NPG Forum

The End of Fossil Fuels

Part 1. How Long the Twilight?

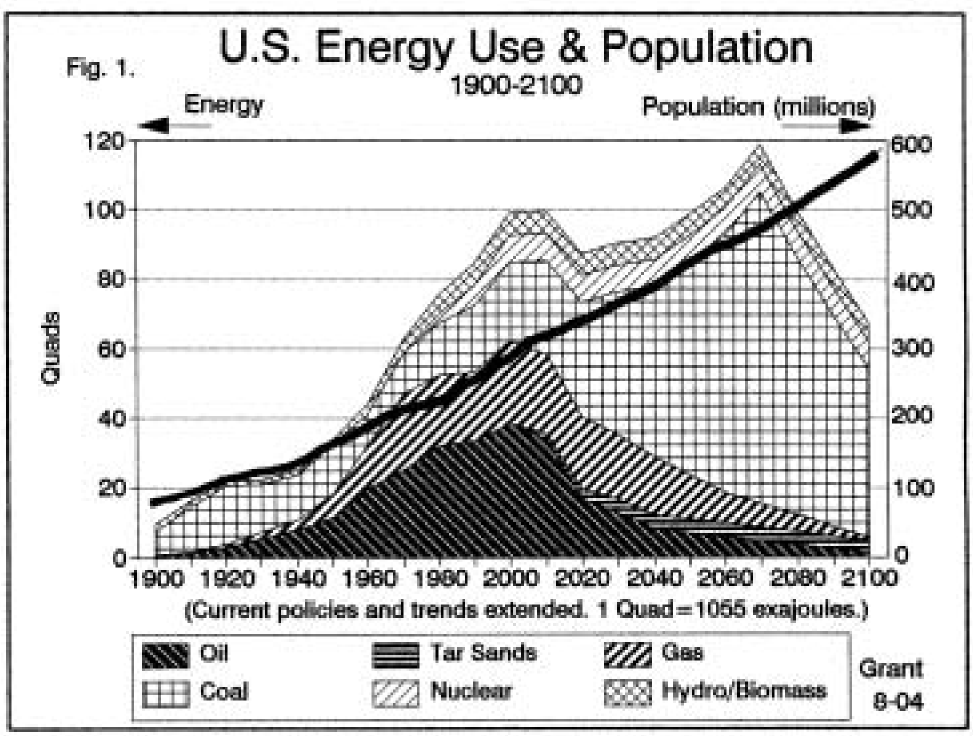
by Lindsey Grant

This country and the world are in for profound change as the petroleum boom winds down. I find that even specialists in the fields that will be most affected have not seriously considered what that transition will be like or how they will handle it. This study is an effort to describe the transition and to explore what lies beyond it.

In Part 1, I will examine the period of decline of petroleum and gas, which will be swift. The petroleum era has been a brief spike that has contributed to a quadrupling of world and U.S. population and rising consumption levels. We are entering an age of overshoot. There may be opportunities for an orderly withdrawal, if we are wise enough to manage the environmental threats and unlearn the faith in growth that has developed in the fossil fuel era. There will be disasters if we do not. Part 2 will look at a much more speculative future beyond fossil fuels and suggest that current populations cannot be supported without them. We may come to see the Industrial Age as the most intense human disturbance of our natural support systems in history. With the judicious employment of the technologies we have learned – and with a bit of luck – we may be able to create a more harmonious balance with the rest of the biosphere, but at much lower population levels and less consumptive habits.

The "Business As Usual" Scenario

In the old journalistic tradition, I will summarize the projections at the beginning and explain them later. Figure 1 is a stacked graph showing the history of U.S. conventional energy consumption and a speculative projection of its likely path in this century, based on current trends and assuming no fundamental policy changes (such as those I advocate). Superimposed on it is a line showing past U.S. population growth and the Census Bureau middle projection of future growth.[1]



The decline of petroleum and gas is pretty much out of our hands. Fission energy is limited by uranium resources, and hydropower by a lack of sites. With a growing population, biomass energy has little room for growth. The key is coal. There is enough coal to support a two percent annual growth rate for most of the century, but it raises major environmental concerns not shown on the graph. Nor does the graph deal with the evidence, which I will present in Part 2, that a sustainable future beyond the transition will require a population much smaller than now. The graph is optimistic in several respects. It assumes continuing petroleum imports and rising gas imports, and there are no surprises or interruptions of international energy trade.

The Petroleum Spike

World crude oil production rose from negligible in 1900 to about 80 million barrels per day (mbpd) a century later. U.S. consumption of crude oil and natural gas have both risen more than 100-fold since 1900[2]. In that period, world and U.S. populations nearly quadrupled, but the dramatic per-capita increase in petroleum use lies at the heart of "The American Century."

The age of reliance on fossil fuels has been extraordinary both for its swift rise and its prospective brevity. It has supported a remarkable growth in prosperity in the industrial world. The return to reliance on the sun's annual radiation of energy to the Earth will be a painful comedown.

Our political and business "leaders" seem generally oblivious to the unique character of the fossil fuel age. They consider growth the natural and desirable order of affairs and call for more of it – an outlook influenced more by greed than reflection. When warned of the brevity of the fossil era and the dangers it is creating, they defend the status quo or, when pressed, offer simplistic panaceas such as the hope that hydrogen or wind and solar energy will solve our problems. By themselves, they will not.

Fossil and Renewable Fuels in the U.S. In the United States, we consume 97 quads (quadrillion British Thermal Units) or 102 exajoules (quintillion joules) of commercial energy each year. Of that, petroleum furnishes 39 percent, natural gas 24 percent, and coal 23 percent. Taken together, fossil fuels contribute over 86 percent of our total energy. Nuclear power, which is a fossil fuel in the sense that it relies on ores from earlier geological times, provides another 8 percent. Renewable energy provides just 6 percent, almost entirely from hydroelectric power and biomass; wind energy provides 0.1 percent and solar electricity – which is presently much in vogue – much less than that, or 1/1500th of the total.[3]

Fossil Fuels' Role in the Economy. The U.S. economy is built on fossil fuels. Of those 97 quads of total primary energy, 40 percent (mostly from coal, natural gas and nuclear energy) goes to produce electricity, which of course is then used throughout the economy, 27 percent (almost all of it petroleum) goes directly to transportation, and 22 percent goes to industry and agriculture (divided about equally between petroleum and natural gas). The remaining 11 percent goes to the household and commercial sectors.

Fossil fuels provide services other than energy. About 9 percent of total primary fossil fuel use is used as industrial feedstocks, not as energy: fertilizer, pesticides, pharmaceuticals, plastics, textiles and artificial leathers, tires, asphalt, lubricants and waxes – many of the things we rely on. Roughly 28 percent of those feedstocks come from petroleum, 24 percent from natural gas liquids, 11 percent from natural gas itself, 9 percent from coal, and the remaining 28 percent from cellulose materials such as wood scraps, sawdust, other by-products of the lumber industry, cane sugar bagasse and paper mill pulp.[4] No discussion of the role of fossil fuels in modern economies can afford to ignore their role as feedstocks.

The Future of Oil and Gas

What Energy Transition? The experts say that, so far, the world has consumed less than half, and perhaps less than one-third, of recoverable petroleum resources. Why are they so worried about running out of oil? The answer lies in the astonishing growth of the enterprise. The oil era really got under way only about 1940, and yet already – because of the speed at which consumption has grown — we can foresee the end of the petroleum era and of the economic system that has grown on it. For the United States, the domestic game is about over. Our crude oil production has been declining at an accelerating rate for thirty years. We now import 62 percent of our crude oil and, with less than 5 percent of the world's population, we consume one-quarter of world production. We can eke out a few decades of dependence on oil and gas only if we can import it.

Worldwide discoveries of new oil fields peaked over 40 years ago, despite intensified and increasingly sophisticated exploration efforts and extraction techniques. Non-OPEC production has probably peaked, and worldwide production is expected to peak very soon.

The U.S. Geological Survey (USGS) publishes one of the more optimistic estimates of oil and natural gas resources. Their estimates are summarized in Table 1 below.[5]

Table 1. USGS world summary estimates of conventional petroleum and gas resources, 50% confidence level.

[BBOE, billions of barrels of oil equivalent. Six thousand cubic feet of gas = one barrel of oil equivalent. Natural gas liquids included in petroleum figures.]

	OIL	GAS	
	Billions Barrels	Trillion Cubic Feet	BBOE
World (excluding U.S)			
Undiscovered conventional	796	4,333	722
Reserve growth (conventional)	654	3,305	551
Remaining reserves	927	4,621	770
Cumulative production	546	898	150
Total	2,923	13,157	2,193
United States			
Undiscovered conventional	83	527	88
Reserve growth (conventional)	76	355	59
Remaining reserves	32	172	29
Cumulative production	171	854	142
Total	362	1,908	318
World Total	**3,285**	**15,065**	**2,511**

That table takes a bit of reading. Let me focus on the oil figures. To begin with, the figures for "undiscovered conventional" resources and "reserve growth" represent USGS' 50 percent confidence level estimates. If you asked, "how much of that oil are you really confident about?" the 3285 figure would go down to 2452 billion barrels. If you then asked, "... and that's what the world has left?" the answer would be, "Well, no; 717 billion barrels have already been consumed. We would bet 19:1 that there are more than 1735 billion barrels left, and we would bet 50:50 that there are 2568 billion barrels left. There may be 3343 billion barrels left, but we would bet 19:1 against it."

"Reserve growth" is a concept recently developed by the USGS. It is their guess as to how much more oil can be obtained by expanding existing known fields and applying new technologies to them. Growth enthusiasts greet every news report about the increasing efficiency of oil extraction, as if it vitiated old estimates of the limits of the resource. What they ignore is that allowance has been made for such improvements in the "reserve growth" estimate. And there is no assurance that those expectations will be borne out. Royal Dutch/Shell recently reduced its estimated reserves by 20 percent. That downsizing is ominous, because it reflects a failure of a new technology, horizontal drilling.[6]

Why this statistical exercise? It shows that the USGS – one of the more optimistic players – is really confident only of about 1.7 trillion barrels of conventional oil remaining on Earth, with the odds diminishing to an even bet at less than 2.6 trillion.

How big is 1.7 trillion barrels? There are various ways of trying to make such stupendous numbers more concrete. One way is to divide the number by current annual consumption to arrive at a figure for a "resource/consumption ratio" or "years of consumption." Dividing the 1735 billion barrel estimate above by current annual worldwide consumption (29bb per year) gives a figure of 60 years. But this calculation is flawed. It assumes that world oil consumption will stay constant, which it won't. The Energy Information Administration (EIA) expects it to grow 1.9 percent per year from 2001-2025.[7] At that growth rate, the resource life shortens to 41 years.

That is still an unlikely scenario. Production will peak and then move down unpredictably, perhaps for a century. The important question really is, when will it peak? From that date on, rising demand will pursue a diminishing supply – and that is a recipe for intense competition and rising prices. The USGS does not put a date on the peak, but we can derive one by applying the statisticians' bell curve to the USGS world resource estimates. (That approach assumes that the peak will come when half the ultimate recoverable resource has been extracted.) The peak will come in 2015 if we use the USGS 95% probability estimate of 1735 bb and the 1.9% growth rate. The USGS 50% probability estimate would move it back to 2025.

Other less optimistic experts believe that the USGS overstates undiscovered oil and prospective reserve growth. Using a country-by-country bell curve analysis, they put remaining world oil resources at about one trillion barrels.[8] They calculate a peak before 2010, probably by 2007. The difference of opinion itself shows that this is hardly a precise exercise, despite the spurious 4-digit precision of the USGS numbers. Nevertheless, the differences simply move the peak a few years one way or the other.

In Figure 1, I projected U.S. oil consumption declining from 25 percent of world production now to 12 percent in 2020 and thereafter (given our declining production, the rising competition on the world market and our balance of payments deficit), using the Duncan-Youngquist projection of world production. And although it is a risk-laden world, I assumed no supply interruptions.

The analysis of natural gas is parallel to that of oil, though gas resources are harder to predict. Natural gas is a replacement for oil in many applications but a temporary one, since gas production will probably peak shortly after the oil peak. The USGS estimates for both fuels are similar (Table 1), as are the resource/consumption ratios. The United States is fast running out of natural gas. Petroleum can be moved around the world cheaply by tanker, but moving gas by sea requires a cumbersome and costly process of liquefying the gas, shipping it by special tanker, and reconverting it to gas.

In Figure 1, I made some conjectural assumptions: a continuation of the slow decline in U.S. production, accelerating somewhat over the decades; and imports from overseas rising to replace diminishing imports from Canada until 2040 and then declining with the swift decline of world production.[9]

Intensifying competition. Economists will try to adjust to the tightening world demand/supply equation and the entry into the market of new players such as China (where the automobile era is just taking off, and energy consumption – mostly petroleum – for transportation is projected to grow an astonishing 5.3 percent per year through 2025.[10] That would be a quadrupling by 2025, which requires a very optimistic view of availability.) Prices of oil and gas have already been rising, but those increases are negligible compared to those we may anticipate after the oil peak.

How far will prices rise? Nobody knows. Oil producers will try to maximize production from aging fields, which itself will drive up the price. Secondary price increases will occur in energy-intensive industries, as they pass on higher energy prices. Demand itself is unpredictable. Consumers will face a sharp decline in their standard of living as they absorb the higher price of energy, and this in turn will affect their purchasing power and propensity to consume. The monetary authorities – the Alan Greenspans – of the industrialized nations will face a juggling act much more difficult than anything they now have to deal with. The strains could precipitate a collapse of world fiscal and trading systems. The collapse would be most immediate and disruptive in the industrialized world and in the cities of the developing countries. It would have less effect on the rural folk in the less developed countries (LDCs) – who still constitute 60 percent of LDC population. They are already at or close to subsistence levels; but their countries would lose a part of their export markets and such food and aid as they have gotten from abroad.

The competition for energy resources may well spell the end of free trade. The United States is still betting that under the banner of free trade it will be able to buy the oil and natural gas that it wants. That may not work. In a few decades, when coal is king, the United States will have the largest endowment. Will we share it? With memories of the suspension of soybean exports by the United States when there was a poor crop, and similar European behavior when they had a poor grain crop, I am dubious. Welcome to the new era.

Few political leaders seem to recognize that the decline of petroleum is a new and fundamental issue. The U.S. Government seems to be mesmerized or in denial, and state and local governments continue to plan for growth and more traffic as though there were no energy crisis ahead. We may stay in that state of mind and stumble dumbly into disaster. More likely, we will search for every possible source of energy – but without addressing the population growth that drives the problem. There are several policy choices and energy sources to stretch out the crisis. I will itemize them below.

The Search for Alternatives

Conservation. At the next crisis, there will be strong pressures to conserve energy and use fuel more efficiently, and laws and tax policies should be changed to encourage it. The transportation sector is particularly vulnerable. SUVs will be a dying breed, and industrialists will become much less tolerant of energy inefficiency. There is very little to criticize in both those developments – though automobile manufacturers will lose their most profitable market. Climate will be under less human stress, and the environment will benefit. The United States has room for substantial savings. Look at Europe and Japan, which use about half as much energy per capita as we do, without suffering deprivation.

Unconventional oil. There are immense deposits of bitumen in tar sands in Canada and unconventional "Orinoco extra heavy oils" (asphalts) in Venezuela. How big? The World Energy Council (WEC) estimates that there are 3.6 trillion barrels of oil in place in those two countries. That is more than the remaining conventional oil resources, but there will be a point at which it takes more energy to mine and convert those resources than they will produce. The WEC is less sanguine about those resources than the "oil in place" figure would suggest. It puts proven reserves at just 46 billion barrels, with another 193 billion barrels in probable reserves. They are being exploited now. The Canadian fields produce 500,000 barrels per day, and production is being upped to one million barrels. It is said to be profitable at today's oil prices, even though extensive processing is needed to convert it to conventional oil. Petroleum geologist Walter Youngquist observes that there would be "enormous" problems in scaling unconventional oil production up to five million bpd. If that rate can be achieved, the proven and probable reserves would last over a century, adding over two percent to present world oil production, which is the single biggest boost in sight for hydrocarbons.[11]

In Figure 1, I assumed that the United States could purchase two million of those five million barrels until about 2085 and then taper off slightly as the "probable reserves" pass their peak.

Problem: Tar sands and extra heavy oils are loaded with pollutants such as heavy metals, and in processing they release large quantities of carbon dioxide, which will force climate warming.

Oil shales introduce the question: when is a resource an economic source of energy? Hydrocarbon-bearing rocks, worldwide, may well contain tens of trillions of tons of kerogen, which is related to oil but must be extensively processed to become oil. It must be mined, subjected to intense heat, and reconfigured to add another hydrogen molecule (which requires a great deal of water), and there are immense tailing piles to be managed. There was an oil shale bubble in northwestern Colorado in the 1970s, where several major oil companies lost literally billions of dollars. Since then, the general wisdom has been that oil shale is an impossibly expensive way to make petroleum (although a few small plants are operating in Australia). The richer shales can, however, be mined and simply shoveled into a boiler and used to generate electricity, a process already in use in Estonia.[12] How much of this can be done is anybody's guess; it is too far from realization to offer an estimate.

Problem: the volume of wastes is huge. Like popcorn, the material expands as it is processed. And the air pollution and carbon dioxide releases have yet to be quantified.

Coal. Coal was the first of the fossil fuels, the dirtiest, the slowest-growing, and it will be the last to go. Estimates of the resource are based on different assumptions and definitions. The DOE/EIA puts world reserves at 1018 billion tons and U.S. "demonstrated coal reserves" ("proven" plus "indicated") at 455 billion metric tons.[13] The World Energy Council (WEC) puts proven world reserves at 984 billion tons and proven U.S. reserves at 250 billion tons.[14]

Americans can draw some comfort from the WEC estimate. It assigns the proven reserves this way: United States 25%, Russia 16%, China 12%, India 9%, Australia 8%, Germany 7%, and South Africa 5%. The other half of the world's population will have to import coal or get by on the remaining 18%.

That distribution will be a major determinant of different nations' long term economic prospects. Coal is a major source of electricity, and it can be liquified (at a loss of half the energy) into a substitute for petroleum. Germany made synthetic gasoline in World War II, and a commercial synfuel operation is running in South Africa now.

Coal reserves of 984 billion tons are equivalent in energy value to 4.6 trillion barrels of oil. That is more than the USGS estimate of 4.5 trillion barrels of oil equivalent (tboe) of remaining oil and gas in Table 1, and the figure for coal does not include the undiscovered exploitable resources, whatever they may be. The comparison suggests that coal is a huge resource, but not an infinite one, and it is costlier to extract than oil. The WEC "reserve/production ratio" for coal reserves for six of the seven leading countries (except China) comes out to over 200 years' supply, but that calculation is nearly meaningless, both for the reasons I cited in the petroleum discussion and because the demand for coal will skyrocket. It provides just 27 percent of world fossil fuel consumption now[15]; it will be called on to provide much of the other 73 percent as oil and gas wind down.

Coal can thus play a pivotal role in the energy transition, providing both energy and chemical feedstocks until we can get our house in order and learn to live within a renewable resource economy (Part 2). If the numbers are right, the United States would still have diminishing production until after 2150, but the energy transition will be dangerous and difficult, and we would be wiser to cut back on coal production when we can, thus preserving it as a backstop and chemical feedstock for a longer time.

About half the reserves consist of anthracite and bituminous coal and nearly half of sub-bituminous coal and lignite. Coal is bulky and dirty in just about every way, and lignite is the worst.

... and that leads us to the central question about coal. It can help to soften the transition as oil and gas production decline, but the environmental costs could be immense. The WEC 2001 report offers the following table:

Table 2. Comparison of Air Pollution from Different Fuels
Kg of Emissions per TeraJoule of Energy

	Natural Gas	Oil	Coal
Nitrogen Oxides	43	142	359
Sulfur Dioxide	0.3	430	731
Particulates	2	36	1333

Source: Worled Energy Review 2001

Moreover, the WEC estimates that, over the production/consumption cycle, coal emits 50 percent more carbon than natural gas and 25 percent more than petroleum, per unit of energy, and thus is a worse source of climate warming.

For those in doubt about coal's noxiousness, one has only to remember stories of the killing smog in London, the product of countless little coal fireplaces, or breathe the acrid smoke that envelops Chinese cities as housewives light their coal-and-mud briquettes to make supper.

Reliance on coal and oil sands is a dangerous course. Aside from the greenhouse gases and atmospheric pollution, coal mining always disturbs the land. Strip mining, which sometimes involves cutting the tops off mountains, is the most destructive, and efforts to enforce restoration of the land have had mixed success. Coal mining uses and degrades valuable water resources that are particularly scarce in the U.S. West. But the atmospheric pollution can be markedly reduced, and the by-products may be useful as feedstock, through a process with the forbidding title of Integrated Gasification Combined Cycle (IGCC).

In the IGCC process, the coal is gasified, the impurities removed, and it can then be burned as a gas for electric power generation or converted to a liquid energy substitute for petroleum. Among various experiments with IGCC, the most notable was one conducted by a consortium of energy producers and users at Cool Water, near Barstow, California, in the 1980s. It could use high-sulfur coal and even sell the sulfur at a profit. That experimental plant was not competitive at the prices of that period. It was dismantled and its components reassembled in Kansas as a way to convert coal into urea fertilizer.

Interestingly, that plant is thriving now, when many factories that use natural gas as a feedstock are in trouble because of the rising price of gas.[16]

At least two new, larger IGCC projects are under way in this country, one in Florida and one in Indiana sponsored by the DOE Clean Coal Demonstration Program.

Coal consuming countries face a momentous choice: will they burn coal the way they have been doing, and set environmental disasters in motion, or will they go to IGCC and pay a higher price for clean power and feedstock from coal?

That still doesn't solve the biggest problem. The IGCC process does not address the climate problem. It can use some carbon dioxide as a chemical feedstock, but not enough to significantly reduce the overall carbon emissions from burning coal. If we are to avoid compounding the human effect on climate (discussed later), other ways must be found to achieve that reduction.

As oil and gas taper off, the overall rate of global warming will depend largely on whether we can learn to sequester the carbon dioxide released by the use of coal and oil sands. That hasn't happened. The present proposals call for injecting it as a gas into old mines or wells. I have yet to see an inventory of existing subterranean spaces, and CO_2 takes up much more space than coal, so every ton of coal burned will generate hundreds of thousands of cubic feet of CO_2.

The proposal may also be a very dangerous one. As a gas, the CO_2 will seek to escape, particularly if it is under pressure. If it does escape, sequestration will fail. Moreover, CO_2 can be a silent killer. This has happened. Natural CO_2 seeps up through two "killer lakes" in Africa. Such releases a few years ago killed some 5000 lakeside dwellers. CO_2 is odorless and heavier than air; it simply suffocated the unsuspecting villagers.

It would be better if the CO_2 could be incorporated into some inert solid, but CO_2 is one of the most stable of molecules, and no proposal has been forthcoming that would immobilize it in a solid form, economically and without major environmental costs.

Problems: 1. Sub-bituminous and lignite coal apparently cannot be used in IGCC plants, which means the best that can be done is to scrub them, which itself creates huge quantities of used limestone slurry. 2. The industrial nations have yet to go for the expense of IGCC. Developing countries such as China and India seem even less likely to do so, because it is expensive. 3. Sequestration by whatever means is a monumental task. What do you do with some 16 billion tons of CO_2 a year? (For a sense of the scale, consider that that is eight times as much tonnage as all the world's annual grain production, and it is vastly larger because it is a gas.) DOE has a target of doing it, eventually, for $10 per ton, but that is only a target, set by a protagonist of sequestration. By another estimate (or rather, guess), it would cost $80-$100 per ton "assuming that those technologies can be developed"[17] – and that too is simply a speculation. It may not be doable.

In Figure 1, I increased U.S. coal production 2 percent per year until 2070. (Remember, Figure 1 assumes no policy change, and our present policy is growth.) By then, we will have reached the midpoint of known reserves and, following the bell curve, I project declining future numbers. This projection may be low if some of the USGS "indicated reserves" prove out; it could be high if the environmental disruption and climate damage become overwhelming. Current net exports are less than four percent of production. I assumed they would continue but not increase in an era marked by energy stringency. By the latter part of this century, the rest of the world will be in a much more desperate energy crunch than the United States, and that assumption about exports may not hold true if they can find ways to pressure us to increase them.

After coal, we move into energy sources that cause less air pollution and do not contribute to climate warming, but that are more problematic as a way of replacing oil and gas.

Nuclear energy. Nuclear fission is an established source of electric power. Nuclear power plants – over 400 of them – exist in many countries. France generates over 70 percent of its electricity with nuclear power. The United States has about one-fourth of the plants and one-fourth of world production, but we stopped building new plants a generation ago.

The resistances to nuclear power have limited its introduction elsewhere. Those resistances arise from (1) the fear that rogue states may divert uranium from nuclear power production to make nuclear weapons, and (2) the concern that radioactivity from high-level nuclear wastes will escape storage and pollute the environment, or that widespread nuclear pollution may result from accidents such as that at Chernobyl. The threat is nearly perpetual, given the radioactive half-life of 10,000 or even 300,000 years of some of those materials. Nuclear proponents counter that nuclear energy has been remarkably safe. Even the extent of the damage from Chernobyl is hotly contested, and the safety of a proposed disposal site in Nevada is a major political issue. The debate has polarized, and it is very hard to arrive at an objective judgment of the seriousness of the threats, partly because to a unique degree they depend on human behavior.

As energy shortages develop, however, it is a good bet that countries will turn increasingly toward nuclear power. For the uncommitted, the reasoning will be that, whatever its faults, nuclear power is better than no power. Let us hope that, in exchange for that acquiescence, a world system is created that can manage the threats.

That acceptance would not obviate another problem. Fission energy is itself limited, because uranium resources are finite. The International Energy Agency (IEA) estimates "reasonably assured resources" of uranium (at $130/kg or less) as three million tons, with "estimated additional resources" of nearly another million tons. Annual consumption has been flat at about 62,000 tons. If it stays flat, that would provide enough uranium for 49 to 65 years. It is estimated that U.S. uranium resources would last for 35 to 58 years even if the country were to quadruple its nuclear electricity production.[18] (These numbers may go up with new discoveries.)

In Figure 1, I elected to project U.S. nuclear power production as flat, assuming that new plants will replace those being retired. If we did indeed multiply the production, it would be so short a future that it would be a questionable investment. My projection is conservative; we might increase the capacity, particularly if we go in for reprocessing, if some new resources turn up, or if rising uranium prices lead to increases in the reserves.

The WEC points out that the limited nature of the resource has been partly obscured in recent years, because some 40 percent of the uranium needed for power generation was acquired from existing stockpiles and the conversion of nuclear weapon stocks.

The French extend the horizon somewhat. They own the Cogema mines in Canada, the largest uranium producers in the world. They also reprocess the spent fuel rods. However, the rods are reprocessed only two or three times, after which the different radioactive byproducts become so nasty that the French put them into vitrified storage and start anew.[19] The French and Japanese, both without fossil fuels, experimented with sodium-moderated breeder reactors, but that is indeed a dangerous game. Liquid sodium is a superb heat sink but a very tricky material to handle, and as of this writing both experiments were on hold.

Australia has 20 percent of the exploitable uranium resources, Kazakhstan 18 percent, the United States 11 percent, Canada 10 percent, and South Africa 9 percent. The remaining 32 percent is widely distributed, so an OPEC-style oligopoly is some distance off.

Problems: Fission produces only electricity, not concentrated mobile energy or chemical feedstocks. That limits its use to less than 40 percent of the energy market, and like fossil fuels it has a limited time horizon. And if our demand for energy leads us to go with fission, we are making a Faustian trade-off of energy for ourselves, in exchange for our descendants' having to live with the threat of radioactivity escaping from confinement.

Energy, the Environment and Global Warming

Let me go back to the earlier discussion of the petroleum peak. Turn those calculations around: humankind has burned less than half the petroleum that we expect to burn. The environmental problems it has created will double, or more. We have used only 12 percent of the estimated ultimately recoverable gas, so we have eight times as much pollution yet to come. If we burn the estimated reserves of coal without extracting the pollutants, the total nitrogen oxide emissions will be about five times as much as we may expect from oil (Tables 1 and 2). About 3.4 times more sulfur oxides will come from that coal than from petroleum, 2.5 times more carbon and about 60 times as many particulates. If we knew the amounts, we could add the damage from heavy oils. The numbers suggest a dire conclusion: we are in an overshoot mode, not just because the fossil fuels are running down, but because of what they are doing to the environment and the climate. By extracting carbon, nitrogen and sulfur from the lithosphere and injecting them into the atmosphere and biosphere, we are embarked upon a fundamental alteration of our habitat. People seem to have become blasé about that prospect.

We have learned something about controlling air pollutants. The lesson is yet to be applied in the less developed countries. Even in the United States, the EPA reported in 2002 that aggregate atmospheric pollutant emissions are again on the rise. And we haven't mastered the CO_2 emissions.

Atmospheric CO_2 began to rise in the 1700s, as coal came into general use for power and home heating. It accelerated with the petroleum/gas era. All fossil fuels generate atmospheric CO_2 and drive climate warming. The anticipated consequences have been discussed at length elsewhere: multiple health hazards; hotter and drier tropics, and less food production where it is most needed; changes in forest cover, and a loss of forests if climate warming moves faster then tree species can migrate; heat waves; increasingly erratic droughts and storm cycles; the alteration of stream flows; a warming and rising ocean. Of that literature, I will focus on only one issue: the effect on sea level.

The sea is in farther retreat down the continental shelves than at any time in the past 200 million years, except for the glacial periods of the past million years.[20] However, sea level has risen in recent decades, and the International Panel on Climate Change (IPCC) estimates that it will rise about 20 inches in this century. That very small rise can drive shorelines miles inward on a very gently sloping shelf such as in Florida, and it will expose new areas to storm surges. The current rise in sea level is the result of thermal expansion alone. The Ross shelf ice in Antarctica has been breaking up, and the sea ice in the Arctic has thinned by almost one-half in the past half century. Those events have not affected sea level, because that was floating ice and, obeying Archimedes' law, its melting did not change sea level. Mountain glaciers have been retreating worldwide, but the melting glaciers' effect on sea level will become noticeable only when the Antarctic and Greenland ice caps start melting.

The IPCC analyses are confined mostly to effects within this century, although it has pointed out that even the present level of anthropogenic greenhouse gases will affect climate for centuries to come. Unpredictably, and probably over a long time frame, the sea may recover some of the coastal plains that it has given up. Melting of the ice caps could raise sea level about 100 meters. (It was apparently higher than that in the late Cretaceous.) Over half the U.S. population lives in coastal counties. A substantial share of the Earth's population lives in potentially threatened zones below 100 meters elevation. Unlike a recent movie about global warming, the change will take a long time, and people will have a chance to retreat from inundated areas or those swept by storm surges. But where would they go? On a fully occupied Earth, the upland residents would resist the movement.

Turning this threat around is not an easy task. The IPCC in 1995 calculated that the only way to hold the climate impact of human activity at its present level would be to reduce carbon emissions by 50 to 70 percent right away, "and more later." Nothing on the political agenda even begins to address that challenge.

What can we do about the environmental threats and expectation of climate warming? The only reasonable ways are to (1) minimize the threats we can manage, and (2) slow down the rate of emissions by reducing demand. That second policy is a powerful argument for a deliberate policy of reversing human population growth. It offers the hope of escaping the penalties of fossil fuels, even though there will be tremendous problems of adjustment.

Renewables

One way to minimize the threats would be to go to less polluting renewable sources. That is, by and large, a long term process demanding many fundamental changes, and will be discussed in Part 2. Let me here mention the renewables that play a role in the present energy budget.

Hydropower is a known quantity. It already provides about three percent of U.S. energy, but it is unlikely to go higher. The best sites have been occupied, and some old dams are being retired because of their impact on salmon runs. The world outlook is not much better. The WEC estimates that world undeveloped hydro potential is twice the current capacity, but population density in the less developed countries generally means that the valleys behind the proposed dams are thickly occupied. As China is finding out, new hydropower sites involve some painful tradeoffs between the costs of displacement and the power, flood control and irrigation gains that the dams make possible. The Three Gorges Dam on the Yangtze required the removal of more than a million farmers. It is a high cost source of power.

Hydropower is classified as renewable, but the term is relative. The reservoirs behind the dams will silt up – in something like a century or two in eroding areas – and the hydropower will simply become run-of-river, i.e. utilizing the river's variable flow but with no storage capacity.

Climate change enters here. The models agree that global warming will result in more concentrated and erratic storm systems and faster runoff from winter alpine snowpacks, and that seems to be happening now. That is bad news for hydroelectric generation: more erratic streamflows, more erosion into reservoirs,

Problem: Hydropower will be a minor source of new energy at best. Little or no additional capacity is likely in the industrial world, somewhat more in the less developed countries. If total hydroelectric production were doubled (a very optimistic assumption), it would meet less than seven percent of present world electric power needs and progressively less in the future.

Biomass is already a significant source of energy, worldwide. As we shall see, its potential for expansion is presently limited in the U.S. and particularly elsewhere by the competition for the land on which we must produce energy for biomass energy. However, it needs to be encouraged and developed now, along with **Wind, Photovoltaics**, and the more speculative future sources, to play its eventual role. The transitional fuels I have inventoried are simply that. They give us some time to move beyond them, but it would be foolhardy to wait until they are gone before we stop and say: now what?

In Figure 1, I have held U.S. renewable energy at its present level, since significant increases will require far more dramatic actions than those presently in sight and are the subject of Part 2.

Preparing for the Post-Fossil Fuel Era

The Slowly Gathering Storm. That discussion of energy options suggests that for most of this century, dwindling oil and gas resources can be augmented by unconventional hydrocarbons, coal and nuclear fission, but those alternatives are dangerous, limited, and/or expensive (particularly if we try to avoid escalating environmental damage) and only coal has the potential to accommodate the projected growth of U.S. population in this century.

Beyond those transitional forms of energy, there looms an immense qualitative change as the fossil era comes to an end, and as we move from competition for a diminishing resource to the need to find new energy sources to replace those on which modern economies have been built.

Most of us use the word "transitional" to speak of the pending energy shift. The word implies a bridge from one state to another. Usually, when building a bridge, the engineers understand the nature of the terrain at both ends. In the energy transition, however, we are proposing to build a bridge into a void. We don't know what is at the other end. That void will be the subject of Part 2 of this paper.

The Choices Before Us. In that uncertain condition, there are several strategies available to the United States and, less certainly, to other countries.

- Prolong the transition as long as we can. Energy consumption can be lowered by reorganizing our living patterns, by energy-efficient business and manufacturing processes and by promoting public transportation, more house insulation and passive solar house heating. Some of these changes will result from rising energy prices. Others may require a willingness to deliberately substitute long term energy savings for short term convenience. That willingness has been suicidal in modern American politics; it will come about only if it is demanded by an environmentally literate public.

- Minimize the impact that the dirty transitional fuels will have on climate change and the environment. We must find a way to sequester the carbon emissions from fossil fuels including coal and heavy oil. If we cannot, we are heading straight into a worldwide environmental disaster.

- Prepare for an unknown future on the best possible terms. Political leaders everywhere will need to give up their fixation on growth as a panacea for economic ills, because growth abbreviates the transition and rushes us into a future for which we are not prepared. Planners will need to abandon their enthusiasm for energy-intensive economic models such as suburban living, skyscrapers, superhighways and automobiles, and airplanes. Common folk must be prepared to live a simpler life as rising energy costs erode their real incomes – and businesses should be ready to provide workable alternative transportation and living arrangements to which they can resort. Scientists should be mobilized to try to clear the murk ahead and to describe the alternative energy systems that may work, so that we may begin serious work on building that bridge.

- Above all, seek the solution on the demand side. The United States must stop and reverse its population growth so as to match the decline of conventional energy with declining demand, and to free more resources for the investments that lie ahead in converting to renewable energy. We must come to a consensus and start the move now if – as I think Part 2 will document – we learn that the post-fossil energy resources will not support the population we have, at a level above penury – or if we learn that we cannot limit the damage from burning coal. We must learn to put such calculations ahead of the parochial agendas that have stood in the way of a population policy, such as the unwillingness to address the mass immigration that presently drives U.S. population growth, or the political posturing that has crippled U.S. programs to help third world countries stop their population growth. We must, in short, embark on a new agenda that seems hopelessly out of touch with present political realities but that may become more realistic as we recognize the extraordinary changes that must be accommodated as we move toward the end of fossil fuels.

NOTES:

1. 2000 Census Bureau middle projection 2000-2100, modified by 2002 interim projection 2000-2050 and my adjustments 2060–2100.

2. Bureau of the Census, *Historical Statistics of the United States: Colonial Times to 1957*, Table M71-87 and *Statistical Abstract of the United States, 2003*, Table 895; U.S. Department of Energy, Energy Information Administration (DOE/EIA), *Annual Energy Report 2002*, Table 1.3.

3. DOE/EIA *Annual Energy Report 2003*, Table 2.1a "Energy Consumption by Sector, 1949-2002".

4. DOE/EIA unnumbered table "Feedstock Energy..." dated 1998, and www.eia.gov/emeu/mecs/trends/feedstock.htm.

5. Executive Summary, USGS World Energy Assessment 2000, Digital Data Series 60, Table 1. The Assessment gives 5%, 50%, mean and 95% confidence levels for undiscovered oil resources and reserve growth. The mean estimates for undiscovered resources are slightly higher than the 50% confidence levels: 649bb for oil, 4669tcf for gas, and 207bb for natural gas liquids. Its figures for natural gas liquids are included in the U.S. petroleum estimates but not in the rest of the world figures. I have included them in petroleum throughout.

6. Jeff Garth & Stephen Labaton, “Oman’s Oil Yield Long in Decline, Shell Data Show”, *New York Times*, 4/8/04.

7. DOE/EIA, *International Energy Outlook 2004*, Table A2. “World Total Energy Consumption by Region & Fuel, Reference Case”. EIA is an excellent source for past and current data but carries its projections only to 2025, and they show no evidence that the possibility of resource constraints was considered.

8. Colin J.Campbell, “Forecasting Global Oil Supply”, *Submission to H.M. Government Consultation on Energy Policy*, undated,(2003); A.M.S. Bakhtiari (National Iranian Oil Company), “World Oil Production Capacity Model Suggests Output Peak by 2006-07”, *Oil & Gas Journal*, April 26, 2004, pp.18-20; Richard C. Duncan & Walter Youngquist, “Encircling the Peak of World Oil Production”, in International Association for Mathematical Geology *Natural Resources Research*, Vol.8, No.3, 1999.

9. From Colin J. Campbell’s projection of a plateau 2015-2040 followed by a sharp and unheralded decline, in “Submission to H.M. Government Consultations on Energy Policy”, (above), pp.6-8. www.dti.gov.uk/energy/energyep/index.com

10. DOE/EIA International Energy Outlook 2004.

11. Walter Youngquist, “Spending Our Great Inheritance – Then What?”, *Geotimes*, July 1998.

12. Walter Youngquist, “Shale Oil – The Elusive Energy”, in *Hubbert Center Newsletter* 98-4,Colorado School of Mines, Golden, CO.

13. *Statistical Abstract of the United States 2003*, Table 891; International Energy Outlook 2004, www.eia.doe.gov/oiaf/ieo/coal.html.

14. World Energy Council (WEC), 2001 *Survey of Energy Resources*. This is the most comprehensive synoptic survey of world energy. The figures it gives for unproven coal resources are so incomplete and the assumptions so various that they are best ignored in this article. *The BP Statistical Summary of World Energy 2004* coal projections are drawn from the WEC figures.

15. Statistical Abstract, op cit, Table 1363.

16. Personal communication July 8, 2004 from Neville Holt, Electric Power Research Institute, Palo Alto, CA.

17. Paul Roberts, *The End of Oil* (Boston: Houghton, Mifflin, 2004), p.269.

18. Paul B. Weisz, “Basic Choices and Constraints on Long Term Energy Supplies”, Vol. 57, 7/04 (www.physicstoday.org/vol-57/iss-7/p47.html).

19. Thomas Hirons, Los Alamos National Laboratory, personal communication July 2, 2004.

20. Paul G. Falkowski et al, “The Evolution of Modern Eukaryotic Phytoplankton”, *Science*, Vol. 305, 7-16-2004, p.354ff, Fig.3.

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