Where Has the Energy Picture Gone Wrong?

Under Pressure Society Explores Forlorn Directions Such as Bio-fuels, Windmill Farms, and Hybrid Cars

by Theodore Modis

There is hardening evidence against such popular beliefs as the linking of oil prices to scarcity and the likening of renewable energies to panacea. There is also mounting pressure to urgently find the right direction for a concerted worldwide effort to meet energy needs. In what follows, a science-based approach offers far-reaching insights.[1]

Natural Growth in Competition

Natural growth in competition follows S-shaped patterns (S-curves). The simplest mathematical function that produces an S-curve is called a logistic and the natural law behind it states that at any given time the rate of growth is proportional to both the amount of growth already accomplished and the amount of growth remaining to be accomplished. If either one of these quantities is small, the rate of growth will be small. This is the case at the beginning and at the end of the process. The rate is greatest in the middle, where both the growth accomplished and the growth remaining are sizable.

This is a remarkably simple and fundamental law. It has been used by biologists to describe population growth within a species; for example, the number of rabbits in a fenced off grass field. It has also been used in psychology to describe a learning process, and in medicine to describe the spread of epidemic diseases. J. C. Fisher and R. H. Pry used it as a diffusion model to quantify the spreading of new technologies into society.[2] One can immediately see how ideas or rumors may spread according to this law. Whether it is ideas, rumors, technologies, or diseases, the rate of new occurrences will be proportional to how many people have it and to how many don't yet.

The S-curve analogy has also been used to predict competitive growth of inanimate populations such as sales of a successful new product. In the early phases of growth, sales go up in proportion to the number of units already sold. As the word spreads — a learning process — each unit sold brings in more new customers. Sales begin to grow exponentially. This is the first bend of the S-curve. But as the niche fills up, growth slows down and goes into the second bend of the S-curve, the flattening out. Finally, we reach zero growth and the end of the life cycle; the growth process in question comes to an end. The bell curve depicting the rate of natural growth goes back to zero, while the S-curve of cumulative growth reaches its ceiling.

What is hidden under the graceful shape of

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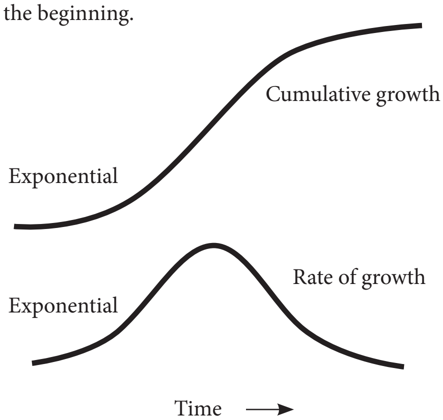
Figure 1

An S-curve and its corresponding life cycle. Both curves behave as simple exponentials in the beginning.



the S-curve is the fact that natural growth obeys a strict law, which includes a final ceiling, the amount of growth *remaining to be accomplished.* Therefore, accurate measurements of the growth process can be used to determine the law quantitatively, thus revealing the final size (the value of the ceiling) ahead of time. This is why the S-curve approach possesses predictive power.

U.S. Crude Oil

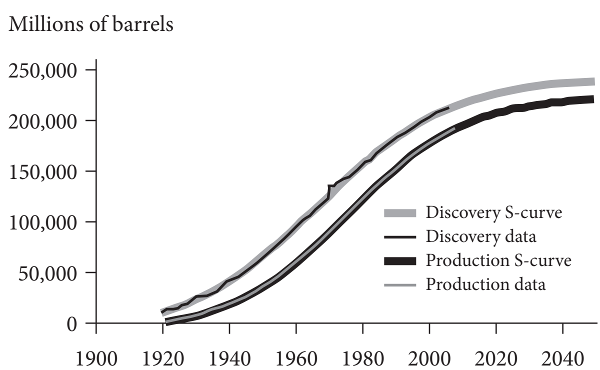
We can look at the surfacing of oil as if it was a "population" growing to fill (or empty) — a "niche." The niche may be the amount of oil Mother Earth has in store underground for us. Alternatively, the niche may simply be the amount of oil for which we have a well-defined need.

Oil started being produced commercially in 1859, but production only picked up significantly in the early twentieth century. From the beginning, extraction of oil stimulated exploration for new reserves. Exploration, however, was expensive and it was pursued only to the extent necessary at any given time. Figure 2 shows both production and discovery of oil reserves for the United States. The historical data represent cumulative production and cumulative discovery of reserves. Oil production gives rise to a smoother curve than discovery, which features random fluctuations due to the fact that all search-and-discover operations are characterized by an element of randomness. Both sets of data are amenable to good fits by S-curves (depicted by thick lines).

The two curves are remarkably parallel, with a constant separation of about ten years. Such a rigid correlation between production and discovery over almost a whole century is proof of an underlying regulatory mechanism based on a feedback loop. In feedback loops, cause may become effect and vice-versa. Finding more oil may result in increased production, but increases in production may also provoke intensification of efforts to find more oil. In any case, history demonstrates that we discover oil ten years before we consume

Figure 2. U.S. Crude Oil (Cumulative)

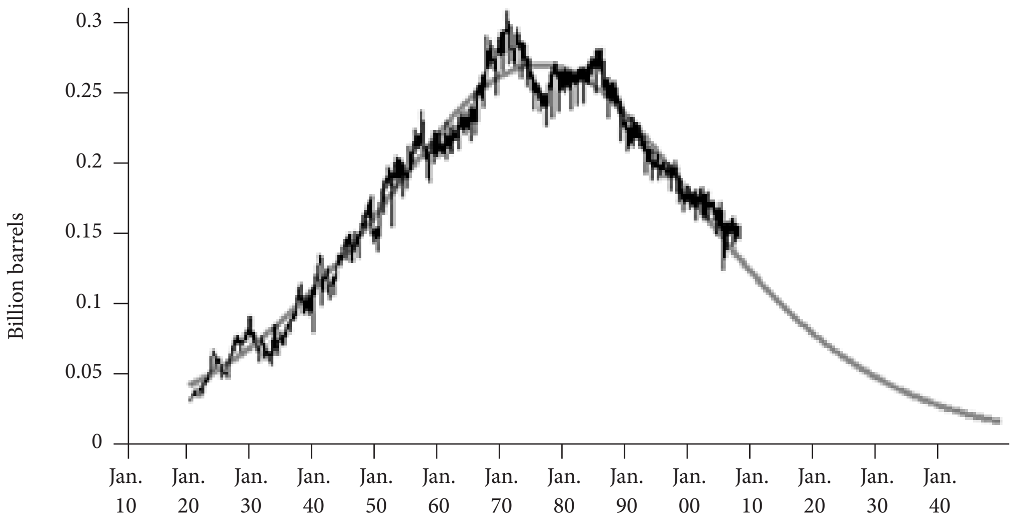
Yearly data and S-curve fits (thin lines) for oil discovery and production in the United States. The agreement between production data and the corresponding S-curve is impressive.



Data source: http://tonto.eia.doe.gov/

Figure 3. U.S. Crude Oil Production (Monthly Rate)

Monthly data. The gray life-cycle curve corresponds to the S-curve of Figure 2.



Source: http://tonto.eia.doe.gov/

it, not earlier or later.

This equilibrium has not resulted from any conscious decision. On the contrary, experts in oil have often forecasted imminent doom, with oil shortages and even depletion in a few years. In contrast, Figure 2 seems to indicate that the more you milk the reserves, the more reserves will be made available to you.

The projections of the S-curves yield rather reliable forecasts, given how closely and how extensively the two growth processes have followed the natural-growth pattern. As we move into the future, the time difference between oil discovered and oil produced will progressively increase from today's ten years. I believe that deep into the 21st century, there will remain a permanent excess of proven oil reserves of about 20,000 million barrels that will never become objects of production.

More extensive monthly data, shown in Figure 3, quantify the phasing out of oil production in the U.S. Today's level of production is less than half what it was in the mid 1970s. Interestingly, oil shocks — one in 1974, another in 1981, and one today — leave no particular price mark on the evolution of the oil-production trend.

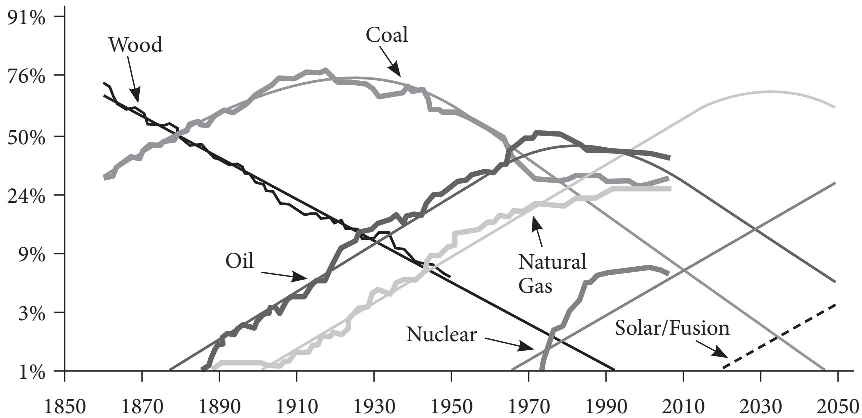
The World Energy Picture

The Fisher-Pry diffusion/substitution model has been generalized by IIASA[3] to handle the many-competitor market.[4] The emerging picture of the energy mix is shown in Figure 4. During the last one hundred years, wood, coal, natural gas, and nuclear energy have been the main protagonists in supplying the world with energy. More than one energy source was present at any time, but the leading role passed from one to the other. Wind power, waterpower, and other sources have been ignored because they command too small a market share.

Figure 4 makes use of the logistic vertical scale that transforms S-curves into straight lines.

Figure 4. Substitution Between Primary Energy Sources (Worldwide Consumption)

Data, fits, and projections for the shares of different energies consumed worldwide. For nuclear, the straight line is not a fit but a trajectory suggested by analogy. The futuristic source labeled "Solar/Fusion" may involve solar energy and thermonuclear fusion.



Data sources: C. Marchetti "Infrastructure for Movement," *Technological Forecasting and Social Change,* vol. 32, no. 4 (1987):373-93.

Statistical Review of World Energy 2008 http://www.bp.com/multipleimagesection.do?categoryId=9023755&contentId=7044552

This scale is nonlinear and has 100% at + infinity whereas 0% is at – infinity. It becomes evident from this picture that the century-long history of an energy source can be described quite well with only two constants, those required to define a straight line. (The curved sections are calculated by subtracting the straight lines from 100 percent.) The destiny of an energy source is decided as soon as the two constants describing the straight line can be determined.

There are other messages in Figure 4. By looking more closely at the data, we see that seemingly world-shaking events such as wars, skyrocketing energy prices, and recessions have had little effect on the overall trend. Strikes may sometimes be more visible. In the coal industry, for example, such actions may result in short-lived deviations, but the previous trend is quickly resumed.

Another observation is that there is no relationship between the utilization and the reserves of a primary energy source. It seems that the market moves away from a certain primary energy source long before that source becomes exhausted, at least at world level. This was true for wood and coal. It should also be true for oil. Despite the ominous predictions made in the 1950s that we would run out of oil in twenty years, we never did; more oil was found as the demand grew. Oil reserves will probably never be exhausted because other energy sources will be introduced in time. Well-established substitution processes with long time constants are fundamental in nature and will not be influenced by "lesser" reasons such as the depletion of reserves.

Environmentalists have opposed nuclear energy vehemently. This primary energy source reached a one percent share in the world market in the mid 1970s. The rate of growth during the first decade, however, seems disproportionately rapid compared to the entry and exit slopes of wood, coal, oil and natural gas, all of which conform closely to a more gradual rate. At the same time, the opposition to nuclear energy also seemed out of proportion, when compared to other environmental issues. Could it be that environmentalists did not react to nuclear energy per se but to its *rate of growth* instead?

"Nuclear is the only energy source that would remain indefinitely at our disposal if the sun went out."

As a consequence of intense criticism, the growth of nuclear energy has slowed considerably, and has now approached the straight line proposed by the model. One may question what was the prime mover here — the environmental concerns that succeeded in slowing the rate of growth or the initial nuclear energy craze that forced environmentalists to react?

The coming to life of such a craze is understandable. Nuclear energy made a world-shaking appearance in the closing act of World War II by demonstrating the human ability to access superhuman powers. The word superhuman is appropriate because the bases of nuclear reactions are the mechanisms through which stars generate their energy. Humans for the first time possessed the sources of power that feed our sun, which was often considered a god in the past. At the same time, mankind acquired independence; nuclear is the only energy source that would remain indefinitely at our disposal if the sun went out.

Figure 4 suggests that nuclear energy has a long future. Its share should grow at a slower more *natural rate,* with a trajectory parallel to those of oil, coal, and natural gas. A more mature, less hasty, diffusion of nuclear energy will meet less resistance from environmentalists, if for no other reason than the fact that a mature technology is less accident-prone. Indeed, in the last twenty years there has been less than one major accident in five years whereas in the early 1980s we witnessed five such accidents in three years.

There is a hypothetical primary energy source shown in Figure 4 — fusion and/or solar and/or other — projected to enter the picture in the 2020s supplying nearly one percent of the world's needs. This projection is reasonable because such a technology, once demonstrated to be feasible, would require about a generation to be mastered industrially, as did nuclear energy. But even if we had such an energy source available today, it would have to diffuse at the natural rate, the rate at which other types of energy have entered and exited in the past; otherwise it could meet opposition comparable to that from environmentalists to early nuclear. One way or another, the gas and nuclear cycles would still be traced out, if somewhat earlier and smaller. Both these energy sources need to take their turn in playing a role comparable in importance to that of oil at its time.

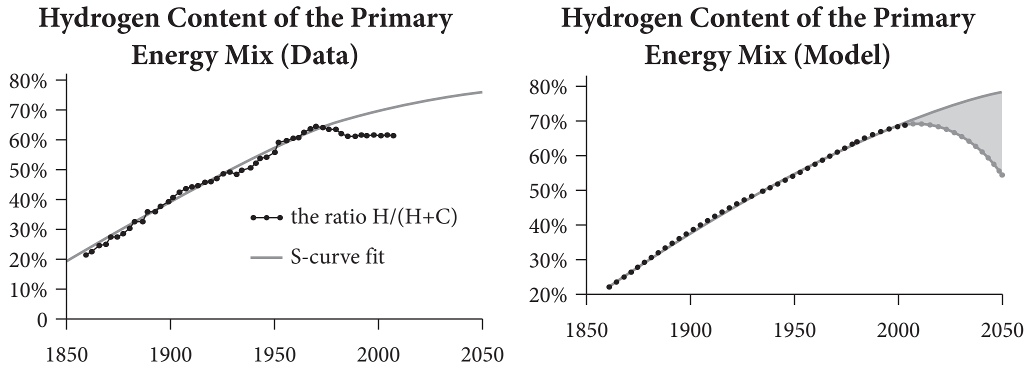
But there is a significant "glitch" in the otherwise coherent energy picture of Figure 4. The share of coal stopped declining along the model's natural-growth trajectory in the early 1970s at the expense of natural gas. This may not only be due to aggressively developing countries such as China who use coal ravenously. Developed countries such as the UK have also proven reluctant to give up coal. Whoever the culprit, the widening gap between the persistent level of coal use and coal's naturally declining trajectory becomes a source of pressure to the system, which could manifest itself in unexpected ways (possibly another case like the environmentalists vs. nuclear in the 1980s).

When Will Hydrogen Come?

There is a secret concealed in Figure 4. As society moves from wood to coal to oil to gas to nuclear, society pursues a strategy of fuel improvement, not only because each new fuel is cleaner fuel but also because each new fuel has a higher energy content. Wood is rich in carbon but natural gas is rich in hydrogen. When hydrogen

Figure 5. Hydrogen in the Energy Mix

The black dots indicate the evolution of the hydrogen-content percentage according to the energy mix of Figure 4 from the data points (graph on the left) and from the model lines (graph on the right). The thick gray lines are S-curve fits to the black dots over the period 1860-1972 (graph on the left) and 1860-2008 (graph on the right). The gray area reflects the amount of hydrogen that needs to be provided from non-fossil types of energy.



burns it produces water as exhaust; when carbon burns it releases CO_2. When wood burns, very little hydrogen becomes oxidized to become water. Most of the energy comes from the carbon that oxidizes into CO_2. On the contrary, when natural gas burns, lots of hydrogen molecules become water and very little carbon becomes CO_2. The molar ratio hydrogen/carbon for wood is about 0.1, for coal about 1, for oil about 2, and for natural gas (e.g., methane) about 4. For a fuel like hydrogen this ratio becomes infinite and the CO_2 emissions to the atmosphere null.

Biofuels such as ethanol have a molar ratio of 3 and therefore on a quality basis they belong between oil and natural gas. Thus introducing biofuels on a big scale today would represent a move backward in the evolution of fuels in society.

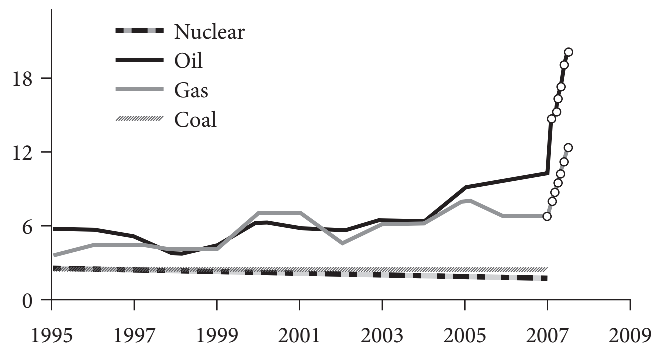
The energy substitution described in Figure 4 took place in such a way that fuels rich in hydrogen progressively and consistently replaced fuels rich in carbon, and all that happened in a *natural* way (i.e., following an S-curve). The combination of energy sources, according to the shares shown in Figure 4, yields a hydrogen content that increases along an S-curve (see Figure 5). Society followed this S-curve on a global scale without the conscious intervention of governments or other influential decision makers. Bottom-up forces have safeguarded for one hundred years a smooth transition to energies that perform more efficiently and pollute less.[5]

The black dots in the top graph of Figure 5 have been obtained using the data points in Figure 4. Coincidental with the "glitch" mentioned earlier, there is now a deviation from the S-curve pattern beginning around 1972. It seems that hydrogen-enrichment process (decarbonization) stopped at that time. The persistent use of coal and its impact on natural gas, however, are not alone to blame for the missing hydrogen in our fuels today. Had coal continued declining and gas ascending along their natural paths, we would still be missing some hydrogen today.

The black dots in lower graph of Figure 5 have been obtained using the smooth trend lines, as defined by the substitution model in Figure 4. Here too, there is a deviation from the S-pattern

Figure 6. U.S. Electricity Production Costs (in 2007 cents per kilowatt-hour)

The evolution of the cost of energy in the U.S. The little circles are estimates accounting for oil and gas prices during the first half of 2008.



Data sources: Global Energy Decisions http://www.census.gov/compendia/statab/cats/energy_utilities/prices_expenditures_sales.html
http://www.neo.ne.gov/statshtml/124.htm

beginning around year 2000. This is because there is no hydrogen content in nuclear energy or in solar/fusion. As a consequence, the deviation from the S-curve becomes progressively more pronounced toward year 2050.

The gray area in the figure represents the "missing" hydrogen content. This amount of hydrogen should somehow be contributed by nuclear energy, if we want to continue the well-established natural course of decarbonization. Nuclear energy can indeed do this in a number of different ways. For example, seawater can be split into hydrogen and oxygen via electrolysis or by direct use of nuclear heat. It must be noted that nuclear energy is not indispensable for maintaining the natural path. I have identified other energy sources such as solar, wind, hydroelectric, thermonuclear fusion or a combination thereof, that could do the job, but these technologies are still responsible for only an insignificant contribution to the energy picture worldwide. Moreover, some of these technologies — e.g., exploitation of wind energy and wave power go against a yet another natural-growth process: the diminishing size of installations required to produce a certain amount of electricity. From Edison's time until today, power generators have increased in output but not in size. Be it coal burning, oil burning, or even a nuclear plant, the energy generator is generally housed inside a large building. In sharp contrast, equivalent amount of electricity produced by windmill farms or wave power would require thousands of square miles.

I am convinced that society will eventually use hydrogen as its principle fuel because it is the most potent fuel and progress cannot be stopped. It is only a question of time. After all, no niche in nature was ever left partially filled under natural circumstances, and an S-curve that has been evolving for one hundred years will most certainly proceed to completion. The catch phrase here is "natural circumstances." Can we trust circumstances to be natural? Figure 4 indicates an anomaly; coal consumption began deviating from its naturally declining trajectory in the early 1970s.

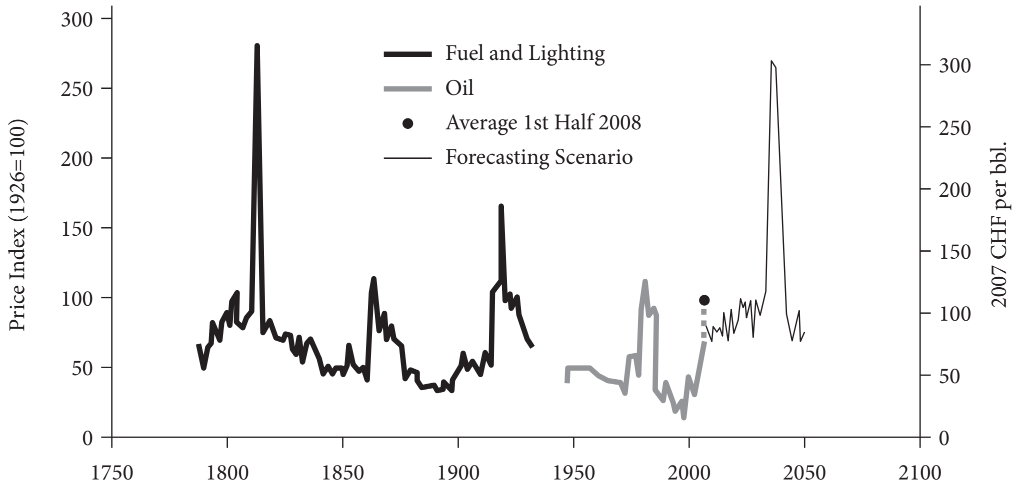
The Price of Primary Energy

Another thing nuclear energy has going for it is price. Figure 6 shows that if we consider only productions costs (i.e., operations, maintenance, and fuel costs) the price of electricity produced from nuclear energy is the cheapest today. The figure also indicates the price hikes of oil and gas during the first half of 2008.

The price of primary energy is somewhat of

Figure 7. The Price of Primary Energy

Average prices paid for energy in the U.S., corrected for inflation. The oil price, depicted on the right vertical axis, is expressed in Swiss francs. The thin purple line is a scenario for the future inspired by the pattern of the other four peaks.



Sources: *Historical Statistics of the United States, Colonial Times to 1970,* vols. 1 and 2 (Washington D.C.: Bureau of the Census, 1976).

http://inflationdata.com/inflation/inflation_rate/Historical_Oil_Prices_Table.asp

a sacred cow because energy is like food for society. Suddenly doubling the price of bread in a large country like India would produce a social uprising. The "steady-state" price of oil has more than doubled in the last ten years and yet there has been no social uprising. Could it be that the price of oil has reached its mature level only recently?

A 200-year chart — Figure 7 — of the energy price shows an intriguing pattern. Huge spikes stand out about 56-years apart echoing the Kondratieff economic cycle.[6] In between spikes, energy prices are confined to significantly lower levels.

These spikes are so pronounced compared with the usual day-to-day price fluctuations and are so regularly spaced that they inspire confidence in making some daring forecasts, for example that the next significant peak in the price of energy should take place around 2036, not much earlier.

In the last fifty years, oil has been the major primary energy source and therefore the second line in Figure 7 shows the price of oil. Because of the dollar's significant loss of value in recent years, oil prices are shown here in Swiss francs, one of the world's most stable currencies.

The first three peaks in Figure 7, depicting Fuel & Lighting prices, are not all of the same size. What if the 1980 oil peak was more like the 1864 peak of Fuel & Lighting? That would imply that oil has generally been too cheap for the most of its existence. The background under the first spike at the left is almost at the height of the tip of the second spike. By analogy, oil's recent high prices could be part of the background under a much higher spike, to be expected around 2036. Such a scenario has been sketched with the thin line to the far right in Figure 7. In between spikes, a general steady-state price for oil should then be expected in the range 70–110 Swiss francs of December 2007. This corresponds to roughly the same range in today's dollars, but the 2036 spike could correspond to well above $305 if the dollar declines further in the future.

World Energy Needs

Worldwide energy consumption has grown significantly over the last two centuries. Figure 8 shows the evolution of worldwide energy consumption per capita. One can discern two S-curve steps and imagine a third one. Natural-growth processes are known to cascade, with a new one beginning where the last one left off. It is not surprising that the low-growth periods, one around the 1920s and another one in the 1980s, correspond to economic recession/depression. The regular alternation between high-growth and low-growth phases again echoes Kondratieff's economic cycle.

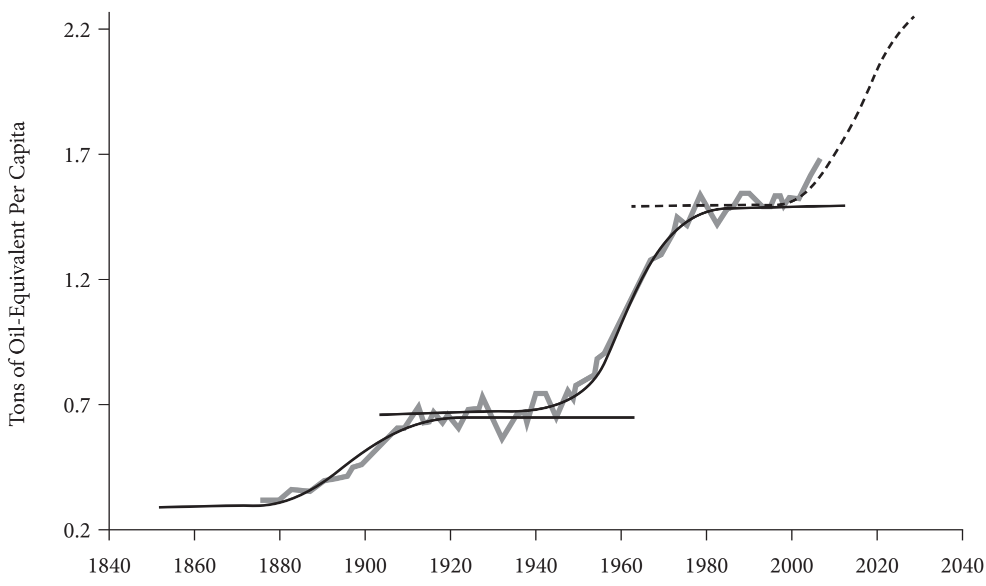
It must be pointed out that both growth steps represent an increase of about a factor of two. A similar factor must be expected during the third step just beginning. But a factor of only four since mid 19th century can hardly explain the abundance of work carried out in society since then. What also increased during the same time were improvements in the efficient use of the energy we consume.

In Brief

At present, the stress points to the social system are climate warming (carbon emissions), the

Figure 8. Per-Capita Energy Consumption Worldwide

Data, S-curve fits, and a scenario for the future (intermittent line).



Data sources: *2008 Statistical Review of World Energy* http://www.bp.com/multipleimagesection.do?categoryId=9023755&contentId=7044552

J. Ausubel, A. Grubler, N. Nakicenovic, "Carbon Dioxide Emissions in a Methane Economy," *Climate Change,* vol. 12 (1988): 245-63.

price of oil, and food shortages. It is not obvious, however, where this stress comes from or what needs to be done. Stress is a symptom of interference with the evolution of a natural-growth process; the greater the interference, the higher the stress.

One natural-growth process interfered with is decarbonization (moving toward energies with higher hydrogen content). It has deviated from its natural-growth pattern in the 1970s and has stagnated ever since. The deviation (and consequently some of the stress) would diminish if deployment of nuclear energy were to begin increasing again at the natural rate and served to produce hydrogen. But that would not suffice. The excessive consumption of coal worldwide must also diminish in favor of more consumption of natural gas.

There is no shortage of oil, and high oil prices are not caused by production issues. In fact, oil at $100 per barrel (2008 dollars) may be a natural price. Price fixing, speculation, and warfare are not likely to raise the price of oil much above this level for periods longer than a few months to a year. The next manifold price hike should normally take place sometime in the mid 2030s.

The proposals for biofuels seem anachronistic. Biofuels not only waste food resources, they also yield lower energy content and pollute more than natural gas. Our cars (and airplanes) should already be running on natural gas, as many municipal bus systems already do. Cars that use natural gas would be less polluting and much simpler and cheaper to build than hybrid cars. Increasing efficiency is good, but is not worth pursuing at all costs. Moreover, efficiency alone will never yield the factors of two and three that the world needs to grow in energy consumed per capita over the next fifty years, which is another natural-growth process not to tamper with.

Notes

1. The work presented here updates and complements work by several scholars summarized in Theodore Modis, *Predictions — Society's Telltale Signature Reveals the Past and Forecasts the Future,* Simon & Schuster, 1992.
2. J. C. Fisher and R. H. Pry, "A Simple Substitution Model of Technological Change," *Technological Forecasting and Social Change,* vol. 3, no. 1 (1971):75-88.
3. The International Institute of Applied Systems Analysis headquartered near Vienna, Austria.
4. Cesare Marchetti, "Primary Energy Substitution Models: On the Interaction between Energy and Society," *Technological Forecasting and Social Change,* vol. 10 (1977):345-56.
5. These arguments were first published by C. Marchetti in "When Will Hydrogen Come?" *Int. J. Hydrogen Energy,* 10, 215 (1985).
6. N. D. Kondratieff was a Russian economist who in 1926 deduced an economic cycle of about fifty years (N. D. Kondratieff, "The Long Wave in Economic Life," *The Review of Economic Statistics,* vol. 17 (1935):105-115.)