Global Energy Flows and their Food System Components[1]

by

William J. Chancellor[2]

Abstract:

The rate at which the Earth's surface receives high-utility energy from the Sun is 11,000 times as great as the rate at which humans use commercial energy. Despite this, 88 percent of the commercial energy used comes from non-renewable, fossil-fuel sources. Fossil fuel use each year adds 3 percent more carbon-dioxide to the atmosphere than natural sinks can remove. The task for humans is to find ways to obtain utility from a greater portion of solar radiation. The one natural process that achieves this goal is photosynthesis, which is neutral to carbon-dioxide accumulation and which provides all the human food on Earth. Past efforts to enhance the productivity of human-managed photosynthesis systems have involved energy inputs in non-solar forms – mainly from fossil fuel sources – causing such systems to be non-sustainable from the long-term perspective. There exist both technological and sociological opportunities to make non-fossil-fuel energy more economically feasible. These include accounting systems that link costs associated with atmospheric pollution avoidance and with natural capital depletion, to the market prices of fossil fuels, and also include the use of information-intensive processes (so that less energy of any type is needed) to manage high-productivity photosynthetic systems. The long-term goal is to bring high productivity achievement to all the World's citizens, while using sustainable energy forms. This productivity level is expected to be associated with reduced rates of population increase and with increased attention to global pollution reduction.

Resumen:

La tasa a la cual la superficie de la Tierra recibe energía de alta utilidad del Sol es 11,000 veces más grande que la tasa a la que los humanos usamos energía de tipo comercial. A pesar de esto, 88% de la energía comercial utilizada proviene de fuentes no-renovables, principalmente combustibles derivados del petroleo, i.e., hidrocarburos. Cada año, el uso de hidrocarburos provoca la acumulación en la atmosfera de 3% más dioxido de carbono del que es posible remover por medio de procesos de fijamiento naturales. La tarea a realizar es encontar formas que permitan utilizar una mayor porción de la radiación solar. Un proceso natural que logra este propósito es la fotosíntesis, el cual provee todas

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[2] Professor Emeritus, Biological and Agricultural Engineering Department, University of California, Davis, CA 95616, USA, wjchancellor@ucdavis.edu. The author wishes to acknowledge with appreciation the assistance of Mr. Pedro Andrade Sanchez in writing the Spanish language version of the Abstract.

nuestras necesidades alimenticias siendo neutral a la acumulación de dioxido de carbono. A la fecha, ha sido frequente que los esfuerzos para acrecentar la productividad de sistemas fotosintéticos manejados por el hombre involucren el uso de energía de fuentes no-solares, principalmente hidrocarburos; provocando falta de sostenibilidad en la perspectiva a largo plazo. Existen oportunidades tanto tecnológicas como sociales para hacer factible el uso de fuentes de energía que no sean hidrocarburos. Algunas de estas oportunidades incluyen sistemas de contabilidad que ligan los costos asociados con evitar la contaminación ambiental y el agotamiento del capital natural, con los precios de mercado de combustibles hidrocarburos. También, el uso de procesos de información intensiva (para reducir las necesidades de energía de cualquier tipo) se puede aplicar al manejo de sistemas fotosintéticos de alta productividad. El objetivo a largo plazo es lograr que todos los ciudadanos del mundo alcancen alta productividad mientras que se utilicen formas sostenibles de energía. Este nivel de productividad se espera que esté asociado con una reducción en las tasas de crecimiento de la población y con una creciente atención a reducir la contaminación mundial.

Global Energy Flows:

The Earth intercepts 173,000 x 10^{12} Watts of radiated solar energy of which 121, 000 x 10^{12} Watts reach the Earth's surface (Dorf, 2001) (Fig. 1). This energy is in an extremely unique form - radiation in the wavelengths of from 0.3 to 3 micrometers representing temperatures approximately that of the surface of the Sun's surface, 6000°K. These wavelengths and temperatures give this energy an especially high utility. In addition it is directional and polarized making control easy. It can be used to activate processes and produce phenomena associated with its short wavelengths

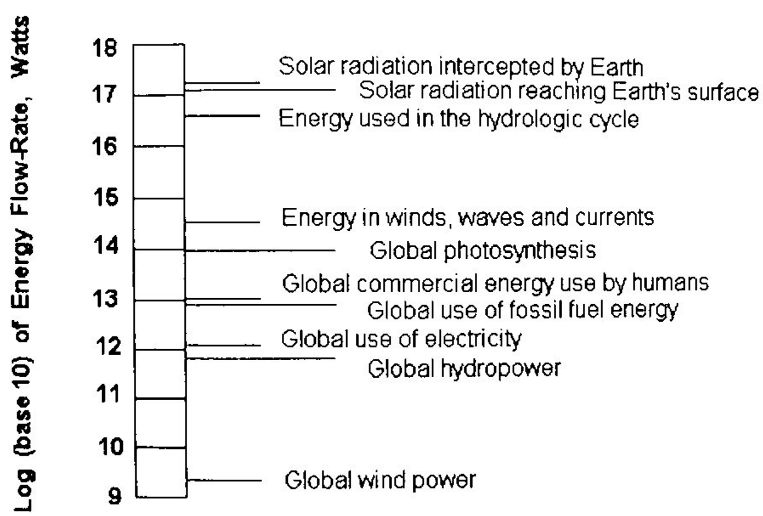

Figure 1. Logarithmic scale showing the relative magnitudes of various energy flow-rates on a global basis.

Because the Earth is in approximate thermal balance with its surroundings, it radiates approximately 121,000 x 10^{12} Watts back to space. This radiation has an approximate wavelength range of from 5 to 100 micrometers, representing a temperature of 292° K (19° C. or 66° F.). This energy is very difficult and expensive to transfer to any process because almost everything on the Earth's surface is at a temperature near 292° K, and so this energy is in thermal equilibrium with most Earthly things, making one-way energy transfers difficult. Thus, this energy has very little utility here on Earth.

This high-utility energy from solar radiation can be converted almost instantly to low-utility Earth's-surface-temperature energy merely by its striking some inert object on the Earth's surface. However, there exist both natural and human-made systems which allow the temporary preservation of the utility of solar radiation – utility that powers both natural phenomena and human-made systems which give the Earth its character and which give humans the opportunity to change both the Earth's character and the nature of life of people as well as of other living things.

Natural Energy-Utility-Preservation Systems:

Of interest here are: (a) the systems for preserving the utility of the energy delivered to the Earth as solar radiation, and (b) what is obtained as this preserved utility is expended. The great majority of this solar radiation merely strikes inert objects on the earth's surface and is allowed to be converted to low-utility, low-temperature energy of little use for anything other than maintaining the Earth's surface temperature. The largest temporary-utility-preserving system for solar radiation is the hydrologic cycle, in which approximately 40,000 x 10^{12} Watts (Dorf, 2001), or 33 percent of the solar energy reaching the Earth's surface, is used to evaporate, purify, elevate and then drop water to the Earth's surface from heights ranging up to 10,000 meters. Human-made systems for capturing this water 237 meters above the point at which it will be released can extract useful and controllable energy from this water in the amount of 0.1 percent of the solar radiation that went into its elevation. But, on a world average only 0.0017 percent of the hydrologic cycle is captured as hydroelectric energy (0.675 x 10^{12} Watts) (Dorf, 2001, Klass, 1989). The great bulk of the energy in the hydrologic cycle appears as low-temperature heat released in the atmosphere as the water vapor is condensed into rain.

The next most prominent group of energy-utility-preserving systems is that of winds, waves and currents (370 x 10^{12} Watts) (Dorf, 2001). Waves and currents are important features of the Earth's surface, but technologies for extracting energy utility from these phenomena have appeared in experimental form only. On the other hand the capture of energy utility from wind has been the basis for prehistoric technologies for transport as well as for stationary applications in grain grinding and water lifting. Current wind energy utility capture systems (0.0028 x 10^{12} Watts) (Dorf, 2001) represent about 0.006 percent of the total energy in winds, waves and currents. The world potential for wind energy capture is anticipated to be many times this amount, to the extent that it might be equal to that of existing facilities for hydroelectric energy capture. The part of wind energy not so captured appears as frictional warming of the Earth's atmosphere, with similar fates applying to waves and currents.

The third major mode of solar energy utility capture is photosynthesis. About 98 x 10^{12} Watts are captured this way globally (approximately 0.08 percent of the solar energy striking the Earth, or about 9 times the rate of global energy use by humans in 1990) (Klass, 1998). Of the solar energy fixed globally by photosynthesis, 5.3 percent is on cultivated land, 11 percent in savanna and grasslands and 42 percent in forests (Klass, 1998). Solar energy in wavelengths of 0.4 to 0.5 micrometers and 0.6 to 0.7 micrometers can activate the combining of carbon-dioxide from the atmosphere and water into carbohydrates in the cells of green plants.

World photosynthesis consumes 770 x 10^9 metric tons of carbon-dioxide per year, while 797 x 10^9 metric tons per year are emitted by all sources into the atmosphere (Klass, 1998). The difference between these two figures, 27 x 10^9 metric tons per year, can be compared with the amount emitted due to fossil fuel combustion, 22.36 x 10^9 metric tons per year (Klass, 1998). The total amount of carbon-dioxide in the Earth's atmosphere is 2567 x 10^9 metric tons (Klass, 1998), so it can be seen that photosynthesis utilizes about 30 percent of global carbon-dioxide each year, and that the amount by which global carbon-dioxide emissions exceed global photosynthetic absorption (27 x 10^9 metric tons per year) represents about one percent of the global total (or an approximate doubling of atmospheric carbon-dioxide concentration in 100 years if emission and absorption rates do not change). Doubling of atmospheric carbon-dioxide content from 1995 levels is anticipated to result in the increase of global temperatures on the order of 2 to 3 degrees Celsius due to increasing interception of long-wave radiation from the Earth's surface by carbon-dioxide molecules in the atmosphere (Klass, 1998).

Estimates of the maximum efficiency of the photosynthetic process in capturing solar energy in the form of fixed carbon are typically in the 6 to 8 percent range after an assumed 25 to 33 percent of the carbohydrate produced is used in respiration to accomplish plant functions prior to the energy being sequestered in plant parts (Klass, 1998, Loomis et al., 1971). For typical crops, grasslands and forests the efficiency of capture is less than 1 percent. In the process of energy capture by terrestrial plants using photosynthesis, roughly 1000 kg of moisture is transpired for each kg of dry cellulosic biomass produced (Klass, 1998, Giampietro et al., 1992). The solar energy from the hydrologic cycle needed to produce this transpiration is approximately 145 times the energy that could be obtained by digesting or burning that biomass.

Photosynthesis in the distant past is believed to have been the source of biomass materials sequestered in the Earth's surface which became formed into coal, oil and natural gas. There is no knowledge of such large scale sequestering of biomass materials taking place in the period of written history. Despite this, these fossil fuels constituted about 88 percent of the energy used by humans worldwide in 1990. This percentage ranged from 62 percent for Africa to 94 percent for Europe (Klass, 1998).

Food and Human-Managed Photosynthetic Systems:

Plant materials produced by photosynthesis during the last few years constitute the only known source of today's fuel for human beings (food energy). Each person requires approximately 10 MJ (2400 kcal) per day of food energy (the United States food system provided, on the average, 1.45 times this amount as available food energy in 1963) (Hirst, 1973), or a global total of 0.725×10^{12} Watts, which is about 0.7 percent of global photosynthesis or 14 percent of the photosynthetic product captured by plants on cultivated land worldwide. Animal agriculture and wild game hunting gathered additional human fuel from savanna and grasslands so that the percentage of the photosynthetic product from cultivated lands appearing as human food was perhaps somewhat lower than the 14 percent figure. Savanna and grasslands capture twice as much photosynthetic product as do cultivated lands, but the conversion of the savanna and grassland photosynthetic product to human food is less direct and less efficient than is the conversion of the photosynthetic product from cultivated land.

Human–managed photosynthetic systems for capture of solar energy as fixed carbon are constrained by the facts that:

1. solar energy is received at very low intensity levels, thus requiring that significantly large surface areas be managed if amounts of photosynthetic material are to be collected which can provide food for the people involved in the management,
2. the plants or animals used for the capture are small in comparison with the surface areas managed, so a great deal of management detail must be handled,
3. the large amounts of water needed for transpiration and, their natural patterns of arrival limit both the zones and the seasons in which agriculture may be practiced, and also limit the amount of photosynthetic product that may be generated,
4. the actual rate at which mineral nutrients from the soil become available to support photosynthetic operations tends to limit the terrestrial production of grains to about 1000 dry kg per hectare per crop (Food and Agriculture Organization, 1972) (with approximately another 1000 kg per hectare of dry above-ground material and perhaps another 1000 kg of dry below-ground material – both of which are not digestible by humans),
5. the structuredness of human-managed agriculture makes the plants and animals so managed, easy targets for pests, diseases and competing plants and animals, thus making protection and control an economic necessity,
6. the plants and animals used in agriculture generally contain a great deal of non-food material including water, husks, stalks, bones etc. requiring large amounts of material be handled and processed for each unit of food obtained,
7. many of the photosynthetic products appear as fruits or grains etc., all at one time each year and at certain specific locations, while food consumption needs are more or less constant throughout the year and at all locations where people are living, and
8. in many areas the cropping season is limited by periods of high or low temperatures as well as periods of excessive or deficient rainfall.

Consequently, high levels of productivity depend on using the land a high proportion of the time. Supporting resources such as water and nutrients from nature, as well as human-controlled operations for crop culture, harvest and conservation do not or can not flow to the production site in proper amounts and on proper schedules to obtain high photosynthetic productivity. By using special technologies which require fuel and electrical energy inputs drawn from outside the agricultural production site, these supporting resources may be made more adaptable or mobile so that they may flow on different schedules, at increased maximum rates and in increased total amounts – schedules, rates and amounts which may be better matched to the requirements of the photosynthetic process in a given climatic system (Chancellor, 1978).

World Population and World Food:

Traditional agriculture as practiced in India and China for the past several hundred years was essentially sustainable in nature. Food grain yields were typically on the order of 1000 kg per hectare, and approximately 70 percent of the productive capacity of the population was required for food production. All energy inputs came from the immediate area in which it was used, and fossil fuel use was a rarity.

Recently, decreases in death rates due to improved public health practices have resulted in major increases in the number of people to be fed from a fixed amount of land (Fig. 2). Crop varieties which can respond to the energy-using technologies described above have been developed and these varieties and practices put into place to avert global food shortages.

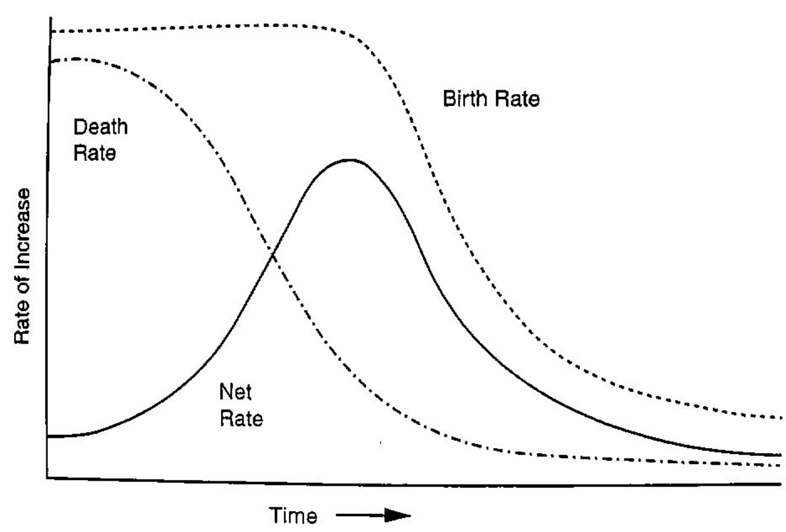

Figure 2. Relations among World birth rate, death rate and net population growth rate. Currently we are at the time for which the World birth rate is about 60 percent of the maximum value shown (from: Dorf, 2001).

Now, as long as energy supplies hold out, modern agricultural technologies can provide adequate world food. But, if the great majority of the energy supplies used are from non-renewable, fossil fuel sources, the world food system is no longer sustainable.

In the United States the food system in 1963 provided 3490 kcal of food energy per person per day (nearly 1.5 times the typical food energy consumption rate for adults of 2400 kcal per person-day). In order to put this food energy on the dinner plate the United States food system required (in 1963) the consumption of 22,369 kcal per person-day of primary energy resources (mainly from fossil fuel sources) (Hirst, 1973). This amount is 6.41 times the food energy delivered by the system. By 1970 this ratio had increased to approximately 7.4 (Hirst, 1973). The results of an analysis of where this primary energy was used in the food provision process in 1963 (Hirst, 1973) are given below:

Primary Energy Use Item	kcal/person-day	Watts/person	% of Total
Used directly on the farm	1820	88	8.1
Embodied in farm inputs	2185	106	9.8
Used in food processing	7318	355	32.7
Transportation to market	621	30	2.8
Wholesale and retail trade	3590	174	16.0
Used in the home for food	6835	331	30.6
Total	22,369	1084	100.0
Energy in the food supplied	3490	169	15.6

In the food systems of India and China in the 1800's essentially no fossil fuel resources were used. However, population numbers are now so great that we can not go back to the food systems of previous times without global catastrophe. We must look for other ways to provide adequate world food – ways that are sustainable.

The connection of fossil fuel resources to the institution of agriculture, as practiced on broadly distributed surfaces of the globe, has become possible only when agriculture, and the economies with which it is associated undergo "structural transformation" (Johnston and Kilby, 1975). In a structurally transformed economy each production unit specializes in the efficient production of a limited number of products using special-purpose tools, materials and knowledge. These products are then shared among all consumers at prices reflecting the economy of their production.

This means that in order to afford off-farm resources each farm must produce a surplus of products and sell them into the economy. In California agriculture this transformation has gone so far that approximately 90 percent of the farm-gate value of farm products consists of purchases from off-farm sectors of the economy. Among these purchases are not only fossil fuels for on-farm use, but also other products such as nitrogen fertilizers, which require large amounts of fossil fuel use for their manufacture. Furthermore, the farm-gate value of agricultural products constitutes only about 35 percent of the value that those items will have when purchased by the consumer – due mainly to costs associated with handling, transport, processing and storage inputs (many of which are energy intensive) by post-farm sectors of the food system.

Food System Sustainability:

In the United States we have a food system based on an agriculture which is highly productive per unit land area and per unit labor input, but one that is dependent on non-renewable fossil fuel use, not only on the farm and for many purchased farming inputs, but also for the system that links farm outputs to their source of value on everyone's dinner plate.

One definition of a sustainable economy (Daly, 1996 as cited in Dorf, 2001) is one in which:

> Rates of renewable resources do not exceed regeneration rates; rates of use of nonrenewable resources do not exceed rates of development of renewable substitutes; rates of pollution emissions do not exceed assimilative capacities of the environment.

Because we do not have under development renewable energy resources which can substitute for our rates of fossil fuel use, and because our atmosphere is unable to maintain annually stable levels of carbon-dioxide concentration, due in large part, to fossil fuel combustion, the sort of structurally transformed agriculture and food systems described above – agriculture and food systems which are now essential for supporting the current level of the Earth's population – do not qualify as being sustainable.

Some of the factors that make more difficult direct action to achieve sustainability of our food systems are:

1. world population is continuing to increase, though at a rate approximately half of its peak value in the mid-1960's,
2. the majority of world population growth is in countries with low per-capita productivity, where citizens aspire strongly for higher productivity levels,
3. there seems to be a strong correlation between per-capita productivity and per-capita energy use (Fig. 3) with only minor variation from country to country in the ratio of these two parameters,
4. the lowest-price source of additional controllable energy is, in most locations, fossil fuel, and most fossil fuel supply organizations see it as their primary objective to continue to supply these fuels at a competitive price,
5. in structurally transformed economies each producer has control of their own process, but not of the processes of their input suppliers, thus individual energy conservation efforts seem to have little impact on overall system energy efficiency,
6. in structurally transformed economies one of the main suppliers to production operations are households which supply labor, and since the productivity per-capita is reflected in per-capita consumption levels, the energy use to produce all

products in an economy is inextricably linked to the consumptive patterns of households (Costanza, 1980),

7. currently, environmental pollution problems associated with fossil fuel use increase only slowly and are at critical levels in only a few places, thus most people tend to ignore them.

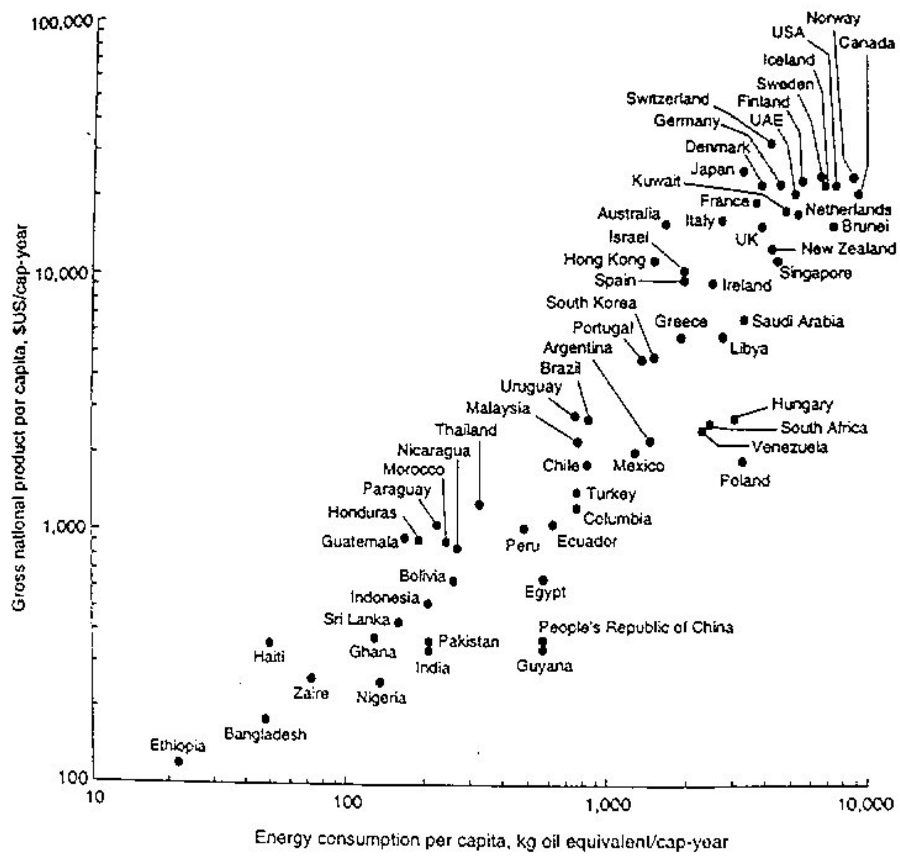

Figure 3. Correspondence between per capita energy use and per capita productivity for various nations in 1990 (note that both scales are logarithmic) (from: Klass, 1998).

Ideas on the Dynamics of Energy, Productivity and Sustainability:

There are a group of ideas on how to deal with these sustainability issues, which ideas involve continued and even accelerated development of energy-using technologies for increasing general productivity levels in currently low productivity societies. These seemingly counter-intuitive ideas are:

1. Energy use reduces the drudgery of most low-productivity jobs - jobs otherwise considered essential for food production in many societies - and allows individuals to work in higher-productivity roles (Denison, 1974).

2. Once per-capita economic productivity reaches a certain level, birth rates start to decline tending to mitigate future demands on energy resources (Meadows et al., 1972) (Fig. 4).
3. Several economists have theorized that: (a) low-consumption, low-productivity economies have low emissions of pollutants, (b) they also aspire to, and tend to progress to, higher productivity/consumption levels – levels involving more emissions – while they do not have the resources to devote to reducing emissions, and (c) only when these economies reach high productivity levels do they have adequate resources to be able to devote some to reducing emissions (Arrow et al., 1996, Ayers et al., 2001 as cited in Dorf, 2001) (Fig. 5). Others believe that this theory does not apply to all economies or to all types of emissions.

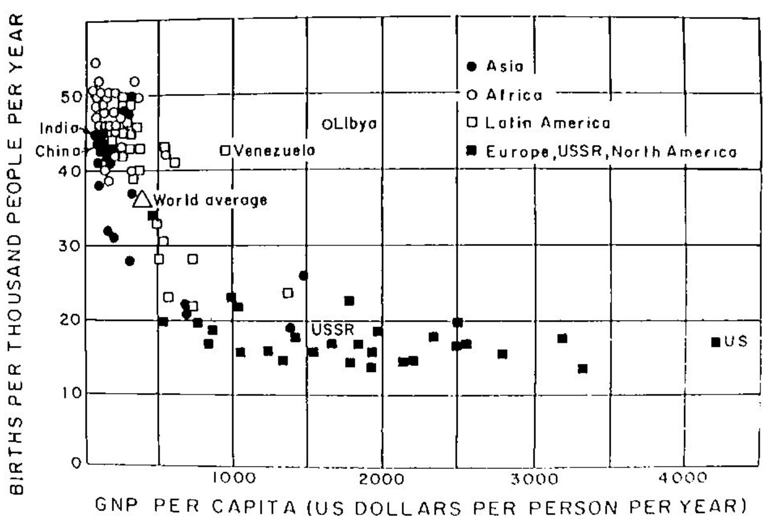

Figure 4. Relations between productivity and birth rate in 1970 (from: Chancellor and Goss, 1976, as derived from Meadows et al., 1972, by permission of Universe Books). The current World average birth rate is about 22 births per thousand people per year.

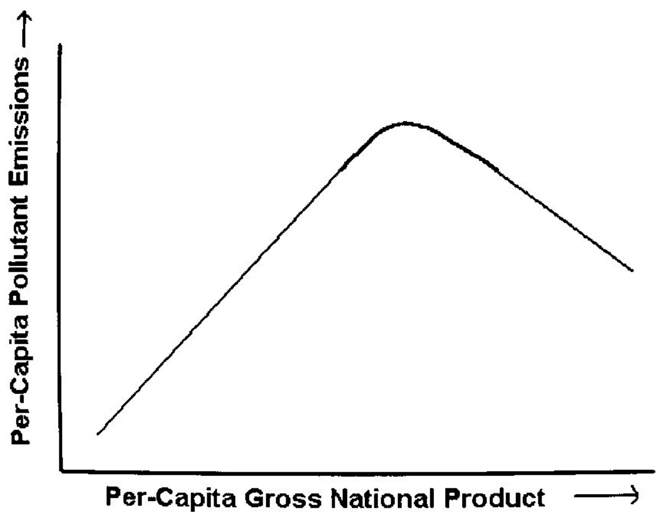

Figure 5. Hypothesized relationship "inverted U form" between productivity and pollution on a per capita basis for a given nation as time progresses and development takes place (see: Arrow et al., 1996 and Ayers et al., 2001).

The Goal of Reducing Dependence on Fossil Fuels:

In the face of the need to increase the use of technologies with distinct energy input requirements there remains reasons why efforts should be intensified to reduce fossil fuel dependence of our structurally transformed economies. These are the avoidance of the total depletion of the Earth's fossil fuel reserves and the associated economic disturbances, the saving of fossil fuel materials for critical use in special chemical applications and the slowing of atmospheric contamination with excessive amounts of carbon-dioxide with the associated global warming.

There are enabling factors which indicate not only that reduced dependence on fossil fuel use is possible, but also which approaches might be useful in achieving this end:

1. the amount of high-utility, high-structure solar energy that is delivered to the Earth's surface (121,000 x 10^{12} Watts) far exceeds human energy use (11 x 10^{12} Watts),
2. the interception of (and maintenance of the structuredness of) this solar energy by natural or human-made systems does not violate any natural laws, will not upset any global temperature balances and can give humans control of this energy for their own purposes,
3. even the energy captured and saved by global photosynthesis (98 x 10^{12} Watts) is 9 times the energy used globally by humans,
4. replacement of fossil fuel energy use with solar energy use can stop the recent trend toward increased carbon-dioxide levels in the atmosphere, and, can – through the increased global storage of photosynthetic product - reduce

atmospheric carbon-dioxide concentrations (IGBP Terrestrial Carbon Working Group, 1998, Kaiser, 2000),

5. many of the operational objectives for which energy use is employed can be obtained by using a combination of information and energy, so that the energy used is much more effective – this being abetted by the fact that technology for obtaining, handling and storage of information is growing rapidly in availability and dropping rapidly in cost (Chancellor, 1981),
6. among the reasons that fossil fuels seem to be the lowest cost source of easily controllable energy is that prices do not reflect decreases in "natural capital", which includes the costs associated with not having fossil fuel materials in the future when they may be critically needed, and costs associated with environmental degradation linked to emissions from fossil fuel use, and
7. the use of "emission credits" or "carbon credits" as included in the Kyoto Protocol offers an international, inter-industry basis for at least partial "natural capital" accounting to enter the fossil fuel system, which accounting may allow other types of energy sources to assume a more economically viable status (Dorf, 2001).

Conclusion:

The high productivity levels to which so many people in the world aspire are linked, in the form of current developed-country procedures, to intensive use of fossil fuels. Such systems, including the production of food through human-managed photosynthesis, are, thus, not sustainable in their present form. However, the flux of high-utility energy from the Sun, and even the small fraction captured by global photosynthesis, are many times the rate of human use of commercial energy. There is need to focus future work on further development of solar-energy-utility-preserving processes and on the comprehensive accounting of the costs of – as well as the reduction of dependence on – fossil fuel energy use.

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