Energy Analyses as a Tool for Sustainability: Lessons from Complex System Theory

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INTRODUCTION

Part 1 of this paper presents an innovative approach for study of the evolution and stability of socioeconomic systems. The approach is based on (1) several distinct views of socioeconomic systems obtained by non-equivalent descriptions of those system on different hierarchical levels and (2) equations of congruence of flows of matter, energy, human time and money across different hierarchical levels to link non-equivalent views. Because a socioeconomic system may be described as a nested dissipative adaptive system (holarchy), a few related concepts in complex system theory are discussed. Particular focus is on the crucial analysis of unavoidable conflict between short-term goals and long-term goals that affect every holarchy. Part 1 also presents a method for describing evolution of socioeconomic systems in parallel, on different hierarchical levels, an approach allowing study of the exergy budget of various nested elements of a holarchy.

Part 2 first describes the procedure used to set up a database of 107 countries and comprising more than 90% of world's population. Four applications of the approach described in Part 1 are presented: (1) BEP is an indicator of development obtained by combining only biophysical variables. BEP is better than GNP in correlating with a set of more than 20 traditional indicators of development used by the World Bank. (2) A common trajectory of development for the 107 countries and their evolution is described in an appropriate state space. (3) Equations of congruence across levels can link demographic variables, level of development, existing technology, and availability of natural resources. (4) "demographic transition" based on the dataset and approach used can be studied in terms of a shift from one metastable equilibrium of the dynamic societal energy budget to another.

PART 1: THEORETICAL MODEL

Rationale of the Model

The triadic reading of dissipative hierarchical systems proposed by Salthe[32] allows definition of three levels of interest: (1) the socioeconomic system as the focal level; (2) the ecosystem within which the socioeconomic system operates as the

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higher level; and (3) the set of individual households and economic sectors operating within the socioeconomic system as the lower level.

The present methodological approach is discussed in detail in Giampietro,[8,10] Giampietro *et al.*,[15] and Giampietro and Mayumi.[16] Practical applications and validation are in Giampietro,[9,11–13] Giampietro *et al.*,[18] Giampietro and Pastore,[17] and Pastore *et al*.[27] The current approach has two main characteristics: (1) several distinct views of the same socioeconomic system are obtained on different space–time scales and (2) a set of equations of congruence of flows of matter, energy, human time, and money across levels can link these different nonequivalent views. Each distinct, view-dependent description (e.g., what is perceived as "good" or "bad" by individual households, by national economies, by natural ecosystems) defines a set of indicators of "good" and "bad." Clearly, different sets of indicators of performance depend on both space-time scale and "encoding," select description of the interaction between human and ecological systems over a defined space–time scale.

Choice of a method of encoding is unavoidably arbitrary. However, biophysical constraints allow a check of whether or not different scenarios are feasible and those constraints can examine reciprocal effect of parallel changes on different hierarchical levels.

Main Theoretical Concepts

Socioeconomic Systems as Nested Dissipative Hierarchical Systems (Holarchies)

A dissipative system is hierarchical when it operates on multiple space–time scales with different process rates.[26] Such a system can be analyzed through division into successive sets of subsystems (see Simon,[34] p. 468). Alternative nonequivalent methods of description (encoding) exist for the same system.[38]

Each component of a dissipative nested hierarchical system may be called a "holon," a term introduced by Koestler[21] to stress that a holon has a double nature. A holon is a whole made of smaller parts that is simultaneously part of a larger whole (Allen and Starr,[2] pp. 8–16). Holons have implicit duality and composite structure at the focal level. Because of their interaction with the rest of the hierarchy, however, holons perform functions that contribute to "emergent properties" observable only from higher levels of analysis. A nested hierarchy of dissipative systems can be termed a "holarchy."[21]

Because of peculiar means of functioning in cascade on parallel scales, the behavior of a holarchy requires examination of both structural stability and relational functions. In fact, analyzing a holarchy only in terms of structures (ceteris paribus or steady-state) implicitly assumes (1) initial conditions reflecting the history of the holarchy and (2) a stable higher level holon for which structures of the holarchy perform functions. Similarly, functions in a certain holon require structural stability of other holons at the lower level.[34] Description of the dynamics of a focal-level holon such as society as a whole must face both the issue of structural constraints (how or what occurs at lower level holons) and the issue of functional constraints (why or what occurs at higher level holons). The complex behavior of holarchy needs complementary descriptions.

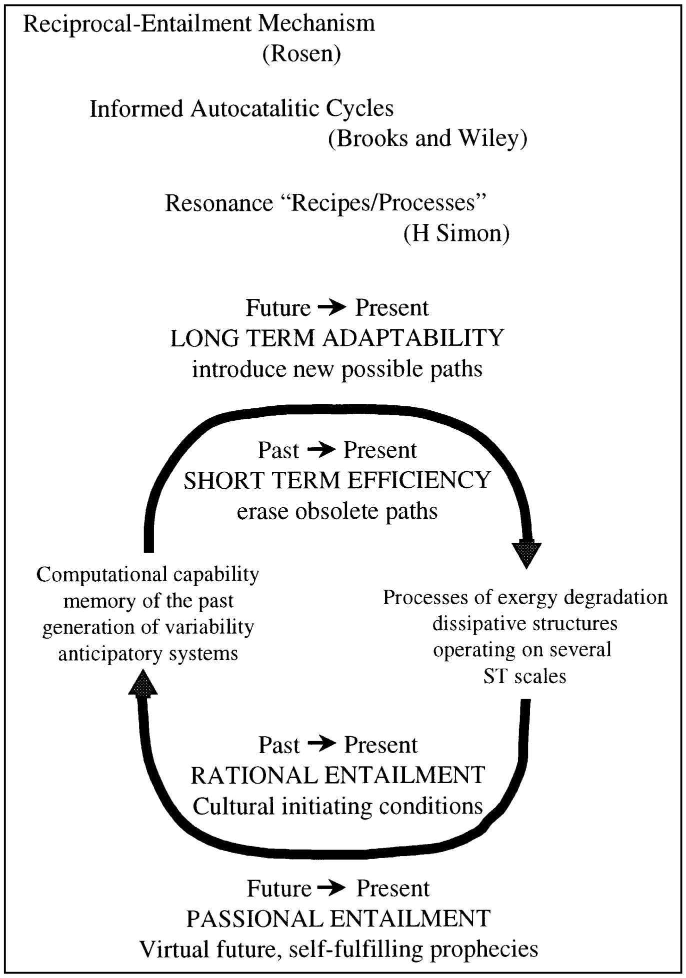

FIGURE 1. Resonance between controls and processes.

Resonance between Useful Energy and Useful Information

According to Simon (see pp. 477–482),[34] dissipative systems may be described in terms of a resonance, "recipes inducing processes which in turn makes better recipes." Prigogine[29] observes that living systems can establish resonance between coded information (e.g., DNA) that induces physical process (e.g., metabolism) and physical processes that generate coded information.

The triadic model in FIGURE 1 shows resonance between the "computational capability of society" and the "processes of exergy degradation," resonance of the sort described by Simon and Prigogine. Both human societies and ecosystems may be seen as nested dissipative hierarchical systems stabilized by "informed autocatalytic cycles"[3,4] or by a "mechanism of reciprocal entailment between two systems of entailments operating across hierarchical levels."[30,31]

The proxy that assesses investments of "computational capability" defined at the hierarchical level of society is the profile of allocation of human time on different activities. A given level of technology can be assessed according to the magnitude of the ratio of exosomatic to endosomatic energy metabolized by society, and it is important to calculate how much the biological metabolism of humans is amplified by the exosomatic energy metabolism of machines. This exosomatic metabolism based on the level of technology can be seen as a measure of the amplification of human activity that boosts process of self-organization by adding new levels of organization to human biological metabolism.

The proxy that assesses investments of "useful energy" (controlled processes of exergy degradation) is energy input consumed in various economic sectors. Assessments of this energy can be used as indicators of the investment in terms of exergy degradation allocated to stabilizing structures and functions.

Brooks *et al.*[4] epitomize resonance between energy flows stabilizing information flows and information flows stabilizing energy flows: "biophysical systems are complex, thermodynamic systems stabilized far from thermodynamic equilibrium by a process of self-organization induced by informed autocatalytic cycles."

Efficiency versus Adaptability

H. T. Odum[24,25] indicates that in economic and ecological systems based on a dynamic equilibrium of energy flows, cost of energetic investment must be repaid in order for those systems to be stable. According to Lotka[22] and Morowitz,[23] the autocatalytic process that sustains dissipation of economic and ecological systems must be able to increase its rate of exergy degradation through larger and faster matter cycling.

The autocatalytic process is related to two functions in the evolution of dissipative systems,[33] and dissipative systems must be able to stabilize a specific rate of exergy degradation related to two goals. The first goal of dissipative systems is to guarantee short-term stability of current dissipative structures that maintain existing metabolism of matter flows by using existing favorable gradients. Short-term stability relates to efficiency according to boundary conditions, a set of aims and information about boundary conditions stored in the systems. The second goal of dissipative systems is to guarantee long-term stability of the process of dissipation through maintaining high compatibility of patterns of self-organization in the face of a changing environment. Long-term stability relates to adaptability,[6] the ability to be efficient according to unknown future aims and unknown future boundary conditions of the systems. Adaptability can only be obtained by developing and maintaining a repertoire of diverse possible behaviors within dissipative systems. In other words, adaptability can be obtained by expanding state space, which in turn depends on expanding the computational capability of the dissipative systems of controls determining possible behaviors of those systems.

Description of Socioeconomic Systems through Encoding

Investments in Adaptability and Efficiency

Ulanowicz[36] divides the network of matter and energy flows in an ecosystem into two parts, a hypercyclic part and a purely dissipative part. A hypercycle is a net energy producer for the rest of the ecosystem, comprising activities that use free energy outside the ecosystem (e.g., solar energy, stocks of energy inputs). The hypercycle generates positive feedback into an ecosystem by introducing degradable exergy at a higher rate than exergy is consumed. The hypercycle drives the whole ecosystem and keeps it away from thermodynamic equilibrium. The purely dissipative part of an ecosystem comprises activities that are net energy degraders, but this dissipative part controls the entire process of energy degradation and stabilizes the whole system. A purely hypercyclic ecosystem cannot remain stable, for without the dissipative part positive feedback "will be reflected upon itself without attenuation, and eventually the upward spiral will exceed any conceivable bounds " (see Ulanowicz,[36] p. 57).

Following Ulanowicz's idea, it is possible to assume that (1) processes of exergy degradation and the fraction of computational capability (human time) invested in productive economic sectors aim at improving "efficiency" and (2) processes of exergy degradation and computational capability invested in household and service sectors aim at improving "adaptability." FIGURE 2 shows the total amount of energy consumed by society (ET) divided into CI (energy for activities related to efficiency) and FI (HH + SS) (energy for activities related to adaptability).

1. HH is energy investment in household sector activities, purely dissipative activities consuming net energy in the short term. These activities are not strictly in the form of defined roles or protocols and include sleeping, per-

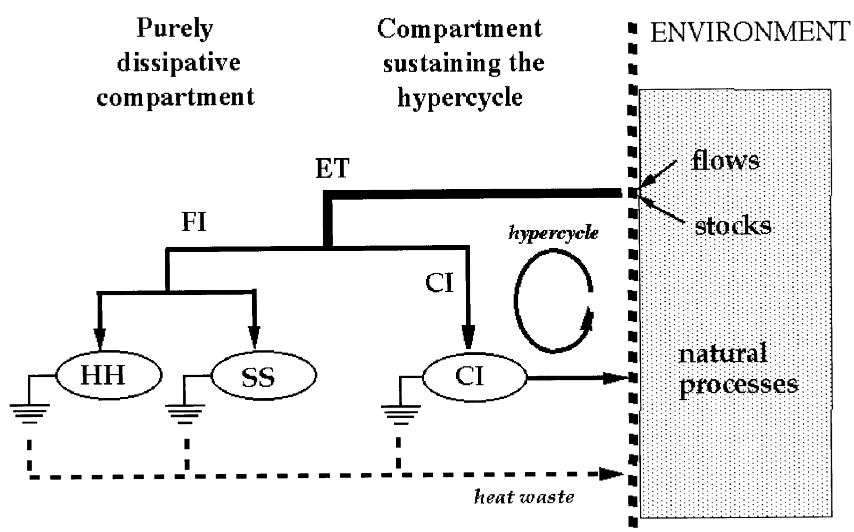

FIGURE 2. Structure of exosomatic energy flows in society.

sonal care, leisure time, and activities performed by the economically inactive population.

2. SS is energy investment in service sector activities, which are also dissipative, but take the form of defined social roles such as job positions and service activities like police, army, health care, education, and insurance.
3. CI is energy investment in activities in productive economic sectors having positive return in terms of energy flows. These activities take the form of defined social roles (e.g., job positions), in the energy and mining sector, the manufacturing sector in modern economies, the food security sector, and the environmental security sector. These activities generate hypercycle.

Regarding investment of human time (selected proxy for computational capability), the total time available to a society is:

- THT = total human time = number of individuals (population) × hours in a year (hy)
- hy = 8760 (hours in a year)
- WS = work supply = B + C = amount of time (hours) that the economically active population allocates to work annually as opposed to sleeping, leisure, and so forth
- A = THT − WS = Non working time, including sleeping time, leisure time, and all the time of the non-working population;
- C = hours of work delivered in productive sectors of the economy
- B = hours of work delivered in the service sector of the economy

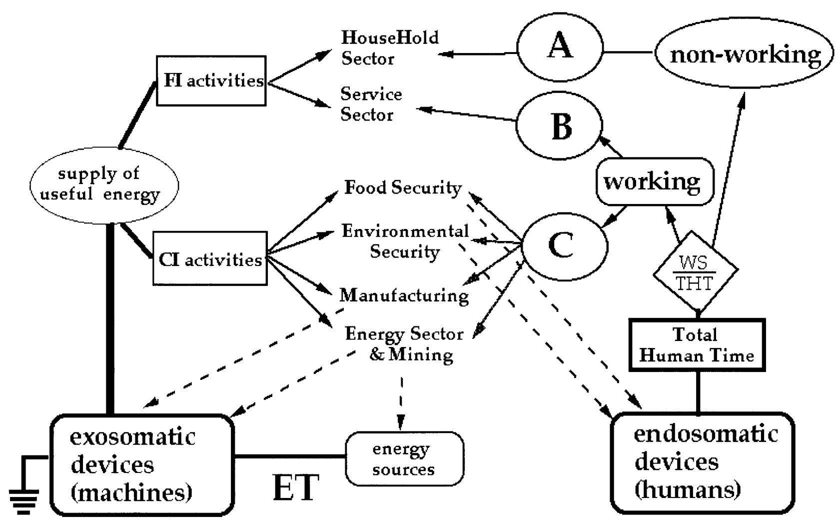

FIGURE 3. Parallel allocation of exosomatic energy and human time in society.

FIGURE 3 shows parallel allocation of energy and human time on various activities of the economy, balancing efficiency and adaptability.

Dynamic Exergy Budget

The energy throughput at which society's exergy budget can be stabilized (demand = supply) is defined by (1) socioeconomic characteristics of society generating demand and (2) characteristics of the exosomatic autocatalytic loop generating supply. Several variables can characterize the socioeconomic organization of society (demand side) and the nature of the exosomatic autocatalytic loop of energy (supply side). The dynamic equilibrium between demand and supply can then be studied by using existing relationships between groups of parameters determining demand and supply.

Demand side. The flow of exosomatic energy consumed by society (ET) can be expressed as:

$$\text{ET} = (\text{MF} \times \text{ABM}) \times (\text{Exo/Endo}) \times \text{THT} \qquad \textbf{(1)}$$

where ET = energy throughput or flow of exosomatic energy (joules/year); MF = metabolic flow = flow of metabolic energy per kg of body mass of humans (joules/kg hr); ABM = average body mass = total mass (kilogram) of population divided by population; and Exo/Endo = ratio between exosomatic and endosomatic energy flows.

The ratio of working time to total human time can be expressed as:

$$\text{WS/THT} = (\text{B} + \text{C})/(\text{population size} \times \text{hours in a year}) \qquad \textbf{(2)}$$

Combining relations (1) and (2) definies bioeconomic pressure (BEP), which measures exosomatic energy throughput consumed at the level of society per hour of labor time in productive sectors of the economy:

$$\text{BEP} = \text{ET/C} = (\text{ABM} \times \text{MF}) \times (\text{Exo/Endo} \times (\text{THT/C}) \qquad \textbf{(3)}$$

Supply side. CI/C = exosomatic energy throughput per hour of labor in productive sectors (MJ/hr). The value of this parameter is defined by technical coefficients (inputs/outputs of productive sectors) which in turn are affected by (i) existing technology and (ii) quality of accessible natural resources.

C/THT = fraction of total human time (THT) allocated to activities in productive sectors. ET/CI = return for the socioeconomic system of energetic investment in productive sectors. The value of this parameter is also defined by a set of technical coefficients for productive sectors.

$$\text{SEH} = \text{ET/C} = (\text{ET/CI}) \times (\text{CI/C}) \qquad \textbf{(4)}$$

where strength of the exosomatic hypercycle (SEH) is defined as the exosomatic energy throughput (societal power) generated at the level of society per unit of work delivered in productive sectors. SEH on the supply side is the analog of BEP on the demand side, and SEH depends on two characteristics of the exosomatic compartment:

1. ET/CI measures how much exosomatic energy throughput of society is "eaten" by the hypercycle. ET/CI relates to the output-to-input energy ratio of processes that

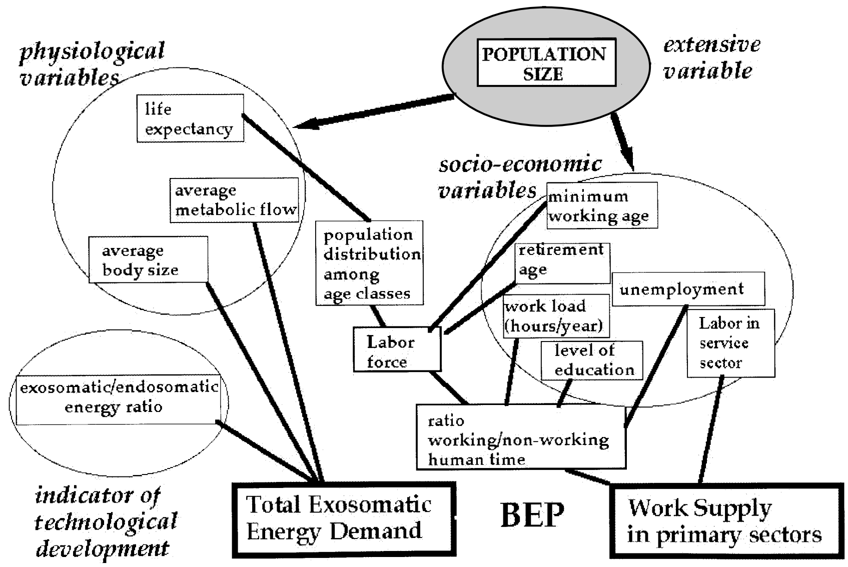

FIGURE 4. Variables defining the bioeconomic pressure (BEP).

make resources available to the economy. ET/CI can be expressed as a combination of technical coefficients (input/output ratios) for each of the productive sectors.

2. CI/C measures power level per worker in productive sectors. WS/THT decreases in developed countries because of an aging population, longer education, and smaller work load. In developed countries B/(B + C) increases because the service sector absorbs a large fraction of available work supply. Continuous decrease of C/THT is feasible only if there is concomitant increase in CI/C.

Identities and Congruence of Biophysical Flows across Levels

Relations between BEP and SHE lead to dynamic exergy budget:

$$(\text{ABM} \times \text{MF}) \times (\text{Exo/Endo}) \times (\text{THT/C}) = (\text{ET/CI}) \times (\text{CI/C}) \qquad \textbf{(5)}$$

A dynamic exergy budget links the physiological and socioeconomic variables in FIGURE 4 with and technological variables in FIGURE 5. Technical coefficients (input/output values) in FIGURE 5 include labor as input and the household sector as an economic sector. Dynamic equilibrium between demand and supply can be studied in terms of relationships linking groups of parameters that determine demand and supply.

The model in this paper defines quantity (ET/C) by using three different encodings of relevant qualities of socioeconomic systems:

1. ET/C is determined by parameters reflecting socioeconomic characteristics such as demographic structure, income, retirement age, and work load at the hierarchical level of the whole society. For example, ET/C = (ABM × MF) × (Exo/Endo) × (THT/C).

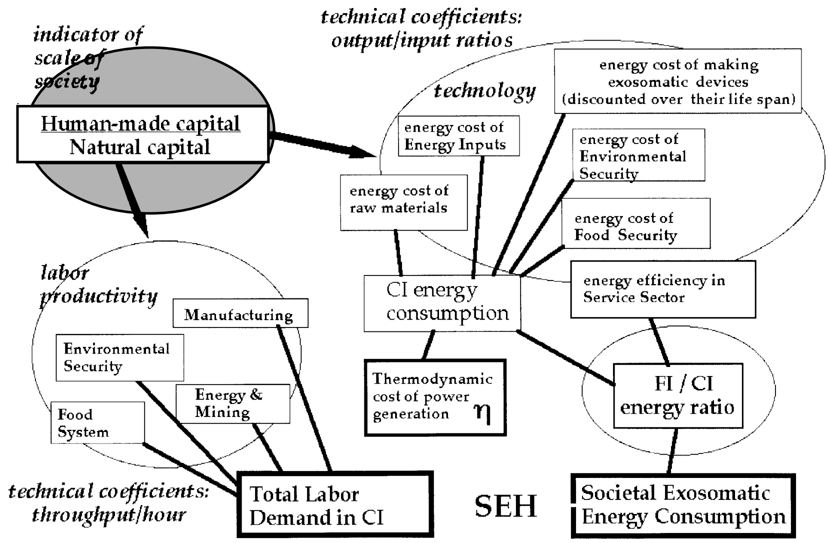

FIGURE 5. Variables defining the strength of the hypercycle (SEH).

2. ET/C is also determined by parameters reflecting technology, such as technical coefficients or input/output of different economic activities in different economic sectors. For example, in ET/C = (ET/CI) × (CI/C), the value of ET/CI and CI/C can be expressed as the sum of values of corresponding parameters describing performance of individual productive sectors such as agriculture, energy, and mining.

3. ET/C results from characteristics of the existing set of household types (existing range of life-styles) and distribution of individual households over that set. For example, in ET/C = $\Sigma ET_i/\Sigma C_i$, ET_i is the metabolism of household type i, and C_i is the amount of working time that household i invests in productive sectors.

The result of three different encodings may appear trivial (ET = ET), but each formulation of this identity links different characteristics of society at different hierarchical levels. This new model defines the same flows in redundant ways, but each time the model uses a different combination of nonequivalent descriptions. For example, the new model considers overall data assessed at the national level, data referring to different economic sectors reflecting technical coefficients, demographic variables, data characterizing metabolism of household types, and curves of distribution of households over the set of possible types. Parameters values obtained by adopting these non-equivalent descriptions are affected by internal constraints determined through forcing congruence of biophysical flows across different hierarchical levels.

Checking Sustainability across Hierarchical Levels

Interface focal/lower level (based on intensive variables). This new model can deal with the question of whether or not the current material standard of living is techni-

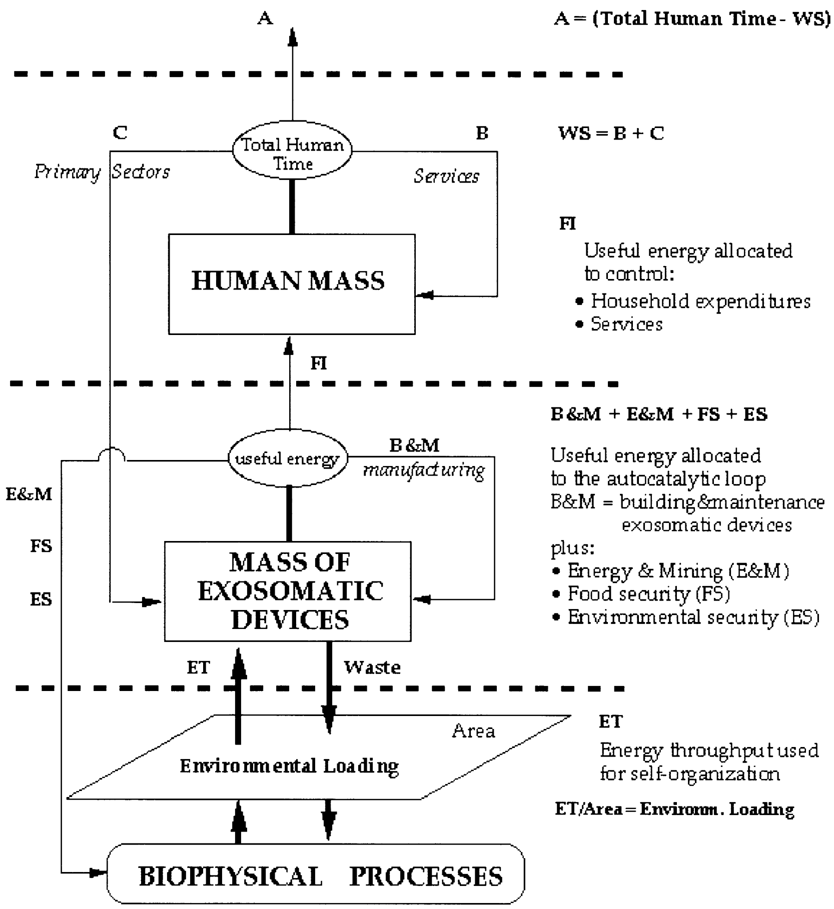

FIGURE 6. Intensive and extensive variables describing the economic process within its biophysical environment.

cally feasible and culturally acceptable, because the model considers congruence between three parameters:

1. BEP is a good indicator of development.
2. BEP* is the minimum acceptable level of material standard of living, below which lower level components (individual households) lose their sense of belonging to the holarchy. Aspiration for improvement in standard of living expressed by individual households generates "internal pressure," pushing the socioeconomic system to increase SEH continuously in order to make energy and matter throughputs faster and faster. Aspiration for improvement is particularly important when there are big gradients of BEP values among countries. Rapid increase in BEP is necessary for developing countries to approach BEP values of developed countries.

3. SEH is determined by technical coefficients dependent on technology and quality of natural resources.

There are two questions regarding the compatibility focal/lower level: (1) Is it possible to have a BEP value desired by people greater than the SEH value achievable by technology? (2) Can BEP be greater than BEP* by Λ? (Λ is the difference that people are willing to accept to preserve societal identity).

Interface focal/higher level (using intensive and extensive variables). It is necessary to consider whether amounts of inputs taken from ecosystems and amounts of wastes dumped into ecosystems are compatible with stability of processes of self-organization occurring in ecosystems with which a society interacts. To consider this topic, two concepts are necessary: (1) environmental loading (EL) and (2) critical environmental loading (CEL) (H.T. Odum, 1983, 1986).[24,25] EL is defined as human interference in the activity of natural systems, and can be obtained by comparing (i) assessments of the scale of human activity (input demand and waste production) with (ii) assessments of the scale of ecosystem activity (regenerative capacity and absorbing capacity). CEL may be defined as the maximum level of EL compatible with stability of the process of self-organization of ecosystems with which society interacts. Consideration of the compatibility focal/higher level leads to the question of whether or not current EL is less than CEL.

FIGURE 6 shows that the hierarchical nature of the model permits linking information related to the internal organization of the system (BEP and parameters determining SEH) to information about environmental loadings (size and nature of societal metabolism in relation to size and nature of ecological processes providing the life-support system for the economy).

PART 2. VALIDATION OF THE MODEL USING HISTORICAL DATA

Database

Database in this paper is based on 107 countries comprising more than 90% of the world's population, using official data of the UN, FAO, and World Bank.

Parameters for Calculating BEP

(1) "ABM × MF"

- ABM is calculated by considering average weights (by age and sex classes) and population structure as reported in James and Schofield,[20] based on the total population of 1992 reported in *World Tables*, published by the World Bank.[40]
- MF is computed separately for age and sex classes of each country following database and protocols in James and Schofield[20] and merged into national averages.

(2) "Exo/Endo"

- The annual flow of exosomatic energy is evaluated according to UN energy statistics[37] for commercial and traditional biomass consumption in 1992, using a conversion factor of 29.3076 terajoules per thousand metric tons of coal. A minimum value of 5/1 is adopted for countries, with a resulting value of exo/endo <5 since official statistics tend to underestimate the contribution of animal power, and biomass for cooking and for building shelters in rural communities.[14]

- Computation of the annual flow of endosomatic energy starts with "ABM × MF" value and population size of 1992 as reported in *World Tables*.[40]

(3) "THT/C"

- The fraction of economically active population and distribution of labor force in different economic sectors derive from UN statistics, including 1990–1993 data.
- For each country, transport is divided between productive sectors and service sectors, according to working time spent in productive sectors and service sectors.
- Workload is a "flat" value of 1800 hours/year, including vacations, absences, and strikes.

Material Standard of Living and Socioeconomic Development

Basically, conventional indicators are from *World Tables*,[40] with 24 indicators divided into three groups. Data used in calculating these 24 indicators come from the FAO (*FAO Yearbook*[7]), the UN (*Statistical Yearbook*[37]), and the World Bank (*Social Indicators of Development*[39]). Data refer to the latest available year between 1991 and 1993. Data on prevalence of malnutrition in children come from ACC/SCN.[1]

(i) *Nutritional status and physiological well-being (8 indicators)*: (1) life expectancy, (2) energy intake as food, (3) fat intake, (4) protein intake, (5) average BMI adult, (6) prevalence of child malnutrition (Wt/Ht < 2 z-score of NCHS reference growth curve), (7) infant mortality, and (8) percent low birth weight.

(ii) *Economic and technological development (7 indicators)*: (9) GNP per capita, (10) percent GDP from agriculture, (11) $ARL_{\$}$ (average return of labor in terms of added value = GNP/WS), (12) percent of labor force in agriculture, (13) percent of labor force in services, (14) energy consumption per capita, (15) percent of GDP expended for food.

(iii) *Social development (9 indicators)*: (16) television/1000 people, (17) cars/1000 people, (18) newspaper/1000 people, (19) phones/100 people, (20) population/physician ratio, (21) population/hospital bed ratio, (22) pupil/teacher ratio, (23) illiteracy rate, (24) access to safe water (percent of population).

BEP as an Indicator of Development for Socioeconomic Systems

The more developed a society is, the smaller is the fraction of human time used to run productive economic sectors. However, energy throughputs within productive economic sectors dramatically increase as asociety develops. These two trends can be explained in terms of balancing adaptability and efficiency. With a high rate of energy dissipation (faster consumption of natural resources), it is highly probable that the society will eventually face changes in boundary conditions. Systems consuming more must invest more in developing adaptability.

The database in this paper can be used to check whether or not BEP can be an indicator of development within the present model of analysis. The database shows that BEP correlates strongly with classic economic indicators of development (TABLE 1). Therefore, BEP could replace GNP as an indicator of development according to a socioeconomic perspective. BEP is a good indicator of material standard of living, according to the conventional economic perspective and also directly links different perspectives (readings) of the process of development, reflecting various nonequivalent descriptions on different scales.

BEP reflects three views of the material standard of living in a society, from three different hierarchical levels of analysis:

1. "ABM × MF" (endosomatic metabolism per capita (MJ/hour) refers to physiological hierarchical level. The higher this value is, the better human physiological conditions are in that society. The present database shows that the feasibility domain of ABM × MF is within a minimum of 0.33 and a maximum value of 0.43.

2. "Exo/Endo energy ratio" (exosomatic metabolism per capita) refers to socioeconomic hierarchical level and short-term efficiency. According to our database and previous studies on preindustrial societies, the feasibility domain of the Exo/Endo energy ratio is within a minimum value of 5 and a maximum value of 90.

3. "THT/C" (total human time available in the society/working time allocated in productive economic sectors) refers to socioeconomic hierarchical level and long-term adaptability. The database shows that the feasibility domain of THT/C is within a minimum value of 10 and a maximum value of 45. THT/C reflects the social implications of development, assessing allocation of human controls on long-term returns rather than on short-term returns (adaptability versus efficiency).

The database shows that the feasibility domain of BEP is within a minimum value of 18 MJ/hr, and a maximum value of 1500 MJ/hr. Increased value of this parameter reflects ability to increase the fraction of resources that a socioeconomic system actually invests in adaptability

Internal Constraints on the Evolutionary Pattern of Socioeconomic Systems

The model should show similarities in trajectories of development of various societies. The need for congruence of flows of energy and human time across hierarchical levels imposes constraints on the shape of possible paths.

FIGURE 7 graphs the path of development of six indicators against BEP and shows that 107 countries cluster around a given trajectory. Even more striking is the analysis of the same trajectory if one of the three factors determining BEP appears on the x-axis. In FIGURE 8, values taken by six indicators of development graph against the value of Exo/Endo and it is easy to identify a threshold value for Exo/Endo of 25/2, above which trajectory of development seems to reach a plateau. Similar observations apply to other two factors making up BEP: for ABM× MF, the plateau is about 9 MJ/day or 0.4 MJ/hour; for THT/C, the threshold value is 30/1.

TABLE 1. Correlation between BEP and some major indicators of development

Economic Indicators of Development	log (BEP), r
log (Gross National Product)	0.89
% of GNP from agriculture	0.85
US$ of added value per hour of paid labor	0.90
% of work force in agriculture	0.93
% of work force in services	0.88
log (energy consumption per capita)	0.98
% of income spent on food	0.89
Physiological Indicators of Development	**log (BEP), r**
Life expectancy	0.88
Energy intake (in the diet)	0.83
Fat intake (in the diet)	0.80
Protein intake (in the diet)	0.79
Children malnutrition	0.83
Infant mortality	0.86
Low birth weight	0.62
Social Indicators of Development	**log (BEP), r**
Log (TV sets/inhabitants)	0.90
Log (cars/inhabitants)	0.90
Log (newspapers/inhabitants)	0.89
Log (phones/inhabitants)	0.89
Log (population/physician)	0.87
Log (population/hospital bed)	0.76
Pupils/teacher	0.74
Illiteracy rate	0.67
Primary school enrollment	0.58
Access to safe water	0.81

Links across Levels and Feasibility of Future Scenarios

Analysis of socioeconomic systems interacting in biophysical terms with their environment applies to discussion of feasibility of future scenarios. A set of characteristics describing a given socioeconomic system's demographic structure and material standard of living may be defined. Then it is possible to calculate: (1) technical coefficients required in specific economic sectors to match SEH demand generated by the "envisioned society" and (2) correspondent environmental loading , technological achievement required to keep environmental loading of a society below a critical value.

Two applications deserve consideration:

1. It is possible to analyze performance of farming systems using several sets of indicators reflecting different perceptions of "improvements" on different hierarchical levels. It is also possible to link various effects generated by changes within the

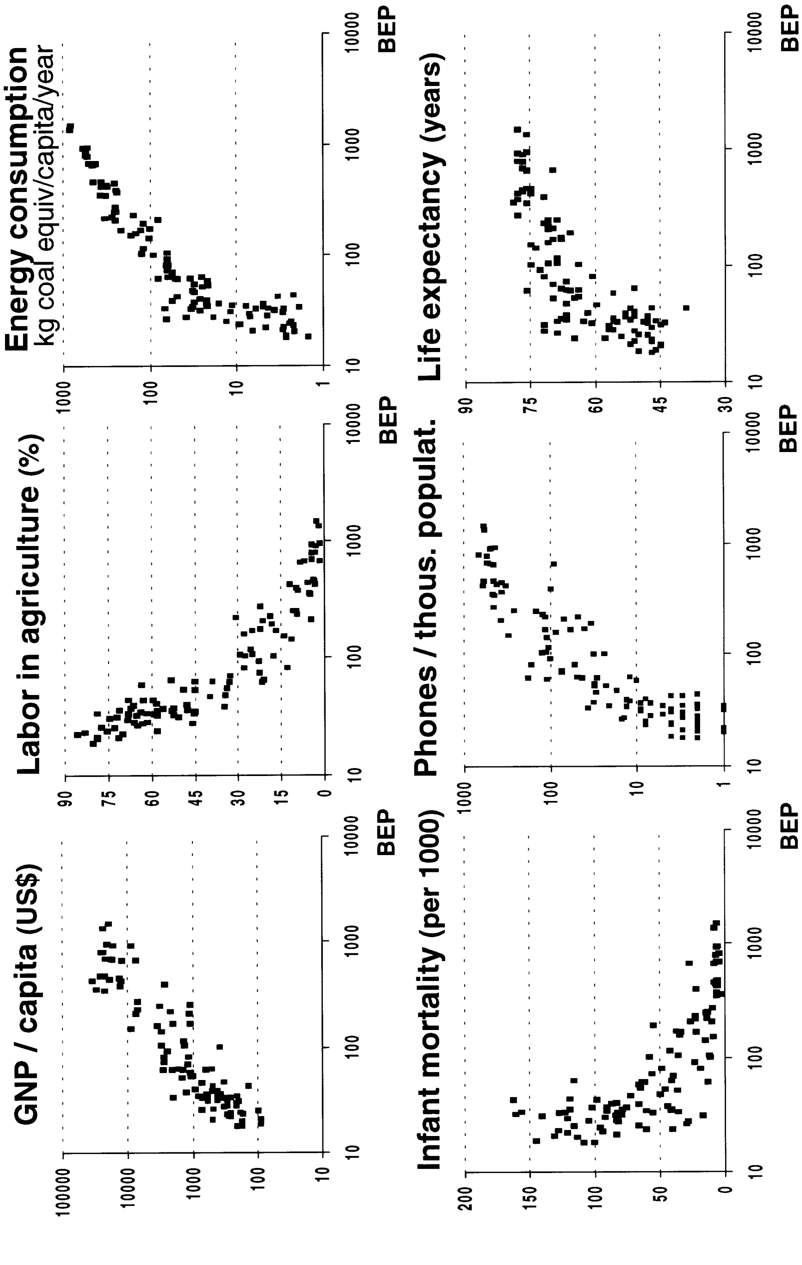

FIGURE 7. Correlation between BEP and major indicators of development.

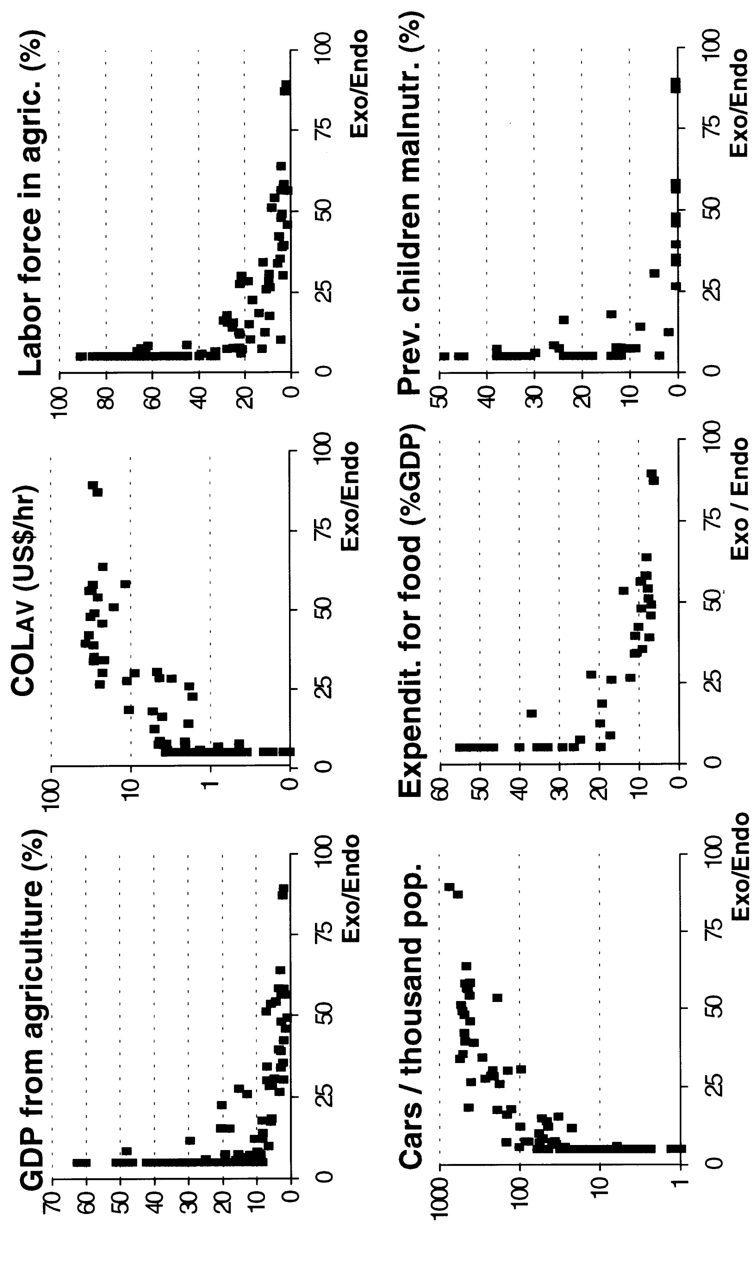

FIGURE 8. Correlation between Exo/Endo ration and major inidcators of development.

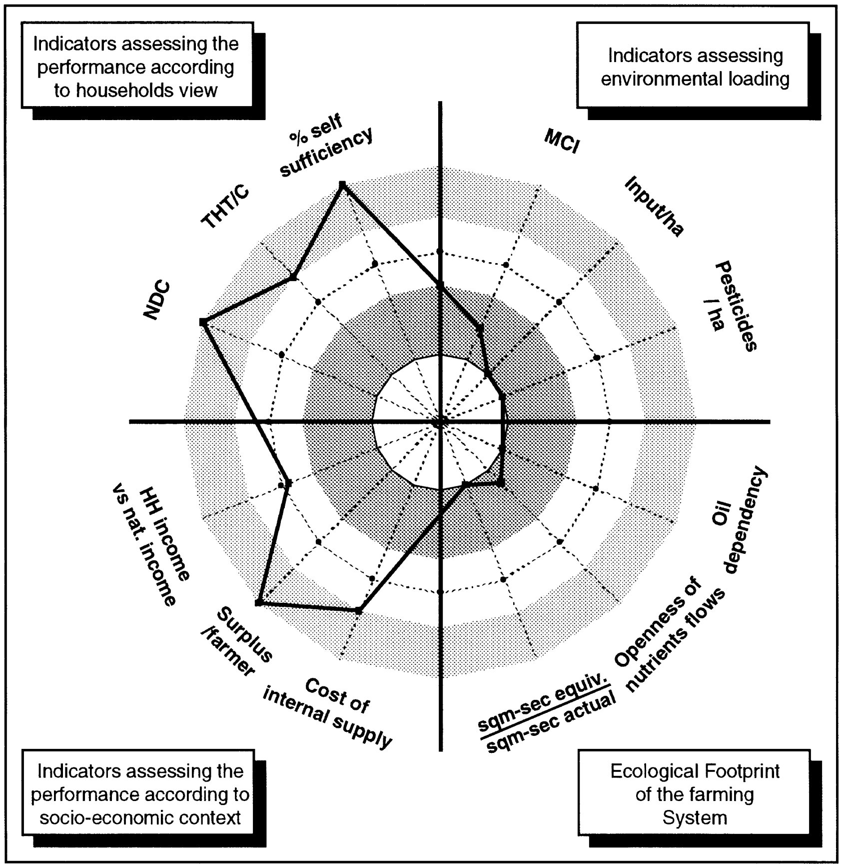

FIGURE 9. Indicators from four different perspectives.

hierarchical system. The application in FIGURE 9 has been developed in a four-year field project in China to study the mechanism of intensification of rural areas in relation to the issue of sustainability.[27] In this radar-type graph, several sets of indicators are divided into four quadrants, each of which contain a set of indicators related to the perspective of a particular holon (e.g., farmer household, national economy, agroecosystem). Each axis has a "viability domain," the range of values within which the holon can be considered stable. Equations of congruence link changes in values of indicators within a quadrant and changes induced in values of indicators within another quadrant. For example, lowering the price of rice by imposing a "fixed price" policy results in a worsening of the situation for "holon" farmers (reduction of income) and improvement of the situation for the "holon" government of China (reduction of food cost for the cities). Considering the distance of the indicators from the edges of the viability domain (minimum acceptable values) and blending socioeconomic and biophysical readings allow evaluation of correspondent trade-offs between economy and ecology.

2. It is possible to discuss whether or not large-scale biofuel production is a feasible option for a fuel-developed society heavily dependent on fossil energy stocks.[18] An energy sector running on biofuels must be compatible with the socioeconomic characteristics of society providing a SEH compatible with existing BEP. The energy sector should also be compatible with ecological constraints and have a demand for natural resources such as arable land and fresh water that is compatible with current supply. Available data on modern biofuel systems can be used to estimate biophysical requirements per unit of net energy supply. Depending on production system, requirements per gigajoule (1 GJ = 10^9 joules) of net energy are 0.015–0.100 ha of arable land, 200–400 tons of fresh water, and 0.6–5.5 hours of labor.[15] In a developed society (BEP > 400 MJ/hour) work supply in the energy sector is only a small fraction (generally less than 5%) of the work force in productive sectors. To achieve a small fraction of the work force in productive economic sectors, throughput per hour of labor in the energy sector must be on the order of 10,000 MJ/hour of labor.

In Italy, with a population of 57 million, only 7.3% of 499 billion hours of human time available in 1991 were spent in paid work. Of this labor supply, 60% was absorbed by the service sector, 30% by the industrial sector, and 9% by agriculture, fishery and forestry, leaving only 1% (360 million labor hours) for the entire energy sector.[19] Total energy consumption in Italy in 1991 was 6,500,000 terajoules, implying that the Italian energy sector delivered almost 18,000 MJ of energy throughput per hour of labor. This throughput was achieved through using mainly fossil energy (about 90%), suggesting that a developed society requires energy throughput per hour of labor in the energy sector in the range of 10,000 to 20,000 MJ/hr. Such levels are well beyond the 250–1,600 MJ/hr range of values achievable with biofuels.[15] To use biofuels as energy sources with a much smaller throughput per hour of labor and high levels of energy consumption per capita, an energy sector would have to absorb between 20 and 40% of the labor force. Such a scenario is incompatible with the current profile of labor allocation in various economic sectors.

Demographic Transition and Dynamic Exergy Budget

BEP is the product of three terms, two of which are affected by demographic changes. SEH depends on two parameters linked to technological development and availability of natural resources, parameters both scale-dependent and affected by population size. Constraint of balance (BEP = SEH) is in reality affected by demographic changes, making it necessary to add extensive variables. It is possible to impose congruence between ET supply (as a function of SEH and population size) and total ET demand (as a function of BEP and population size). Some useful relations are:

$$(\mathrm{THT/C}) \times (\mathrm{C/CI}) \times \mathrm{CI} = \mathrm{pop} \times \mathrm{hy} \quad \mathbf{(6)}$$

$$\text{ET supply} = \mathrm{SEH} \times \mathrm{C} = (\mathrm{ET/CI}) \times (\mathrm{CI/C}) \times \mathrm{C} \quad \mathbf{(7)}$$

$$\text{ET demand} = \mathrm{BEP} \times \mathrm{C} = \mathrm{BEP} \times (\mathrm{C/THT}) \times \mathrm{pop} \times \mathrm{hy} \quad \mathbf{(8)}$$

ET at a particular point *i* in time can be expressed as:

$$\mathrm{ET}_i = (\mathrm{Exo/Endo})_i \times \mathrm{pop}_i \times (\mathrm{ABM} \times \mathrm{MF})_i \times \mathrm{hy} \quad \textbf{(9)}$$

When SEH > BEP, socioeconomic systems adjust parameters to increase ability to use surplus useful energy and to expand activity assessed by larger ET. At a given point in time $i + 1$:

$$\mathrm{ET}_{i+1} > \mathrm{ET}_i \quad \textbf{(10)}$$

which can be formulated as:

$$(\mathrm{Exo/Endo})_{i+1} \times \mathrm{pop}_{i+1} \times (\mathrm{ABM} \times \mathrm{MF})_{i+1} > (\mathrm{Exo/Endo})_i \times \mathrm{pop}_i \times (\mathrm{ABM} \times \mathrm{MF})_i \quad \textbf{(11)}$$

Relation (11) can also be written as:

$$(\mathrm{ET/C})_{i+1} \times (\mathrm{C/THT})_{i+1} \times \mathrm{pop}_{i+1} > (\mathrm{ET/C})_i \times (\mathrm{C/THT})_i \times \mathrm{pop}_i \quad \textbf{(12)}$$

Relation (12) gives a different view of possible ways of expanding ET. When surplus is absorbed by an increase in the Exo/Endo ratio rather than by an increase in population, the solution implies an increase in ET/C linked to a reduction of C/THT. Fraction of working time in productive sectors is also an indicator of development. Put another way, depending on path of expansion followed by the socioeconomic system, increases in ET can transform either into either (1) increased population size or (2) improved material standard of living (combined change of ET/C and C/THT).

Changes in ET/C and THT/C are subject to (1) lag time in building technical infrastructures needed to expand Exo/Endo (job positions available in economic sectors), (2) speed of demographic changes determining dependency ratio within existing households, and (3) cultural constraints to change the profile of allocation of human time on different sets of activities (moving to a different job or different housing type). These three factors create an "intrinsic" lag-time in the adjustment of values of ET/C and THT/C to new conditions, a lag-time that determines how much of the increase in ET results in population growth rather than improved BEP.

The Path of Expansion of ET

Starting from Relation (12), it is possible to see paths of expansion in ET by examining relative changes among the three parameters. An increase in size of the system (ET) can imply changes in (1) ET/C, (2) ET per capita (Exo/Endo), and (3) C/THT. Population becomes stable when ET/C increase on the supply side matches a combination of changes in C/THT and Exo/Endo on the supply side. Due to the limited range of possible values of the ABM × MF, where maximum increase amounts to about 20% of initial value, increase in ET per capita translates almost directly into increase of Exo/Endo ratio.

It may be helpful to imagine a process of expansion of ET, starting from a hypothetical socioeconomic system characterized by stable population due to high fertility and mortality. It is assumed that parameter population is subject to fluctuations and initial population size is small. Also, it is assumed that improvements in exosomatic autocatalytic loop (e.g., new technologies, use of higher-quality resources, better knowledge and management of socioeconomic activities) make surplus of energy (SEH > BEP) available to the socioeconomic system. Surplus energy can be absorbed by increase in population and/or by increase in energy consumption per capita, increases that will be reflected in a changing pattern of human activity (changes in THT/C). In the short term, population growth increases THT/C because of the increased number of children in the system. In the long term, increase in size of the socioeconomic system due to population growth further increases THT/C because of increasing B/(B+C). With the expanding size of the system, fraction of total work supply allocated to administration and other services gradually increases. However, the possibility of increasing ratio THT/C is limited in pre industrial societies, due to lack of devices to amplify the power of workers in productive sectors. CI/C in preindustrial societies is small; and historically, animal, wind, and water power were decisive factors in determining local development. "Power devices" are by their very nature location-specific, do not provide a continuous, reliable flow of power, and prevent preindustrial socioeconomic systems from reaching type 2 equilibrium on a large scale. Large-scale complex societies require division of population into widely different social classes to allow effective taxation of farmers by a central administration. However, the process of economic development could not avoid a high degree of instability in preindustrial societies.[15,35]

In modern industrialized society, population growth does not imply reduction in SEH because (1) supply of energy input no longer relates to land availability and (2) surplus of ET is easily absorbed by an increase in exo/endo ratio.

FIGURE 10 shows two possible points of equilibrium. All variables are intensive to avoid complicated three-dimensional representation, but an extensive variable such as population size can easily be introduced on a third axis perpendicular to the plane that indicates changes in the size of the system (ET or population). Clearly,

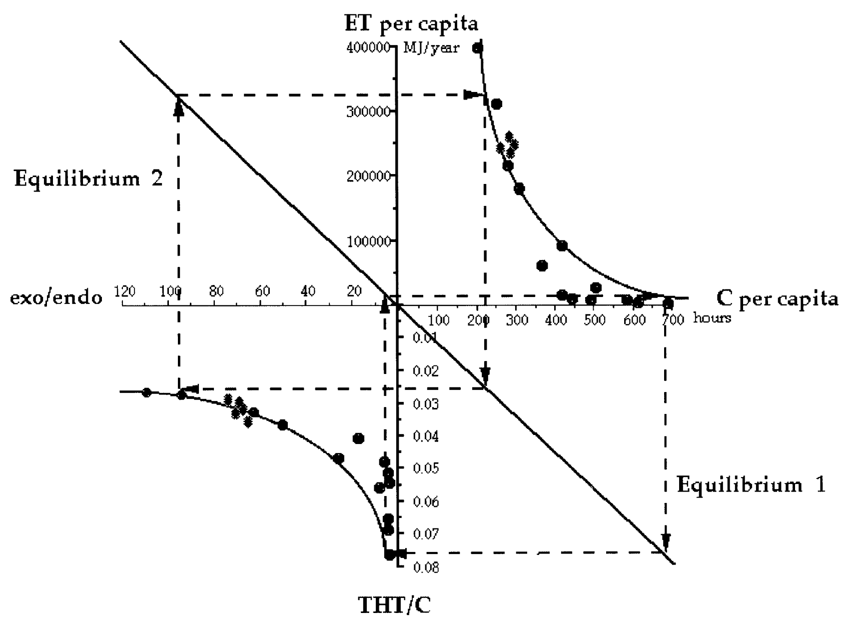

FIGURE 10. The two equilbria of the demographic transition.

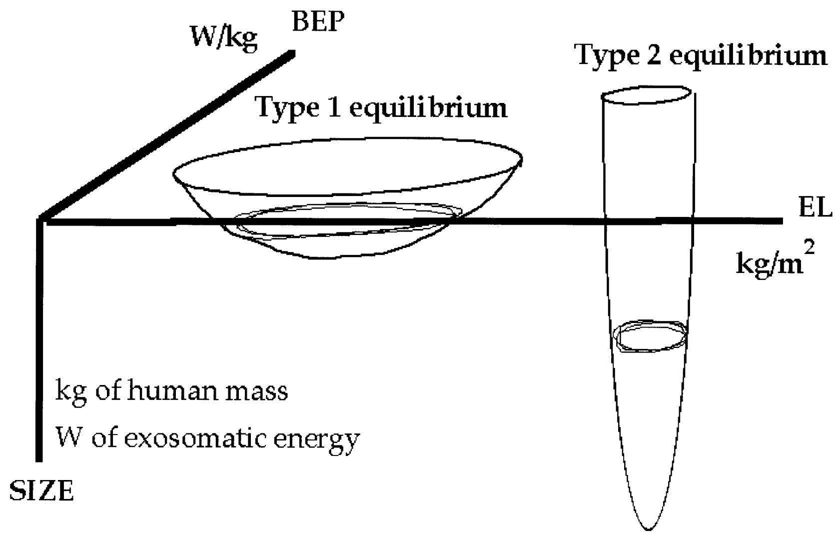

FIGURE 11. Two basin attractors for socioeconomic systems in the space BEP-EL-SIZE.

type 2 equilibrium is achieved only in a system of much larger size than a system of type 1 equilibrium. The figure shows synchronic analysis of 107 countries (*white dots*) grouped in clusters and diachronic analysis of average values for OECD countries from 1970 to 1990 (*black dots*) calculated over historic series of OECD countries.[28] Note that values resulting from both synchronic and diachronic analysis are on the same curve.

The reciprocal relation among a set of variables generates two basins of attraction for the energy budget of a socioeconomic system. Trajectory of development of socioeconomic systems can be described in a three-dimensional phase space with

Axis 1, energy dissipation per unit of human control (ET per capita); Axis 2, size of the system (population size); Axis 3, environmental loading.

Axis 3 indicates the intensity of self-organization socioeconomic activity relative to the intensity of the natural processes that guarantee stability of boundary conditions. This ratio affects ET/C, and therefore THT/C and is itself affected by population size. Type 1 and type 2 equilibria in FIGURE 10 can be imagined as the three-dimensional phase space shown in FIGURE 11.

Reconsidering the Classic Representation of Demographic Transition

Traditional graphic representation of demographic transition is a sigmoid curve connecting two values of stabilized population sizes, and the horizontal axis generally represents time. However, data for societies that have completed demographic transition (e.g., France and Sweden) and societies in different stages of transition (e.g., Burundi and Singapore) suggest that speed of transition differs dramatically from country to country.[5] So, the variable "time" is not directly linked to changes during transition from one metastable equilibrium to another.

Exo/Endo ratio may be a better variable for the horizontal axis, providing a better explanation for the transition process. At the beginning of the transition (stage 1), socioeconomic systems cannot assume larger ET values and can replicate themselves only through "seedlings," expanding into other ecosystems. Growth generates redundancy; there is more of the same thing (replication), but no real development (no qualitative changes).

Socioeconomic systems that can expand their autocatalytic loop of exosomatic energy enter a transitional phase in which they can maintain SEH > BEP. In this phase, socioeconomic systems can expand size (ET) by increasing both population and Exo/Endo ratio. These two forms of expansion have different intrinsic lag times, and therefore the two processes proceed at different speeds.

Changes in structure of the exosomatic autocatalytic loop (industrialization) enable socioeconomic systems to absorb the entire surplus of ET by increasing Exo/Endo ratio while maintaining fixed population size. After these changes, socioeconomic systems have completed demographic transition. The final stage is coupled to increased material standard of living and changes in profile of human time allocation over different activities (increased THT/C). This transformation is linked to dramatic change in social patterns of organization.

Current description of demographic transition in terms of indicators of fertility and mortality is just one possible description of the demographic transition. As discussed in Part 2, a plot of 24 indicators of development against Exo/Endo ratio for different countries (FIG. 8) shows another description of the trajectory that countries follow in their transition between two metastable equilibria of a dynamic energy budget. The process of demographic transition based on our model can be a good alternative to the traditional description of the same process.

SUMMARY

Part 1 presents an energy analysis model for the study of the evolution and stability of socioeconomic systems. The model describes socioeconomic system as a nested dissipative adaptive system (holarchy), allowing study of the exergy budget of various nested elements of a holarchy. Part 1 also deals with the unavoidable conflict between short-term goals and long-term goals affecting the holarchy.

Part 2 first sets up a database referring to 107 countries and presents four applications of the model presented in Part 1: (1) BEP (an indicator of development) is better than GNP in correlating with traditional indicators of development; (2) a common trajectory of development for the 107 countries and their evolution in state space; (3) equations of congruence across levels linking demographic variables, level of development, technology, and natural resources; (4) description of "demographic transition" in terms of a shift from one metastable equilibirum of the dynamic exergy budget to another.

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