is almost entirely lacking in heavier hydrocarbon components that can be recovered by a separator at the surface.
dy	*Day,* abbrev.
Efficiency	In an engineering system, the ratio of energy output to energy input through a particular control volume.
EIA	Energy Information Administration, an organization of the U.S. Department of Energy.
Electrolysis	The process of separating the ionic components of a chemical compound by passing an electric current through it. In electrolysis of water, hydrogen and oxygen are produced.
Endothermic	A chemical reaction which absorbs net energy from its surroundings is *endothermic.*
Endowment	The amount of oil or petroleum, either gross or recoverable, originally in a particular province or reservoir.
Enhanced (oil) recovery	*Tertiary recovery* (q.v.). Also applied to secondary recovery sometimes.

EOR	*Enhanced oil recovery.*
Ethane	Second most prevalent constituent of natural gas, C_2H_6
Ethanol	An alcohol, C_2H_5OH, that is the active ingredient of alcoholic beverages but can also be burned as a fuel.
Ether	Any of a wide class of chemical compounds composed of hydrogen and carbon atoms, with a single oxygen. In an ether, the oxygen joins two hydrocarbon chains. See also *alcohol.*
Ethyl alcohol	Ethanol.
Exothermic	A chemical reaction which releases net energy to its surroundings is *exothermic.*
Field	A single isolated reservoir or a compact group of closely-spaced or overlapping reservoirs.
Fischer-Tropsch process	An industrial chemical process which involves reacting CO and H_2 over a catalyst to form various hydrocarbon species with water and/or carbon dioxide and considerable heat as byproducts.
Fleischmann-Pons cell	An electrochemical cell with platinum and palladium electrodes in an electrolyte based on heavy water. It is claimed (with very little evidence) that under certain conditions an F-P cell may produce an excess of energy in the form of heat at low temperatures. It is further claimed (wrongly) that this supposed heat production is a result of *cold fusion.*
Fraction	A component or group of components in a petroleum mixture that vaporize at a common temperature.
Fractional distillation	Separation of volatile components of different boiling points in a petroleum mixture by the gradual increase of temperature and the separate collection of each component. Pressure may be reduced to aid in separating the least volatile fractions.
F-T process	*Fischer-Tropsch process* (q.v.)
Fuel cell	A reverse electrolytic cell in which chemical reactions between a fuel and oxidizer are used to generate an electrical current.
Gas hydrate	A clathrate in which gas molecules are enclosed in a matrix of water ice.
Gasoline	A mixture of volatile light liquid hydrocarbon fractions adapted to the needs of spark-ignition engines.
gbbl	*Gigabarrel,* meaning one billion barrels.

Geological Survey	USGG (q.v.)
Geology	The science of the dynamics and physical history of the Earth, the rocks of which comprising it, and the physical, chemical, and biological changes that the Earth has undergone or is undergoing
Geophysics	The science of the physical mechanisms of geological processes.
Geotherm	The relationship between temperature and depth in the Earth at a given location.
Grain alcohol	Ethanol, esp. when made by fermentation of grain.
Greenhouse effect	A phenomenon that causes the Earth's atmosphere to be significantly warmer than otherwise it would be. Short wave heat radiation from the Sun passes through the atmosphere with little absorption. But when it is absorbed the earth, longer wave radiation is emitted. These longer wavelengths are strongly absorbed by the "greenhouse gases", which most notably include carbon dioxide, methane, and water vapor, thus heating the atmosphere.
H	Chemical symbol for *hydrogen*.
Hotelling	Harold Hotelling (1895-1973), economist and mathematical statistician.
Hotelling's Rule	A supposition that the value of a deposit of a mineral ought to rise at a rate commensurate with the rate of return on other investments, such as bonds. While it forms a convenient basis for analysis, the "rule" is not borne out by empirical data.
hr	*Hour,* abbrev.
Hubbert	M. King Hubbert (1903-1989), a pioneering geophysicist.
Hubbertist*	One who expects (with Hubbert) that production of limited natural resources such as oil will follow a symmetric logistic curve, with production rates declining after the point of 50% exhaustion.
Hydrate	*Gas hydrate* or *methane hydrate* (q.v.)
Hydrocarbon	Any of a wide range of compounds consisting entirely of hydrogen and carbon.
Hydrogen	A chemical element, symbol *H*.
IEA	International Energy Agency. http://www.iea.org/

Incrementalist*	One who expects than any eventual tightening of oil supplies will be delayed until at least several decades from now and that when it does occur it will prompt higher prices, which in turn will lead to incremental and orderly development and substitution of other energy sources.
Kerogen	An insoluble waxy substance rich in precursors to hydrocarbons, from which a hydrocarbon oil may be obtained by heating to 500°C in a retort.
Kilometer	A unit of distance equal to 1000 meters, and equivalent to 3280.8 feet.
Kilowatt	A unit of energy, equal to 1000 Watts.
km	*Kilometer,* abbrev.
Knot	A derived international standard unit of speed used in marine and aerial navigation; equal to 1 nmi/hr or 1.852 km/hr.
kt	*Knot,* abbrev.
kW	*Kilowatt,* abbrev.
Lift	*Produce* (q.v.)
LNG	Liquefied natural gas.
m	*Meter,* abbrev.
Market power	A potential possessed by any market participant or governor to move quantity or price away from competitive equilibrium. In a perfectly competitive market, no participant has market power.
mbbl	*Megabarrel,* abbrev., meaning one million barrels.
Meter	The international standard unit of distance, equivalent to 39.37 U.S. inches.
Methane	The lightest hydrocarbon species, chemical formula CH_4. Principal component of natural gas.
Methane hydrate	A *gas hydrate* in which the gas molecules are largely methane.
Methanol	An alcohol, CH_3OH, that can be burned as a fuel.
Methyl alcohol	Methanol.
NAFTA	North American Free Trade Area—used as shorthand for the US, Canada, and Mexico.
Natural gas	*Petroleum* in gaseous form. Its hydrocarbon content is chiefly *methane* and *propane* (q.v.).

Natural gas liquids	Hydrocarbons that are liquid at ordinary temperatures and pressures, separated from natural gas.
Nautical mile	A derived international standard unit of distance used in marine and aerial navigation; equal to 1,852 meters and equivalent to 6,076.1 ft or 1.151 U.S. statute miles.
nmi	*Nautical mile,* abbrev.
NGL	Natural gas liquids
NYMEX	New York Mercantile Exchange. A commodities exchange which offers facilities in trading selected oil and oil-related spot, futures, and options contracts.
Oil	Crude oil or a product obtained from it by refining.
Oil deadline	The depth in the Earth (varying from place to place with the geotherm) below which the temperature is too great to permit the survival of liquid petroleum
Oil lord*	(Formed by analogy to *landlord.*) One who exercises ownership rights over deposits of crude oil.
Oil shale	Kerogen-containing source rocks whose geologic history has never carried them to the depth/temperature regime at which the kerogen would be converted to oil.
Oil window	The range of depths within the Earth (varying from place to place with the geotherm) over which kerogen is converted to crude oil.
OPEC	Organization of Petroleum Exporting Countries.
Petroleum	The literal meaning is "rock oil", but *petroleum* has come to be used as a catch-all term for crude oil, natural gas, and natural gas liquids.
Pool	A *reservoir* (q.v.). It should not be thought that oil lies in literal open pools—in fact it is held in the pore space of the source rocks.
Produce (petroleum)	To bring petroleum up from its underground reservoirs to the surface. Also *lift.*
Propane	A hydrocarbon often found in natural gas, chemical formula C_3H_8
Recovery	The percentage of the petroleum in a deposit or group of deposits that can be produced. Variable with economic and technical conditions for any given reservoir, and greatly variable from reservoir to reservoir due to natural conditions.

Refine, refinery	Refining is the set of industrial chemical processes by which raw petroleum is converted to a variety of products (including some feedstocks for further chemical processes). Fractional distillation and cracking are the principal refinery processes.
Reserves	1. *Strictly:* (a) Deposits that have been fully developed to the point of production. (b) The estimated volume of such a reserve that can be produced under specific (and stated) economic and technical assumptions (which may or may not be fixed over the projected duration of production). Often referred to as *proven reserves* to draw a distinction with meanings 2 and 3. In this paper, *reserves* always is used in this sense except as otherwise specified. 2. *Broadly:* (a) Petroleum deposits that have been clearly identified and assessed as to location, amount, composition, and access. (b) The estimated volume of such deposits. 3. *Very broadly:* All petroleum deposits known or believed to exist, found or unfound, or the volume of such deposits. 4. (A quite different sense): A *strategic petroleum reserve* (q.v.)
Reservoir	A compact mass of petroleum trapped within the Earth susceptible, in principle, of being fully produced from a single well bore. (In practice, multiple well bores often drain a single reservoir for economic reasons.) Also *pool.*
Secondary recovery	Petroleum recovery accomplished by supplementing the natural drive with artificial means, such as injecting gas under pressure in some wells to drive the oil to others.
Seep (of oil)	A place on the Earth's surface at which petroleum is expressed.
Shut in (a well)	To stop production temporarily.
Source rock	The rock within which organic residues were originally trapped and converted to petroleum. Often at a considerable distance from the reservoir rock due to petroleum migration.
SPR	*Strategic Petroleum Reserve* (abbrev.)
Strategic petroleum reserve	Petroleum that has already been produced and is held in storage as buffer stock in the event of a supply or price shock.
Syncrude	An oil produced by *Fischer-Tropsch* or other chemical process from non-petroleum feedstocks and taken as an input for re-

	fining in the same manner as crude oil.
Syngas	A $CO + H_2$ mixture (which will also generally contain a variety of other substances in lesser concentration) which is the feedstock for a *Fischer-Tropsch* process. It is formed from a carbon-rich feedstock (such as coal) by processing with heat and pressure with the addition of oxygen and steam.
Synthesis gas	*Syngas* (q.v.)
Tar sand	Unconsolidated sediments that contain bitumen, a tarry substance rich in hydrocarbons, thought to have been created by biodegradation of oil.
Tertiary recovery	Any of a variety of processes to promote petroleum flow into the well bore, distinguished from *secondary recovery* by their sophistication and complexity.
Thermogenic	Formed by the action of heat.
Trap	A geologic formation in which *cap rock* traps petroleum in underlying reservoir rock.
UAE	United Arab Emirates.
USGS	The U.S. Geological Survey, an organization of the Department of the Interior.
Vacuum energy	*Zero-point energy* (q.v.)
W	*Watt,* abbrev.
Watt	The international standard unit of energy.
Wood alcohol	Methanol
Yield	In a chemical process, the products actually obtained as a percentage of the theoretical maximum.
yr	*Year,* abbrev.
Zero-point (vacuum) energy	The residual energy remaining in a volume of space entirely devoid of matter and thermal energy. It is (wrongly) supposed by some to represent a usable energy source.

Appendix H
Suggestions for on-screen use of this document

Most people do not like to read documents on screen. To some extent this is a result of limitations inherent in the technology of current computer displays. But it also reflects inadequate attention to formatting for easy readability on screen.

This paper has been formatted and structured to make it suitable either for printing out or for reading on screen. Reading on screen offers some advantages (beyond saving paper and printing expense): it makes it much easier to find specific topics and follow cross-references.

In this appendix I present some ideas about how to make on-screen reading as productive as possible.

Read with Adobe Acrobat Reader (or Adobe Acrobat)

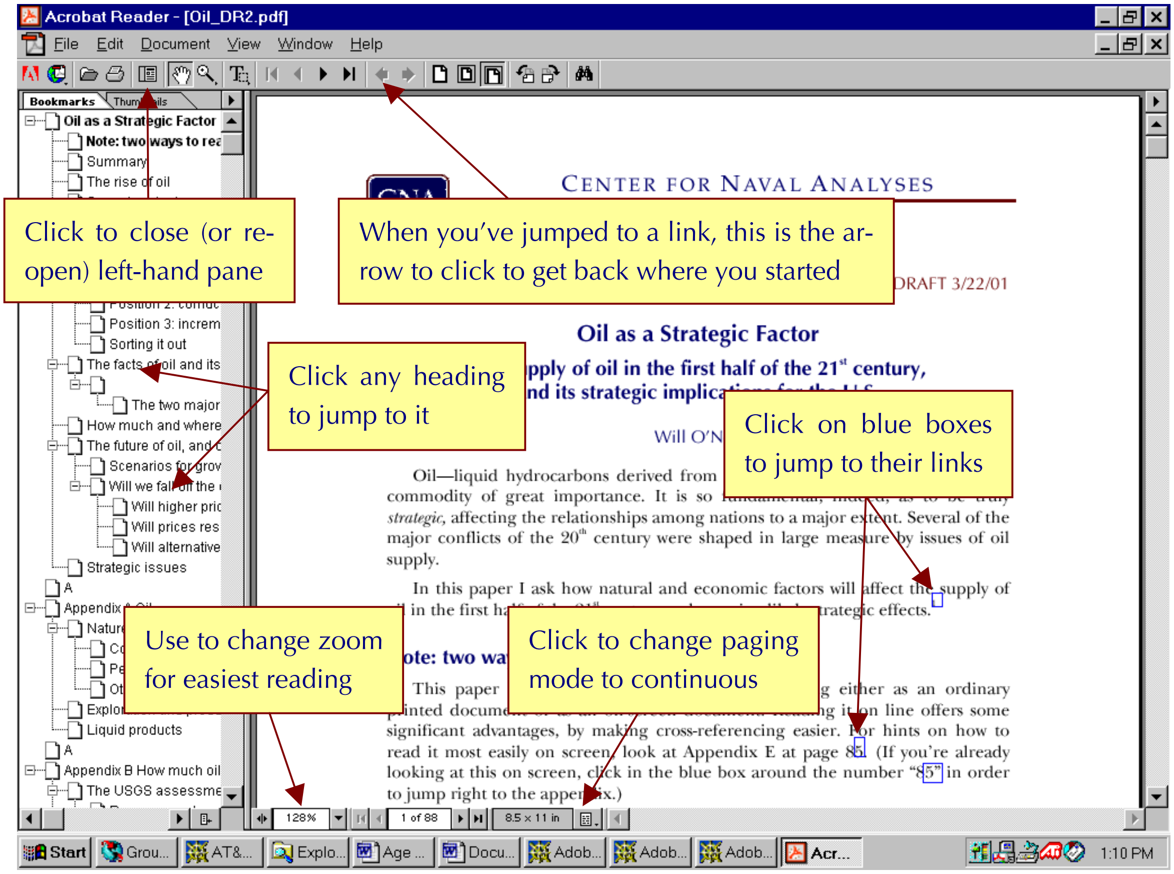
This paper will usually be distributed in electronic form as a PDF (portable document format) file. The most practical way to read it on screen (or to print it) is with the Adobe Acrobat Reader or Adobe Acrobat software, made by Adobe Systems, Incorporated. The Adobe Acrobat Reader is available for free distribution from Adobe, via their Web page at http://www.adobe.com/. (There's a "button" that says, "Get Acrobat Reader"; click on it with your mouse cursor.) Versions are available for almost all computer operating systems.

This paper was converted to PDF using Adobe Acrobat 4.05. If you have difficulty with it, the most likely cause is an older version of Acrobat Reader. It's best to upgrade to the most current version.

If you have Adobe Acrobat (which is sold by Adobe), you may find that there are advantages in using it to read this paper (and other PDF documents). It allows you to annotate and highlight sections of the PDF text.

Navigation

When you open the paper in Adobe Acrobat Reader, it will look something like what is shown in the image below. I've added annotations to indicate some of the tools and techniques for navigation.



If a cross-reference is presented in the form "Appendix X, page n", it will be better to click on the page number, as this will usually lead to the specific page within the appendix that contains the material of interest.

Bibliography

In an effort to keep the bibliography to manageable length, I have omitted references to many older works that have been consulted in cases where there are newer sources that discuss them and provide references to them. Exceptions have been made where specific facts or points have been drawn from the older work. In a few cases, I include works that have provided important structure or background information even though I make no specific citation in the text.

Links to locations of electronic copies on the World Wide Web have been provided where known. Obviously, these are impermanent and may change with no notice. In some cases, access may be by subscription only. All recent articles cited from the following publications may be found at their Web sites, by subscription:

- *The Economist* http://www.economist.com/
- *Nature* http://www.nature.com/nature/
- *Science* http://www.sciencemag.org/

[Access*Science*] Access*Science*@McGraw-Hill http://www.access*Science*.com/ [Accessed Jan 2001] Note that this is an online version of the *McGraw-Hill Encyclopedia of Science & Technology*.

[Adelman 1972] M[orris] A[lbert] Adelman, *The World Petroleum Market,* Baltimore: Johns Hopkins UP & Resources for the Future, 1972

[Adelman 1974] —, "Politics, Economics, and World Oil," *Am. Econ. Rev.*, 64; 2: 22-26 (May 74)

[Adelman 1991] —, Oil Fallacies," *Foreign Policy,* Spring 1991: 3-16

[Adelman 1993] —, *The Economics of Oil Supply: Papers by M. A. Adelman, 1962-1993.* Cambridge: MIT Pr., 1993

[Adelman 1995] —, *The Genie Out of the Bottle: World Oil Since 1970,* Cambridge: MIT Pr., 1995

[Adelman 1997a] —, "My education in mineral (especially oil) economics," *Annu. Rev. Energy Environ.* 22 (1997):13-46

[Adelman 1997b] —, "No OPEC," *International Assoc. for Energy Economics Newsletter,* Winter 1997 http://www.iaee.org/newsltr/97win9.htm

[Adelman 2001] —, "The Clumsy Cartel: OPEC's Uncertain Future," *Harvard International Review,* 23, 1 (Spring 2001): 20 et seq

[Adler] Ronald J. Adler, "Relativity: General Theory," [Access*Science*]

[Ahlbrandt 2000] Thomas S. Ahlbrandt, “Introduction,” in [Ahlbrandt et al 2000], Chapter IN http://energy.cr.usgs.gov/WEcont/chaps/IN.pdf

[Ahlbrandt et al 2000] —, et al, *U.S. Geological Survey World Petroleum Assessment 2000—Description and Results,* Digital Data Series – DDS-60, 4 CD-ROMs, Version 1.0 http://greenwood.cr.usgs.gov/energy/WorldEnergy/DDS-60/ [Note that this material is available for download from the Web site. Due to its volume, however, the CD-ROM set is far more convenient. The Web site provides details on obtaining a copy of the CD-ROM set.]

[Alhajji 2000] A. F. Alhajji, “OPEC cannot manage world oil markets,” *World Oil,* 221, 10 (Oct 2000): 129 et seq

[Alhajji & Huettner 2000] — & David Huettner, “OPEC and World Crude Oil Markets from 1973 to 1994: Cartel, Oligopoly, or Competitive?” *Energy Journal,* 21, 3 (2000) 31 et seq

[Anderson 1998] Roger N. Anderson, “Oil Production in the 21st Century,” *Scientific American,* March 1998: 86-91

[APERC 2000] Asia Pacific Energy Research Centre (APERC), “Emergency Oil Stocks And Energy Security In The APEC Region,” Tokyo, Mar 2000 http://www.ieej.or.jp/aperc/final/oilstocks.pdf

[API 1999] American Petroleum Institute, *Basic Petroleum Data Book: Petroleum Industry Statistics,* XIX; 1 (Jan 99)

[Appleby 1999] A. John Appleby, “The Electrochemical Engine for Vehicles,” *Scientific American,* Jul 1999: 74-79

[Ask Experts 6] *Scientific American: Ask the Experts: Physics* http://www.sciam.com/askexpert/physics/physics6.html [Accessed 5 Jan 2001] Answers regarding “cold fusion”.

[Ask Experts 33] —, http://www.sciam.com/askexpert/physics/physics33.html [Accessed 5 Jan 2001] Answer regarding zero-point energy and vacuum energy.

[Attanasi 1995] Emil D. Attanasi, “Economics and the 1995 National Assessment of U.S. Oil and Gas Reserves,” U.S. Geological Open-File Report 95-75-M http://energy.er.usgs.gov/products/openfile/OF95-75-M/econ_oil&gas.htm

[Bains 2000] Santo Bains, et al, “Termination of global warmth at the Paleocene/Eocene boundary through productivity feedback,” *Nature,* 407 (14 Sept 2000): 171-174

[Baker Institute 1998] James A. Baker Institute for Public Policy, Rice University, “Unlocking the Assets: Energy and the Future of Central Asia and the Caucasus. A Political, Economic, and Cultural Analysis,” Baker Institute Study #6, April 1998 http://riceinfo.rice.edu/projects/baker/Pubs/BakerPub/publications/studies/study6.html

[Banks 1998] Ferdinand E. Banks, “An Outlook on the Supply of Oil,” *International Assoc. for Energy Economics Newsletter,* Winter 1998 http://www.iaee.org/newsltr/98win6.htm

[Boetius 2000] Antje Boetius, et al, “A marine microbial consortium apparently mediating anaerobic oxidation of methane,” *Nature,* 407 (5 Oct 2000): 623-626

[Borenstein 2001] Severin Borenstein, "The Trouble With Electricity Markets (and some solutions)," PWP-0181, U. of California Energy Inst., Jan 2001 http://www-path.eecs.berkeley.edu/ucei/PDF/pwp081.pdf

[Boyer 1985] Timothy H. Boyer, "The Classical Vacuum," *Scientific American,* Dec 1997: 70-78

[BP 2000] *BP Statistical Review of World Energy 2000,* London: BP Amoco, 2000

[Brydges & Drake 2000] Jane E. Brydges & Elisabeth M. Drake, "Running Buses on Hydrogen Fuel Cells: Barriers and Opportunities," e-lab, Jul-Sep 2000 http://web.mit.edu/energylab/www/e-lab/july-sep00/art2.html

[Campbell 1996a] Colin J. Campbell, "The Twenty First Century: The World's Endowment of Conventional Oil and its Depletion," Jan 1996 http://www.hubbertpeak.com/campbell/index.html

[Campbell 1996b] —, "An Open Letter to Mr. Porter, Author of, 'Are we running out of oil?'" 8 April 1996 http://www.ganesa.com/ecotopia/hubbert/camport.htm

[Campbell 1997] —, *The Coming Oil Crisis,* Multi-Science Pub. & Petroconsultants, 1997

[Campbell & Laherrère 1998] — & J. H. Laherrère, "The End of Cheap Oil," *Scientific American,* Mar 1998: 78-83

[Cooper 1998] Gareth Cooper, "Organic Matter in Sediments," Petroleum Exploration Society of Australia, 1998 http://www.latrobe.edu.au/www/pesa/vitrinite/Vitinfo/guide.html

[CSM 1996] "Center for Petroleum Supply Studies Opens at CSM," press release by Colorado School of Mines, Sep. 30, 1996 http://www.mines.edu/All_about/public/prrel27.shtml

[Daalder & O'Hanlon 2000] Ivo H. Daalder & Michael O'Hanlon, *Winning Ugly: NATO's war to save Kosovo,* Washington: Brookings, 2000

[Dahl et al 1999] J. E. Dahl, et al, "Diamondoid hydrocarbons as indicators of natural oil cracking," *Nature,* 399 (6 May 1999): 54-57

[Darnell 1990] Adrian C. Darnell, "The Life and Economic Thought of Harold Hotelling," in [Darnell (ed) 1990]

[Darnell (ed) 1990] — (ed), *The Collected Economic Articles of Harold Hotelling,* New York: Springer-Verlag, 1990

[Dasgupta & Heal 1979] Partha S. Dasgupta & Geoffrey M. Heal, *Economic Theory and Exhaustible Resources,* Welwyn (UK): Jas. Nisbet; Cambridge: Cambridge UP, 1979

[Deaton & LaRoque 1992] Angus Deaton & Guy LaRoque, "On the Behaviour of Commodity Prices," *Rev. Econ. Studies,* 92 (1992): 1-23

[DeGolyer & MacNaughton 1997] DeGolyer and MacNaughton, *Twentieth Century Petroleum Statistics,* 1997

[De Santis 2000] Roberto A. De Santis, "Crude Oil Price Fluctuations and Saudi Arabian Behaviour," Working Paper 1014, Kiel Institute of World Economics, Oct 2000 http://www.uni-kiel.de/IfW/pub/kap/2000/kap1014.pdf

[Devarajan & Fisher 1981] Shantayanan Devarajan & Anthony C. Fisher, "Hotelling's 'Economics of Exhaustible Resources': Fifty Years Later," *J. Econ. Lit.,* XIX (Mar 81): 65-73

[Donaldson 1996] A. J. Donaldson, "Submarine Power Sources for the Mission," *Naval Engrs. J.*, May 1996: 129-146

[Dos Santos & Cueille 1997] Edmilson Moutinho Dos Santos and Jean-Philippe Cueille, "An Evolutionist Analysis of Oil Competition and Oil Competitiveness Throughout Oil History," *International Assoc. for Energy Economics Newsletter,* Fall 1997 http://www.iaee.org/newsltr/97fall6.htm

[Dostrovsky 1991] Israel Dostrovsky, "Chemical Fuels from the Sun." *Scientific American,* December 1991, 102-107

[Drennan & Erikson 1998] Thomas E. Drennan & Jon D. Erikson, "Who Will Fuel China?" *Science*, 279 (6 Mar 1998): 1483

[Drew 1997] L. J. Drew, *Undiscovered Petroleum and Mineral Resources: Assessment and Controversy,* New York: Plenum Pr., 1997

[EB] *Encyclopædia Britannica Online.* http://www.eb.com/ [Accessed Dec 2000 & Jan 2001]

[Economist 1997a] "At last, the fuel cell," *The Economist*, October 25th, 1997

[Economist 1997b] "Plenty of gloom," *The Economist*, December 20th, 1997: 19-21

[Economist 1999] "Fuel cells meet big business," *The Economist*, July 24th, 1999

[Economist 2000a] "How green is your hydrogen?" *The Economist*, April 1st, 2000

[Economist 2000b] "Selling fuel cells," *The Economist*, July 1st, 2000

[Economist 2000c] "All that glisters," *The Economist*, December 9th, 2000

[Economist 2001a] "The fuel cell's bumpy ride," *The Economist*, March 22nd, 2001

[Edwards 1997] John D. Edwards, "Crude Oil and Alternate Energy Production Forecasts for the Twenty-First Century: The End of the Hydrocarbon Era," *Am. Assoc. of Petroleum Geologists Bull.,* 81, 8 (Aug 1997): 1292-1305

[EIA 2000a] Energy Information Administration (U.S. Dept. of Energy), *International Energy Outlook 2000,* DOE/EIA-0484(2000), Mar 2000 www.eia.doe.gov/oiaf/ieo/index.html

[EIA 2000b] —, *Long Term World Oil Supply (A Resource Base/Production Path Analysis),* Jul 28, 2000 http://www.eia.doe.gov/pub/oil_gas/petroleum/presentations/2000/long_term_supply/

[EIA 2000c] —, *Annual Energy Outlook 2001: With Projections to 2020,* DOE/EIA-0383(2001), Dec 2000 www.eia.doe.gov/oiaf/aeo/

[EIA 2000d] —, *Costs and Indices for Domestic Oil and Gas Field Equipment and Production Operations, 1996 Through 1999,* DOE/EIA-0185(2000), March 2000

[EIA 2001a] —, *International Energy Annual 1999,* DOE/EIA-0219(99), Feb 2001 http://www.eia.doe.gov/iea/

[EIA 2001b] —, "Selected Crude Oil Spot Prices," http://www.eia.doe.gov/emeu/international/crude1.html [Accessed 4 Apr 2001]

[EIA 2001c] —, *International Petroleum Monthly, April 2001* http://www.eia.doe.gov/pub/pdf/international/05200104.pdf

[ERSP 1995] Energy Resources Surveys Progr., USGS, DoI, "A New Approach to Estimating Hydrocarbon Resources," Jan 1995. http://energy.usgs.gov/factsheets/HydroRes/estimat.html

[Evans & Peattie 1997] David C. Evans & Mark R. Peattie, *Kaigun: Strategy, Tactics, and Technology in the Imperial Japanese Navy, 1887-1941,* Annapolis: Nav. Inst. P., 1987

[Fehn, Snyder & Egeberg 2000] Udo Fehn, Glen Snyder & Per K. Egeberg, "Dating of Pore Waters with 129I: Relevance for the Origin of Marine Gas Hydrates," *Science*, 289 (29 Sept 2000): 2332-2335

[Ferry 1993] J. Reeves Ferry, *Petroleum Reserve Responsiveness in the United States: A Comparison of Alternate Forecasting Methods,* New York: Garland Publishing, 1993.

[Foxwell & Scott 1999] David Foxwell & Richard Scott, "Diesel subs depart from convention," *Jane's Navy International,* 104, 3 (Apr 1999): 16-24

[Fouda 1998] Safraa A. Fouda, "Liquid Fuels from Natural Gas," *Scientific American,* March 1998: 92-95

[Fredrickson & Onstott 1996] James K. Fredrickson & Tullis C. Onstott, "Microbes Deep inside the Earth," *Scientific American,* Oct 1996: 68-73

[Gately 1995] Dermot Gately, "Strategies for OPEC's Pricing and Output Decisions," *Energy J.*, 16; 3: 1-38 (Jul 95)

[Gentile 2001] Gian P. Gentile, *How Effective is Strategic Bombing? Lessons Learned from World War II to Kosovo,* New York: N. Y. U. P., 2001

[George 1998] Richard L. George, "Mining for Oil," *Scientific American,* March 1998: 84-85

[Gold 1993] Thomas Gold, "The Origin of Methane (and Oil) in the Crust of the Earth," USGS Professional Paper 1570, The Future of Energy Gases, Washington, DC: 1993 http://www.people.cornell.edu/pages/tg21/usgs.html

[Gold 1996] —, "Can There Be Two Independent Sources of Commercial Hydrocarbon Deposits, One Derived from Biological Materials, the Other from Primordial Carbon and Hydrogen, Incorporated into the Earth at its Formation?" Nov 1996 http://www.people.cornell.edu/pages/tg21/origins.html

[Gold 1999] —, *The Deep Hot Biosphere,* New York: Copernicus Books; Springer-Verlag, 1999

[Gordon 1994] Richard L. Gordon, "Energy, Exhaustion, Environmentalism, and Etatism," *Energy J.,* 15; 1: 1-16 (Jan 1994)

[Haq 1998] Bilal U. Haq, "Gas Hydrates: Greenhouse Nightmare? Energy Panacea or Pipe Dream?" *GSA Today,* 8, 11 (Nov 1998): 1-6 http://www.geosociety.org/pubs/gsatoday/gsat9811.htm

[Haq 1999] —, "Methane in the Deep Blue Sea," *Science*, 285 (23 Jul 1999): 543-544

[Harries et al 2001] John E. Harries, et al, "Increases in greenhouse forcing inferred from the outgoing longwave radiation spectra of the Earth in 1970 and 1997," *Nature*, 410 (15 March 2001): 355 - 357

[Hart 1994] Jim Hart, "World Dependence on Persian Gulf Oil: Strategic Concerns and Market Reality," *Nav. War Coll. Rev.*, Spring 1994: 111-117

[Hatfield 1997a] Craig Bond Hatfield, "Oil Back on the Global Agenda," *Nature* 387: 121 (8 May 1997)

[Hatfield 1997b] —, "The Oil We Won't Have," *Washington Post,* Oct 22, 1997: A21

[Hatfield 1997c] —, "How Long Can Oil Supply Grow?" Hubbert Center Newsletter #97/4 http://hubbert.mines.edu/news/v97n4/mkh-new5.html

[Hatfield 1998] —, "Global Fuel Supply Problems," Doerman Lecture, U. Toledo, April 23, 1998 <http://www.geology.utoledo.edu/department/faculty/cbh/DL/Lec.htm>

[Heal & Chichilnisky 1991] Geoffrey M. Heal & Graciela Chichilnisky, *Oil and the international economy,* Oxford: Clarendon P., 1991

[Hesselbro et al 2000] Stephen P. Hesselbro, et al, "Massive dissociation of gas hydrate during a Jurassic oceanic anoxic event," *Nature*, 406 (27 Jul 2000): 392-395

[Hinrichs et al 1999] Kai-Uwe Hinrichs, et al, "Methane-consuming archaebacteria in marine sediments," *Nature*, 398 (29 Apr 1999): 802-805

[Holbrook et al 1996] W. Steven Holbrook, et al, "Methane Hydrate and Free Gas on the Blake Ridge from Vertical Seismic Profiling," *Science*, 273 (27 Sep 1996): 1840-1843

[Hotelling 1931] Harold Hotelling, "The Economics of Exhaustible Resources," *J. Polit. Econ.*, 39: 137-175 (1931); reprinted in [Darnell (ed) 1990]

[Houthakker 1997] Hendrik S. Houthakker, "A Permanent Decline in Oil Production?" (correspondence) *Nature* 388: 618 (14 August 1997)

[Hubbert 1949] M. King Hubbert, "Energy from Fossil Fuels," *Science*, 109: 103-109 (Feb 4, 1949)

[Hubbert 1956] —, "Nuclear Energy and the Fossil Fuels," Amer. Petroleum Inst. Drilling and Production Practice, Proc. Spring Mtg., San Antonio, TX: 7-25

[Hubbert 1971] —, "Energy Resources of the Earth," *Energy and Power,* San Francisco: Scientific American Books; W. H. Freeman, 1971

[Hubbert Center 1996] "The M. King Hubbert Center For Petroleum Supply Studies" http://hubbert.mines.edu/news/v96n1/newltr2.html

[IEA 2000] International Energy Agency, *Oil Supply Security: The Emergency Response Potential of IEA Countries in 2000,* Paris: IEA, 2000

[IEA 2001a] —, "Stocks of IEA Net Importers" http://www.iea.org/public/studies/oilsuppl.gif

[Ivanhoe 1995] L. F. Ivanhoe, "Future world oil supplies: There is a finite limit," *World Oil,* October 1995 < http://dieoff.org/page85.htm>

[Ivanhoe 1997] —, "King Hubbert—Updated," Hubbert Center Newsletter, #97/1, http://hubbert.mines.edu/news/v97n1/mkh-new2.html

[Kartha & Grimes 1994] Sivan Kartha & Patrick Grimes, “Fuel Cells: Energy Conversion for the Next Century,” *Physics Today,* Nov 1994: 54-61

[Katz et al 1999] Miriam E. Katz, et al, “The Source and Fate of Massive Carbon Input During the Latest Paleocene Thermal Maximum,” *Science*, 286 (19 Nov 1999): 1531-1533

[Kendall 2000] Kevin Kendall, “Hopes for a flame-free future,” *Nature*, 404 (16 March 2000): 233-234

[Kennett et al 2000] James P. Kennett, et al, “Carbon Isotopic Evidence for Methane Hydrate Instability During Quaternary Interstadials,” *Science*, 288 (7 Apr 2000): 128-133

[Kerr 1997] Richard A. Kerr, “Paleoceanography: Did a Blast of Sea-Floor Gas Usher in a New Ice Age?” *Science*, 275 (28 Feb 1997) 1267

[Kerr 1998] —, “OPEC’s Second Coming,” *Science*, 281 (21 Aug 1998): 1129

[Kerr 1999] —, “A Smoking Gun for an Ancient Methane Discharge,” *Science*, 286 (19 Nov 1999): 1465

[Khaselev & Turner] Oscar Khaselev & John A. Turner, “A Monolithic Photovoltaic-Photoelectrochemical Device for Hydrogen Production via Water Splitting,” *Science*, 280 (17 Apr 1998): 425-427

[Kheshgi, Prince & Marland 2000] Haroon S. Kheshgi, Roger C. Prince & Gregg Marland, “The Potential of Biomass Fuels in the Context of Global Climate Change: Focus on Transportation Fuels,” *Annu. Rev. Energy & Envron.* 2000, 25: 199-224

[Kleinberg & Brewer 2001] Robert L. Kleinberg & Peter G. Brewer, "Probing Gas Hydrate Deposits," *American Scientist.* 89, 3 (May-Jun 2001): 244-251

[Klemme & Ulmishek 1991] H. D. Klemme & G. F. Ulmishek, “Effective Petroleum Source Rocks of the World: Stratigraphic Distribution and Controlling Depositional Factors,” *Am. Assoc. of Petroleum Geologists Bulletin,* 75,12 (1991): 1809-1851 http://energy.er.usgs.gov/products/papers/World_oil/AAPG/bulletin/

[Klett & Ahlbrandt 2000] Timothy R. Klett and Thomas S. Ahlbrandt, “Data Sources and Compilation,” in [Ahlbrandt et al 2000], Chapter DS <http://energy.cr.usgs.gov/WEcont/chaps/DS.pdf>

[Klett et al 1997] —, et al, “Ranking Of The World's Oil And Gas Provinces By Known Petroleum Volumes,” USGS Open-File Report 97-463, 1997 http://greenwood.cr.usgs.gov/energy/WorldEnergy/OF97-463/

[Krugman 2000] Paul Krugman, “The Energy Crisis Revisited,” March 2000 http://web.mit.edu/krugman/www/opec.html

[Laherrère 1995] Jean H. Laherrère, “World oil reserves: which number to believe?” *OPEC Bulletin,* February 1995, pp 9-13 http://www.hubbertpeak.com/laherrere/opec95.htm

[Laherrère 1996] —, “Discovery and production trends,” *OPEC Bulletin,* February 1996, pp 7-11 http://www.hubbertpeak.com/laherrere/disctrnd.htm

[Laherrère 1997] —, “Multi-Hubbert Modeling,” Jul 1997 <http://www.hubbertpeak.com/laherrere/multihub.htm>

[Laherrère 2000] —, "Is USGS 2000 Assessment Reliable?" Reportedly "published on the cyberconference of the [World Energy Conference] on May 19, 2000." http://www.hubbertpeak.com/laherrere/usgs2000/

[Landau & Rosenberg 1991] Ralph Landau & Nathan Rosenberg, "Innovation in the chemical processing industries," Technology and Economics, Washington: National Academy P., 1991; Nathan Rosenberg (ed), *Exploring the Black Box: Technology, Economics, and History,* Cambridge: Cambridge U.P., 1994.

[LeClair 2000] Mark S. LeClair, *International Commodity Markets and the Role of Cartels,* Armonk: M. E. Sharpe, 2000

[Lynch 1995] Michael C. Lynch, "Limitations in Forecasting Petroleum Supply," *Geo-politics of Energy,* June 1, 1995

[McDonald 1994] Stephen L. McDonald, "The Hotelling Principle and In-Ground Values of Oil Reserves," *Energy J.,* 15; 3: 1-17 (Jul 94)

[McFarland 1995] Stephen L. McFarland, *America's Pursuit of Precision Bombing, 1910-1945,* Washington: Smithsonian, 1995

[MacKenszie 2000] James J. MacKenzie, "Oil as a Finite Resource: When is Global Production Likely to Peak?" World Resources Institute, Mar 1996; updated Mar 2000. http://www.igc.org/wri/climate/jm_oil_000.html

[McKie 1974] James W. McKie, "The Political Economy of World Petroleum," *Am. Econ. Rev.,* 64; 2: 51-57 (May 94)

[McWilliams 1997] Gary McWilliams, "The New Economics of Oil," *Business Week,* Nov 3, 1997: 140-148

[Maddison 1995] Angus Maddison, *Monitoring the World Economy, 1820-1992,* Paris: OECD, 1995

[*Maritime Defence* 1995] "Air independent propulsion," *Maritime Defence,* 20, 10 (Dec 1995): 242-245

[Marks 1978] Theodore Baumeister, Eugene A. Avalone & Theodore Baumeister III (eds), *Marks' Standard Handbook for Mechanical Engineers,* Eighth Edn., New York: McGraw-Hill, 1978

[Marty & Jambon 1987] B. Marty & A. Jambon, "C/3He in volatile fluxes from the solid Earth: implications for carbon geodynamics," *Earth and Planetary Science Letters,* 83 (1987): 16-26

[Masters, Attanasi & Root 1994] C. D. Masters, E. D. Attanasi, & D. H. Root, "World Petroleum Assessment and Analysis," *Proceedings of the 14th World Petroleum Congress, Volume 2: Exploration, Production and Reserves,* New York: Wiley, 1994: 529-541 http://energy.er.usgs.gov/products/papers/WPC/14/

[Masters, Root & Attansi 1991] —, D. H. Root, & E. D. Attanasi, "Resource Constraints in Petroleum Production Potential," *Science* 253: 146-152 (12 July 1991).

[Masters, Root & Turner 1997] —, — , & R. M. Turner, World of Petroleum http://energy.er.usgs.gov/products/papers/World_oil/

[Miller & Upton 1985] Merton H. Miller & Charles W. Upton, "A Test of the Hotelling Valuation Principle," *J. Polit. Econ.,* 93; 1: 1-25.

[MMS 1997] Minerals Management Service, DoI, *An Assessment of the Undiscovered Hydrocarbon Potential of the Nation's Outer Continental Shelf,* OCS Report MMS 96-0034. Washington, DC: Jun 1997

[MMS 2000] —, *Outer Continental Shelf Petroleum Assessment, 2000.* Washington, DC: 2000

[Morehouse 1997] David F. Morehouse, "The Intricate Puzzle of Oil and Gas 'Reserves Growth'," Energy Information Administration, DoE, *Natural Gas Monthly,* July 1997: vii-xx http://www.eia.doe.gov/pub/pdf/feature/morhouse.pdf

[Myerson 1998] Allen R. Myerson, "Technology Tames the Wildcatting Industry," *The New York Times,* March 20, 1998

[Nadis 1998] Steve Nadis, "Utah university finally drops out of cold-fusion patent chase," *Nature,* 393 (7 May 1998): 7

[*Nature* 1997] "Japan ends funding for 'cold' fusion project," *Nature,* 389 (4 Sep 1997): 10

[Nicholson 1985] Walter Nicholson, *Microeconomic Theory: Basic Principles and Extensions,* 3rd edn., Chicago: Dryden P., 1984

[NIMA 1999] National Imagery & Mapping Agency (NIMA), *Distances Between Ports,* 10th edn., Publication No. 151, Bethesda, 1999

[Nordhaus 1974] William D. Nordhaus, "Resources as a Constraint on Growth," *Am. Econ. Rev.,* 64; 2: 22-26 (May 94)

[NRC 1990] National Research Council, *Fuels to Drive Our Future,* Committee on Production. Technology for Liquid Transportation. Fuels, Energy Engineering. Bd., Commission on Engineering & Technical Syst., Washington: Nat'l Acad. of Sci., 1990

[NRC 1995] —, *Coal: Energy for the Future,* Bd. on Energy & Environmental Syst., Commission on Engineering & Technical Syst., Washington: Nat'l Acad. of Sci., 1995

[O'Nions & Oxburgh 1988] R. K. O'Nions & E. R. Oxburgh, "Helium, volatile fluxes and the development of continental crust," *Earth and Planetary Science Letters,* 90 (1988): 331-347

[OFE 1998a] Office of Fossil Energy, DoE, "Clean Coal Fuels: Developing Tomorrow's Fuels" http://www.fe.gov/coal_power/clnfuel.html

[OFE 1998b] —, "A Strategy for Methane Hydrates Research & Development," DoE/FE-0378, Aug 1998

[Ourrison, Albrecht & Rohmer 1984] Guy Ourrison, Pierre Albrecht and Michel Rohmer, "The Microbial Origin of Fossil Fuels," *Scientific American,* 251, 2 (Aug 1984): 44-51

[Pape 1996] Robert A. Pape, *Bombing to Win: Air power and coercion in war,* Ithaca: Cornell U.P., 1996

[Park, Vohs & Gorte 2000] Seungdoo Park, John M. Vohs & Raymond J. Gorte, "Direct oxidation of hydrocarbons in a solid-oxide fuel cell," *Nature,* 404 (16 March 2000): 265-267

[Platt 1998] Charles Platt, "What If Cold Fusion Is Real?" *Wired,* 6.11 (Nov 1998) http://www.wired.com/wired/archive/6.11/coldfusion_pr.html

[Porter 1991] E. D. Porter, *World Petroleum Supply: History, Prospects, and Policy Issues,* Amer. Petroleum Inst., Discussion Paper 066, May 1991

[Porter 1995] —, *Are We Running Out of Oil?* Amer. Petroleum Inst., Discussion Paper 081, Dec 1995

[Pindyck 1978] Robert S. Pindyck, "The Optimal Exploration and Production of Nonrenewable Resources," *J. Polit. Econ.,* 86 (1978): 841-861

[Puller 2001] Steven L. Puller, "Pricing and Firm Conduct in California's Deregulated Electricity Market," PWP-080, U. of California Energy Inst., Jan 2001 http://www-path.eecs.berkeley.edu/ucei/PDF/pwp080.pdf

[Radetzki 1990] Marian Radetzki, *A Guide to Primary Commodities in the World Economy,* Oxford: Blackwell, 1990

[Reddington et al 1998] Erik Reddington, et al, "Combinatorial Electrochemistry: A Highly Parallel, Optical Screening Method for Discovery of Better Electrocatalysts," *Science*, 280 (12 Jun 1988): 1735-1737

[Riezenman 1995] Michael J. Riezenman, "The Search for Better Batteries," *IEEE Spectrum,* May 1995, 51-56

[Robinson 1989] T. J. C. Robinson, *Economic Theories of Exhaustible Resources,* London: Routledge, 1989

[Rogner 1997] H[ans]-H[olger] Rogner, "An assessment of world hydrocarbon resources," *Annu. Rev. Energy Environ.* 22 (1997):217-62

[Romm & Curtis 1996] Joseph J. Romm & Charles B. Curtis, "Mideast Oil Forever?" *The Atlantic Monthly,* 277, 4:57-74 (April 1996) http://www.theatlantic.com/issues/96apr/oil/oil.htm

[Rowe & Muehlenbachs 1999] Devon Rowe & Atis Muehlenbachs, "Low-temperature thermal generation of hydrocarbon gases in shallow shales," *Nature*, 398 (4 Mar 1999): 61-63

[Salameh 1997] Mamdouh G. Salameh, "Crude Oil Prices on an Upward Trend?" *International Assoc. for Energy Economics Newsletter,* Summer 1997 http://www.iaee.org/newsltr/97sum9.htm

[Schmooker & Klett 2000] James W. Schmooker & Timothy R. Klett, "Estimating Potential Reserve Growth of Known (Discovered) Fields: A Component of the USGS World Petroleum Assessment 2000," in [Ahlbrandt et al 2000], Chapter RG http://energy.cr.usgs.gov/WEcont/chaps/RG.pdf

[Schoell & Carlson 1999] Martin Schoell & M. K. Carlson, "Diamondoids and oil are not forever," *Nature*, 399 (6 May 1999): 15-16

[Seife 1997] Charles Seife, "Quantum Mechanics: The Subtle Pull of Emptiness," *Science*, 275 (10 Jan 1997): 158

[Service 1998a] Robert F. Service, "A Record in Converting Photons to Fuel," *Science,* 280 (17 Apr 1998): 382

[Service 1998b] —, "The Fast Way to a Better Fuel Cell," *Science*, 280 (12 Jun 1998): 1690-1691

[Service 1999] —, “Bringing Fuel Cells Down to Earth,” *Science*, 285 (30 Jul 1999): 682-685

[Sherry 1987] Michael S. Sherry, *The Rise of American Air Power: The Creation of Armgeddon,* New Haven: Yale U.P., 1987

[Simon 1996] Julian L. Simon, *The Ultimate Resource 2,* Princeton: Princeton U. P., 1996

[Simpson 1999] Sarah Simpson, “Gas Blasts,” *Scientific American: Explore,* Dec 20, 1999 http://www.sciam.com/explorations/1999/122099hydrate/index.html

[Solow 1974] Robert M. Solow, “The Economics of Resources or the Resources of Economics,” *Am. Econ. Rev.,* 64; 2 (May 94): 1-14

[Spectrum 1997] “Nuclear energy: special report,” *IEEE Spectrum,* Nov 1997: 23-48

[SPR 2001] Strategic Petroleum Reserve Project Management Office (U.S. Dept. of Energy), “Profile of the SPR” http://www.spr.doe.gov/default.htm [Accessed May 2001]

[Srinivasan et al 1999] Supramaniam Srinivasan, et al, “Fuel Cells: Reaching the Era of Clean and Efficient Power Generation in the Twenty-first Century,” *Annu. Rev. Energy & Environ.* 1999, 24: 281-328

[Stevens 1995] Paul Stevens, “Understanding the Oil Industry: Economics as a Help or a Hinderance,” *Energy J.,* 16; 3 (Jul 95): 125-139

[Stone 1993] Jack L. Stone, “Photovoltaics: Unlimited Electrical Energy from the Sun,” *Physics Today,* Sep 93: 22-29

[Talwani, Belopolsky & Berry] Manik Talwani, Andrei Belopolsky & Dianne L. Berry, “Geology and Petroleum Potential of Central Asia,” James A. Baker Institute for Public Policy, Rice University, [n.d.]. http://riceinfo.rice.edu/projects/baker/Pubs/BakerPub/publications/gppca/gppca.html [Accessed 19 January 2001]

[Thomas & Zalbowitz] Sharon Thomas & Mardia Zalbowitz, *Fuel Cells: Green Power,* Los Alamos National Laboratory, n.d. (c. 1999) http://education.lanl.gov/resources/fuelcells/

[Tippee 1993] Bob Tippee, *Where's the Shortage? A Nontechnical Guide to Petroleum Economics,* Tulsa: PennWell Publishing, 1993.

[Udachin & Ripmeester 1999] Konstantin A. Udachin & John A. Ripmeester, “A complex clathrate hydrate structure showing bimodal guest hydration,” *Nature*, 397 (4 Feb 1999): 420-423

[USGS 1995] U. S. Geological Survey, Central Region Energy Resources Team, *1995 National Assessment of United States Oil and Gas Resources,* USGS Circular 1118 http://greenwood.cr.usgs.gov/energy/execsum.html

[Voss 1999] David Voss, “Company Aims to Give Fuel Cells a Little Backbone,” *Science*, 285 (30 Jul 1999): 683

[Warren 1998] Susan Warren, “Oil Production Stays Profitable Despite Fall in Price of Crude,” *The Wall Street Journal,* March 17, 1998

[Watkins 1996] G. C. Watkins & Shane S. Streifel, *World Crude Oil Resources: Evidence from Estimating Supply Functions for 41 Countries,* World Bank policy research working paper

1756, Dec 1996
http://www.worldbank.org/html/dec/Publications/Workpapers/WPS1700series/wps1756/wps1756.pdf

[Weiss et al 2000] Malcolm A. Weiss, et al, *On The Road In 2020: A life-cycle analysis of new automobile technologies,* Energy Laboratory Report # MIT EL 00-003, Cambridge: MIT, Oct 2000 http://web.mit.edu/energylab/www/pubs/el00-003.pdf

[Windolph 1998] Wolfgang Windolph, "The Better AIP," *Naval Forces,* XIX, 4 (1998): 114-120

[Wollstadt 1991] Roger Wollstadt, *Petroleum Industry Technology to Meet Today's Challenges,* Amer. Petroleum Inst., Discussion Paper 067, June 1991

[WRI 1996] World Resources Inst., the United Nations Environmental Progr., the United Nations Development Progr., & the World Bank, *World Resources 1996-97: A Guide to the Global Environment* http://www.wri.org/wr-96-97/

[WTRG 1998] WTRG Economics, "Oil Price History and Analysis" <http://www.wtrg.com/prices.htm>

[Yam 1997] Philip Yam, "Exploiting Zero-Point Energy," *Scientific American,* Dec 97: 82-85

[Yergin 1991] Daniel Yergin, *The Prize: The Epic Quest for Oil, Money, and Power,* New York: Simon & Schuster, 1991.

[Yonas 1998] Gerald Yonas, "Fusion and the Z-Pinch," *Scientific American,* Aug 1998: 41-47

[Youngquist 1997] Walter L. Youngquist, "Myths and Realities of Mineral Resources," *GeoDestinies,* National Book Co., 1997. http://dieoff.org/page132.htm

References

[1] [Economist 2000c]
[2] [EIA 2001a]
[3] [API 1999] table III-4, [EIA 2000d]
[4] [API 1999] table III-5
[5] [Adelman 1995] p 237
[6] [Adelman 1972] p 47
[7] [Adelman 2001], [Alhajji 2000]
[8] [De Santis 2000], [Krugman 2000]
[9] [Adelman 1995]
[10] [EIA 2000b]
[11] [EIA 2001a]
[12] [EIA 2001a]
[13] [EIA 2000a] pp 28-29
[14] [Evans & Peattie 1997] pp 406-412
[15] [SPR 2001]
[16] [EIA 2001c] p 11
[17] ibid
[18] [IEA 2001a]
[19] [APERC 2000]
[20] [APERC 2000] pp 47-50
[21] [Hotelling 1931]
[22] [Solow 1974]
[23] [Hubbert 1949]
[24] [Hubbert 1956]
[25] [Klemme & Ulmishek 1991]
[26] [Ourrison, Albrecht & Rohmer 1984]
[27] [Klemme & Ulmishek 1991]
[28] [Gold 1993], [Gold 1999]
[29] [Gold 1996]
[30] [Gold 1999]
[31] [Fredrickson & Onstott 1996]
[32] ibid
[33] [Klemme & Ulmishek 1991]
[34] [Ahlbrandt *et al* 2000]
[35] [Drew 1997], [Morehouse 1997], [Schmooker & Klett 2000]
[36] [Schmooker & Klett 2000], [ERSP 1995]
[37] [Schmooker & Klett 2000]
[38] [Klett & Ahlbrandt 2000]

[39] [Masters, Attanasi & Root 1994], [Ahlbrandt *et al* 2000]
[40] [Ahlbrandt 2000]
[41] [Laherrère 2000]
[42] [Campbell & Laherrère 1998]
[43] [Edwards 1997], [Hatfield 1998], [Ivanhoe 1995], [MacKenszie 2000], [Youngquist 1997]
[44] [Fouda 1998]
[45] [NRC 1995]
[46] [Rogner 1997] p 241
[47] [George 1998]
[48] [Service 1998a], [Khaselev 1998]
[49] [Riezenman 1995]
[50] [Kendall 2000], [Park, Vohs & Gorte 2000]
[51] [Brydges & Drake 2000]
[52] [*Economist* 2000c]
[53] [Reddington *et al* 1998]
[54] [Platt 1998]
[55] [*Nature* 1997], [Nadis 1998]
[56] [Adler], [Boyer 1985]
[57] [Seife 1997]
[58] [Yam 1997]
[59] [Daalder & O'Hanlon 2000], [Gentile 2001], [McFarland 1995], [Pape 1996], [Sherry 1987]
[60] [Adelman 1995], [Adelman 1997a], [Adelman 2001]
[61] [Adelman 1995] pp 9, 201 & 271