REPRINTED FROM
Tropical Ecology 16 (1) 1976

ENERGY QUALITY AND CARRYING CAPACITY OF THE EARTH

HOWARD T. ODUM

Environmental Engineering Sciences, University of Florida, Gainesville, U. S. A.

ENERGY QUALITY AND CARRYING CAPACITY OF THE EARTH*

HOWARD T. ODUM

Environmental Engineering Sciences, University of Florida, Gainesville, U. S. A.

(Accepted for Publication on September 29, 1975)

Mr. President, Members of the Jury, Institute La Vie, Honored Guests, today's speakers. Thank you for this honor to our science and recognition of the importance of environment for man and its link with energy. A ceremony should be a time for renewing human purpose. A theory of energy quality hierarchy suggests the human role on earth and the carrying capacity of the world for man. Because no system can understand its own complexity, we use overview models to see the energy role of man. Using the same scientific concepts with which we look outward to the stars or inward to the atoms, let us examine the middle-sized realms of energy in which civilization exists to learn how energy flow operates environments, economics, and the community of nations.

A HIERARCHY OF ENERGY QUALITY

Shown in Fig. 1 is the basic pattern of energy flow and structure that is believed to develop at all levels of size because it draws more power in competition. The system draws more power because it develops higher quality energy as structural order, maintains the order against depreciation, and uses the storage as a means to feedback high quality services to pump in more energy. See Fig. 1 (*a*).

Shown at (*b*) is a chain of such energy transformations. Dilute low quality energy of sunlight is on the left and as energy is passed through each stage of concentrating and increasing of quality, most of the potential energy is used, being degraded as dispersed heat with entropy increase. The chain of energy transformations and structural systems constitutes a hierarchy of energy quality with the highest quality energies on the right. *Energy quality* is measured by the energy used in the transformation. Most scientists are familiar with energy chains that they graph as power spectra, for example, turbulence, food chains, molecular energies, cosmic rays, sea surface waves, etc.

When evaluations are made, an energy quality scale is obtained relating the amount of one type of energy required to develop another. Sunlight and dilute heat gradients are low quality energy; fossil fuels, rainwaters, animal carnivores, storms, and human food products are high quality energies; elevated mountains, biological genetic processes, and human intellectual activities are very high quality energy flows. An energy quality factors is defined as the ratio of Calories of energy of sunlight necessary to be converged in support of the Calories of high quality energy developed. See the Table 1.

High quality energy develops more work only when it has lower quality

*A response at prize awarding ceremony of Institute de La Vie, Paris, June 18, 1975.

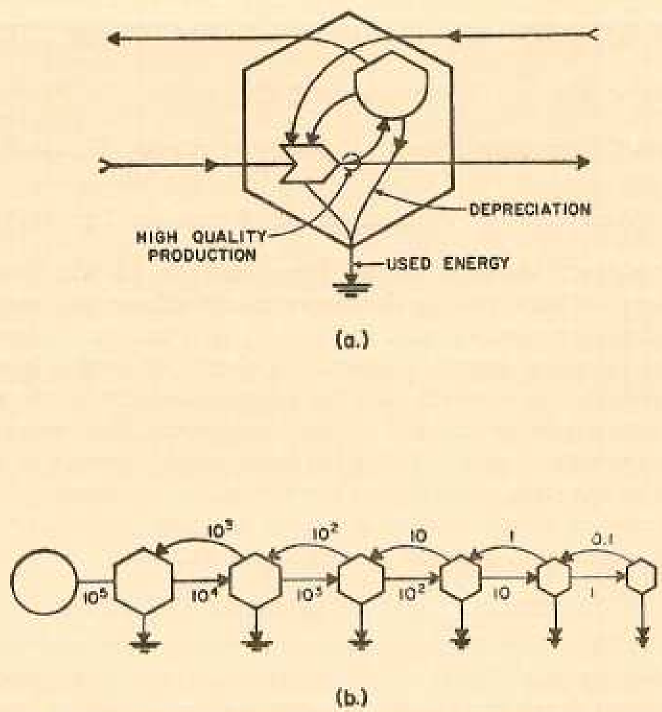

Fig. 1. Hierarchy of energy quality transformations. (a) energy flows in one unit; (b) chain of units.

TABLE 1. *Energy Quality Factors**

Type of Energy	Kilocalories of sunlight required per Kilocalorie
Sunlight	1
Gross plant production, dispersed	100
Net production of wood	1000
Fossil fuel at point of use	2000
Electricity	7000
Elevated rain water	8000
Supermarket food	20,000
Geological uplift	2,000,000
Book manuscript production	2,000,000,000

*For more explanation see Odum and Odum (1976)

energy in large quantity that it can amplify thus justifying the energy cost of its development. Using high quality energy alone does not yield the work potential of which it is capable. Using high quality energy without amplification is a drain on the system's ability to compete rather than a means for maximizing its power flow.

THE HUMAN PLACE

As shown in Fig. 2, human activities are high quality energies on the right of the long chain of life support transformations. The human system is supported and competitive so long as it feedsback its service as an amplifier and servant to the biosphere.

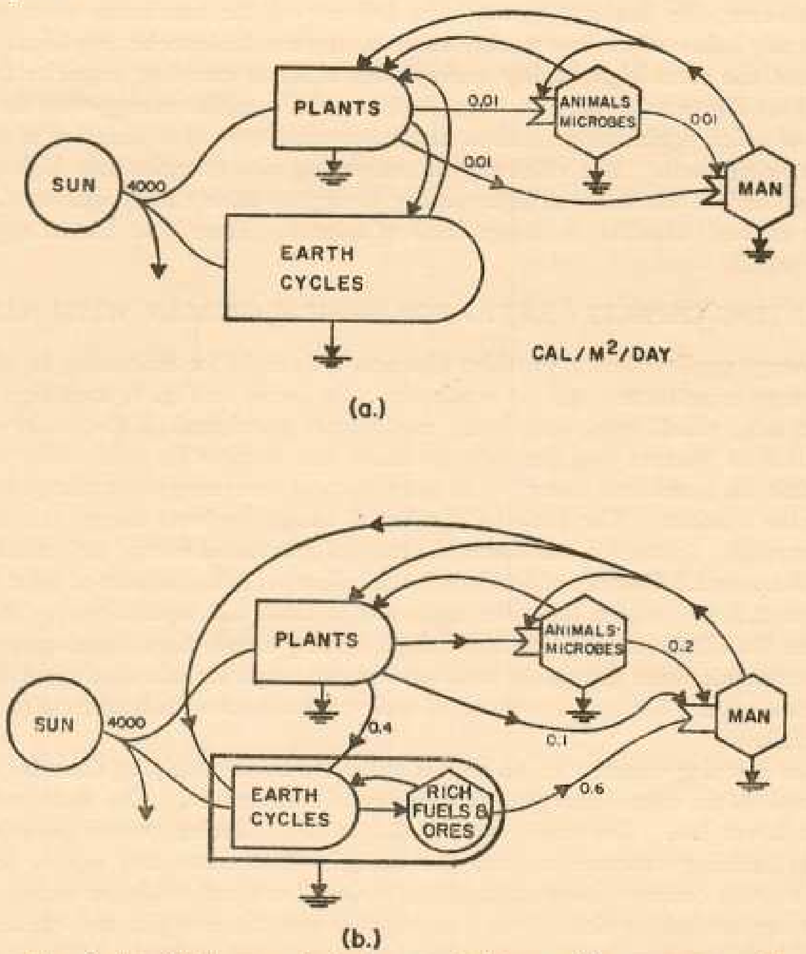

Fig. 2. Simplified energy chains in support of man. (a) man on renewal resources; (b) man using energy of earth cycles; at first he use storages faster than the renewable rate.

LOW QUALITY ENERGY LIMITS TO HIGH QUALITY MAN

The ultimate carrying capacity of the earth for man is determined by the energy flows available to his life support system. Since man is a high quality energy flow, energy quality theory requires that his work amplify low quality energy if it is to deliver the maximum work output possible. The systems that try to operate without matching energy use their high quality energy for low quality purpose, produce less yield than their competitors and are eliminated. The close feedback of human service that was characteristic of life on renewable energy is shown in Fig. 2*a*.

More recently rich accumulations of high quality energy are being used to divert low quality energy from its old system as shown in Fig. 2 (*b*). The so called high standard of living is the high quantity of high quality energy in use per person.

However, the limiting quantity in delivery of the maximum work possible is the steady inflow of the low quality solar energy available to be amplified. With or without the extra high quality energy, the ultimate carrying capacity for man depends on dilute solar energy. Fig. 3 shows the support energy flow for man's systems of cities, agriculture, tourism and other earth uses as a function of the rich energies being used. The efficiency of converting rich energies into high quality work declined as the ratio of high quality energy to solar energy increased. The limiting curve is familiar in many fields of science. Here is its use in aggregate for the world.

A CARRYING CAPACITY RATIO FOR DESIGN OF MAN WITH NATURE

Energy quality theory provides planners a formula for estimating in advance what energy expenditures will be economic. As shown in Fig. 4, local free energy (such as sun, wind, rain, and land) can attract purchased, high-quality energy with which to interact and generate products and services for sale. The systems that match the purchased energy with more natural free energy can charge less and capture the markets. The ratio of purchased energy to local energy is called investment ratio. In the United States the ratio of purchased energy to free matching energy is about 2.5 Calories of fossil fuel equivalent to 2000 Calories of solar energy (or about 2.5 to 1 where both are expressed in fossil fuel equivalents). Plans to put more than 2.5 units of purchased high quality energy in a development may not be economic since the goods and services produced for sale cost more and the prices charged are higher than those of their competitors with better ratios of free energy inflow.

The carrying capacity of an area is indicated by multiplying the solar energy by the ratio of purchased energy to free energy of competitors. The ratio in France is about 1.9 to 1.0. The world ratio is 0.3 to 1.0. During growth periods those ahead in building structure capture the energies from those that lag in development. In this century industrialized countries developed a higher ratio. When energies are no longer rich enough to support growth, energies are captured by those with a better ratio of local energy to purchased energy. More even distributions of energy are to be expected in the future as soon as the rich oils are gone. The relative dominance of nations with high ratio of purchased to free energies will decline.

The investment ratio suggests a utopian plan for allocation of high quality energies over the earth for the good of all. Each area should be allowed to purchase rich energies (fossil fuel, water, scarce minerals) in proportion to the flow of natural energies in their geographical area including their territorial seas. The

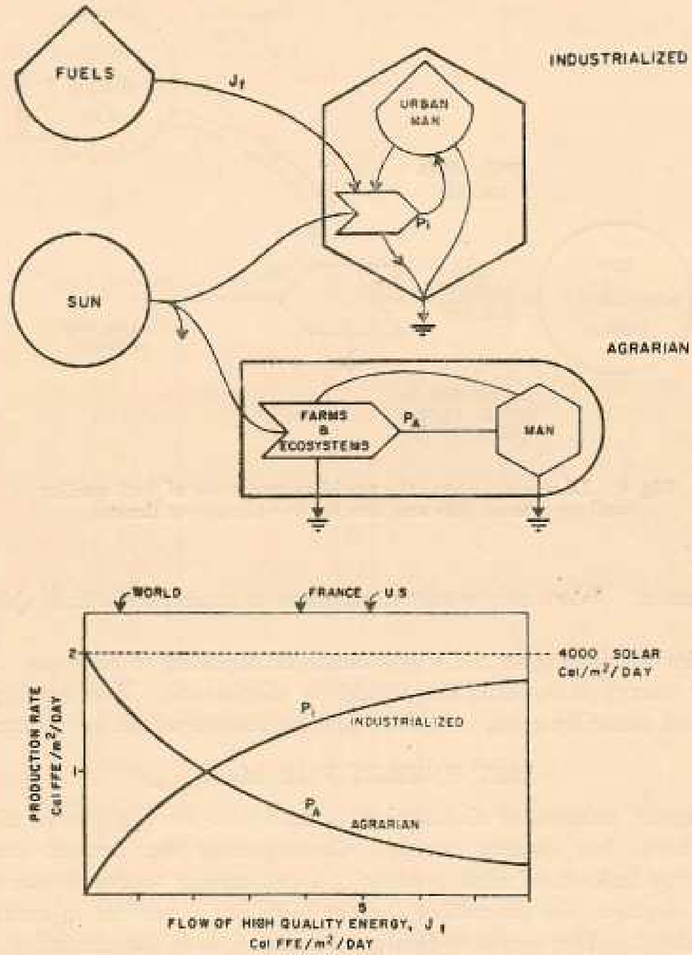

Fig. 3. Carrying capacity for man and the inflow of high quality energy. (a) energy diagram showing the role of rich energy in diverting solar energy from agrarian to industrial patterns; (b) graph of carrying capacity as a function of flows rich energy.

ratio of high quality energy allocated to resident free energies should be that of the world as a whole. Currently the ratio of fossil fuel to solar energy expressed in fossil fuel equivalents is 0.3 to 1.

By this distribution the environmental energies and the rich mineral energies interact to generate maximum work; the plan encourages good utilization of the earth's environments and renewable resources and inhibits the waste of the rich energies. With work developing in proportion to area, energy inequalities may be less, competition less, excess energies for wars less, and destructive rates of growth reduced. International tension may be most likely where energies are increasing relative to neighbors, whereas declining energies cause countries to pull back their

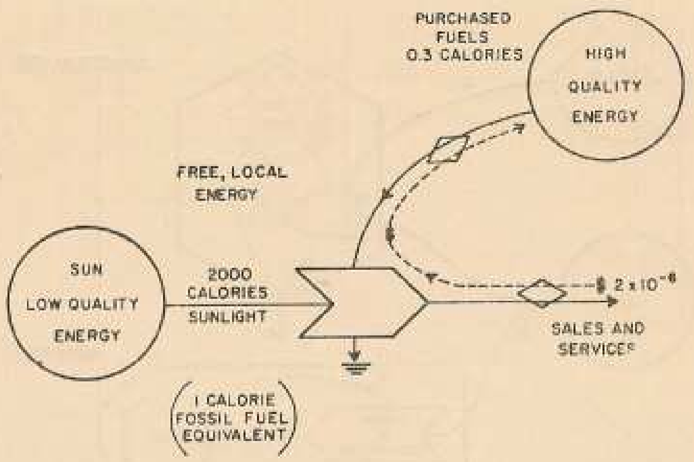

Fig. 4. Diagram showing the world's current use of high quality fossil fuels to amplify and develop free energies of the sun.

zones of influence. Wars may result when there are miscalculations about relative power.

If monies circulating in the world could be adjusted to have an unchanging ratio to total energy flow, inflation would be eliminated. The buying power of money for work done by man, machine, and by nature would be constant.

NET ENERGY FOR MAN

The present pattern of civilization is based on having much high quality energy to control low quality energy. Consequently our present ways require large net energy inflows of high quality. A net energy source is one that yields more than it requires for processing (where both are expressed in energy units of the same quality). The world is finally concerned with the declining reserves of high quality fuels that support the present civilizations. Are there alternate sources?

An examination of alternative energy sources shows that many proposed sources yield less energy than they require for processing. Others yield some net energy, but not enough to be competitive. Many net energy calculations are misleading because they do not use energy quality factors to determine the full energy costs of higher quality inputs. Many calculations underestimate the work of developing high quality goods and services that comes from throughout the economy of developed countries. These can be estimated in proportion to the money involved. The general work of the economy allocated to a process is to the total work of the economy as the money circulating in the process is to the total money circulating. For each Calorie of energy in equivalent fossil fuel delivered one may estimate the Calories used in getting the energy. Buying fuels from the near east now yields 6 Calories for one delivered back in exchange. Mining coal in the western United States yields 8 Calories for one invested in the work (Ballentine

1975). Nuclear energy may eventually yield 2.5 Calories for one invested, although there is almost no net yield yet (Lem 1973). Our oil shale calculation finds in initial pilot plants less energy delivered than invested (Gardner 1975). A calculation of the potential north sea oil suggested little if any net energy. With most proposed energies less net yielding than the present ones and with these becoming less net energy yielding each year, it is only a matter of time until the carrying capacity for man's high energy life styles decline moving to the left of the curve in Fig. 3.

ENERGY TOO RICH TO USE

Some hope there will be a new energy source such as nuclear fusion that is unlimited, so that it can be used both for low and high quality roles. Then growth could not be stopped. The ecological principle of ecological exclusion would eliminate those restricting their energy use, and another explosive growth period would result. Whereas the growth of this century has involved total metabolism by humanity of 4% of the organic budget and 0.005% of the heat budget; the new growth would be at least an order of magnitude higher and could displace the earth's billion year old life support system.

There are, however, reasons to think that such energy, fortunately, will not become available to man. The realm of man cannot use energy of much lower quality until it has been concentrated into higher quality, and this requires most of it to be degraded with entropy increase. Perhaps, similarly, energy that is several orders of magnitude more concentrated than the realm of man also cannot be used until it has been diluted down to lower concentration. Even ordinary nuclear fission may be barely a net energy yielder because much of its high intensity energy is dispersed in the process of getting its temperature down to a usable range. Nuclear fusion is even more intense than fission and may require even more dilution. Energy costs of the structures may be even greater.

RENEWABLE FUELS AND MINERALS

Commonly we regard the fossil fuels and rich material ores as non-renewable resources, but this may be too pessimistic. The sedimentary mountain building and volcanic cycles of the earth are still generating new reserves as part of their normal cycle. Estimates of the ratio of deposition of organic matter (0.4 Calories per square meter per day) are of the same order of magnitude as man's present rate of oil use (0.6 Calories per square meter per day). Some part of the organic matter going into sedimentary deposition will continue to be developed in form available to man as a renewable flow of fuel but at a reduced rate. There will be some material resources generated too. One may imagine life for man based mainly on the energy flows of sun, wind, water, and tides with the fossil fuels and key earth materials used judiciously for medicine, maintenance of information, communication, and other valuable necessities.

TOWARD STEADY STATE

In the long run the self designing aspects of the dynamic biosphere may achieve distributions of energy use like those we described in the utopian even distribution of the investment ratio, because this pattern ultimately generates more real work. It may be man's role as programmable servant of nature, whether he is aware of it or not, to facilitate and maximize the flow of energies producing growth from storages when it is possible and evenly distributed steady states when the only available energy flows are steady. Human systems of the earth may be expected to prevail that facilitate the maximum useful work. Even some of the intensive chemical processing of industry that is considered a pollution locally, on a larger scale may be facilitating a more rapid and ultimately more stable flow of earth cycles.

As the remaining rich energies of oil become deeper and deeper in the ground and further at sea, net energy from the rich stored deposits become less important, the investment ratio declines, and the high quality energy once again becomes only that generated by upgrading the sun through the transformations of productivity and earth cycle. The world habitat for humanity and the ecosystems should be more stable without the explosive flash of energy consumption of this century.

What we most need now are political leaders to learn about these systems, explain the trends to the world's people, and help lead human culture to the lower energy steady state. What better use is there for the remaining rich oil than helping to plan transitions and lead the way. The high energy aspects of man's present pattern may decline, but the basic role for man seems assured as high quality feedback of complex service facilitating the use of the sun and insuring the carrying capacity of the biosphere for us all.

REFERENCES

Ballentine, T. 1975. A Net Energy Analysis of Northern Great Plains Surface Mined Coal in Midwestern Power Plants. M. E. Thesis, Dept. of Environmental Engineering Sciences, Univ. of Fla., Gainesville.

Gardner, G. 1975. Preliminary Net Energy Analysis of the Production of Oil Shale. pp. 33:117. *In* H. T. Odum and C. Kylstra (eds.) *Energy Models for Environment, Power and Society* Report to Energy Research and Development Administration. Contract E-(40-1)-4398.

Lem, Pong. 1973. Energy Required to Develop Power in the United States. Ph. D. Dissertation, Dept. Environmental Engineering Sciences, Univ. of Fla., Gainesville. 197 pp.

Odum, H.T. and E.C. Odum. 1976. *Energy Basis of Man and Nature.* McGraw-Hill, N.Y. 297 pp.