Energy, Hierarchy and Money*

Howard T. Odum

Environmental Engineering Sciences
University of Florida, Gainesville, FL

Abstract

Energy hierarchy concepts are used to understand the distribution of money. Monetary convergence concept is explained by the universal energy transformation hierarchy. In an energy transformation series, the available energy decreases at each work step, but the transformity, concentrations, turnover times, and spatial convergence increase. These patterns are explained by the natural selection of designs that reinforce their sources. To reinforce effectively with less energy, downstream processes have to be concentrated in space, accumulate, and pulse their feedbacks. Because every real process requires available energy, materials, information, and people organize into pulsing centers. In this essay the distribution of monetary circulation is also linked to the energy hierarchy, providing some quantitative insights on the self organization of an economy. A suggestion is made for a 7th energy law.

---

* Paper presented at the International Society of Systems Sciences meeting in Toronto, Canada, July 20, 2000.

We often take for granted the intensive economy in population centers. But these centers may have energetic explanations that follow from the principle of energy hierarchy. Let's consider how the circulation of money is coupled to the hierarchy of energy. Most people would agree that all systems require energy and that economic systems are no exception. But the relationships are perceived as complex and subject to human behavior in markets.

This paper suggests there is a more fundamental, top-down principle: that the circulation of money is distributed according to the hierarchy of energy. In spite of the appearance of unregulated individual actions and randomness, energy transformation rules may control. During self organization, natural selection of human trial and error guides people and their spending into hierarchical patterns because this brings energetic reinforcement.

Background

There is a large literature of economic geography, relating the distribution of economic activity, energy, materials, and people (Berry, Conkling, and Ray, 1976). Older literature was summarized by the author's book on ecological and general systems (Odum, 1983, Chapters 17-18, 21). That humans and their cities are distributed hierarchically over the landscape was documented long ago (Cristaller, 1933). The empirical Zipf's Law (Zipf, 1919) found the number of cities and towns inverse to their size. Doxiadis (1977) found increasing concentration of buildings and increasing scale of transportation circulation toward centers.

Anne Marie Jansson and J. Zucchetto (Jansson and Zucchetto, 1978; Zucchetto and Jansson, 1985) made detailed study of the flows of energy, materials and money on the Swedish island of Gotland in the Baltic Sea. While relating energy flows to market values, they postulated that monetary values would increase with embodied energy.

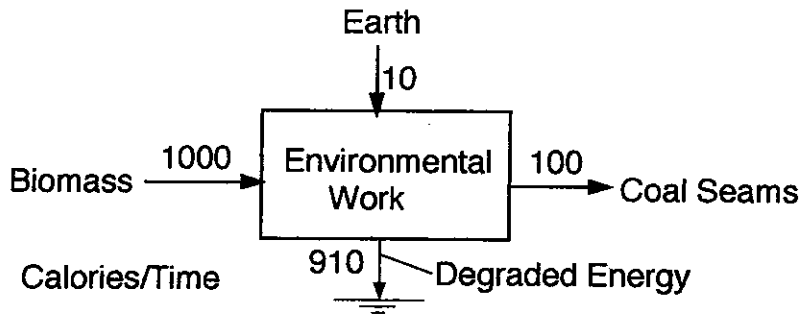
Energy Hierarchy Concepts

In energy transformations, available energy (exergy = potential energy) is used up in processes of work to generate a small output of available energy of a different kind (Figure 1). So far as we know, all of the energy transformities of the universe can be arranged in a series network suggested by the web in Figure 2a. This is an energy hierarchy because many joules of one level converge to generate a few joules of higher quality. In most, if not all systems, the higher quality energy feeds back

F1

F2

(a) Energy Transformation



(b) Value Added with Money Flow

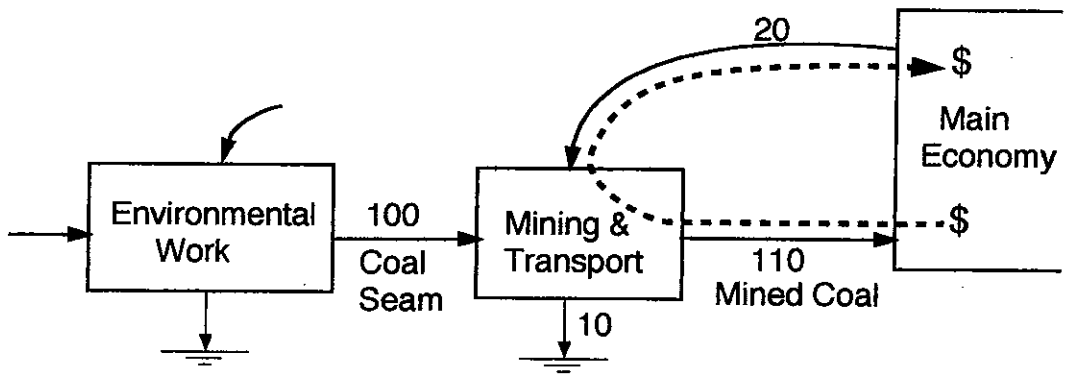


Figure 1. Energy transformed in work. (a) Process without money; (b) a process accompanied by a counter-current of money representing value added.

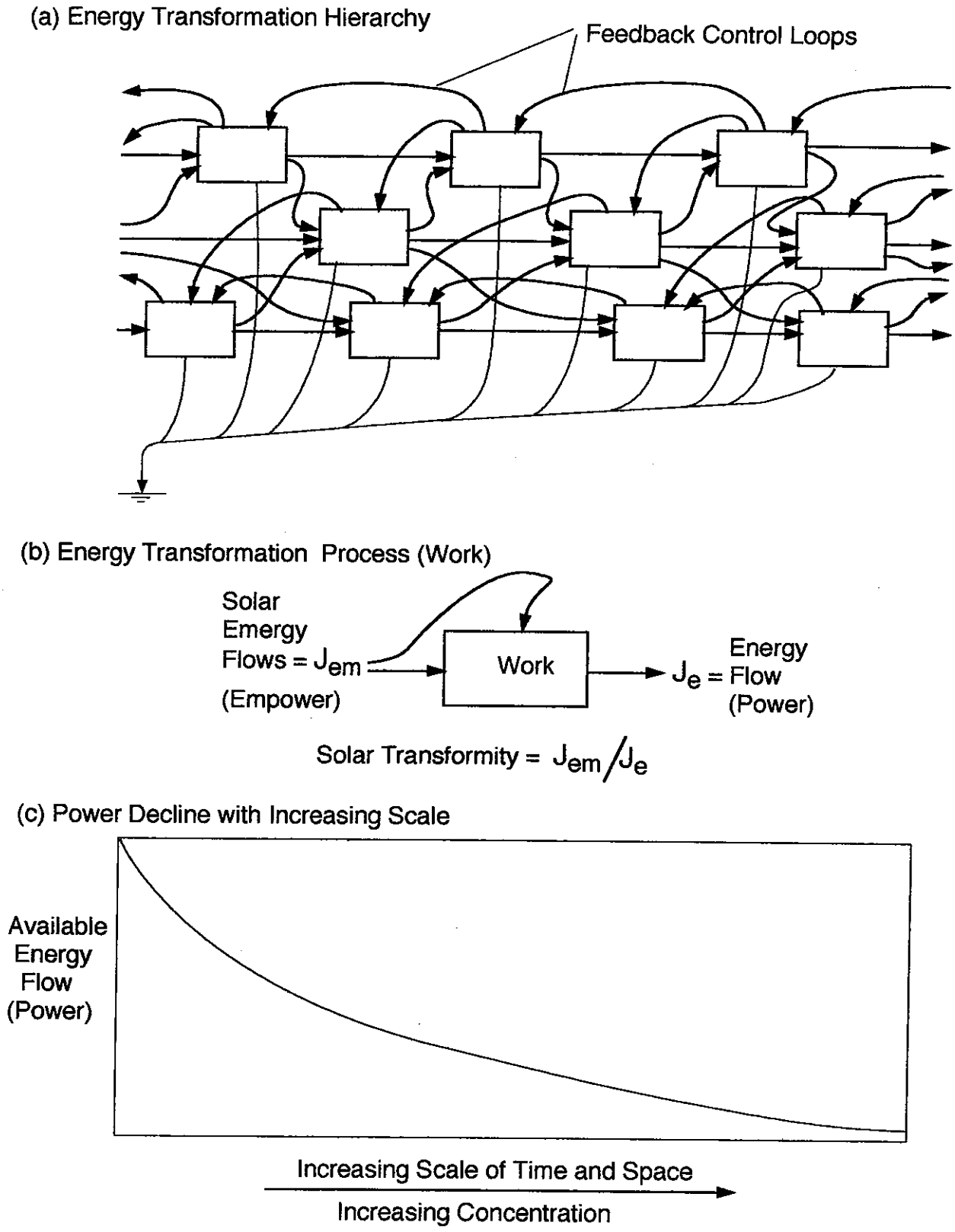


Figure 2. Diagram of the universal energy hierarchy. (a) A network of energy transformations; (b) one energy transformation and the definition of solar transformity; (c) decrease in power through the web of work processes that generates units on a larger scale of time and space with higher transformities.

services and materials in control loops to amplify its input process (Figure 2a).

The available energy flows decreases with each transformation step from left to right in the energy transformation web (Figure 2b), but the scale of the processes increases (Figure 2c). The position in the universal energy hierarchy is indicated by the *transformity*, which is defined as the available energy of one kind required to generate a unit of energy elsewhere in the web. The one kind of energy selected for calculating transformities is defined as the *emergy (spelled with an "m").* The unit of emergy is the *emjoule.* The *transformity is the quotient of emergy per unit energy.* In Figures 1 and 2 the transformity increases from left to right.

In recent years we used solar energy as the form of energy for calculating emergy. Thus, solar emergy in solar emjoules measures the available energy of one kind which is embodied in any product or service. The flow of useful energy per time is *Power.* Similarly, the flow of emergy per time is defined as empower (Figure 2b).

The emergy of something is readily calculated by multiplying the quantity by the emergy per unit from tables summarizing previous studies. For example, multiply available energy by its transformity to obtain its emergy. There is now an extensive literature on emergy valuation, and many transformities have been calculated. The author's book (Odum, 1996) summarizes concepts and earlier work. The first folios of a handbook of emergy valuation containing transformities and emergy values per mass, per person, per bit, etc., have been issued (Odum, Brown, and Brandt-Williams, 2000).

Power Plant Example

An example of an energy transformation series in Figure 3 connects the solar emergy inputs to the output and use of electricity in a power plant. Because the emergy flow is the same along the series, as the available energy flow (= power) decreases, the transformity increases in inverse relation. At each step the available energy decreases but the solar transformity increases.

Properties of the Energy Hierarchy

The following are properties of the energy hierarchy in space and time as explained in more detail before (Odum, 1987, 1996, 2000). These

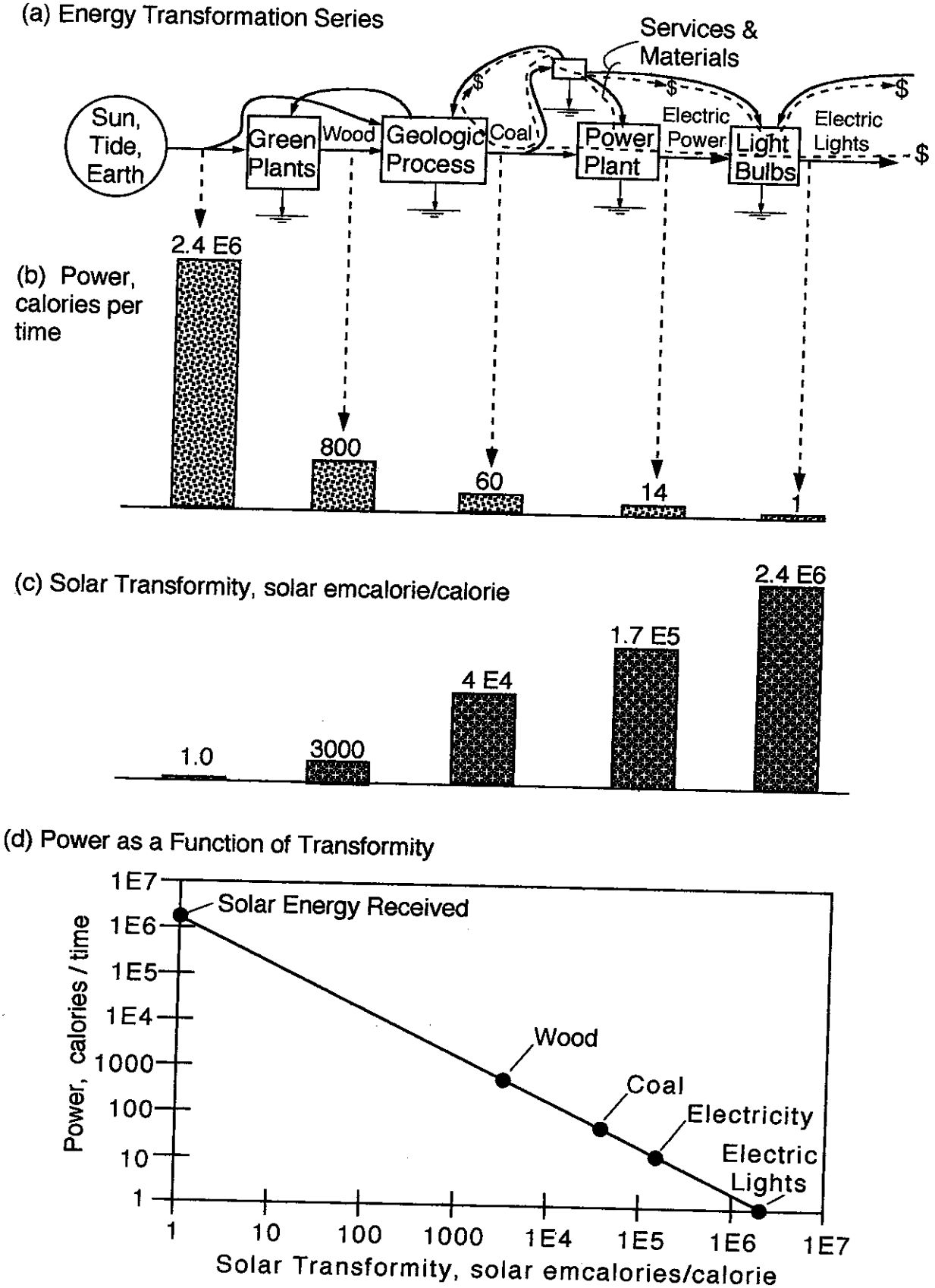


Figure 3. Energy transformation series showing the necessary solar emergy for generating a joule of electric light using electricity from a coal-fired power plant. (a) Systems diagram; (b) available energy used in work in each transformation step; (c) solar transformity of the work products; (d) power used as a function of transformity on logarithmic coordinates.

characteristics result when each product of energy transformation is stored and reinforces its own energy chain with feedback interaction. The natural selection of designs that have feedback reinforcement (maximum power principle) causes the following:

(1) Convergence spatially of energy transformation to form centers (Figure 4) because less energy can have a commensurate feedback effect if it is spatially concentrated.

(2) Energy is accumulated in storages in the centers, delivering its feedback reinforcement in pulses because less energy can have a commensurate feedback effect if it is concentrated in time.

(3) Materials are concentrated in space and time in each transformation step because the available energy which drives material cycles is being concentrated. This means that the quantity of materials concentrated has to decrease in each step because the available energy at each step is less. The emergy per unit mass increases with each step.

(4) The concentration of storages of energy and materials increases with steps along energy transformation series, which is a necessary consequence of using less energy to have a commensurate reinforcement that requires a longer period of accumulation. Examples are reefs in nature and cities in human organization.

(5) The concentration of emergy flow increases since the available energy is being concentrated. Empower per area is called empower density.

(6) Because information requires transformations of available energy to maintain its system of replacement, testing, selecting, and sharing, information is also organized by energy hierarchy with decreasing quantities but high concentrations at higher centers.

Figure 4 summarizes these properties of the energy transformation hierarchy where the emergy flow (empower) is the same through all steps. The properties of power and materials flow decrease inversely to the increasing concentration of energy, materials flow, storages, empower density, and transformity.

When empower J_{em} is constant, the inverse relationships in Figure 4 are represented with the equation:

$$Y = J_{em}/X$$

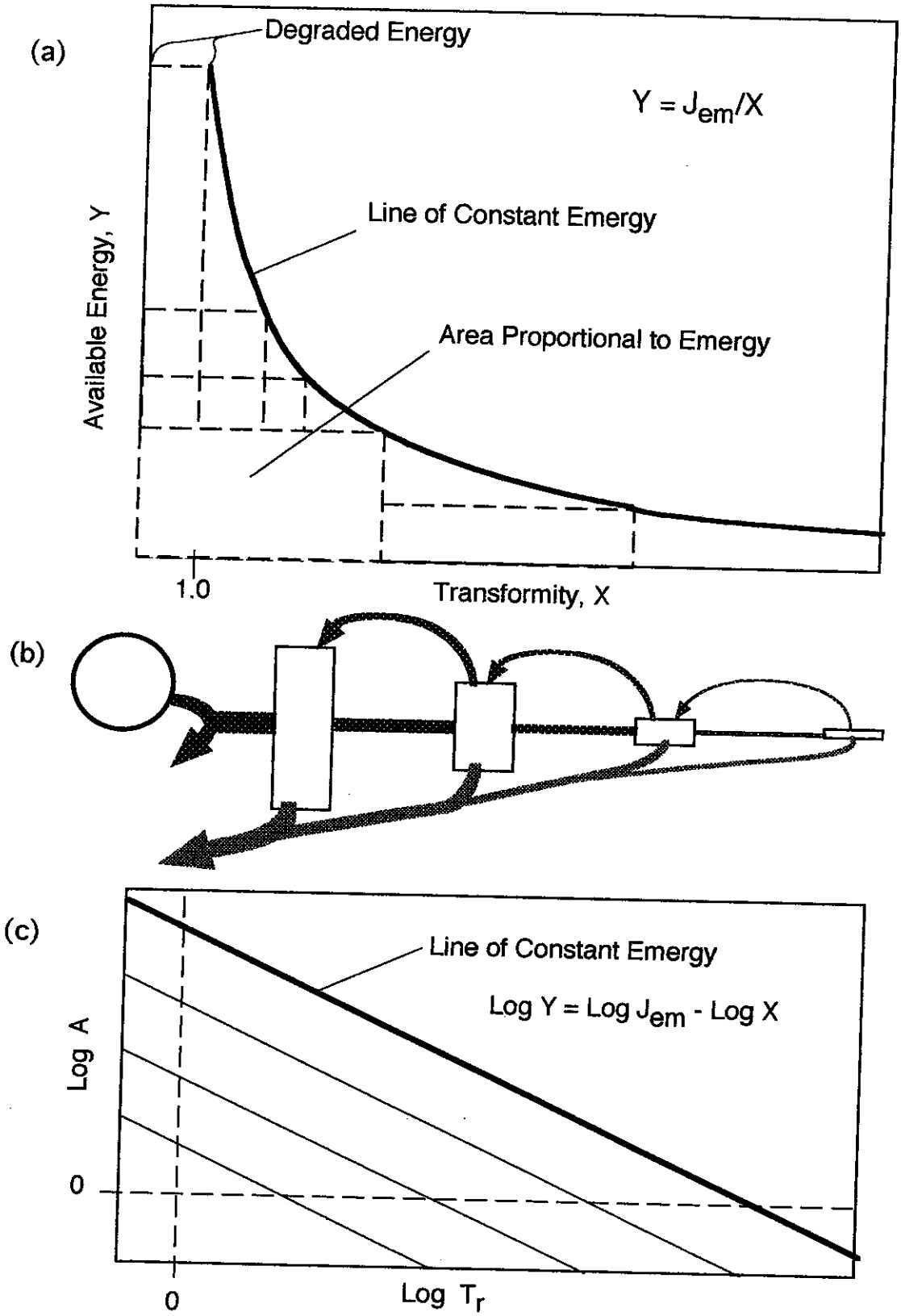


Figure 4. Generalized plot of the energy hierarchy relating the decreases of energy and materials to the increasing concentrations required for commensurate reinforcement feedbacks. Y and X can be any of the following pairs:

Available energy flow and transformity;
Available materials and emergy per mass;
Available area and empower density;
Useful information available and emergy/unit information.

(a) Linear coordinates; (b) energy diagram; (c) logarithmic coordinates.

where Y is the decreasing quantity, and x is the increasing concentration. Series with many transformations involve so many orders of magnitude that they cannot be represented on regular coordinates (Figure 4a). Data can be readily plotted on logarithmic coordinates. The equation becomes:

$$\log Y = \log Jem - \log X$$

a straight line. For example, the power and transformities in the electric power series are plotted in Figure 3d.

The energy hierarchy may explain Zipf's law in which city size Y was found to be the inverse square of the city's rank X: $Y = 1/X^2$. The larger the city (hierarchical center), the larger is the territory, and the more energy and steps in the energy transformation series are converging. Because more area is concentrated and accumulated, the concentration is greater. Graphs of cities of different size are straight on a logarithmic plot.

Money and the Emergy Transformation Series

Although we think of money circulation as something people do, each transaction involves an energy transformation. Money flows as a counter current to things it buys. Circulation of money is shown using dashed lines in an energy transformation process in Figure 1b and the power plant example (Figure 3). Figure 5 shows the way additional money flows (value added) with each transformation step toward the hierarchical centers on the right. If money circulation increases with transformation steps (Ts), it increases with the transformity (Jem/Je).

$$J\$ = k\,(Jem/Je)$$

When the emergy flow (Jem) through a series (Figure 5) is constant, then the emergy per unit money (Jem/J$) is proportional to the energy flow (Je).

$$Je = k\,(Jem/J\$)$$

The reciprocal of emergy/money is generalized price (price = J$/Jem).
Price = J$/Jem = K/Je

As the energy decreases in successive transformations, the price of real wealth as measured in emergy units increases.

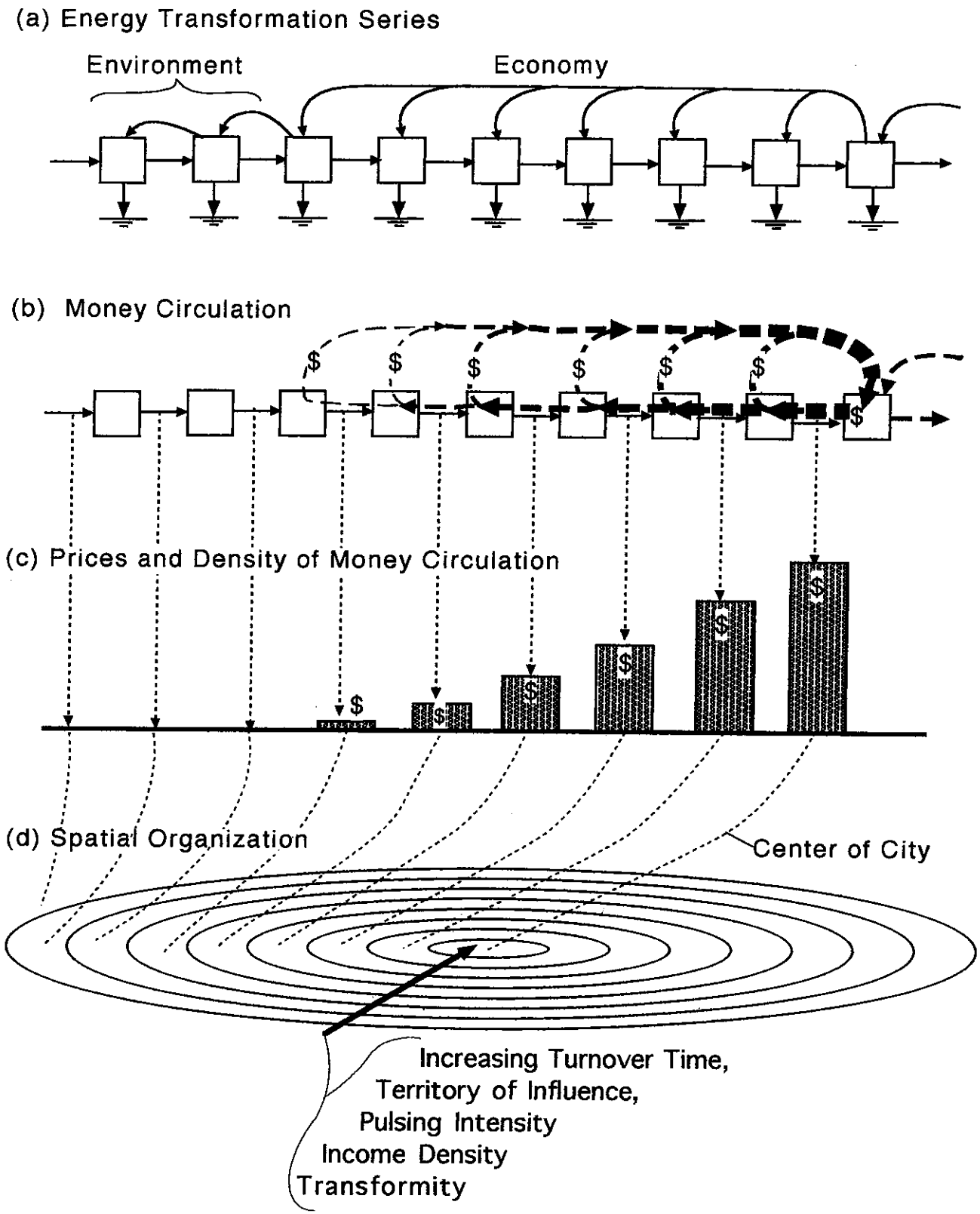


Figure 5. Money circulation in the energy hierarchy with money added at each transformation step. (a) Energy systems diagram; (b) counter current of circulating money (dashed lines); (c) increases in price ($ per unit emergy) with transformation steps toward economic centers; (d) spatial pattern of energy hierarchy with convergence, increased concentrations, and money circulation toward the centers.

If area A decreases with transformation steps

$$A = k_2/T_S$$

And money circulation J$ increases with transformations steps T_S

$$J\$ = k_3\ Ts$$

Then the circulation density (J$/A) may increase quadratically with steps.

$$J\$/A = (k\ T_S)/(k_2/T_S) = k_3\ T_S^2$$

Summarizing: money is coupled to energy transformation series (energy hierarchy), and is constrained by the properties of the hierarchy as summarized in Figure 4. Its properties change in passing to higher centers of concentration, the cities (Figure 5). At the low levels on the left are free environmental transformations with no money. At each higher step there is value added, and thus the money circulation increases as does the money/energy ratio. The emergy per unit money decreases, and vice-versa, the money per unit emergy (price) rises. In the centers, the circulation of money is more concentrated but the buying power of money is less. These are familiar patterns that people take for granted. They result from the energy hierarchy principles.

Discussion

The relationships given here link the universal energy hierarchy to the circulation of money. In one sense, energy and money are causally related. Traditional views about the creativity of human choices might regard these coupled relationships as constraints. Others might conclude that human economic behavior, including the free markets, is really not so free of system determinism and natural law.

Whereas the contribution of environmental resources to the economy is not measured by circulating money (Odum, 1986, 1996), money circulating in the markets increases with the emergy and transformity of products once they are above a threshold for economic use and processing within the economy. Thus, this essay supports the Jansson-Zucchetto hypothesis that market values increase with embodied energy (emergy).

In year 2000, with economic growth still in progress, self organization is generating a hierarchy of sub-economies with controversies about the relationship of economic power to other information. The broad base of global energy is supporting high diversity super-circulation. There appears to be a struggle for control between monetary power and the shared information of an emerging world public opinion. The coupling described here helps anticipate the future, as fuel shortages reduce the energy hierarchy, concentrations in centers, and the circulation of monetary buying power. Since emergy is a general measure of inherent real wealth, rising costs of emergy means rising prices.

By recognizing the money-energy connection we can look for other properties expected with energy hierarchy such as increase in period and strength of economic pulses toward the centers. In a reciprocal way, the facts that these concepts seem to explain are also evidence that reasoning based on the maximum power principle is good.

It is customary in science to call a fundamental principle a law after its generality has been widely used and tested. The energy hierarchy concepts are likely to gain this status in time. If we accept the maximum power and empower principle as the 4th energy law, and the energy hierarchy as a 5th, the hierarchy of materials becomes the 6th and the hierarchy of money the 7th. Or perhaps all these will be regarded as corollaries of one energy hierarchy concept.

References

Berry, B.J.L., E.C. Conkling, and D.M. Ray. 1976. The Geography of Economic Systems. Prentice Hall, Englewood Cliffs, NJ. 529 pp.

Cristaller, W. 1933, 1966. Central Places in Southern Germany, Translated by C.W. Baskin, Prentice-Hall, Eglewood Cliffs, NJ.

Doxiadis, C.A. 1977. Ecology and Ekistics. Westview Press, Boulder, CO. 91 pp.

Jansson, A.M. and J.J. Zucchetto. 1978. Energy, Economics and Ecological Relationships for Gotland, Sweden. A Regional Systems Study. Ecological Bull. #28, Swedish Natural Resource Council. 154 pp.

Odum, H.T., E.C. Odum, and M.T. Brown. 1997. Environment and Society in Florida. Lewis Publishers, Boca Raton, FL. 449 pp.

Odum, H.T. 1983, 1994. Ecological and General Systems: An Introduction to Systems Ecology (Revised edition of: Systems Ecology, 1983, John Wiley, 644 pp.) Univ. Press of Colorado, P.O. Box 849, Niwot, CO. 80544. 644 pp.

Odum, H.T. 1988. Self organization, transformity, and information. Science 242(Nov. 25, 1988):1132-1139.

Odum, H.T. 1996. Environmental Accounting: EMERGY and Decision Making. John Wiley, NY. 370 pp.

Odum, H.T. 2000 (?). An energy hierarchy law for biogeochemical cycles. In Proceedings of the International Workshop on Emergy and Energy Quality, Sept., 1999., Center for Environmental Policy, Univ. of Florida, Gainesville. (In press)

Whitfield, D. 1994 Emergy Basis for Urban Land Use Patterns in Jacksonville, FL, M.S. Thesis, Dept. of Landscape Architecture, Univ. of Florida, Gainesville. 224 pp.

Zipf, G.E. 1919. Human Behavior and the Principle of Least Effort. Addison-Wesley, Reading, MA.

Zucchetto, J. and Ann-Mari Jansson. 1985. Resources and Society A Systems Ecology Study of the Island of Gotland, Sweden. Ecological Studies #56, Springer-Verlag, NY. 246 pp.