# 12 THE EMERGY OF NATURAL CAPITAL

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## ABSTRACT

This chapter addresses several notions that have to do with the evaluation of natural capital, that is, the assets in the natural world that have required energy over a period of time to be built and organized. Soils, for example, require photosynthetic production by plants and the accumulation of the resulting plant matter over a period of time to build a useful soil layer for a human activity like agriculture. Calculating the natural energy over time required to build a given ecological asset is one means of trying to determine its replacement value, independent of the vagaries of using market values that depend on social desires at a given moment. The methods for determining the direct and indirect solar energy, or Emergy, required to make a service or product have been under development for some years and can be used in environmental evaluations. In conducting these evaluations, all energies are expressed in equivalent units, that is, conversion factors have been developed to express the ability of one form of energy to do work in comparison to other forms.

## INTRODUCTION

An important aspect of emergy analysis is that it tries to evaluate the contributions of nature that are not identified by the economic system. In human economies, an exchange of goods and services from one sector to another is accompanied by countercurrent exchange of money. This is also true of some exchanges of the human economy with the natural world, (e.g., the taking of fish from the oceans is usually accompanied with some payment). However, there are many contributions from nature, that is, work that is done for the human economy that does not have any monetary exchange associated with it. These services, then, are not valued in the accounting schemes that humans use to assess economic activities. The emergy approach seeks to value both those transactions that have money flows associated with them, as well as these other contributions from nature that are not recognized in the usual exchanges involved in the economy. For transactions that have associated money, emergy evaluations include two calculations, one for the human services contributed and one for the environmental resources used up.

Odum, H.T. 1994. The EMERGY of natural capital.
pp. 200-217 in Investing in Natural Capital, A.M. Jansson,
M. Hammer, C. Falke, and R. Costanza, eds. Island Press,
Covelo, CA.

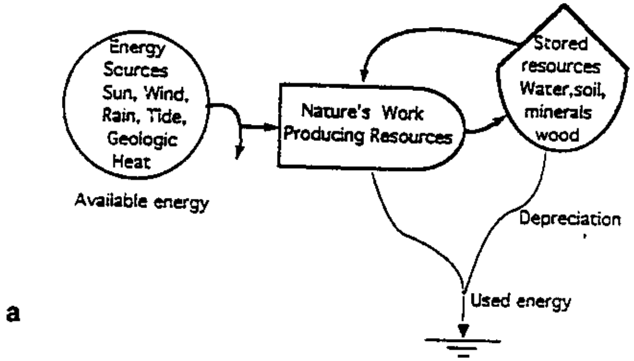
One important point to recognize is that the natural world has built up and accumulated impressive storages over very long periods of time—solar energy being the basis for much of this stored capital. Fossil fuels, phosphates, abundant forest land, tropical rain forests, large pelagic fish stocks, and soils are some examples. The human species in the 20th century has had the good fortune and technology to exploit these accumulated storages with increasing rapidity. The human species in undertaking this behavior may be obeying the "maximum power principle," which in its simplest form states that those systems that maximize power (rate of doing work) in the competition for energy resources are the ones that win out and succeed. Consequently, systems may not necessarily be seeking behavior to maximize efficiency during times of plentiful resources, rather they may seek to get as much as they can in the struggle for growth and survival. Recently, as the human community recognizes the finiteness of the environmental storages that are an important component of our prosperity, calls for management for sustainability have been heard. The usual notion is that we can somehow reach a steady state in which the size of our economy reaches a relatively constant size, one which can be maintained by a consumption of resources that is sustainable. But we may find, as with many natural ecosystems, that sustainability will involve oscillations, with human economies building during times when environmental storages are depleted, and declining during times when environmental storages recover and grow again.

This chapter explores these notions, presents emergy calculations for various components of natural capital, and presents some simple simulations for oscillating systems of man and nature.

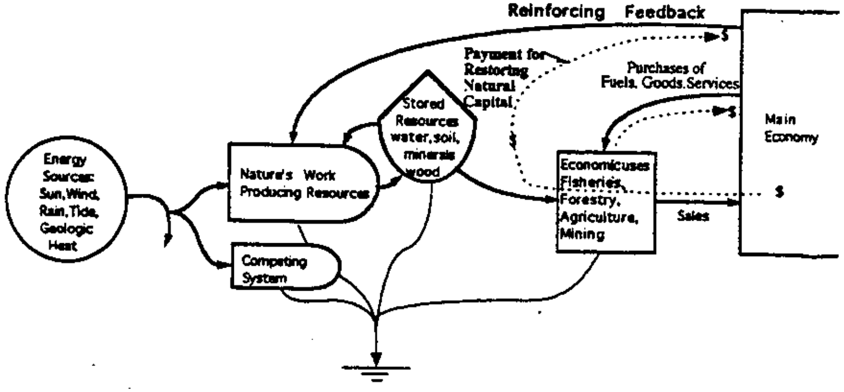
## STORAGE, EMERGY AND TRANSFORMITY

The literature on evaluation of nature is extensive, much of it reporting ways of estimating market values of the storehouses and flows in environmental systems. In recent approaches to environmental evaluation (Repetto 1992), monetary measures were sought for the storages of nature. Others have used the simple physical measures of stored resources, especially energy.

Shown in Figure 12.1a is a storage of environmentally generated resources. Energy sources from the left are indicated with the circular symbol. Energies from sources are used in energy transformation processes to produce the quantities stored in the tank. Following the second law, some of the energy is degraded in the process and is shown as "used energy" leaving through the heat sink, incapable of further work. Also due to the second law, the stored quantity tends to disperse, losing its concentration. It depreciates, with some of its energy passing down the depreciation pathway and out through the used energy heat sink.



Energy Basis for Wealth



b Feedback Necessary to Maximize Wealth

Figure 12.1. Systems diagrams of natural capital and its relationship to economic use. (a) Resource production, storage, and depreciation; (b) Economic use of stored resources.

To build and maintain the storage of available resources, work requiring energy use and transformation has to be done. Work is measured by the energy that is used up, but energy of one kind cannot be regarded as equivalentto energy of another kind. For example, one joule of solar energy has a smaller ability to do work then one joule of energy contained in coal, since the coal energy is more concentrated than the solar energy. A relationship between solar and coal energy could be calculated by determining the number of joules of solar energy required to produce one joule of coal energy. The different kinds of energy on earth are hierarchically organized with many joules of energy of one kind required to generate one joule of another type. To evaluate all flows and storages on a common basis, we use solar emergy (Odum 1986; Scienceman 1987) defined as follows:

> Solar emergy is the solar energy availability used up directly and indirectly to make a service or product. Its unit is the solar emjoule.

Although energy is conserved according to the first law, according to the second law, the ability of energy to do work is used up and cannot be reused. By definition, solar emergy is only conserved along a pathway of transformations until the ability to do work of the final energy remaining from its sources is used up (usually in interactive feedbacks).

Solar transformity is defined as follows:

> Solar transformity is the solar emergy required to make one joule of a service or product. Its unit is solar emjoules per joule.

For example, environmental contributions to storages of spruce forest wood in Sweden are estimated to be about 3800 solar emjoules per joule of wood produced (Doherty, Nilsson, and Odum 1992). Emergy calculations make estimates and comparisons of the magnitude of the work involved in the creation and maintenance of storages and flows of energy, matter, and information in the system of man and nature.

Solar transformity is calculated from data on energy flows in real networks by evaluating all the inputs observed contributing to an energy flow including those of nature and those from the economy.

The emergy calculations below are based on an analysis of the major energy flows of the biosphere (Odum 1988). For detailed calculations, see Odum (1984, 1987) and (Odum, Odum, and Blissett 1987).

The importance of any flux or storage is determined as the proportion that its emergy is of the total annual emergy flux of the economy within which it is found (for convenience it is usually a national economy). In order to help people visualize emergy contributions, we have sometimes expressed the proportion of total national emergy in dollars of GNP:

> EM$ (Macroeconomic dollar value) of a flux or storage is defined as its solar emergy value divided by the emergy/money ratio for an economy for that year.

Calculated in this way, the macroeconomic value of an environmental resource is usually much higher than its market value. Whereas market values are what is important to the small scale transactions of individuals and businesses, macroeconomic values are suggested as the proper evaluation for public welfare and maximizing overall wealth and prosperity. One value should not be substituted for the other.

## DIFFERENTIAL EQUATIONS FOR EMERGY EVALUATION OF A STORAGE

Emergy of a storage is defined with the equations given in Figure 12.2. Emergy storage is not affected by the inherent depreciation required from a storage (energy flow to the heat sink). The energy dispersed in depreciation is a necessary part of the process of storing emergy. The transformity of the storage at any time is the emergy of the storage divided by the energy stored.

When dynamic models are simulated, there are equations for the state variables that may be calibrated in energy, mass, or monetary units as may be appropriate for each. After the model is running in the usual way, equations that calculate the emergy and transformity of each storage and flow can be added and values included in tabular or graphical output.

**Quantitative Definitions**

Energy Stored = Q; $dQ/dt = J - k1*Q - k2*Q$

EMERGY Stored = E:

If $dQ/dt > 0$ then $dE/dt = Tr_J*J - Tr_Q*k_2*Q$

If $dQ/dt = 0$ then $dE/dt = 0$

If $dQ/dt < 0$ then $dE/dt = Tr_Q*dQ/dt$

where transformity of Q = $Tr_Q = E/Q$

and the transformity of J = $Tr_J$

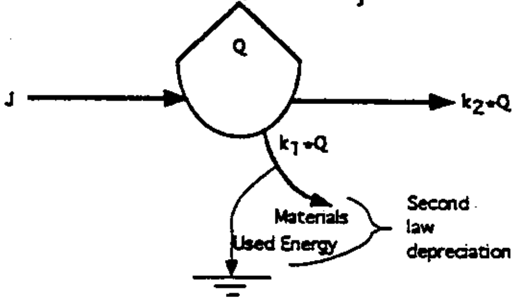


Figure 12.2. Definitions of flow and storage variables.

## CAPITAL FORMATION AND FEEDBACK USE

In both ecological and economic systems developing stored assets as part of an accelerating growth pattern is observed. Accompanying growth is the feedback from storage to interact and stimulate the production process multiplication in both ecology and economics. The simplest of general systems minimodels shows the kinetics and energetics of storage and process. The typical curve of growth with time is sigmoid because of the source limitation.

As systems develop storages, the turnover time increases, that is the storage per unit flux increases. Percent depreciation is less. Those who see maximizing storage (e.g., biomass in an ecosystem or assets in an economy) as an objective of succession and growth plot storage as a function of production and interpret the greater mass per unit production as increased efficiency and achievement. Their hypothesis is that systems organize to maximize storage (biomass, capital, money, stored wealth, etc.).

An alternative view is that there is an optimum storage that maximizes production. Only over a small range does building storage increase efficiency.

This shows how both viewpoints about storage, production and growth are alternate ways of looking at storage development (capital formation), even in the simplest of systems designs that emerge with self-organization for maximum intake and feedback of power.

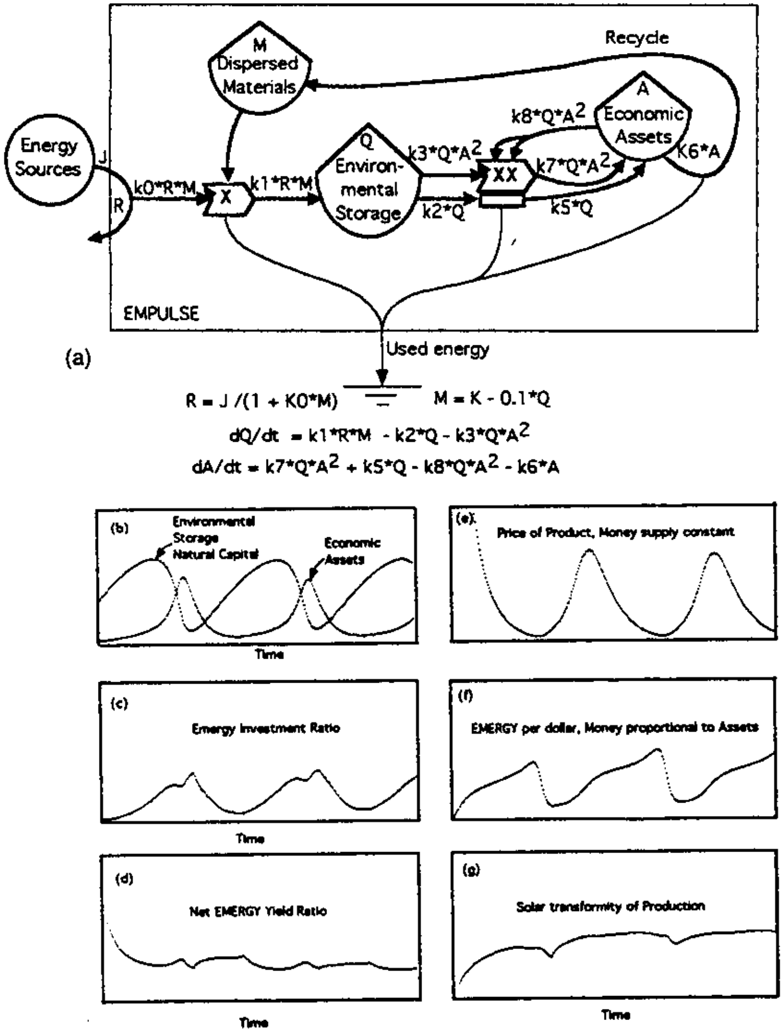
## ECONOMIC USE INTERFACES, EMERGY, AND MARKET VALUES

Figure 12.1b shows the interface between environment and economy, with work contributed by the environment and by human inputs that are purchased, such as fuels, goods, and services. Systems with products of no direct economic value are competing for available energy sources. There is emergy value added from purchased inflows. The further transformed products may be stored, available for use at yet higher levels in the economic part of the hierarchy.

When the resources from the environment are abundant, little work is required from the economy, costs are small and prices low. But this is when the contribution of real wealth is greatest. This is when everyone, assuming the human population is not large, has abundant resources from the natural environment.

When the resources are scarce, acquisition costs are higher, prices are high, and the market puts a high value on the product. But this is when there is little net contribution of the resource to the economy, real, natural wealth is scarce and standards of living low. In this sense market values are inverse to real wealth contributions from the environment and cannot be used to evaluate environmental contributions or environmental impacts.

With emergy evaluation all pathways are measured on the same basis, namely the solar emergy previously used up. Contributions from nature and those by humans are evaluated in common units.



$$R = J/(1 + K0*M) \qquad M = K - 0.1*Q$$

$$dQ/dt = k1*R*M - k2*Q - k3*Q*A^2$$

$$dA/dt = k7*Q*A^2 + k5*Q - k8*Q*A^2 - k6*A$$

Figure 12.3. Simulation model for examining the behavior of emergy analysis indices during oscillations. (a) systems diagram and equations; (b) oscillation of storages with alternating dominance of production and consumption; (c) emergy investment ratio; (d) net emergy yield ratio; (e) price of economic products when the money supply is held constant; (f) emergy/currency ratio when money supply is kept in proportion to economic assets; (g) solar transformity of economic products.

## ECONOMIC REINFORCEMENT OF ENVIRONMENTAL PRODUCTION

With the environmental use pattern in Figure 12.1b, the desirable resources are used up by growth of demand. As stored resources become scarce, prices rise, encouraging further depletion. As the desired system is reduced, competing production systems prevail that are not in economic use. Note the competing system in Figure 12.1b. For example, in the Gulf of Maine off the U.S, coast, once-abundant bottom-feeding fishes have been over harvested. Their place has apparently been taken over by less-edible swarms of dogfish (*Squalus acanthias*).

The Atlantic White Cedar (*Chamaecyparies thyoides*) in the eastern United States was a preferred tree for harvesting smooth-grain timber in colonial times and is now scarce, its place taken by other wetland species. However, more sustainable forest systems have persisted in Sweden over several hundred years by human practices that stimulated the regeneration processes.

To maintain or restore an environmental storage, some reinforcement has to be applied to the desirable production subsystem feeding back from the economic users (Figure 12.1b). If money is paid to people so that they contribute, the reinforcement of the environmental producers, it is an investment in natural capital. I used a computer simulation model to demonstrate the way a system like that of Figure 12.1b, but without reinforcing feedback, eliminates the desirable stock, while the system in Figure 12.1b, with a feedback reinforcement, sustains the storage and continues the desired fishery production (Odum 1993).

## UNDERESTIMATING NATURAL CAPITAL WITH MONETARY EVALUATION

Some authors use the monetary cost of replacing a resource storage as a measure of its value. This is incorrect, underestimating the wealth required for replacement, because the free environmental contributions are not included. For example, the figures by Repetto (1992) for natural capital are only for the human contributed part of those resources. Notice in Figure 12.1b the way the emergy for the economic feedback to help restore natural capital is only part of the emergy required. The rest is derived from the energy sources on the left.

Thus, evaluations of natural capital with monetary cost underestimate the contributions to the system's real wealth. If sustainable natural capital is the objective, underestimating their value will further contribute to their loss. Without feedback reinforcement from the human economy the environmental producers that are necessary for maximum economic production are pulled down by the exponential growth tendencies of the consumers, thus diminishing the wealth on which the buying power of money is based.

## HIERARCHICAL DISTRIBUTION OF NATURAL CAPITAL

Because many joules of energy of one kind converge in any energy transformation, producing fewer joules of the next energy type, all the processes are part of an energy hierarchy (Figure 12.4). In the hierarchy from the very small to the very large ,there are storages at each level. Small storages affect small areas and turnover rapidly, whereas the larger storages affect larger areas and have long replacement times, lower depreciation rates, slower turnover times, larger sizes, and larger territories of support and influence that go with higher position in hierarchies.

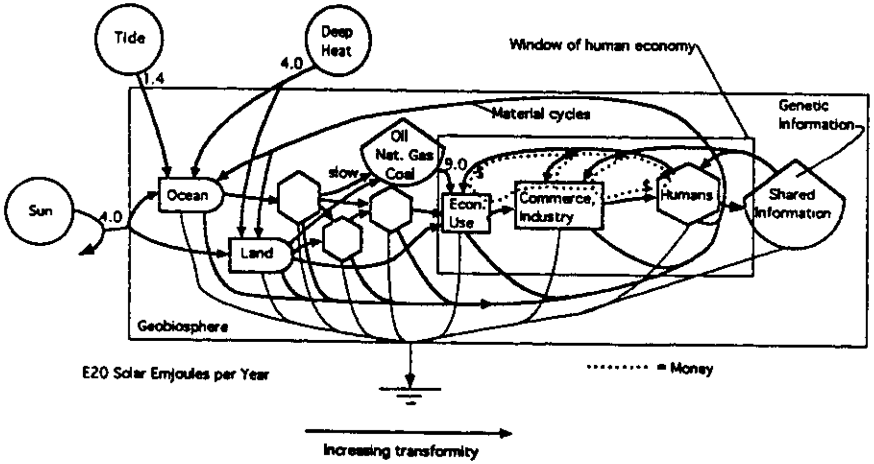


Figure 12.4. Highly aggregated diagram of the global hierarchy of energy transformation, the main emergy sources, and the intermediate position of circulating money. Numbers are annual flux of solar emergy inputs to the global system.

Within the geobiosphere of the earth (Figure 12.4), input energies from the sun, from the tides, and from the heat sources deep in the earth interact as a single coupled system with a network of processes that converge with the production and maintenance of storages of globally-shared information. Solar transformities increase from left to right in Figure 12.4 along the series of successive energy transformations. Solar transformity measures the position in the energy hierarchy and indicates the appropriate range of utility. Some emergy storages of the global system are given in Table 12.1.

Circulation of money provides more efficient processing on the scale of human beings and their businesses. Accumulating storages of monetary capital goes with the phases of accelerating growth, and facilitate the autocatalytic incorporation of the environmental resource storages into the consumer frenzy and its phases of rapid growth that characterize periods of development in human economies.

Table 12.1. Emergy of some Global Storages (Natural Capital)* Possible Orders of Magnitude

| Item | Replacement time, years | Stored Emergy*, sej | Macroeconomic Value, 1992 Em$** |
|---|---|---|---|
| World infrastructure*** | 100 | 9.44 E26 | 6.3 E14 |
| Freshwaters | 200 | 1.89 E27 | 1.26 E15 |
| Terrestrial ecosystems | 500 | 4.7 E27 | 3.1 E15 |
| Cultural & technol. information | 1 E4 | 9.44 E28 | 6.3 E16 |
| Atmosphere | 1 E6 | 9.44 E30 | 6.3 E18 |
| Ocean | 2 E7 | 1.89 E32 | 1.25 E20 |
| Continents | 1 E9 | 9.44 E33 | 6.3 E21 |
| Genetic information of species | 3 E9 | 2.8 E34 | 1.86 E22 |

* Product of annual solar emergy flux, 9.44 E 24 sej/yr and order of magnitude replacement times in column 1.

**See notes in A.

***Highways, bridges, pipelines, etc.

## PHYSICAL VERSUS MONETARY CAPITAL IN A MACROECONOMIC SYSTEM

The accumulation of storage provides the means for operating and controlling a system and for expanding a system, or starting new systems. Accumulating capital is a way of controlling a system, expanding a system or starting new systems. In an economy, however, the flows of money are a coupled counter-current to the flow of goods and services.

Behaviors of money and real wealth assets are on very different time scales. Money has a rapid flux, and storages of money have a rapid turnover time. Storages of real wealth may be large relative to flows and depreciation so that turnover times are much longer. The turnover time of the main features of human society, such as the infrastructure and the information shared in culture, may be 50–300 years. The turnover time of capital accumulations of money may be 1–5 years.

Whereas it is often customary to refer to real storages using the money measures of its formation, in a more complete systems approach to economics, money storages and fluxes are kept separate from those of real wealth, and the various coupling relationships carefully studied. Storage of wealth and the physical wealth are both represented by tank symbols (storage unit symbol). Dynamic models and computer simulations of ecological-economic systems thus avoid the confusion of using one variable to represent another, since the roles and processes are different. Simulation models of macroeconomics of this type were given previously (Odum 1983; 1987).

## CHARACTERISTICS OF OSCILLATING REGIMES

The real world is observed to pulse and oscillate. There are oscillating steady states. In most systems, including those which people are part of, storages are observed to fill and discharge as part of oscillations. Some are chaotic. Maximizing power is a hypothesis that may account for the hierarchical storages and oscillations. Systems that transform energy into forms capable of autocatalytic feedback reinforcement increase both the intake of energy and the efficiencies of its feedback use. There is an optimum loading for maximum power transformation in many kinds of processes (Odum and Pinkerton 1955; Curzon and Ahlborn 1975). Loading is measured by the ratio of output force or concentration to the input force or concentration. One of the reasons oscillating steady states (repeating oscillation) displace steady ones may be that energy transformations have better loading ratios between inputs and outputs if there is an alternation in the growth of interconnected storages (i.e., producers and consumers; Q and A in Figure 12.3).

A number of simple models generate the essence of the observed alternation of production and pulsing consumption. Models that self organize for maximum power in their growth and oscillations should include recycling of materials, competition of consumer pathways, autocatalytic reinforcement, and feedback interactions from storages of transformed energy. For our purposes here, the model in Figure 12.3a (Alexander 1978) makes clear what kind of dynamic design relationships may be consistent with long-term power maximization.

Figure 12.3b shows the alternation of production and consumption of the model that Richardson and Odum (1981) and Richardson (1988) showed is self-organizing for similar power even when different algorithms of spatial organization of dispersed production and hierarchically centered consumption are included. In the complex real world the small oscillations are nested within the larger ones; these give large scale patterns to the smaller ones while filtering and absorbing the small oscillations.

Growth and succession in oscillating ecological and/or economic systems can be visualized as a short segment within the longer continuing oscillations (Figure 12.5). The growth and leveling portions of the curve somewhat represent the old concepts of succession and climax, but now it is necessary to consider the stage of coming down after which there is regrowth again. In the simplest of pulsing models (Figure 12.3a), there are three storages: (1) the dispersed materials, (2) the assembled resource products, and (3) the storage of temporary assets that are part of the consumer frenzy.

According to the pulsing paradigm, there is a period when net production of primary products is positive, with some growth of consumers. Then, when the product of production storage and consumer storage reaches a threshold that accelerates autocatalytic and higher order pathways, the system shifts to a temporary net consumption of products as the consumer assets make a temporary surge. In the case of the global economy, the accumulated products are the environmental resource, and the consumer storages are our economic, informational, and cultural assets.

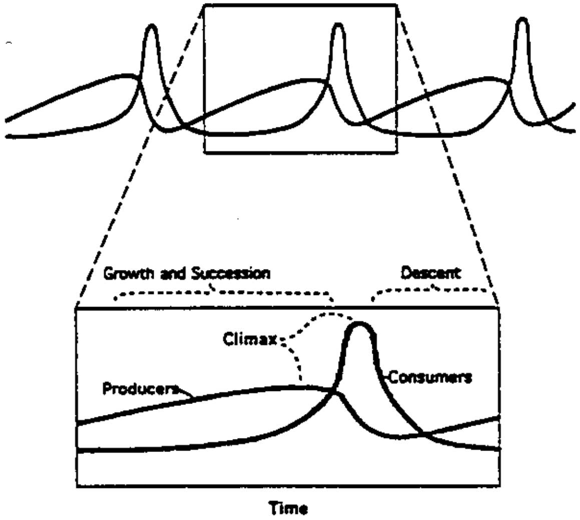


Figure 12.5. Succession, climax and descent seen as a window of time within a power-maximizing oscillatory steady state (Odum 1983, p. 445).

In the past we have sought power-maximizing, thermodynamic limits for efficiencies, transformities, investment ratios, etc. If power is maximized by oscillating systems with storages filling and discharging along the levels of hierarchy, then we have to recognize that energy transformation parameters have a varying baseline, with different values appropriate at different stages in the oscillatory cycle.

Figure 12.3 b–e shows the oscillation of some energy characteristics of the model as it alternately fills storages of natural and economic assets. The top right (Figure 12.3e) was obtained by holding the money supply constant. Prices of production are minimum when the rate of use of resources is largest, when wealth is greatest. The property of decreasing cost per unit resource has been misinterpreted by Simon and Kahn (1984) as evidence of the unimportance of resource shortages to economic vitality. The simulation shows the way resource determinism generates the curves of those authors. The declining cost part of the curve occurs when the resources are being transformed into assets that help process more. The declining cost is the action of resources feeding back to capture more resources. Some of this is resource emergy in the form of technology that increases efficiency (as said by Kahn and Simon) but these are resource-based and depreciate away when their emergy support lessens.

In Figure 12.3f, money was added in proportion to assets, so that there was no inflation. Towards the end of the rapid growth period the emergy/dollar ratio falls, as has been observed in highly developed countries (Huang and Odum 1991).

Even the efficiencies oscillate. The solar transformity varies (Figure 12.3e), becoming less efficient in times of strong feedback acceleration. Higher transformity (lower efficiency) is thermodynamically selected for during the transfer of storage to higher levels, because of the trade-off that favors a lower-than-maximum efficiency for maximizing power.

The net emergy yield ratio is defined as the ratio of the emergy of the yield of a production process divided by the feedback emergy from the economy in the process. It is a useful measure of a primary energy source's ability to support other processes. The net contribution is higher when natural resource storages are large and decreases with exploitation.

The emergy investment ratio is defined as the ratio of the purchased emergy feeding back from the economy to the free contributions of emergy from the environment. It measures the intensity of economic development relative to environmental use. With the development of assets in the period of frenzied growth, the loading on the environment is greater, and the intensity of feedback investment is larger.

## STORAGE MANAGEMENT FOR MAXIMUM PROSPERITY

If this oscillating pattern is the normal one, then sustainability concerns managing, and adapting to the frequencies of oscillation of natural capital that perform best. Sustainability may not be the level "steady-state" of the classical sigmoid growth curve but the process of adapting to oscillation. The human economic society may be constrained by the thermodynamics that is appropriate for each stage of the global oscillation.

In the simplified models presented here, there is an appropriate time in the temporal cycle at which natural storages are built and a time when they are to be consumed. If the model is appropriate, there needs to be a changing public policy to maximize power and production for each stage in the cycle. There is an appropriate efficiency possible at each stage. The transformities also vary in a cycle. The model suggests the way our current realms may be conforming to what is needed for the stage in the thermodynamic cycle.

When this model is simulated with coefficients that accumulate products for a long time, the consumer pulse is very sharp, catastrophic in its severity and with high transformity. The larger emergy required over a longer time of storage achieves a commensurate effect by delivering a consumer pulse in a shorter time. What is regarded as catastrophe at smaller scale of time and space is the normal cycle in the window of the larger scale of time and space. Examples are fires, floods, hurricanes, earthquakes, and volcanoes.

Depending on the indices used, the global economy of 1992 appears to be at or near its climax crest that was reached by using up of natural storages lower in the hierarchy. If so, we go now to a period when the consumer storages come down, and there is a time of net production of environmental products after which another consumer frenzy can repeat.

## SUMMARY

By evaluating the emergy of storages in environment and within the economy, decisions can be made for the short run as to what policies maximize the economy by utilizing appropriately the available capital of several kinds. By measuring emergy and its derived macroeconomic value, uses can be made commensurate with the work required for replacement, thus helping maximize economic performance.

For the longer run, the models of oscillating storage give insights on when to use and when to conserve. Conservation policy should work towards that economic use and feedback reinforcement that oscillates for maximum performance in the long run and the short run.

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