DAVID GOODSTEIN

ENERGY, TECHNOLOGY AND CLIMATE

Running Out of Gas

Let me begin by stating my conclusions. We (the world) will soon start to run out of conventional, cheap oil. If we manage somehow to overcome that shock, and life goes on more or less as it has been, then we will start to run out of all fossil fuels before the end of this century. In that case, there is a very real chance that by the time we have burned up all the fuel, we will have rendered the planet uninhabitable for human life. And even if human life does go on, civilization as we know it will not survive, unless we can find a way to live without fossil fuels.[1]

Technically, it should be possible to accomplish that. Stationary power can be obtained from nuclear energy and from light from the sun. Part of that power can be used to generate hydrogen fuel for use in transportation. There are technical problems to be solved, certainly, but the scientific principles are all well understood, and we are very good at solving technical problems. In fact if we put our minds to it, we could kick the fossil fuel habit now, protecting the planet's climate from further damage, and preserving the fuels for future generations to use as the source of chemical goods. To do that would require political leadership that is both visionary and courageous. It seems unlikely that we will be so lucky.

Thus, we are faced with a grave crisis that may change our way of life forever. We live in a civilization that evolved on the promise of an endless supply of cheap oil. The era of cheap oil will end, probably much sooner than most people realize. To put this looming crisis in perspective, and to judge its significance, it helps to start from the beginning. Here is how it all works.

Nuclear reactions inside the Sun heat its surface white hot. From that hot surface, energy in the form of light, both visible and, to our eyes, invisible, radiates uniformly away in all directions. Ninety-three million miles away, the tiny globe called Earth intercepts a minute fraction of that solar radiation. About 30% of the radiation that falls on the Earth is reflected directly back out into space. That's what one sees in a picture of the Earth taken, say, from the moon. The rest of the radiant energy is absorbed by the Earth.

A body such as the Earth that has radiant energy falling on it warms up or cools down until it is sending energy away at the same rate it receives it. Only then is it in a kind of equilibrium, neither warming nor cooling. In any given epoch, the Earth, like the Moon or any other heavenly body, is in steady state balance with the Sun,

[1] A more complete discussion of the issues raised in this essay can be found in the recent book, *Out of Gas*, by David Goodstein, W.W. Norton (2004).

A. W. Galston and C. Z. Peppard (eds.), Expanding Horizons in Bioethics, 233-245.

neither gaining nor losing energy. That is the primary fact governing the temperature at the surface of our planet.

The rate at which the Earth radiates energy into space depends on its temperature. Because it receives only a tiny fraction of the Sun's energy, it radiates much less energy than the Sun does. So, it can balance its energy books at a temperature much cooler than the Sun. In fact it can radiate as much energy as it receives with an average surface temperature of zero degrees Fahrenheit. The Earth's radiation is not visible to our eyes. It is called infrared, or "below-red," radiation because its color is beyond the red end of what we are capable of seeing.

Fortunately for us, that is not the whole story. If the average surface temperature of the Earth were really zero degrees Fahrenheit, we probably would not be here. The Earth has a gaseous atmosphere. The atmosphere is largely transparent to the white-hot radiation from the Sun. The nitrogen and oxygen that make up nearly all of the Earth's atmosphere are transparent as well to the infrared radiation from the Earth; but there are trace gases, including water vapor, methane and carbon dioxide that absorb infrared radiation. Thus the blanket of atmosphere traps about 88% of the heat the Earth is trying to radiate away. The books remain balanced, with the atmosphere radiating back into space the same amount of energy the Earth receives, but it also radiates energy back to the Earth's surface, warming it to a comfortable average temperature of fifty-seven degrees Fahrenheit. That is what's known as the greenhouse effect.

There is a tiny but vital exception to the perfect energy balance of the Earth-Sun system. Of the light that falls on the Earth, an almost imperceptible fraction gets used up nourishing life. Through photosynthesis, plants make use of the Sun's rays to grow. Animals that eventually die eat some of the plants. Natural geological processes bury some of that organic matter deep in the Earth.

For hundreds of millions of years, animal, vegetable and mineral matter has drifted downward through the waters to settle on the floor of the sea. In a few privileged places on Earth, strata of porous rock were formed that were particularly rich in organic inclusions. With time, these strata were buried deep beneath the sea floor. The interior of the Earth is hot, heated by the decay of natural radioactive elements. If the porous source rock sank just deep enough, it reached the proper temperature for the organic matter to be transformed into oil. Then the weight of the rock above it could squeeze the oil out of the source rock like water out of a sponge, into layers above and below, where it could be trapped. Over vast stretches of time, in various parts of the globe, the seas retreated, leaving some of those deposits beneath the surface of the land. Other theories of how oil originated have been proposed from time to time, but they have not stood up. Modern instruments are even able to detect what sorts of organisms went into making different deposits of oil. Nearly all geologists today agree with this account of how oil came to be.

Oil consists of long molecules of carbon and hydrogen. If the source rock sank too deep, the excessive heat at greater depths broke the hydrogen and carbon molecules into the smaller molecules that we call natural gas. Meanwhile, in certain swampy places on land, the decay of dead plant matter created peat bogs. Over the course of the eons, buried under sediments and heated by the Earth's interior, the peat was transformed into coal, a substance that consists mostly of elemental carbon. Coal, oil and natural gas are the primary fossil fuels. They are energy from the Sun, stored within the Earth.

Not all of the energy from the Sun flows back out into space. A tiny fraction of distilled sunlight gets stored up in the form of fossil fuels. The process is agonizingly slow and inefficient. But it has been going on for an extremely long time. The net result is that the Earth has accumulated a legacy of oil that we in our generation have inherited, discovered, and put to use.

Until only 200 years ago (the blink of an eye on the scale of history), the human race was able to live almost entirely on light as it arrived from the Sun. The Sun nourished plants that provided food and warmth for us and for our animals. It illuminated the day and, in most places, left the night sky sparkling with stars, to comfort us in our repose. A few people traveled widely, even sailing across the oceans, but most people probably never got very far from the villages where they were born. In Europe, the lives of the wealthy were garnished with beautiful paintings, sophisticated orchestral music, elegant fabrics and gleaming porcelain from China. For the majority of people in Europe and around the world, there were more homespun versions of art and music, textiles and pottery. Mercantile sailing ships ventured to sea carrying exotic and expensive cargoes including spices, slaves and, in summer, ice. No more than a few hundred million people populated the planet. A bit of coal was burned here and there for one purpose or another, but, by and large, the Earth's legacy of fossil fuels was left untouched.

The situation has changed dramatically. We now expect illumination at night and air conditioning in summer. We may commute to work every day, traveling up to one hundred miles each way between our homes and offices, and we rely on multi-ton individual vehicles to transport us back and forth on demand. Thousands of airline flights per day can take us to virtually any destination on Earth in a matter of hours. When we arrive at our destination, we can still chat with our friends and family back home, or conduct business as if we had never left the office. In industrialized parts of the world, global commerce ensures that the amenities that were once the purview of the rich are now available to most people. Refrigeration rather than spices preserves food, and machines do much of the work that was once done by slaves, indentured servants, or serfs. Ships, planes, trains and trucks transport goods of every description all around the world. The population of the Earth is approaching ten billion people. We don't see the stars so clearly anymore, but on most counts, few of us would choose to return to the world as it existed several centuries ago.

This revolutionary change in our standard of living did not come about by design. If you asked an eighteenth century sage like Benjamin Franklin what the world really needed, he would not necessarily have described the situations and amenities of which our modern world is composed—except perhaps for the dramatic improvement in public health that has also occurred. Our current world is the result of a series of inventions and discoveries that altered our expectations—not an airtight system of societal design. Our current world is less the result of a long-term vision of modern society than it is the result of what nature and human ingenuity made possible for us.

One consequence of those inventions and changed expectations is that we no longer live only, or even primarily, on direct light from the Sun. Instead we consume the fossil fuels made from sunlight that the Earth stored up over those many hundreds of millions of years. In so doing we have unintentionally created a trap for ourselves. We will, so to speak, run out of gas. There is no question about that, since the Earth's fossil fuel reserves are limited. The question is: When will it happen?

The answer is not simple, but some of those who know best, certain petroleum geologists, predict that the first great crisis will come in this decade.[2] Throughout the twentieth century, demand and supply of oil grew rapidly. These two are essentially equal: oil is always used as fast as it is pumped out of the ground. Until the 1950s, many oil geologists asserted the mathematically impossible expectation that the same rate of increase could continue forever. All cautionary warnings of finite supplies were maligned because new reserves were being discovered faster than consumption was rising. Then, around 1956, a clever and insightful geophysicist named M. King Hubbert predicted that the rate at which oil could be extracted from the lower 48 United States would peak around 1970 and decline rapidly after that. When he turned out to be exactly right, other oil geologists started paying serious attention.

Hubbert used a number of methods in his calculations. The first was similar to ideas that had been used by population biologists for well over a century. When a new population (of humans or any other species) starts growing in an area that has abundant resources, the growth is initially exponential. That means that the rate of growth increases by the same amount each year, like compound interest in a bank account. This logic matched that of the 1950s oil geologists: oil discovery would continue to grow unfettered. However, population biologists also observed that once the population is big enough that the resources no longer seem unlimited, the rate of growth starts slowing down. The same happens with oil discovery: the chances of finding new oil decrease when there is less new oil to find. Hubbert showed that, once the rate of increase of known oil supplies starts to decline, it is possible to extrapolate the declining rate to identify when growth will stop altogether. At that point all the oil in the ground will have been discovered. Further, the total amount of oil in the world is equal to the amount that has already been used, plus the known reserves still in the ground. Hubbert noticed that the trend of declining annual rate of oil discovery was established for the lower 48 states by the 1950s. Others have now pointed out that the rate of discovery worldwide has been declining for decades. The total quantity of conventional oil that the Earth stored up for us is estimated by this method to have been about two trillion barrels.[3]

Hubbert's second method required assuming that in the long run, a graph of the historic record of the rate that oil was pumped out of the ground would be a bell-shaped curve. That is, it would first rise (as it has done); then reach a peak; then decline at the same rate at which it rose. Half a century after Hubbert made that assumption, he has been vindicated in the case of the lower 48. If this theorem is

[2] See, e.g., Hubbert; Youngquist; Campbell and Laherrère; Duncan; Ivanhoe; and Deffeyes.
[3] Deffeyes.

correct for the rest of the world, and if we already have the historical record of the positive slope of the curve plus a good estimate of the total amount of oil that ever was (two trillion barrels, as above), then it is not difficult to predict when "Hubbert's peak" will occur. Hubbert had that information in the 1950s for the lower 48 states, and we now have that information for the whole world. Different geologists, using different data and methods, yield slightly different results; but some (not all) have concluded that the peak will happen at some point in this decade. The point can be seen without any fancy mathematics at all. Of the two trillion barrels of oil we started with, nearly half have already been consumed. The peak occurs when we reach the halfway point. That, they say, can't be more than a few years off.

Hubbert's third method applied the observation that the total amount of oil extracted to date paralleled oil discovery (total already extracted plus known reserves) but lagged behind by a few decades. In other words, we pump oil out of the ground at about the same rate that we discover it, but we pump and consume it a few decades after the initial discovery. Thus the rate of discovery predicts the rate of extraction. Worldwide, remember, the rate of discovery started declining decades ago. In other words, Hubbert's peak for oil discovery has already occurred. That gives an independent prediction of when Hubbert's peak for oil consumption will occur. It will occur, according to that method as well, some time in the next decade.

Not all geologists agree with this assessment. Many prefer to take the total amount of oil known to be in the ground, divide that by the rate at which it is consumed, and conclude that we can go on like this for a long time. In the oil industry, this is known as the reserves-to-production (R/P) ratio. Depending on what data one uses, that number is currently between forty and 100 years.

Another point of disagreement concerns the total amount of oil in the world. Over the five-year period leading up to 2000, the highly respected United States Geological Survey (USGS) made an exhaustive study of worldwide oil supplies. The resulting report concludes that, with 95% certainty, there were at least two trillion barrels before any oil was extracted from the earth. The report also concludes there is a fifty-fifty chance that there were at least 2.7 trillion barrels, a number that would leave much more in the ground today. However, that number is based on the assumption, contrary to the trends we discussed earlier, that new discovery will continue at a brisk rate for at least thirty more years.[4] The additional 0.7 trillion barrels would amount to discovering all the oil in the Middle East all over again.

The fact is that the amount of known reserves is a very soft number. For one reason, it is usually a compilation of government and commercial figures from countries around the world, and those reported figures are at least sometimes slanted by political and economic considerations. Also, what we mean by "conventional" or "cheap" oil changes with time. As technology advances, the amount of reserves that can be economically tapped in known fields increases. The way the oil industry uses the term, the increase in recoverable oil counts as "discovery," and it accounts for much of the new discovery the USGS expects in the next thirty years. Finally, as oil starts to become scarce and the price per barrel increases, the amount recoverable

[4] U.S. Geological Survey, World Petroleum Assessment 2000.

at that price will necessarily also increase.[5] These are all tendencies that might help to push Hubbert's peak further into the future than the most pessimistic predictions.[6]

Nevertheless, all of our experience with the consumption of natural resources suggests that the rate at which we use them up starts at zero, rises to a peak that will never be exceeded, and then declines back to zero as the supply becomes exhausted. There have been many instances of that behavior: coal mining in Pennsylvania, copper in northern Michigan, and many others (including oil in the lower 48).[7] That picture forms the fundamental basis of the views of Hubbert and his followers, but it is ignored entirely by those who depend on the R/P ratio. Given that worldwide demand for oil will continue to increase (as it has for well over a century), Hubbert's followers expect the crisis to occur when the supply peak is reached rather than when the last available drop is pumped. In other words, we will be in trouble when we've used up half the oil that existed, not all of it. If you believe the Hubbert's peak theory (that the crisis comes when we reach the production peak rather than the last drop), but accept the USGS estimate that there may have been 2.7 trillion barrels of oil, then, compared to the earlier estimates, the crisis will be delayed by about a decade.[8]

If Hubbert's followers are correct, we will be in for some difficult times in the near future. In an orderly, rational world, it might be possible for the gradually increasing gap between supply and demand for oil to be filled by a substitute. But anyone who remembers the oil crisis of 1973 knows that we do not live in such a world, especially when it comes to an irreversible shortage of oil. It is impossible to predict exactly what will happen, but we can, all too easily, envision a civilization paralyzed and decaying from lack of oil, the landscape littered with the rusting hulks of useless SUVs. Worse, desperate attempts of one country or region to maintain its standard of living at the expense of others could lead to yet another dubious war over oil. Knowledge of science is not useful in predicting whether such dire political events will occur; but science is useful for predicting the limits of natural supply and conceiving of (or ruling out) various fuel alternatives.

To begin with, conventional oil is not the only fossil fuel. Once all the cheap oil is pumped, advanced methods can still squeeze a little more oil out of almost any field. There is also what is known as oil sands or tar sands and heavy oil (essentially, the remains of depleted oil fields). These are deposits of oil that are more difficult and expensive to extract than conventional oil. Next there is shale oil. As we have seen, conventional oil came about when source rock, loaded with organic matter, sank just deep enough in the Earth to be cooked properly into oil. Oil shale, from which shale oil can be extracted, is source rock that never sank deep enough to make oil. There are very large quantities of it in the ground, and it can be mined, crushed and heated to produce an oil-like substance. Another possible fossil

[5] Lynch.

[6] U.S. Department of Energy.

[7] For further examples see Youngquist.

[8] I have made this calculation using Hubbert techniques. Hubbert represented the rise and fall of oil discovery and extraction by a mathematical form known as the Logistic Curve (also known in business schools as the S-Shaped Curve). Others have used different bell-shaped curves known as Gaussian and Lorentzian Curves. They all give approximately the same results.

fuel is called methane hydrate, which consists of methane molecules trapped in a kind of cage of water molecules. It is a solid that looks like ice, but that burns when ignited. Nobody knows how to mine methane hydrate or how much of it there is, but there may be quite a lot of it in deep, cold regions of the ocean.

Exploiting any of those resources will be more expensive and slower than pumping conventional oil.[9] Once past Hubbert's peak, as the gap between rising demand and falling supply grows, the rising price of oil will make those alternative fuels economically competitive, but it may not prove possible to get them into production fast enough to fill the growing gap. That double bind is called the "rate of conversion" problem. Worse, the economic damage done by rapidly rising oil prices may undermine our ability to mount the huge industrial effort needed to get the new fuels into action.

Natural gas, which comes from overcooked source rock, is another short-term alternative. Natural gas (primarily methane) is relatively easy to extract quickly, and transformation to a natural gas economy could probably be accomplished more easily than is the case for other alternative fuels. Ordinary engines similar to the ones used in our cars can run on compressed natural gas. Even so, replacing the existing vehicles and gasoline distribution system fast enough to make up for the missing oil will be difficult. And even if this transformation is accomplished, it is only temporary. Hubbert's peak for natural gas is estimated to occur only a couple of decades after the one for oil.

Alternatively, there is a huge amount of chemical potential energy stored in the Earth in the form of elemental carbon—that is to say, in the form of coal. With coal, as with the other fossil fuels, to extract the stored energy, each atom of carbon must be converted to a molecule of carbon dioxide. Unfortunately, carbon dioxide is a greenhouse gas, and converting mass quantities of coal in the ground into carbon dioxide would have consequences for the Earth's climate that are not entirely predictable.[10] In addition, coal is a very dirty fuel: it often comes with unpleasant impurities such as sulfur, mercury or arsenic that can be extracted from the coal only at considerable expense.

Nevertheless, coal can be liquefied and used as a substitute for oil. If we take our chances on fouling the atmosphere and turn to coal as our primary fuel, we are told that there is enough of it in the ground to last for hundreds of years. That estimate however is like the R/P ratio for oil. It does not take into account the rising world population, or the fact that the rest of the world would like to consume more fuel. Moreover, we now use twice as much energy from oil as from coal, and since the conversion process is inefficient, we would have to mine coal many times faster than we are doing now. Finally, that estimate does not take into account the Hubbert peak effect, which is just as valid for coal as it is for oil. The simple fact is, the end of the age of fossil fuel, coal included, will probably come in this century.

[9] It will also require more energy input to get a given amount of energy out. Once the energy needed gets to be equal to the energy produced, the game is lost. We already use one fuel that requires more energy than it provides: ethanol made from corn is a net energy loser. We use it for purely political reasons.

[10] It would not deoxygenate the atmosphere, however. Burning all the known coal in the ground would consume less than 1% of the oxygen in the atmosphere.

Perhaps we should examine different sources of energy. Controlled nuclear fusion has long been seen as the ultimate energy source of the future. The technical problems that have prevented successful use of nuclear fusion up to now may someday be solved, though probably not in time to rescue us from the slide down the other side of Hubbert's peak. Then the fuel could be deuterium, a form of hydrogen found naturally in seawater, and lithium, a light element found in many common minerals.[11] There would be enough of both to last for a very long time. However, the conquest and practical use of nuclear fusion has proved to be very difficult. It has been said of both nuclear fusion and shale oil that they are the energy sources of the future, and always will be.

Nuclear fission, on the other hand, is a well-established technology. While the very word "nuclear" strikes fear into the hearts of many people,[12] it could be a potentially valuable source of energy. When the oil crisis occurs, the fear of nuclear energy is likely to recede before the compelling need for it. However, once we bite the bullet and decide to go nuclear again, it will take at least a decade before new plants start coming on line. And even then there will continue to be legitimate concerns about safety and nuclear waste disposal. Also, nuclear energy is suitable only for stationary power plants or very large, heavy moving things (ships, submarines). Don't look for nuclear cars or airplanes any time soon.[13]

Economists seem to believe that the energy supply problem is not real. As oil becomes scarce, they argue that its price will rise; this will promote competition and innovation in fuel technologies, permitting other sources of energy to emerge. However, as we have seen, that argument ignores the fundamental reality that fuel technologies take time to develop. Furthermore, our vehicles, our roads, our cities, our power plants, our entire social organization have evolved on the promise of an endless supply of cheap oil; even if a viable alternative were to be discovered and available tomorrow, it seems unlikely that the era of cheap oil will end painlessly.

It is more likely that when the peak occurs, the confluence of rapidly increasing demand and rapidly decreasing supply will be disastrous. We had a small foretaste of what might happen in 1973, when some Middle Eastern nations took advantage of the declining U.S. supplies and created a temporary, artificial shortage of oil. The immediate result was long lines at the gas stations, accompanied by panic and despair for the future of our way of life. But after Hubbert's peak, the shortage will not be artificial and it will not be temporary. It will be permanent. At the very least, the end of cheap oil will mean steep inflation, due in part to the rising cost of gasoline at the pump, but also due to the rising cost of transportation and

[11] The nuclear reaction envisioned for fusion reactors is the fusion of deuterium and tritium, two isotopes of hydrogen. Tritium doesn't exist in nature, but the fusion reaction yields neutrons, which would be used to make the tritium in a lithium blanket. Thus the actual fuels are deuterium and lithium.

[12] So much so that the utterly innocent technique called Nuclear Magnetic Resonance by scientists had to be renamed Magnetic Resonance Imaging before it could be accepted by the public for medical use.

[13] The fuel for this kind of reactor is the isotope uranium 235. Natural uranium consists of about 0.7% isotope 235, and 99.3% isotope 238. The known reserves could produce enough energy to replace all fossil fuels for no more than one or two decades. However, if it is used in a type of reactor called a breeder reactor (that converts the otherwise useless isotope uranium 238 into plutonium 239, which is a nuclear fuel), the supply becomes much larger.

petrochemicals. In fact, 90% of the organic chemicals we use, including pharmaceuticals, agricultural chemicals and commodities such as plastics are made from petroleum. There are better uses for the stuff than burning it up.

Once Hubbert's peak is reached and oil supplies start to decline, how fast will the gap grow between supply and demand? That is a crucial question, yet it is almost impossible to answer with confidence. I postulate the following. The upward trend at which the demand for oil has been growing amounts to an increase of a few percent per year. On the other side of the peak, we can guess that the available supply will decline at about the same rate, while the demand continues to grow at that rate. The gap, then, would increase at about, say, 5% per year. That means that, ten years after the peak, we would need a substitute for nearly half the oil we use today—something approaching 10-15 billion barrels per year. Even in the absence of any major disruptions caused by the oil shortages after the peak, it is very difficult to see how that can possibly be accomplished.

What about the possibility that a huge new discovery of conventional oil will put off the problem for the foreseeable future? Better to believe in the tooth fairy. Oil geologists have literally gone to the ends of the Earth searching for oil. There probably isn't enough unexplored territory on Earth to contain a spectacular unknown oil field.[14] Remember that despite intense worldwide effort, the rate of oil discovery started declining decades ago, and it has been declining ever since. That is why the USGS assumption of thirty more years of rapid discovery, mentioned earlier, seems questionable even if it is more a prediction about future technology than future discovery. But let us suppose for one euphoric moment that one more really big field is still out there waiting to be discovered. The largest oil field ever discovered is the Ghawar field in Saudi Arabia, whose 87 billion barrels were discovered in 1948. If someone were to stumble onto another 90 billion barrel field tomorrow, Hubbert's peak would be delayed by a year or two, well within the uncertainty of our present estimates of when it will occur. In other words, it would hardly make any difference at all.

That fact points up the sterility of our current national debate about the Arctic National Wildlife Refuge (ANWR) in Alaska. If the ANWR were opened for drilling (and if it really contains oil, not water as some geologists suspect), it could yield enough oil to supply the United States for about three months. The best reason for not drilling there is twofold: first, to preserve the oil for future generations to use in petrochemicals, rather than burning it up in our SUVs; and second, to protect the wildlife.

Besides, burning all the fossil fuel in the ground poses another grave danger for us. Every carbon atom in the fossil fuels we burn turns into a molecule of carbon dioxide gas in the atmosphere. Recall that carbon dioxide is a greenhouse gas. We have been pouring it into the atmosphere since we started burning fossil fuels in large amounts during the nineteenth century. The net result of tinkering in that way

[14] The largest remaining area that is accessible and unexplored is the South China Sea. Geologists consider it a promising, but not spectacular region. It is unexplored because of conflicting ownership claims by various nations, and murky international law governing such mineral rights at sea. Other possibilities that come with big problems include central Siberia and the very deep oceans.

with the atmosphere is not easy to predict. Increasing the amount of carbon dioxide increases the amount of infrared radiation intercepted by the atmosphere and radiated back to Earth. That warms the Earth slightly, causing more water to evaporate. Water vapor is a powerful greenhouse gas, so the effect of the carbon dioxide is amplified. The warming also causes the polar ice caps to shrink, reducing the amount of sunlight reflected directly back to space, which leads to even further warming. On the other hand, the extra moisture in the air tends to condense into more clouds, and clouds reflect sunlight, decreasing the warming effect. And so on. The effect is complex, with both positive and negative reinforcement acting in ways that will have consequences that are not well understood, though theories abound. There is even a theory that the melting of the polar ice caps could lead to a change in the ocean currents that would cause a sudden cooling of the entire planet.

The cozy climate we now enjoy is in what scientists call a metastable state. That means small perturbations do not cause drastic changes. But it also means we could tumble out of that state into a completely different one. There are other possible metastable states that are dramatically different from the one we're in now, without changing the central feature of the Earth's distance from the Sun. Suppose, for example, that there were no greenhouse gases at all. The temperature would immediately drop to zero degrees Fahrenheit. The oceans would freeze, reflecting more sunlight and further cooling the Earth. (Some geologists think the Earth went through periods like that perhaps a billion years ago. It's called the "Snowball Earth" theory.)

On the other hand, suppose we succeed in increasing the greenhouse effect to 100%. What would the temperature of the Earth be then? We don't know exactly, but we do have a real example to look at. The surface of Venus should be somewhat warmer than the surface of the Earth, because Venus is closer to the Sun. However, that difference is not very large. It's possible that Venus could be very Earth-like. But we know it isn't. Venus has a poisonous atmosphere with a runaway greenhouse effect. When a Russian spacecraft sent a probe into the Venusian atmosphere, it recorded a surface temperature hotter than molten lead.

We don't know how big a perturbation it would take to tip the Earth's atmosphere into an entirely different state, one that might not be inhabitable by life at all. However, even the relatively small extant perturbations that the Earth has experienced can have dramatic effects. In various areas, the arctic permafrost has softened; low-lying islands have been inundated; and coastlines will change, to name only a few. We toy with atmospheric dynamics at our own peril. Some optimists believe that the sobering reality of Hubbert's peak will prevent us from doing irreparable damage. Yet this seems akin to hoping that a fatal heart attack will save a patient from cancer.

To be sure, the effects of the looming crisis could be greatly mitigated by taking steps to decrease the demand for oil. For example, with little sacrifice of convenience or comfort, we Americans could drive fuel-efficient hybrid cars. Such changes seem to be beginning, but there are powerful interests opposing them.

Before we turn to prospects for the future, a summation is in order. The followers of Hubbert may or may not be correct in their quantitative predictions of when the peak will occur. Regardless, they have taught us a crucial principle: the crisis will come not when we pump the last drop of oil, but rather when the rate at which oil can be pumped out of the ground starts to diminish. That means the crisis will come when we've used roughly half the oil that nature made for us. Thus, the problem is much closer than we had previously imagined. Beyond that, burning fossil fuels alters the atmosphere and could threaten the metastable state our planet is in. We have some very big problems to address.

So, what does the future hold? We can easily sketch out a worst-case scenario and a best-case scenario.

Worst case: After Hubbert's peak, all efforts to produce, distribute and consume alternative fuels fast enough to fill the gap between falling supplies and rising demand fail. Runaway inflation and worldwide economic depression leave many billions of people with no alternative but to burn coal in vast quantities for warmth, cooking and primitive industry. Dramatic change in the greenhouse effect results and eventually tips the Earth's climate into a new state hostile to life. Human civilization, not to mention all other forms of life in the biosphere, ends. In this instance, worst case really means worst case.

Best case: The worldwide disruptions that follow Hubbert's peak serve as a wake-up call. A methane-based economy is successful in bridging the gap temporarily, while nuclear power plants are built and the infrastructure for other alternative fuels is established. The world watches anxiously as each new Hubbert's peak estimate for uranium and oil shale makes front-page news.

Is there any hope for a truly sustainable long-term future civilization? The answer is yes. Stationary power plants can run on nuclear energy or sunlight. More difficult is a fuel for transportation. The fuel of the future is probably hydrogen. Not deuterium for thermonuclear fusion, but ordinary hydrogen to be burned as a fuel by old fashioned combustion, or to be used in hydrogen fuel cells that produce electricity directly. Burning it or using it in fuel cells puts into the atmosphere nothing but water vapor. Water vapor is a greenhouse gas to be sure, but unlike carbon dioxide, it cycles rapidly out of the atmosphere as rain or snow. Hydrogen is dangerous and difficult to handle and store, but so are gasoline and methane. Nature has not stored up a supply for us, but we can make it ourselves.

Of course you can't get something for nothing. Hydrogen is a high potential energy substance. That's precisely why it is valuable as a fuel. That energy has to come from somewhere. Where will we get the energy to make hydrogen?

Interestingly, one possible source is the potential energy stored in coal. There are extant industrial processes that combine coal and steam to make hydrogen and, inevitably, carbon dioxide. The process does not involve burning the coal. In principle, the carbon dioxide could be separated and stored ("sequestered" is the current buzzword). Where could it be stored? That little problem has not been solved yet. In any case the coal will eventually run out. We're trying to think long-term here.

Civilization as we know it evolved because there was a plentiful supply of oil in the ground, available for the taking. There is another cheap, plentiful supply of energy available for the taking, and this one won't run out for billions of years. It's called sunlight.

We now make very poor use of the sunlight that arrives at the Earth. Farmers use it to grow food and fibers for textiles. A little bit is collected indirectly in the form of hydroelectric and wind power. Here and there a few solar cells provide energy for one use or another. But by and large, it just gets absorbed by the Earth. It will wind up as heat in the Earth, eventually to be reradiated back out into space in any case, but we could learn to make better use of it along the way.

Sunlight is not very intense as energy sources go. The flux of energy from the Sun amounts to 343 watts per square meter at the top of the atmosphere, averaged over the entire surface of the Earth. By comparison, we Americans consume about a thousand watts of electric power each, all the time. Nevertheless, the solar power falling on the United States alone amounts to about ten thousand times as much electric power as even we profligate Americans consume.

Both sunlight and nuclear energy can be used to make hydrogen in a number of ways. There are chemicals and organisms that evolve hydrogen when sunlight is added. Electricity is made directly from sunlight in solar cells. Electricity can also be generated by using sunlight or nuclear energy as a source of heat to run a heat engine, such as a turbine, that can generate electricity. By means of electrolysis, electricity can make hydrogen from water. There is not much reason to doubt that hydrogen can serve as a fuel for transportation needs. At present, nuclear technology is far more advanced than solar for all of these purposes, but that could change in the future.

Technically and scientifically, the possibility and means exist to maintain and develop a civilization that provides everything we think we need, *without fossil fuels*. The future exists. The remaining question is, can we get there? And if it is possible to live without burning fossil fuels, why wait until the fuels are all burned up? Why not get to work on it right now, before we do possible irreparable damage to the climate of our planet?

Scientists are supposed to make predictions, and so I offer one. Civilization as we know it will come to an end some time in this century, when the fuel runs out. What that future looks like remains to be determined. This is different from normal scientific predictions in a crucial way. Usually, the scientist hopes that the prediction will prove to be correct, and merely making the prediction does not change the phenomenon in question. In this case I do hope the prediction will be wrong, and I hope that merely making the prediction will help obviate the problem.

Early life forms released oxygen into the atmosphere and buried carbon in the ground, preparing the planet for creatures like us. Now the planet is in our hands, and unlike early life, we are aware of our responsibilities and the possible consequences of our actions. What happens next is up to us.

Acknowledgements: I wish to acknowledge a number of colleagues who have read versions of this manuscript and made useful contributions to its accuracy: Dr. Robert Mackin, Dr. James Morgan, Dr. John Wettlaufer, Dr. Lynn Orr, Mr. Brad Haugaard, Mr. Mark Goodstein, Dr. Pierre Jungels, Dr. Tom Tombrello, Dr. Judith Goodstein.

REFERENCES

Bartlett, A.A. "Reflections on Sustainability, Population Growth and the Environment." *Population & Environment* 16, no. 1 (September 1994): 5 – 35.

Campbell, C.J. and J.H. Laherrère. "The End of Cheap Oil." *Scientific American* (March 1998).

Deffeys, K.S. *Hubbert's Peak: The Impending World Oil Shortage*. Princeton: Princeton University Press, 2001.

Duncan, R.C. "World Energy Production, Population Growth and the Road to the Olduvai Gorge." *Population and Environment* 22, no. 5 (May-June 2001).

Goodstein, David. *Out of Gas.* New York: W.W. Norton, 2004.

Hubbert, M. King. "Energy from Fossil Fuels." *Science* 109 (February 4, 1949): 103-109.

Ivanhoe, L.F. http://www.hubbertpeak.com/ivanhoe.

Lynch, M. http://sepwww.stanford.edu/sep/jon/world-oil.dir/lynch/worldoil.html http://sepwww.stanford.edu/sep/jon/world-oil.dir/lynch2.html.

U.S. Department of Energy predictions.
http://www.eia.doe.gov/pub/oil_gas/petroleum/presentations/2000/long_term_supply/sld001.htm

U.S. Geological Survey, World Petroleum Assessment 2000: Description and Results. http://www.usgs.gov/public/press/public_affairs/press_releases/pr1183m.html, http://greenwood.cr.usgs.gov/energy/WorldEnergy/DDS-60/index.html#TOP.

Youngquist, Walter. *Geodestinies.* Portland: National Book Company, 1997.