An Introduction Linking Energy Use And Human Development

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28 April 2006 EFHD_R_01

Forward

What is the link between the availability of energy, in the form of electrical power, and the improvement to human development as measured by the United Nations? The subject is vast so this report is only an introduction.

The World Energy Crisis

The world energy crisis is evident from many perspectives: global warming, population growth and environmental degradation, sharply rising oil and gas prices and rapid depletion of their supplies, armed conflicts in regions with major oil deposits, higher energy costs to poor nations seeking to develop higher standards of living, and a growing apprehension that American currency may be undermined by a sudden lack of confidence brought on in part by instability of world energy supplies. The physics of the energy crisis is conveniently described on the internet by Kisslinger. (1)

It is easy to find a variety of prognostications about world energy supplies and the consequent economic activities related to developing, distributing and using them. Each such technical and financial analysis will seek to advance the interests of its sponsors, be they First World governments (2), the US government (3), the oil industry (4), individual oil companies (5), and advocates of conservation and sustainability (6), (7). All of these are excellent sources of information, in their totality they help one visualize the many-faceted reality of world energy.

Perhaps the most vivid reaction one experiences after reviewing a compendium of sources such as this is one of stunned disbelief at the general lack of public consciousness about the immediacy and depth of the energy problem.

Some Rules of Thumb

I have worked out some rules of thumb you may find useful. These relate world population, total oil depletion and average global temperature.

Define terms as follows:

> P = world population (people, in billions = "billion capita" = giga-capita = Gc),

O = total oil depleted (barrels, in billions = giga-barrels = Gb),

T = average global temperature (degrees centigrade = °C);

and define the following constants:

B = 2.7 Gc,

C = 14.7 °C,

bp = 264 b/c, (barrels/person = giga-barrels/giga-persons = Gb/Gc),

pt = 3.3 Gc/°C,

ot = 870 Gb/°C.

The following rules relate P, O and T:

(P - B)*bp = O,	(Rule 1, good from 1950),
(P - B)/pt = T - C,	(Rule 2, good from 1975),
O/ot = T - C,	(Rule 3, good from 1975).

Rule 1 relates world population to the total amount of oil depleted; constant B is the world population in 1953, and this is assumed to have been accumulated with negligible depletion of oil. Rule 2 relates world population to average global temperature; constant C is the temperature that existed for a long period prior to 1920, before global warming by industrialization. Rule 3 relates total oil depletion to average global temperature.

These correlations are very close beyond 1975, while rule 1 correlates very well from 1950. There are no physical assumptions behind these rules, they merely correlate the annual data on population, total oil depletion and global temperature from the first half of the 20^{th} century to the present.

So, the 6 billion people of 1999 "required" the depletion of 871 Gb of oil with a "resulting" global temperature rise of 1 °C above the pre-1920 long-term average. If the correlations hold to 2050, and world population reaches the 9 billion predicted (by the US Census Bureau), then 1663 Gb, or 95% of the estimated 1750 Gb (Colin Campbell, 1996) of world oil will have been used, and the planet will have heated by 1.9 °C to 16.6 °C (61.9 °F). (8)

Figure 1 shows the trend of world population between 1930 and 2050; data is used prior to 2000, and one projection by the US Census Bureau is used beyond 2000.

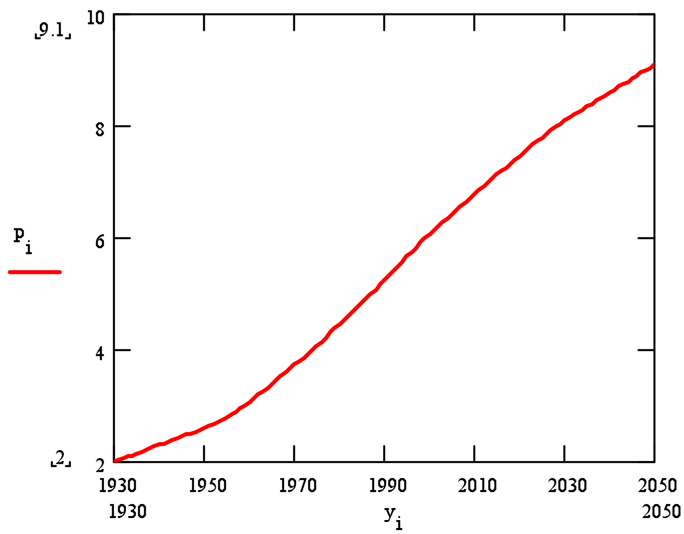

Figure 1, World Population Data (<2000), and Projection (>2000) (billions)

The average global temperature during this same period is shown -- very approximately -- in Figure 2. Again, data is used prior to 2000 and a projection beyond that time [see references in (8)].

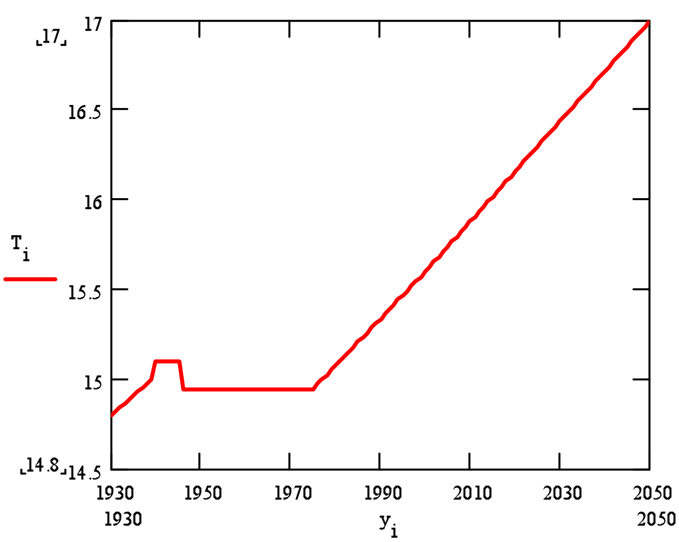

Figure 2, Average Global Temperature in Centigrade Degrees
(data < 2000 < projection)

Population and temperature correlate by Rule 2, both effects are shown in Figure 3 as a temperature offset from C = 14.7 °C.

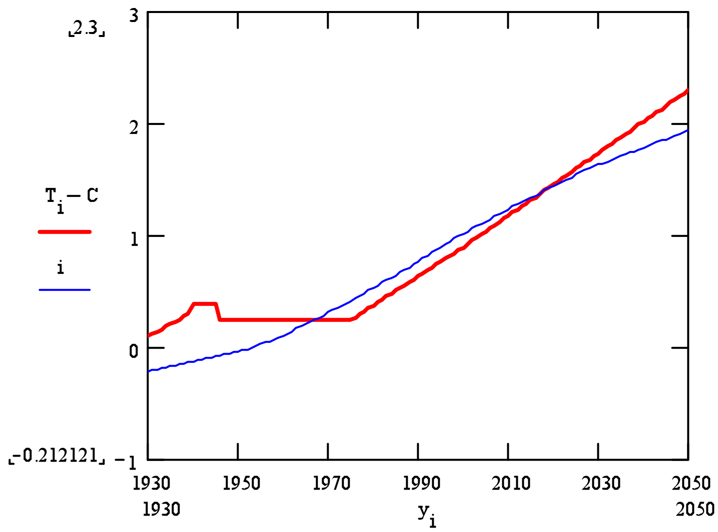

Figure 3, Population (thin) and Temperature (bold) Correlate (Rule 2, as degrees offset from to 14.7 °C)

The accumulated global oil depletion in Gb, as approximated from world population by Rule 1, is shown in Figure 4.

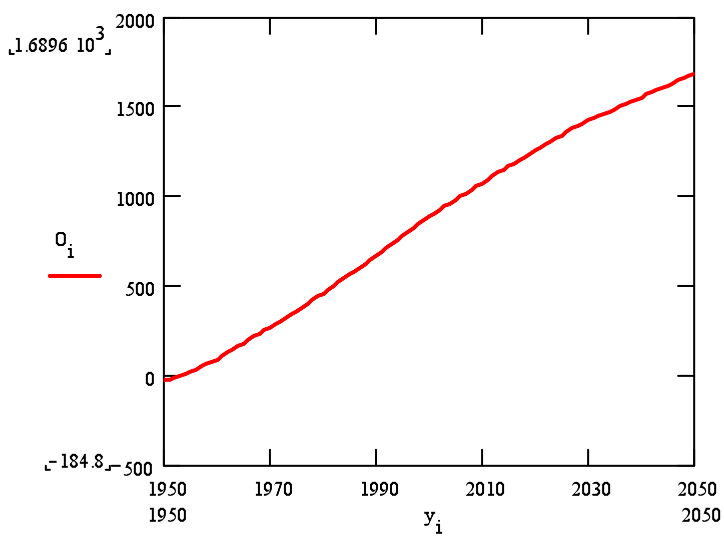

Figure 4, Global Oil Depletion in Gb, Approximated From Population (Rule 1)

Figures 1 through 4 were constructed from nine data points spanning 1930 to 2050, and then linear interpolation between these points to arrive at one population and one temperature for each of the 121 years. We do not require greater refinement to convey the essence of the trends.

However, even though our representations of population and temperature data are somewhat coarse, we can still get an image of the history of the rate of oil depletion by taking the derivative of Rule 1, the correlation between population and oil depletion. The result is an approximation to the history of annual oil production, the Hubbert Peak. Figure 5 is a display of this result, which is converted from giga-barrels per year (Gb/y) to millions of barrels per day (Mb/d) by dividing by 0.36525.

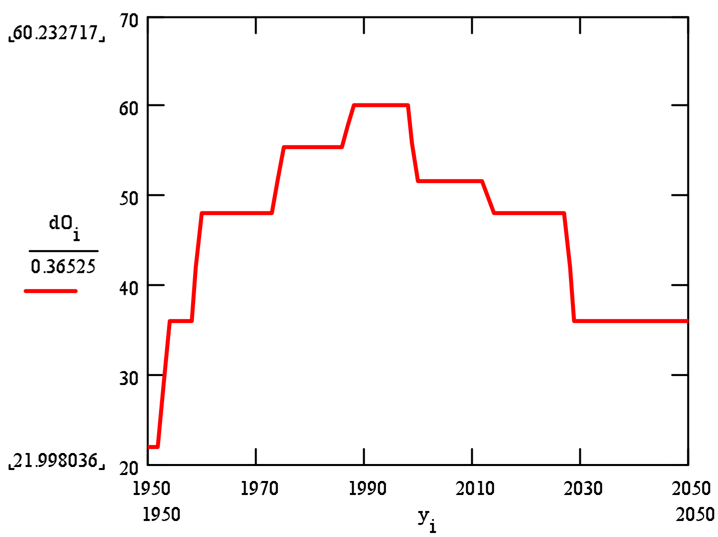

Figure 5, Hubbert Peak Approximated By Differentiated Population Correlation (derivative of Rule 1; shown as Mb/d)

Obviously, one can repeat the exercises of Figures 1 through 5 with more refined population data, and arrive at a more "realistic looking" Hubbert curve. To compare this result with a published Hubbert Peak, see Figure 6, just ahead.

Moving beyond these rules of thumb, can we relate the physics of energy to specific outcomes in human social development?, and can we then make choices about energy use directed by goals for social development?

Extrasomatic Energy and Human Development

> Life on Earth is driven by energy. Autotrophs take it from the solar radiation and heterotrophs take it from autotrophs. Energy captured slowly by photosynthesis is stored up, and as denser reservoirs of energy have come into being over the course of Earth's history, heterotrophs that could use more energy evolved to exploit them. *Homo sapiens* is such a heterotroph; indeed the ability to use energy extrasomatically (outside the body) enables human beings to use far more energy than any other heterotroph that has ever evolved. The control of fire and the exploitation of fossil fuels have made it possible for *Homo sapiens* to release, in a short time, vast amounts of energy that accumulated long before the species appeared.
>
> Today (1995), the extrasomatic energy used by people around the world is equal to the work of 280 billion men. It is as if every man, woman and child in the world had 50 slaves. In a technological society such as the United States, every person has more than 200 such "ghost slaves." (9)

The present rate of extrasomatic energy use by humanity is unsustainable, that is the essence of the world energy crisis. This realization has led many to conclude that our highly technological extrasomatic civilization is only a very temporary phenomena, and that its arc can largely be traced out by the bell-shaped curve of oil production per year. This is the famous "Hubbert Peak," the running integral of which is the total oil depletion to the present. See Figure 6. (10)

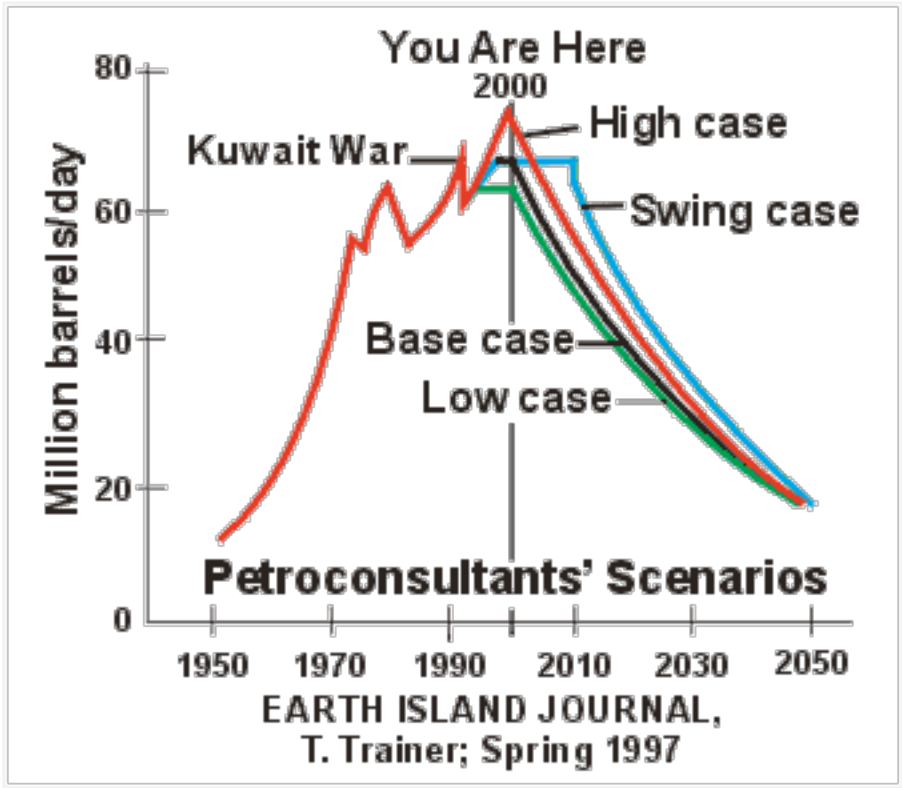

Figure 6, The Hubbert Peak of World Oil (1997), from (10)

What is interesting about the best of these modern "energy Malthusians" is that they base their arguments firmly on thermodynamics and knowledgeable study of energy and energy technology, (6) as well as the inevitability of entropy (11).

Some of the energy Malthusians have produced estimates of the timing and pace of the unwinding of modern civilization, and these presentations can be carefully reasoned, though entirely dependent on the assumption that no radically new energy source -- or efficiency -- will be discovered. (12)

Going Downhill, But How Fast?

In 1979, the world annual per capita energy consumption peaked and it has decreased steadily since. See Figure 7. (13)

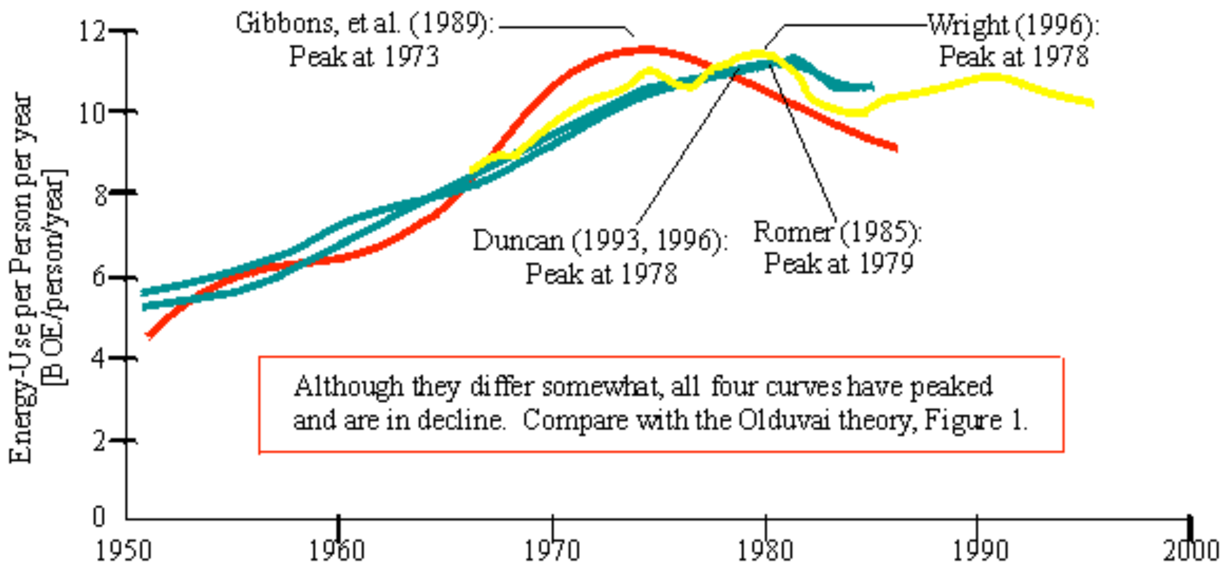

Figure 7, World Annual Per Capita Energy Consumption 1950-1996 [BOE = barrel of oil equivalent], from (13)

The growth rate of population has outstripped the growth rate of energy production, and this trend continues even as both world population and world energy production increase.

A rough model of the world per capita energy history, E(y), for time y marked by year would be:

$$E = 11.15 * e^{-[(1979 - y)/40.]}, \qquad (\sim 1930 < y < 1979),$$

$$E = 11.15 * e^{-[(y - 1979)/300]}, \qquad (1979 < y < \sim 2000).$$

The quantity E rises from about 3.2 BOE/(c*year) in 1929 to 11.15 BOE/(c*year) in 1979, then decreases to 10.4 BOE/(c*year) in 2000. These are good approximations to the data, see Figure 8. (12)

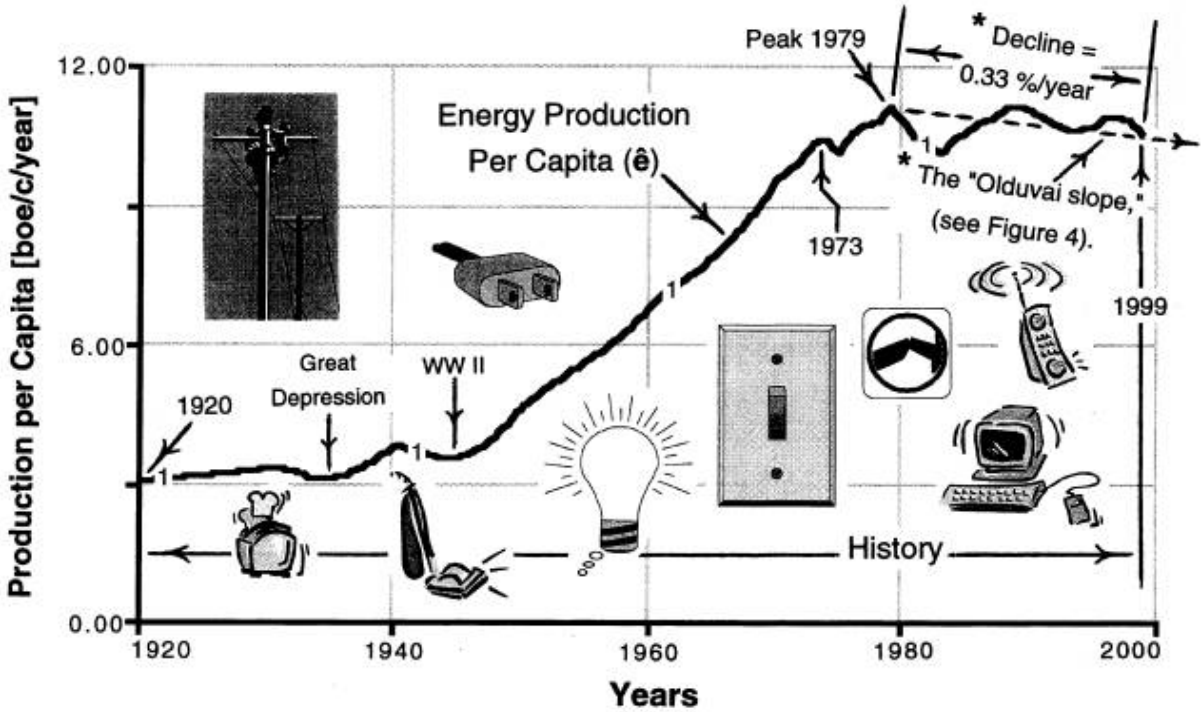

Figure 8, World Annual Per Capita Energy Consumption 1920-1999
[BOE = barrel of oil equivalent], from (12)

We are in the Hubbert Peak during this first decade of the 21st century (see Figure 6), and today's efforts to maintain an unprecedented rate of oil and energy production cannot be sustained. The world emerged from World War 2 with over 90% of its oil still untouched; oil depletion was about 10% in 1970; 50% in 2000; and is projected to be 90% in 2030. It is expected that 80% of all the world's oil will be used up within a sixty year span from 1970 to 2030.

While the total amount of oil on either side of Hubbert's Peak is identical, the downhill side will be a time of scarcity and high prices because there are many more people demanding this resource than there were during the boom years of the runup. Today, the Chinese and Indian economies are experiencing rapid growth, and their people are experiencing a general raising of living standards though not uniformly distributed. These populations represent over a quarter of humanity, and their combined thirst for petroleum rivals that of the United States (with only 4.5% of the world's population).

Many energy analysts and independent oil experts predict an energy Malthusian scenario, at some critical point in the near future there will be a sharp drop in oil and gas production because the "energy return on energy investment” (EROEI) has simply evaporated. It is pointless to expend the energy equivalent of two barrels of petroleum to pump up and refine the energy equivalent of one barrel, regardless of the market price of oil. In fact, the higher the price the less sense it makes because one would simply market the energy already in hand rather than using it to pump at a loss.

A sharp downturn in oil production will result in a sharp downturn to the per capita energy consumption curve, E(y). Inevitably, the time constant in the E(y) exponential must fall from 300 years to something much lower, like 30 years; and E(y) at 2030 might be like that of 1950. To help visualize what this might mean, consider the fact that here in the United States we use about 10 calories of petroleum-based energy to produce every calorie of food energy we consume. How would we adjust to a 50% cut in energy? (14)

What is evident throughout the writings of the energy Malthusians is the recognition of the close relationship between a social group’s access to energy and its ability to evolve a higher standard of living. It was this belief that helped the US Congress fund the large hydropower projects of the 1930’s -- Hoover Dam and the Tennessee Valley Authority -- to raise living standards and accelerate economic activity in the West and South. Interestingly, a decade later this hydroelectric infrastructure would be used to power the uranium enrichment plants at the birth of the “atomic age.”

The most convenient form of energy is electricity. The strong correlation between the availability of electricity and the level of human social development has been known since at least 1895 with the electrification of Niagara Falls with the then new polyphase alternating current (AC) technology invented by Nikola Tesla. (15)

So, at this point our discussion branches: how do we measure “human development” in the sense of social and economic well-being?, and how do we produce electricity in the future in a manner that is sustainable?

First, we will consider the United Nations Human Development Index (HDI), and then how expanding any particular technology for generating electricity might affect it.

The Human Development Index

> The UN Human Development Index (HDI) is a comparative measure of poverty, literacy, education, life expectancy, childbirth, and other factors for countries worldwide. It is a standard means of measuring well-being, especially child welfare.

The index was developed in 1990 by the Pakistani economist Mahbub ul Haq, and has been used since 1993 by the United Nations Development Programme in its annual report.

The HDI measures the average achievements in a country in three basic dimensions of human development:

1. A long and healthy life, as measured by life expectancy at birth.

2. Knowledge, as measured by the adult literacy rate (with two-thirds weight) and the combined primary, secondary, and tertiary gross enrolment ratio (with one-third weight).

3. A decent standard of living, as measured by gross domestic product (GDP) per capita at purchasing power parity (PPP) in USD.

Each year, UN member states are listed and ranked according to these measures. Those high on the list often advertise it, as a means of attracting talented immigrants (economically, individual capital) or discouraging emigration. (16)

The Human Development Index is the average of three indices: the Life Expectancy Index (LEI), the Education Index (EI) and the GDP Index (GDPI).

The Education Index is itself a weighted sum of: the Adult Literacy Index (ALI, weight = 2/3) and the Gross Enrollment Index (GEI, weight = 1/3).

All of these measure have minimum and maximum values, which appear in the differences and normalizations used to construct the three major indices. The formulas are as follows:

LEI = (LE - 25)/(85 -25),   LE = life expectancy in years;

EI = (2/3)*ALI + (1/3)*GEI;

ALI = (ALR - 0)/(100 - 0),   ALR = adult literacy rate;

GEI = (CGER - 0)/(100 - 0),   CGER = combined gross enrolment ratio;

GDPI = [log(GDPpc) - log(100)]/[log(40000) - log(100)],

GDPpc = GDP per capita at PPP in USD;

HDI = [LEI + EI + GDPI]/3.

The Human Development Index is a measure that helps to capture the overall socio-economic health of a country, and a measure that allows for useful comparisons, whether by international bodies like the UN (17), or concerned individuals (18).

Electricity and the HDI

For 2002, the United Nations indicated that the electricity consumption per capita needed in order to experience a society with a medium level of human development was just over 1000 kilowatt-hours. (19) Consider these data from 2002. (17), (19)

Table 1, Selected National HDI and kWh/c

HDI Rank	Country	kWh/capita	HDI value
1	Norway	26,640	0.963
8	Ireland	6560	0.946
10	U.S.	13,456	0.944
11	Japan	8612	0.943
16	France	8123	0.938
20	Germany	6989	0.930
30	Barbados	3193	0.878
40	Qatar	17,489	0.849
52	Cuba	1395	0.817
62	Russia	6062	0.795
85	China	1484	0.755
99	Iran	2075	0.736
108	Viet Nam	392	0.704
127	India	569	0.602
177	Niger	40	0.281
World average		2465	0.741
--->	(19)	<---	(17)

Obviously, with greater availability of electricity there is greater development. But, not all societies use their energy wisely to boost their human development. (18)

Another correlation between HDI and electricity consumption per capita was observed by Alan Pasternak. (20) For a selection of 60 countries in 1997, he found an 84% correlation between HDI and annual electricity use per capita in kilowatt-hours (kWh),

HDI = 0.091*ln(# kWh) + 0.0724.

This curve rises sharply from 0 kWh, through HDIs of 0.3 to 0.6 for the poorest countries of the world with tens to hundreds of kWh; then it goes through a knee of HDIs from 0.6 to 0.9 with energy consumption from 1000 kWh to 4000 kWh. Beyond 4000 kWh, the HDI rises very gradually from 0.9 toward its asymptote at 1, this is the domain of the wealthy nations of the world. See Figure 9.

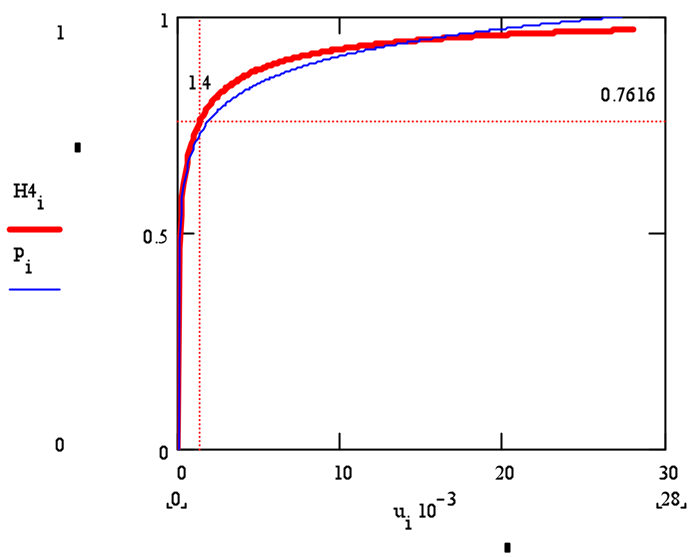

Figure 9, Pasternak (thin) and H4 (bold) HDI Correlations to 28,000 kWh/c

The energy crisis is a different experience along this HDI spectrum. For the poorest nations, the crisis is one of survival, of finding an effective method out of poverty and for this, energy is essential. For the majority of the world's nations, in the knee between the abyss of desperate poverty and the Olympus of multi-thousand kWh affluence, the energy crisis is a challenge to the stability of their societies and their efforts to arrive at a broadly equitable level of human development, HDI = 0.9, maintained efficiently at about 4000 kWh per capita. For what we might term the "SUV nations" on the high plateau of the HDI-kWh space, the energy crisis is one of maintaining their standard of living with much greater efficiency, or competing more ruthlessly for the world's energy resources, or developing new sources of energy that expand the known supplies.

The H4 Correlation and Data

The formula, employing the hyperbolic tangent function tanh(x),

$$HDI = \tanh[(u/u_0)^{(1/4)}],$$

$$u_0 = 1400 \text{ kWh},$$

with u in kWh correlates the national data for HDI and per capita electricity use as reported by the United Nations Development Programme for 2005. (17), (19) This formula duplicates the shape of the Pasternak correlation (20) over the range of the data, and it meets the limits (u, HDI) = (0, 0) and (infinity, 1). There is no "law" or necessity that this formula relate HDI and u, it is simply an observation that it fits the trend of the data. The "proper" HDI for any given u is a matter of speculation, to be inferred by deeper study of how the availability of an energy technology "causes" socio-economic development.

Pasternak's logarithmic form is not ideal because indicated HDI plunges to negative infinity at zero energy, and indicated HDI grows larger than 1 at large energy. A hyperbolic tangent meets the limiting cases exactly, and it has a "knee" in HDI between 0.3 and 0.9, followed by an asymptote to 1 at large energy.

Figure 9 shows the hyperbolic tangent form, called H4, and Pasternak's logarithmic form, called P, both plotted against the energy use parameter u (kWh/c). A hyperbolic tangent form that conforms more tightly to Pasternak's curve can be had by adjusting the power on the energy ratio (here it is 1/4) and the normalization energy u_0 (here it is 1400 kWh/c). However, the H4 curve seems to suit the data, as will be shown.

Figure 10 shows the data for 2005 (177 nations) and the H4 correlation; Figure 11 repeats the display but on a logarithmic scale of energy. The data is shown as data points of HDI and E (recorded electrical kWh/c) pairs, while the correlation is shown as a continuous curve H4(u).

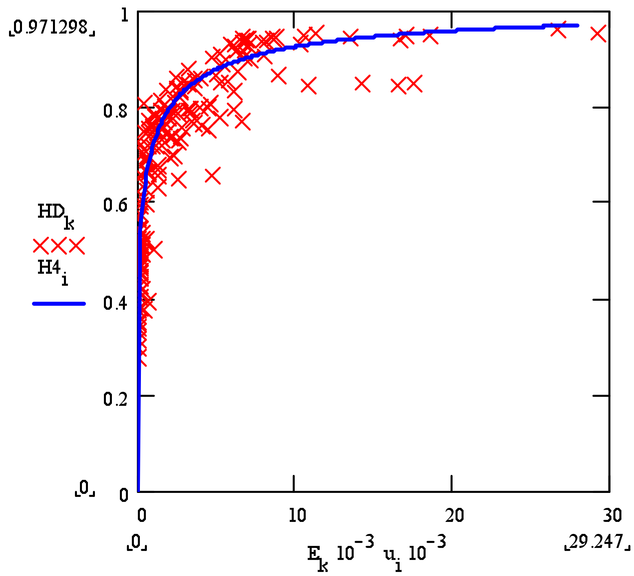

Figure 10, Data (E, HD) and H4 Correlation to 29,000 kWh/c

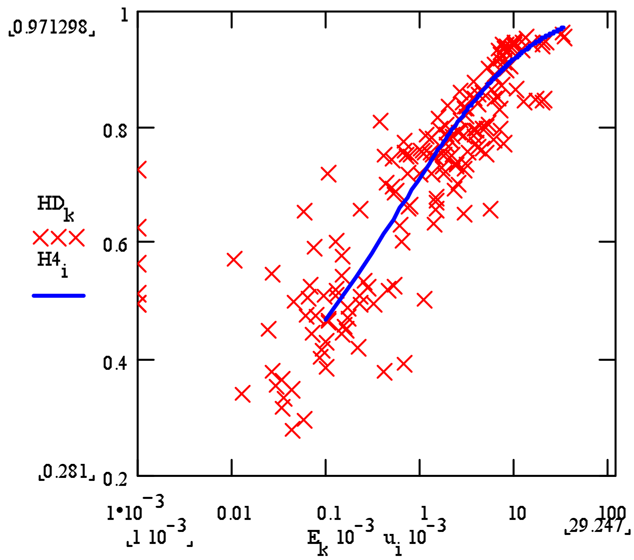

Figure 11, HDI vs. Log of Electricity Use (kWh/c), Data and H4 Correlation [reported E spans from 10 kWh/c to 29,247 kWh/c]

Countries without reported values of electricity use have been assigned 1 kWh/c. This removes them from the energy cluster but preserves the listing and ranking of HDI. One might infer an electricity use for these countries from their reported HDI by the H4 formula.

The next pair of displays, Figures 12 and 13, are linear and semi-log plots of the data and the inferred HDI from the reported electricity use E. To paraphrase, the H4 "expectation" for each nation from its recorded E is shown along with the actual data.

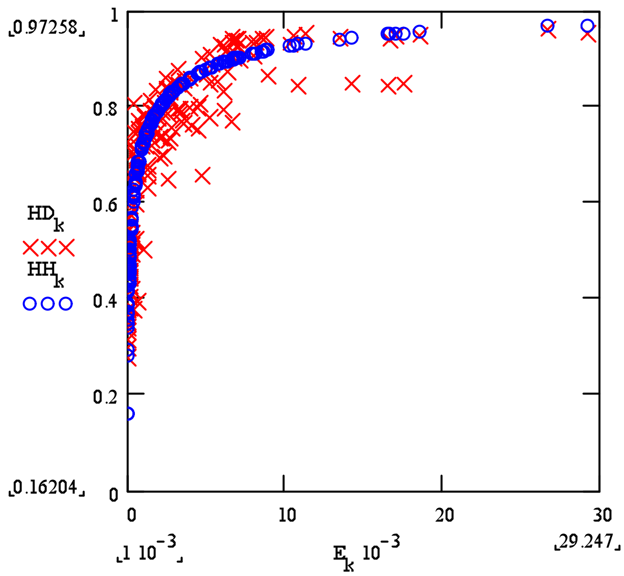

Figure 12, HDI & E Data (x), and H4 Expectation based on E Data (0)

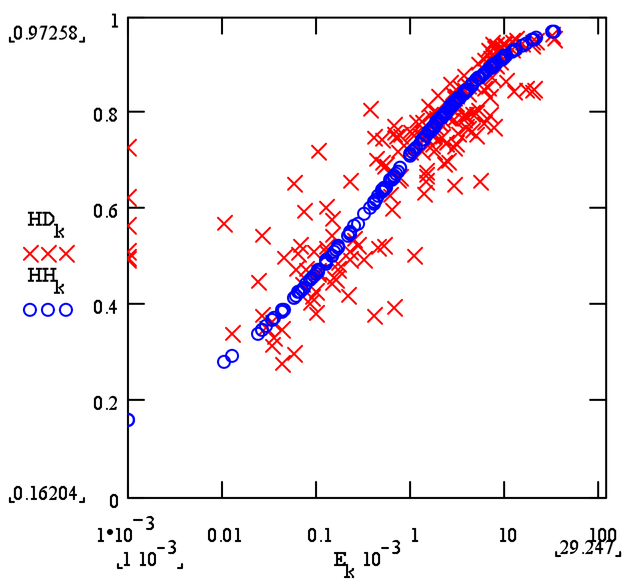

Figure 13, HDI & Log(E) Data (x), and H4 Expectation based on Log(E) Data (0)

HDI-kWh Space and Energy Efficiency

It is evident that for u = 1000 (H4 = 0.726), people have risen above desperate poverty to a stable if rudimentary standard of living (e.g., Columbia, Ecuador, Saint Vincent and the Grenadines, Paraguay). An electrical energy use of 2000 kWh/c (H4 = 0.798), which is close to the world average, can power a society that is a mix of modern technological dynamism and traditional agricultural life (e.g., Brazil, Grenada, Turkey, Iran). At u = 3000 kWh/c (H4 = 0.837), we find a high level of socio-economic development (e.g., Barbados, Chile, Lithuania, Malaysia). At u = 4000 kWh/c (H4 = 0.862), development approaches the "high plateau" of HDI near 0.9 (e.g., Hungary, Poland, Libya, Kazakhstan). At u = 5000 kWh/c (H4 = 0.880), we should see modern technological societies without regional gaps or minority exclusions (Greece, Malta, Slovakia, Oman). At u = 6000 kWh/c (H4 = 0.893), we have entered the realm of the ultimate human development of nation-states (Spain, Hong Kong, Bahamas, Russia)

I am sure you will be disbelieving of some of the examples I quote for each energy level. This is because while each of the quartets shown does in fact have a national electrical energy use close to 1000, 2000, 3000, 4000, 5000 and 6000 kWh/c, respectively, each nation does not necessarily use its energy in a manner that distributes the benefits equitably to raise its HDI. The H4 correlation shows what level of HDI can be achieved for a given per capita energy use. Some countries have HDI above the "H4 expectation" for their energy expenditure, while others are below.

Some nations do a great deal with very little, like Cuba, which has an HDI rank of 52 out of 177 with an expenditure of only 1395 kWh/c. Its actual HDI = 0.817, which is greater than H4(@1395 kWh) = 0.762. An H4 expectation of 0.817 requires 2425 kWh/c. It is as if Cuba generates its social benefits with only 57.5% of the electrical energy one would expect.

So, one can see that there are three types of improvements to be pursued:

1, maximizing HDI at any given energy level;

2, increasing per capita electrical availability if u < 2000 kWh/c;

3, decreasing per capita electrical availability if u > 4000 kWh/c
(without loss of HDI).

We can characterize these as: make the best of what you have however modest, find sufficient energy to power a humane modern society and don't waste energy even when affluent.

Given a world per capita electricity use of 2465 kWh/c (in 2002, as for all energy use numbers quoted here), we would want the elimination of world poverty to be purchased by the elimination of wastefulness among the affluent, and wise use of energy (minimally at H4 expectations) by everyone. In such a case, HDI values would exceed 0.7 *everywhere*, probably as a dense cluster between 0.8 and 0.9, and electricity use per capita would fall between 2000 kWh/c and 8000 kWh/c, probably in a dense cluster between 3000 kWh/c and 6000 kWh/c.

This implies a doubling of world energy production, or a doubling of energy production efficiency.

To achieve these goals with a growing world population will require a major commitment to energy efficiency by the affluent. Since no one wants to experience a reduction of their HDI regardless of the degree of their energy efficiency, it will also be necessary to develop new sources of clean (non-greenhouse) energy. However, one must realize that neglected improvements in efficiency remain as the single largest untapped source of energy.

Given that HDI near 0.9 has been achieved with u near 3000 kWh/c, it is clear that untapped humane socio-economic efficiencies exist for countries that burn up more than 4000 kWh/c annually. Consider these examples of "high burners," all with HDI above 0.93, in Table 2; and the top forty countries ranked by their per capita electrical use, in Table 3.

TABLE 2: Top 20 Countries, with HDI > 0.93, Ranked by u

HDI Rank	Country	u=kWh/c	u Rank	Rank Difference (@u - @HDI)	HDI
2	Iceland	29,247	1	-1	0.956
1	Norway	26,640	2	+1	0.963
5	Canada	18,541	3	-2	0.949
6	Sweden	16,996	4	-2	0.949
13	Finland	16,694	5	-8	0.941
10	U.S.A.	13,456	6	-4	0.944
3	Australia	11,299	7	+4	0.955
4	Luxembourg	10,547	8	+4	0.949
19	New Zealand	10,301	9	-10	0.933
9	Belgium	8749	10	+1	0.945
11	Japan	8612	11	0	0.943
7	Switzerland	8483	12	+5	0.947
16	France	8123	13	-3	0.938
17	Austria	7845	14	-3	0.936
20	Germany	6989	15	-5	0.930
12	Netherlands	6958	16	+4	0.943
14	Denmark	6925	17	+3	0.941
15	United Kingdom	6614	18	+3	0.939
8	Ireland	6560	19	+11	0.946
18	Italy	5840	20	+2	0.934

TABLE 3: Top 40 Countries Ranked by u

HDI Rank * = (Table 1)	Country	u=kWh/c	u Rank * = (Table 1)	Rank Difference (@u - @HDI)	HDI
2*	Iceland	29,247	1*	-1	0.956
1*	Norway	26,640	2*	+1	0.963
5*	Canada	18,541	3*	-2	0.949
40	Qatar	17,489	4	-36	0.849
6*	Sweden	16,996	5*	-1	0.949
13*	Finland	16,694	6*	-7	0.941
44	Kuwait	16,544	7	-37	0.844
41	United Arab Emirates	14,215	8	-33	0.849
10*	U.S.A.	13,456	9*	-1	0.944
3*	Australia	11,299	10*	+7	0.955
43	Bahrain	10,830	11	-32	0.846
4*	Luxembourg	10,547	12*	+8	0.949
19*	New Zealand	10,301	13*	-6	0.933
33	Brunei Darussalem	8903	14	-19	0.866
9*	Belgium	8749	15*	+6	0.945
11*	Japan	8612	16*	+5	0.943
7*	Switzerland	8483	17*	+10	0.947
16*	France	8123	18*	+2	0.938
25	Singapore	7961	19	-6	0.907
17*	Austria	7845	20*	+3	0.936
28	Republic of Korea	7058	21	-7	0.901
20*	Germany	6989	22*	+2	0.930
12*	Netherlands	6958	23*	+11	0.943
14*	Denmark	6925	24*	+10	0.941
26	Slovenia	6791	25	-1	0.904
23	Israel	6698	26	+3	0.915
77	Saudi Arabia	6620	27	-50	0.772
15*	United Kingdom	6614	28*	+13	0.939

8*	Ireland	6560	29*	+21	0.946
31	Czech Republic	6368	30	-1	0.874
22	Hong Kong, China(SAR)	6237	31	+9	0.916
21	Spain	6154	32	+11	0.928
50	Bahamas	6084	33	-17	0.832
62	Russian Federation	6062	34	-28	0.795
18*	Italy	5840	35*	+17	0.934
38	Estonia	5767	36	-2	0.853
29	Cyprus	5323	37	+8	0.891
24	Greece	5247	38	+14	0.912
71	Oman	5219	39	-32	0.781
32	Malta	4939	40	+8	0.867

While every country has its unique story that can hardly be fully captured by the simple measures used here, it is still evident from Tables 2 and 3 that in many cases the expenditure of significant electrical energy per capita does not translate into the level of human development that could be had. In other cases, it is clear that countries make good use of their energy resources for human development.

The difference between a country's u rank and its HDI rank is another indicator of its performance. Notice that nations like Greece and Italy perform very well at fairly modest levels of energy use compared to the norms of North America and Western Europe; they manage to have HDI near 0.9 and HDI rank near 20. Of course, one can assume that the Scandinavian countries need to use more electricity per capita for heating than would be the case elsewhere; their HDIs and HDI rankings are commendably high despite this energy penalty.

How Will New Technology Affect HDI?

Any energy technology will affect HDI through its impacts on life expectancy, education and literacy, and gross domestic product as experienced down at the individual level (GDP/c).

To fabricate a causal model quantifying the impact of a particular energy technology on HDI would require knowing many specific relationships. For example, considering nuclear and fossil fuels: how do the mining, transport and refining of fuel affect life expectancy?; how does the operation of power plants affect the personal economic resources of the individual in the society being served?; how does the new power industry affect education?; how do the necessary security precautions add to or subtract from the public purse?; how do the security threats specific to this technology diminish life expectancy?; what is the energy return on energy invested (EROEI) as a function of time with this technology? No doubt other questions would come to mind on longer reflection.

A great deal of research and thought is required to devise models of this type, and one concedes at the outset that such models will necessarily have major gaps and contentious assumptions. The value of these mental exercises will be to help organize the process of scrutinizing and comparing the potentialities and perils of competing energy technologies.

The "right choice" will certainly depend on where a particular nation sits in HDI-kWh space. As a nation progresses upward in HDI and per capita energy use, it will probably change the nature of some of its energy production infrastructure, most intelligently to reduce waste, pollution, greenhouse gas emission, security concerns, political strife and debilitating financial costs. Evolving to cleaner, safer, renewable and indigenous electrical energy production is an integral part of raising the national standard of living.

Conclusions

The advanced nations of the world, basically those listed in Tables 2 and 3, have the major responsibility for solving the world's energy crisis because they use the lion's share of the world's energy and because they have the infrastructure, resources and sophistication to both dramatically improve their efficiencies -- the largest untapped source of energy today -- and to invent new energy cycles that overcome the deficiencies of existing technology.

The Earth is our cosmic lifeboat. It is good to remember that fixing any leak is always worth our effort because if the boat sinks, the first class passengers will go down along with those in steerage.

The H4 hyperbolic tangent correlation between Human Development Index and annual electricity use per capita is a convenient way to visualize the "HDI-kWh space" of the world's energy use and the interlocking challenges -- socio-economic and technical -- which we call the world energy crisis.

The world today has an average HDI = 0.741 and uses an average of 2465 kWh/c. World HDI is below average as its H4 expectation is 0.818. An H4 expectation of 0.741 only requires 1150 kWh/c. As a world, we use over twice (2.143) as much energy as necessary to arrive at the averaged level of human development we experience. This is hardly a surprising conclusion, for obviously it takes a great deal of energy to pursue the many wars and conflicts we have, and to maintain the many glaring inequities we allow.

In an ideal world, HDI would be above 0.7 *everywhere*, annual electricity use per capita -- all from "green" sources -- would range between 2000 kWh/c and 8000 kWh/c, and (the hat trick) we would have discovered new technology enabling us to maintain the world's population (with humane control on its expansion) at a global average of at least 3500 kWh/c, a 40% boost.

The complete solution of the energy crisis is only partly a matter of physics, perhaps this is the smallest part. A complete solution will mesh together many socio-economic factors, because a complete solution will have to become part of the fabric of the society being powered. Thus, it is essential that physicists and engineers involved in technical developments of any new energy technology become intimately aware of these non-physics externalities so they can then know how to approach their work, how to formulate appropriate goals, and how to judge the actual value of the fruits of their labors.

I plan to learn what I can about energy for human development, and to try to devise ideas that help produce energy to end poverty.

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