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Labor Productivity: A Biophysical Definition and Assessment

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A model of energy analysis is presented to study the concept of labor productivity from a biophysical perspective. It is argued that current methods of defining and assessing labor productivity in the fields of work physiology and input/output energy analysis are relatively poor operational tools for assessing productivity in the economy and society. We propose to adopt society as the hierarchical level of analysis rather than the individual, as labor productivity can best be studied as a function of parameters related to the technological development of society. Parameters considered are: the ratio exosomatic/endosomatic energy used in society, the ratio working/non-working population, the return on the circulating energy investment, and the profile of human time allocated to the economic process. The links between patterns of human time allocation, population structure, standard of living, technological development, and demand on natural resources are analyzed. The results suggest that the role and meaning of human labor differ widely in societies with different levels of technological development.

KEY WORDS: productivity; labor; energy; technological development.

INTRODUCTION

The economic definition of labor productivity refers to the monetary value of what is produced by a unit of human labor (dollar value added per hour of labor), which is generally related to the wage earned by the worker (e.g., Neef and Kask, 1991). However, this definition is not fully satisfactory when dealing with non-monetarized societies or with the biophysical foundation of economic processes. For this reason, several attempts have been made to define and assess the concept of labor productivity outside the economic

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framework of analysis. For example, the discipline of work physiology studies the relationship between the worker's physiological condition and his/her work output, using concepts such as physical work capacity (quantified by parameters such as maximal oxygen consumption, aerobic capacity, endurance) and work produced (usually limited to industrial and agricultural work where the output is based on piece-work), see for example, Spurr et al. (1977), Barac-Nieto et al. (1980); Flores et al. (1984), Beaton (1987), and Spurr (1988).

However, the problem with these biophysical approaches is that the concept of labor productivity must take into account the value of the products and/or services provided by human labor. Such a definition of values is not easy to obtain when only physical measurements are used (Kåberger, 1991).

Finding a link between the economic and biophysical notions of labor productivity is important to understand the technological development of societies and more generally to study the sustainability of the economic process. Energy analysis, because of its ability to explore the biophysical foundations of the economic process, has been proposed as a tool for bridging this gap between the social and physical sciences. However, the concept of productivity of human labor, despite being subject to a great deal of attention, has not gained a holistic perspective by its current energetic description. On the contrary, its assessment has become one of the most elusive and controversial subjects in the energy analysis literature (Fluck, 1981, 1992).

In this paper we discuss (i) the problems faced when assessing labor productivity in terms of energy; (ii) a model of energy analysis to study the links in society among population structure, human time allocation, the nature of the power-supply system, and labor productivity; and (iii) the changing role of human labor in relation to technological development.

LABOR PRODUCTIVITY IN TERMS OF ENERGY

Assessing the *productivity* of human labor requires two measurements: (i) what has been achieved by the work done (e.g., acres tilled, dollar-value produced, kilometers walked); and (ii) a sort of "cost" referring to the work done (e.g., hours of human time required, energy consumed, wage paid). Then a ratio of these two quantities can be used as an assessment of productivity. Unfortunately, in societies that are not fully monetarized the ratio "dollar-value produced/dollar-wage" can often not be obtained because the costs and benefits of human work are measured in different units that are difficult to compare. For these cases, energy analysis has been proposed as a solution by making the units of measure uniform, expressing both costs (energy input) and benefits (energy output) of human labor in terms of energy. However, the parameters "energy input" and "energy output" and their relationship prove to be difficult to measure when the concept of value is added to the picture.

Quantifying Energy Input

The literature on the energetics of human labor (reviewed by Fluck, 1981, 1992) shows many different methods to calculate the energy equivalent of 1 hour of labor. For example, the flow of energy embodied in 1 hour of labor can refer to: (i) the metabolic energy of the worker during the actual work only, including (e.g., Revelle, 1976) or excluding (e.g., Norman, 1978) the resting metabolic rate; (ii) the metabolic energy of the worker including also non-working hours (e.g., Batty et al., 1975; Dekkers et al., 1978; Hudson, 1975); (iii) the metabolic energy of the worker and his dependents (e.g., Williams et al., 1975); or (iv) all embodied energy, including commercial energy, flowing in society (Fluck, 1981; Giampietro and Pimentel, 1990). Depending on the boundary chosen to describe the system "worker," the energy equivalent of 1 hour of human labor can differ up to 100-fold (from hundreds kcal/hour to over 100,000 kcal/hr).

This wide range in the assessment of the energy input consumed by the system "worker" is due to the existence of several space-time scales at which human labor can be described. In other words, the definition of a particular boundary implies a choice of a hierarchical level at which human labor is described and assessed. For example, the field of work physiology is predominantly concerned with small spatiotemporal descriptions (*individual* worker, in the short period), while socioeconomic analyses are more concerned with larger spatiotemporal assessments, including the *society* of which the worker forms part (Giampietro and Bukkens, 1992). Finally, Odum's EMergy analysis (1992) includes in the accounting of the energy embodied in human labor also a share of the solar energy spent by the biosphere in providing environmental services needed for human survival.

Thus, quantifying an energy input in reality means defining the boundary at which we describe the system. Since self-organizing systems (such as a worker or societies) are open systems interacting with their environment, any analysis of these systems faces the so called "truncation problem" (Hall et al., 1986), that is, deciding what has to be included as a part of the system and what not. This implies an unavoidable level of arbitrariness in any assessment.

Quantifying Work-Output

Even though in physics work is measured in terms of energy (unit: Joule, kcal, or BTU), it is generally not possible to assess the achievement of human labor with a simple measure of energy (Giampietro and Pimentel, 1991). In fact, labor productivity implies two consecutive conversions of energy: first, a flow of energy input is converted into a flow of applied power, and second, this flow of applied power is used to perform a particular work.

The power generation cost refers to the first conversion, and is defined as the ratio "Joules of energy input consumed by the system per Joule of applied power delivered by the system" (Giampietro and Pimentel, 1991). Again, such an assessment depends on the choice of the boundary for the system considered as delivering power.

The second ratio, work done per Joule of applied power, introduces a more complicated problem, since generally we do not know how to measure the work done in Joules. This is especially true for services such as teaching, health and veterinary care, and artistic and musical performances. This is the reason why, whenever possible, economic indicators (e.g., economic added value) or physical quantity produced (e.g., bushel harvested, baskets crafted) are used to describe work output.

A numerical example, illustrating the distinction between energy input, applied power, and work accomplished for soil tilling is reported in Table I. In this table four different power applying systems are compared: human power, an oxen pair, a 6 HP and a 50 HP tractor, the data presented refer to the same quantity of work done, that is tilling 1 hectare of soil. Different quantities of applied power and energy inputs are required for different devices to do the same quantity of work. Applied human power is nearly twice as effective as that of oxen, and almost four times that of the 6 HP tractor in terms of work done per unit of applied power (Giampietro and Pimentel, 1990). However, this advantage is completely reversed when the power generation cost is also considered. The gross energy input requirement for tilling 1 hectare of soil shows that the work done by human power is 3.45 times more expensive than the work done by tractor power, and twice as expensive as work done by oxen power. These differences clearly show that by only measuring gross energy requirement or quantity of applied power we do not assess the quantity of work done or productivity.

Table I. Requirement of Energy Input of Different Systems Doing the Same Work (Soil Tillage of 1 Hectare) at Different Power Levels

	Power generation cost[a]	Acquirement index[b]	Power level (HP)	Applied power (MJ)[c]	Gross energy requirement (GJ)
Man power	100	100	0.1	107	10.7
Oxen pair	25	50	1.2	209	5.2
Tractor 6 HP	8	25	6.0	403	3.1
Tractor 50 HP	8	20	50.0	537	4.1

[a] Power generation cost = Joules of energy input/Joule of applied power (data from Giampietro and Pimentel, 1990).
[b] Acquirement index = work output/applied power. An arbitrary unit has been adopted considering the acquirement index of human labor = 100.
[c] Data from Giampietro and Pimentel (1990).

Time Constraints in Work Output: Power Level

The non-linearity of the relationship between energy input and the value of a work output presents an additional problem in the assessment of labor productivity in terms of energy. For example, consider the work "harvesting a defined crop" that requires an input of "700 labor-days." According to this definition, the harvest can be secured either by 100 farmers working for a week, or by 7 farmers working for 100 days. Although the productivity in terms of "kg harvested per hour" or "kg harvested per unit of metabolic energy consumed" is the same for the two solutions, in practice, latter solution may not be possible due to time-constraints, that is the crop may deteriorate after the second week of work. In this situation we have a power bottleneck: the power level available for harvesting, that is the speed at which work is performed, dramatically affects the "value" of the work performed. Therefore, the parameter *"power level"* which is different from the ratio "work done per unit of energy input," has also to be considered when assessing productivity. For example, Rappaport (1971) writes: "I found that the performance of men and women in clearing the bush was surprisingly uniform. Although in an hour some women clear little more than 200 square feet and some of the more robust men clear nearly 300 square feet, the larger men expend more energy per minute than women. The energy input of each sex is approximately equal: some 0.65 kcal per square foot." The performance of men and women reported by Rappaport may be uniform in terms of energy requirement per unit of surface (29,000 J/m^2 using the SI system), but the difference in labor done per unit of time suggests a clear difference in the level of power delivered by workers of the two sexes. Such a difference, in the order of 30%, can

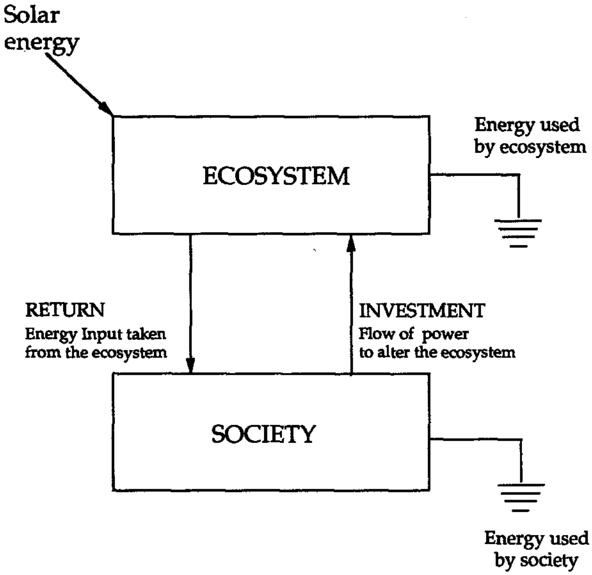


Fig. 1. Dynamic interaction between society and ecosystem.

be important in systems that continuously face power bottlenecks. We will come back to this in the last section of this paper when we discuss a biophysical explanation for sex differentiation of labor in pre-industrial societies.

ANALYZING THE LINKS AMONG SOCIETY'S ENERGY BUDGET, TECHNOLOGY, AND LABOR PRODUCTIVITY

Human Labor in the Socioeconomic Structure of Society

As illustrated in Fig. 1, human labor can be viewed as inducing an iterative loop of energy: energy is invested by humans in the form of applied power in their interaction with the environment and is harvested in the form of energy input (Giampietro and Pimentel, 1990, 1991). Humans apply power (the energy investment) to the ecosystem in order to obtain energy, food, and other resources. The energy input harvested by humans from the ecosystem can be considered the return of human investment. The level of energy expenditure at which a dynamic equilibrium is reached between the energy invested and the energy harvested by society defines the level of technological development of society (Giampietro and Pimentel, 1991). Following the work of White (1943, 1959), Cottrell (1955), Odum

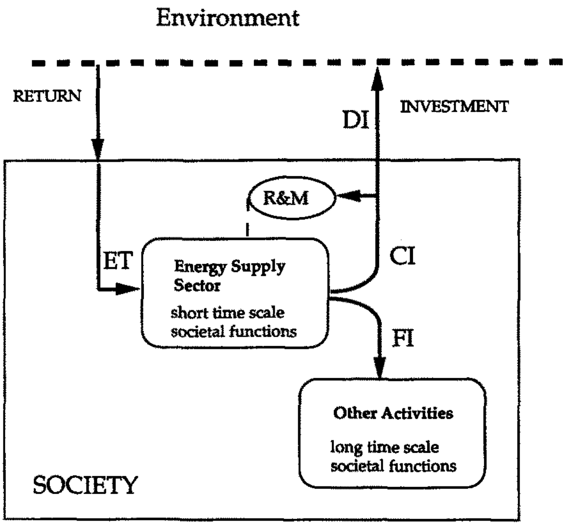
(1971), and Pimentel and Pimentel (1979) we assume the flow of useful energy controlled by a society proportional to its level of development. This implies that industrialized societies invest more energy in their interaction with the environment and get more in return than pre-industrial societies. For example, in the United States equilibrium is reached at approximately 230,000 kcal/day per capita, while in pre-industrial societies equilibrium is reached at about only 10,000 kcal/day per capita.

The "Energy-Supply System" Sustaining Societal Activity

The energy-supply sector can be defined as that part of the economic sector performing all the activities required by the energy-supply chain, that is the procurement, processing, and distribution of the energy input used by society (Holdren, 1982). In an industrialized country mainly based on fossil energy and machine power (which is powered by exosomatic energy conversions) the energy-supply sector includes all the activities related to mining, transportation, processing, and combustion of energy. However, the definition of the energy-supply sector blurs when dealing with pre-industrial societies where humans are at the same time energy converters (devices generating power to sustain economic processes) and end-users of energy. Sustaining human activity is a value in itself; the pure dissipation of energy and resources in human leisure activities still produces an economic value.

Within this frame of analysis, the conversions of energy input into useful energy can be seen as driven by two distinct motivations. Energy is converted into power to (i) run, replace, and maintain the energy-supply system (this useful energy is, per definition, not available for other purposes); and (ii) generate a "spare" power supply that humans can allocate to those activities outside the energy-supply system they judge valuable. This spare power is the useful energy allocated to education, health care, cultural activities, recreation, and other services. It can be assumed proportional to the standard of living. Using an analogy with economic terms this spare power can be considered the "disposable energy income" of society.

The difference in the nature of these two energy flows can also be seen in terms of the hierarchy theory: (i) energy used in the energy-supply system maintains the dynamic energy budget in the *short term* (on the time scale of operation of the converters); and (ii) the "spare" useful energy allocated to activities elsewhere will affect the dynamic equilibrium of society in the *long term* (for example, by accumulation of knowledge and capital, and expansion of human potentialities).

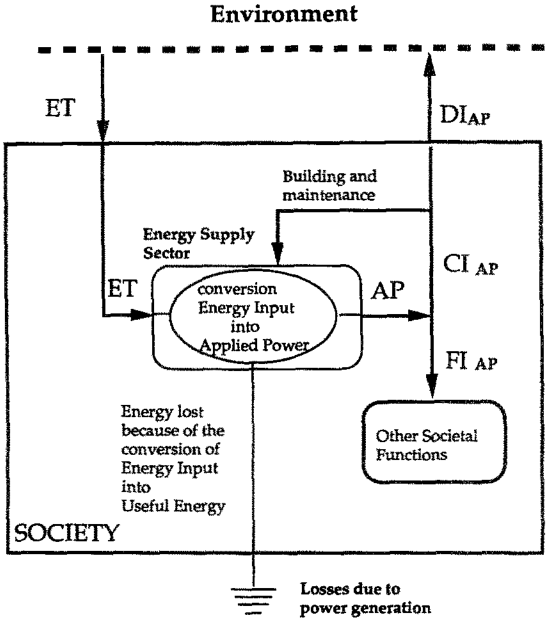


ET = Energy Throughput = the flow of energy input consumed by society to generate the flow of useful energy sustaining all activities
CI = Circulating Investment = the fraction of ET used by the energy supply sector
FI = Fixed Investment = the fraction of ET allocated into other functions of society which do not provide an energy return in the short term
DI = Direct Investment = the fraction of CI directly converted into power spent to get back and sustain ET (note that DI < CI)
R&M = the fraction of CI used to Replace and Maintain the converters
ET/DI = Return on the investment
ET = CI + FI

Fig. 2. Energy flows in society.

Thus, keeping an analogy with economic analyses, the two energy flows that make up the Energetic Throughput (ET) in society are represented by (Fig. 2): (i) the Circulating Investment (CI flow), related to the energy spent directly in the energy-supply sector (operating on a short time scale); and (ii) the Fixed Investment (FI flow) (="spare power") related to the energy spent to sustain the rest of society's activities (operating on a longer time scale).

It is clear that the quantity of useful energy that the society can allocate to stabilize its structure in the long term (FI flow) will depend on the efficiency of the energy-supply system. The higher its efficiency, the lower the fraction of useful energy consumed for its own operation and maintenance.



ET = Energy Throughput = the flow of energy input consumed by society

AP = the flow of useful energy (applied power) made available by the energy supply sector

FI_{AP} = the flow of useful energy (applied power) made accessible to the rest of society (to sustain activities outside the energy supply sector)

$\eta = AP/ET$ = the fraction of ET transformed into Applied Power (Useful Energy)

$\beta = DI/CI$ = the fraction of CI that can be actually invested after discounting the indirect costs (building and maintenance) of converters

$\varepsilon = FI/CI$ = the ratio of useful energy made accesible to the rest of society by spending one unit of useful energy in the power supply sector

$CI_{ET} = CI_{AP}/\eta$ $FI_{ET} = FI_{AP}/\eta$ Return $= ET/DI$

Fig. 3. Parameters affecting the energy budget of society.

A further enlargement of the scheme is presented in Fig. 3. It shows that the cost to operate the energy-supply sector depends on two parameters: (i) the direct cost of the process of conversion of energy input into applied power (η), determined by the efficiency of the converters used to generate power (e.g., joules of gasoline consumed per watt of applied power delivered by a tractor); and (ii) the indirect cost of this conversion (β), that is the fraction of useful energy required by the energy supply system for its own construction and maintenance discounted on its life span (e.g., the flow of energy spent for building and maintaining the tractor discounted on its life span).

The energetic conversion of energy input into power by machines results in a net flow of useful energy available to the system that is dramatically higher than that generated by human power. When a tractor is used to generate power, less than 10 J of energy input are required to produce 1 J of applied power (the ratio CI_{ET}/DI_{AP} obtained by summing direct and indirect costs of CI), whereas 50 to 400J of energy input are required per Joule of applied human power (Giampietro and Pimentel, 1992). This is because machines, unlike humans, can be turned off when through working, nor are they affected by energy consumption during periods of education or retirement. Therefore, the overall weight of the indirect cost is dramatically lower for machines than for humans. (Note that this is true only when the process is described on a time scale small enough to exclude the energy required to develop the human brain and knowledge required to make a machine; however, the time scale adopted by economic descriptions matches well with this assumption.)

The indirect cost of tractor-power (that is all the energy spent in its construction and maintenance discounted on its life-span) amounts to only 20% of the total cost of the power it will deliver during its life-span. Thus, almost 80% of the energy required to generate power with a tractor is in the form of gasoline input. The opposite is true for the generation of human-power, almost 80% of the metabolic energy spent by the population occurs during non-working activities (Giampietro and Pimentel, 1991). This is the first factor that explains why technological development involves the substitution, whenever possible, of human power with machine power.

Power-Level as the Limiting Factor in Pre-Industrial Societies

We define technological development of a society as an increase in the speed of the energy throughput used to sustain its activity. This increase can be limited by two factors: (i) the availability of energy input; this is an *external* constraint which limits feeding more energy input to the available converters. This, in turn, limits the generation of more useful energy to sustain more human activity. In this case, expansion is limited by boundary conditions; and (ii) the ability to convert more of available energy input into useful energy; this is an *internal* constraint that limits the use of more available energy input into power. This can be seen as a limited ability to generate power in the system (lack of devices converting energy input into power).

Since two different types of constraints, the energy input and the power level, can limit the development of society, it is more correct to use the term "power-supply system" instead of "energy-supply system" to describe the sector controlling the Circulating Investment. The former term includes the latter, whereas the reverse is not true (see the example of 700 worker-days requirement for harvesting).

Thus, according to the circumstances, an expansion of the power-supply system can be limited either by a shortage of energy input to feed the current converters, or by a shortage of converters to use more of the available energy input. The "pulsing" history of human development can be seen as an alternate breaking of internal and external constraints. Quantitative growth is an amplification of the existing conversion processes, that is the ability of using more of the same energy resource (e.g., increase of population in an agrarian society), until saturating the external constraint. Qualitative evolution is an introduction of new types of energy conversion which imply the use of new sources of energy input to fuel society's activities. This induces not only a change in the overall speed of the energy throughput in society, but also a change in the internal ratio between FI and CI.

Finally, qualitative evolution requires that the process of power generation be more compatible with the boundary conditions ("sustainability" of the process). For example, the introduction of thermic engines increased the possible sources of energy input for society to include fossil energy. This not only allowed the maintenance of a larger share of services in the economic sector (higher FI/CI ratio) and a higher standard of living (e.g., per capita energy consumption over 100,000 kcal/day), but also decreased the pressure on the ecosystem base of the power-supply system. The current supply of 230,000 kcal/day per U.S. citizen would have a devastating impact on U.S. ecosystems if it were obtained in the "pre-industrial way" by burning massive quantities of biomass [biomass comprised 91% of the exosomatic energy spent in the U.S. in 1850, but only about 4% today (Pimentel et al., 1993)]. Moreover, the "pre-industrial" solution would be impossible to sustain since the amount of fossil energy used yearly by the U.S. exceeds by 40% the total amount of solar energy captured each year by all U.S. plant biomass (ERAB, 1981).

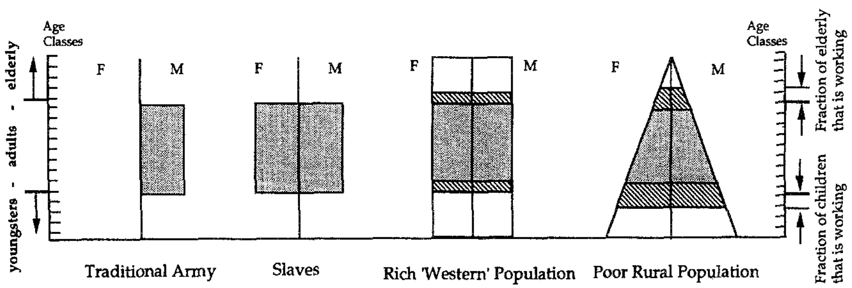
In pre-industrial societies the situation is completely reversed. For example, thousands of kg of standing biomass of tropical forests are available per capita to Pygmies, however, shortage of power per capita prevents that society from reaching the external limit of using all the energy input available. In fact, despite this huge quantity of available energy input in the form of biomass, the per capita consumption of Pygmies is limited by their ability to convert the energy contained in this biomass into applied power. In this case, the bottleneck is that the only process of conversion available to the Pygmies' power-supply system is the physiological conversion of food into applied power by human muscles. Since, there is a limit to the speed at which food can be processed within the human body (range of 1000–5000 kcal/day) the power level available to society to harvest and make use of all the available biomass is limited. It should be noted that again our judgment is based on an arbitrary definition: since wood biomass is an unedible energy input, we could consider the constraint to the expansion of Pygmies as due to lack of energy input (food). This arbitrariness will be dealt with by adopting rules for describing the energy budget of society (see the section on Exosomatic/Endosomatic Energy Ratio) that make a fundamental distinction between endosomatic (conversion obtained within the human body) and exosomatic (conversion obtained outside the human body) energy flows.

Strategies of Pre-Industrial Societies to Cope with Shortage of Power

In general, in pre-industrial societies where the bulk of power is generated by human labor, the ability to increase the "power-supply" is limited to the following three options:

(i) Changing the population age and sex structure by increasing the number of adults relative to children and elderly, and/or by increasing the number of adult men relative to women. The maximum power level is presented by a population composed of only adult men (=traditional army), but, obviously, such a population cannot reproduce itself. Examples of sustainable solutions are: slave-based societies that increase the fraction of kg of working population by continuously adding adults recruited elsewhere, as for example in the early period of the Roman Empire; and societies that have a low percentage of elderly in the population due to a short life-span (this solution reflects the actual population age structure of rural developing societies). Keeping children as replacement for labor but limiting the number of elderly is the cheapest (in energetic terms), sustainable solution available to pre-industrial societies. The improvement in power level that can be achieved by changing the population age and sex structure is limited, ranging from 40 to 90 W per capita (the latter value referring to a non-sustainable solution) (Fig. 4).

(ii) Generating power via animal conversion (decreasing at the same time the cost of power generation). This improvement is also limited. For example, the use of one bullock for every ten villagers in Panayakurichi (India) has the effect of doubling the power level per capita from 42 to 85 W (Giampietro and Pimentel, 1990). These values are still a long way from the power parameters describing developed societies with high levels of machine power: for instance, the average power level per U.S. citizen is 110,000 W (USBC, 1991, p. 566). This is the second reason why devel-



Power level per capita	90 W	75 W	43 W	53 W

Assumptions

Power levels : Adult Man = 90 W; Adult Woman = 60 W; Working elderly and youngsters = 40 % reduction adult power
Non-working population = 0 W.

Population composition: Traditional Army = 100 % adult men, 100 % working;
Group of slaves = 100 % adults, 100 % working, sex ratio 1/1
Rich 'Western' Population = sex ratio 1/1, 60 % working, 10 % of which is elderly and youngsters
Poor rural Population = sex ratio 1/1, 75 % working, 15 % of which is elderly and youngsters

Fig. 4. Population structure and endosomatic power level in society.

oped societies switched to a massive production of power by machines; in this way they are able to effectively deal with peak power demand and eventually minimize the human labor demand.

(iii) Taking advantage of localized sources of exosomatic power, such as waterfalls, wind, and rivers. A detailed description of the enormous importance of exosomatic energy conversions (processes making available power with conversions of energy outside the human body) in pre-industrial societies has been provided by Cottrell (1955), Cipolla (1965, 1978), and Debeir et al. (1991). Actually, the use of fire—often considered the first step of civilization—is nothing else than the introduction of a new, exosomatic way to utilize a new type of energy input, that is unedible biomass. However, despite the great importance in defining local developments, such as city-ports or agricultural areas on river banks, these power sources never managed to dramatically change the structure of the power-supply system of *large* societies. This is due to the location specificity and unreliability in time, generally related to atmospheric conditions beyond human control.

It was only when the internal constraint of the low power level typical of endosomatic conversions was removed (by accumulating enough capital mainly obtained by the massive use of sails and guns) that the external constraint (shortage of energy input supply) became limiting for the expansion of pre-industrial societies [e.g., shortage of wood in Europe in the 18th century (Cipolla, 1978)]. This pushed technological evolution toward the use of new sources of energy, such as the switch to fossil energy during the industrial revolution.

The Exosomatic/Endosomatic Energy Ratio

The terms *"exosomatic"* and *"endosomatic"* conversion of energy were coined by Lotka (1956). With these terms Lotka wanted to stress that the energy spent in society under human control, even if converted outside the human body, should be considered as an expanded form of human metabolism. " . . . it has in a most real way bound men together into one body: so very real and material is the bond that society might aptly be described as one huge multiple Siamese twin" (Lotka, 1956, p. 369).

This concept can be better defined using hierarchy theory. Humans are able to reach a multiplicative effect on their activity when they are organized into a larger hierarchical structure, that is society. Society is able to stabilize a flow of energy consumption under direct human control that is higher than the sum of the endosomatic energy consumption of all the individuals in the society. At the hierarchical level of society we can see human activity as amplified by social knowledge and technology.

Thus, the amplification of the efficacy of human activity is measured by the ratio exosomatic/endosomatic energy consumption, and we propose to use this exo/endo ratio as a measure of technological development of society. The possibility of increasing the exo/endo ratio is affected by the energy supply and technology (power level) available per capita.

In order to assess this exo/endo ratio, endosomatic and exosomatic energy flows have to be defined and measured:

(i) *Endosomatic or Metabolic Energy Flow.* When we adopt society as the hierarchical level of analysis instead of individual humans beings, we can account for changes in endosomatic energy flows in an indirect way. In fact, in our model the flow of endosomatic energy, expressed per kg of population and per unit of time, is obtained by assessing the distribution of kg of population among different sex and age classes and the profile of human time allocation to different societal activities on a year basis. The average metabolic energy flow for the society is then obtained by using age specific equations estimating metabolic energy expenditure from body weight and physical activity levels (Durnin and Passmore, 1967; James and Schofield, 1990; Giampietro and Pimentel, 1992, p. 31). In this way, we do not assess direct endosomatic energy flows, but the effect that aggregate parameters (demographic structure and time allocation) have on the average endosomatic energy flow in society.

Since the exo/endo ratio is always greater than one, changes in the endosomatic energy flow will have an amplified effect on the flow of exosomatic energy that is used to stabilize social structures and functions.

(ii) *Exosomatic Energy Flow.* The exosomatic energy flow includes all commercial energy flows (UN, 1990a) that generally represent over 95% of the total energy consumed in developed societies, as well as biomass energy consumed out of the market control and the utilization of animal power. For our purpose, the contribution of non-commercial exosomatic energy has been estimated using data reported by specific case studies available in the literature.

The exo/endo ratio is obtained by dividing the total exosomatic energy used by society by the flow of endosomatic or metabolic energy in society. Estimates of current exo/endo ratios for major countries in the world are listed in Table II. Most developed countries have an exo/endo ratio higher than 30/1, indicating that the contribution of human power is negligible in the energy budget. Developing countries with negligible subsidies of fossil energy have an exo/endo ratio lower than 6/1. These apparent thresholds in the exo/endo ratio are evident when the richest and poorest countries are considered; these countries are relative homogeneous systems and can be considered operating fully at the "industrial equilibrium" and the "pre-industrial equilibrium," respectively. However, in many developing countries a sensible fraction of societal activity is fueled by fossil energy, depending on the extent of urbanization and the importance of the market mechanism. Hence, the coexistence of two distinct types of energy budgets—one based on fossil energy for the urban population and one based on biomass for the rural population—is difficult to detect by using national data.

Human Time Allocation and Society's Energy Budget

After defining the average metabolic flow (per kg and per time unit) in society and the exo/endo energy ratio we can assume a correlation between flows of "energy throughput in society" and "human time allocation." Each second of human time induces a flow of exosomatic energy that is equal to the product of the average metabolic flow in society (Joules/sec) and the exo/endo ratio. This is outlined in Fig. 5, following the general model of analysis provided in Fig. 2 and 3. This model refers to the energy balance of pre-industrial societies, in which the return on the circulating investment (ET/DI) depends on a biophysical balance between the energy spent and that returned in the exploitation of the ecosystem (e.g., agriculture).

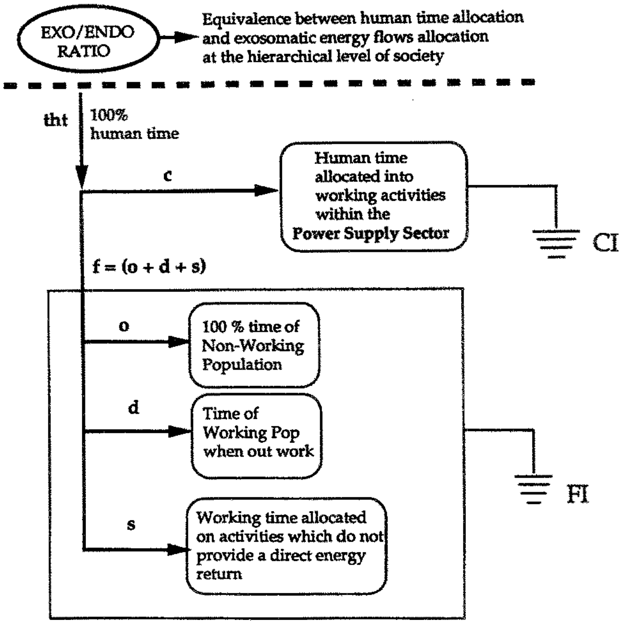
Table II. Exo/Endo Energy Ratio, Exosomatic Energy Throughput (ET) Per Capita, and Average Body Weight (BW) for Major Countries in the World (1988)

Country	Ratio exo/endo[a]	Exosomatic ET[b] (W/capita)	Average BW[c] (kg)
Canada	105	14,490	55.3
United States	75	10,900	57.7
Sweden	67	10,000	59.7
Australia	55	7,370	54.0
Former USSR	55	7,370	53.9
Saudi Arabia	53	5,670	42.9
Former Czechoslovakia	48	6,850	56.5
Former Germany FR	45	6,530	58.1
France	42	5,770	55.4
United Kingdom	39	5,510	56.8
Poland	38	5,090	54.0
Japan	36	4,530	50.5
Italy	28	4,070	58.2
South Korea	21	2,450	43.8
Argentina	19	2,580	50.7
Mexico	18	2,030	42.1
Brazil	15	1,700	43.1
Iran	12	1,460	40.7
Algeria	10	1,350	46.6
China	8 ÷ 9	1,000 ÷ 1,200	43.0
Thailand	8 ÷ 9	940 ÷ 1,100	39.7
Iraq	8 ÷ 9	940 ÷ 1,000	39.0
Peru	7 ÷ 8	890 ÷ 1,000	41.7
Pakistan	6 ÷ 8	610 ÷ 800	34.4
Egypt	6 ÷ 7	820 ÷ 1,000	44.7
Ghana	5 ÷ 7	660 ÷ 900	40.7
Indonesia	5 ÷ 7	580 ÷ 800	37.7
India	5 ÷ 7	560 ÷ 800	36.6
Bolivia	5 ÷ 6	610 ÷ 750	39.8
Sudan	5 ÷ 6	560 ÷ 700	39.1
Nepal	4 ÷ 5	470 ÷ 600	38.1
Ethiopia	3 ÷ 5	360 ÷ 550	35.5
Zaire	3 ÷ 5	450 ÷ 600	42.5
Mali	3 ÷ 4	360 ÷ 500	39.8
Uganda	3 ÷ 4	350 ÷ 500	38.0
Burundi	3 ÷ 4	330 ÷ 500	36.6
Bangladesh	3 ÷ 4	260 ÷ 400	34.3

[a] The metabolic flow has been approximated into three classes: (i) 2.5 W/kg in countries with an exo/endo > 30 and/or body size over 50 kg; (ii) 2.7 W/kg when exo/endo < 30 and > 10 and/or an average body size < 50; (iii) 3 W/kg when exo/endo < 10 and body size < 50 kg.

[b] Data are from U.N. (1990 a,b). Exosomatic energy reported in these statistics refers mainly to commercial energy (expressed in fossil energy equivalents). For the last 18 countries (starting with China) non-commercial biomass energy, as well as exosomatic energy in the form of animal power, biomass used for shelter, seeds, clothing and other uses were estimated from case studies. Values for these countries are given in the form of a range, because of the uncertainty of the assessment.

[c] Data from James and Schofield (1990); averaging body weights of specific age and sex classes.



c = hours of human time allocated into working activities within the Power-Supply Sector

f = hours of human time allocated into activities different from "c"

CI = c/tht x exo/endo x average metabolic rate

FI = f/tht x exo/endo x average metabolic rate

Human time allocated into working activities within the energetic sector must return a flow of exosomatic energy that sustains the exo/endo ratio to the 100% of human time

Productivity = exo/endo x average metabolic rate x tht/c

Fig. 5. Methodological approach to measure labor productivity in pre-industrial societies.

The equivalence between time allocation and exosomatic energy flows can be used to assess how much energy throughput is spent in either the CI or FI sector. For example, the exosomatic energy allocated to the CI sector is obtained by multiplying "the amount of time allocated to this sector" with "the average metabolic flow" and "the exo/endo ratio" (a numerical example is presented in the next section).

In societies powered only by human labor, the CI flow is related to the time spent by the working force during working hours in activities such as producing and processing food, harvesting other biomass, caring for livestock (direct costs of the energy-supply sector) and the time involved in the maintenance and reproduction of society's labor force, including the

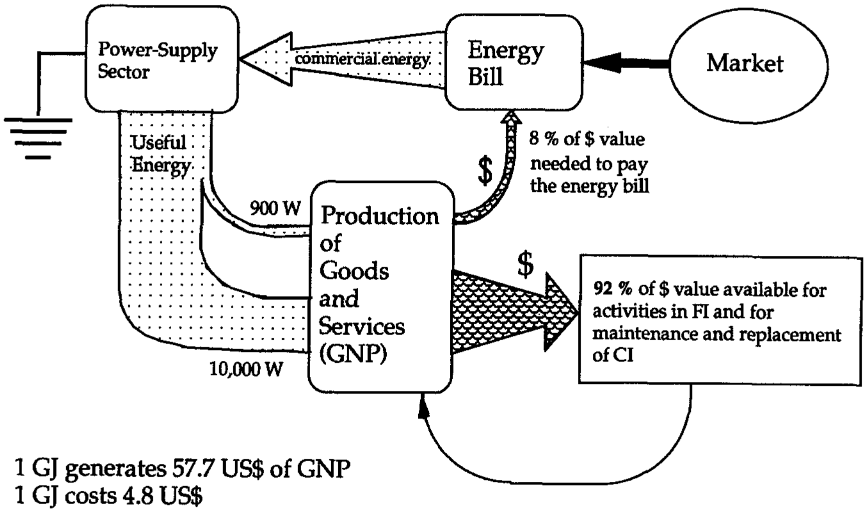


Fig. 6. Flows of commercial energy in the U.S. economy (1988).

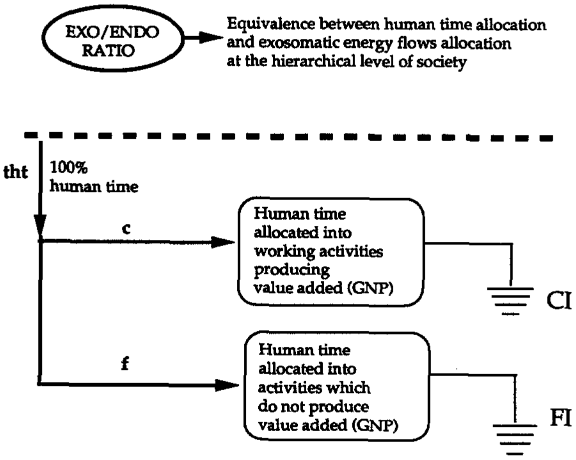
sleeping hours of workers and the activity of children before reaching the working age (indirect costs of the energy-supply sector). The FI flow is related to the time spent in services and cultural activities, which includes activities of workers during non-working hours and the activities of that part of the non-working force that has passed the minimum working age (the retired, disabled, and students).

In industrial societies based on the marked mechanism and extensive specialization, the biophysical energy return of a particular job is difficult to assess. The accessibility to exosomatic energy (commercial energy) is generated by the production of economic added value. Therefore, in fully monetarized societies it is difficult to make a clear distinction between the CI and the FI sector in terms of energy return of human activities. For this reason we will use a different approach, based on two other flows: (i) the flow of added (monetary) value generated on a year basis by the society (GNP); and (ii) the flow of commercial energy used by society to generate that GNP. This flow of commercial energy can also be expressed in monetary terms as the yearly bill for purchasing commercial energy. Therefore we have two monetary flows (related to the activity of human labor) that can be compared: the ratio "dollar produced per Joule spent in the economy" and the ratio "dollar cost of one Joule spent in the economy," the ratio of these two parameters defines the remunerativity of the process converting commercial energy into goods and services within the economy.

The dynamic budget of a society based on commercial energy is presented in Fig. 6 (data referring to the U.S. economy in 1988). In this scheme we can identify the Direct Investment (DI), as the money spent to buy commercial energy, and its return as the flow of energy consumed by the whole society. The ET/DI ratio is quite high, since DI is only 8% of ET. Since the economic activities are all interdependent in terms of energy procurement (all contribute to the GNP) we cannot make a clear distinction between working activities referring to FI and those referring to CI (e.g., the energy return of a journalist vs that of a worker of a power plant). Therefore, we assume that in societies based on commercial energy and the market mechanism, all the working time allocated to paid work within any economic sector is considered as CI sector. The CI sector includes all human activity directly allocated to the generation of the GNP that enables the system to have access to commercial energy. Defined in this way, the CI sector of industrialized societies includes a much wider variety of activities than that of pre-industrial societies. For example, in industrialized societies the work of a nurse in a hospital is considered part of the Circulating Investment (spent in the power-supply sector) since it produces value added. With this assumption the FI sector is now represented only by human time allocated to unpaid activities (recreation, retirement, youngsters, and students). However, changes in the nature of the energy budget of industrial societies due to the massive adoption of exosomatic conversions are so dramatic (increase in the speed of ET) that in spite of this difference in definition of the CI and FI sectors, the increase in the ratio FI/CI in the energy budget resulting from the process of industrialization remains clearly defined. The scheme for assessing the CI and FI energy flows for a society based on commercial energy is illustrated in Fig. 7.

It is important to note here the limits to the application of our model. The exo/endo ratio implies a correspondence between human time allocation and energy expenditure at the level of society. However, this energy equivalent ("energy cost") of one second of human time is not an actual flow of power, but a theoretic assessment of the quantity of energy obtained by averaging energy flows aggregated at the population level on a year basis. This means that this energy equivalent is valid only when it refers to a description at the hierarchical level of the society (the entire system is supposedly in steady state and flows are assessed on a yearly basis). This type of assessment has limited use in assessing specific situations described at a smaller spatio-temporal scale, such as studying the energy budget of a particular plant, farm, family, or economic subsector.

As shown in Fig. 2 and 3, quantitative constraints are operating on the partitioning of the energy input feeding society into fixed and circulating investment. The relative size of different shares of time allocation are



CI = c/tht x exo/endo x average metabolic rate

FI = f/tht x exo/endo x average metabolic rate

Fig. 7. Methodological approach to measure labor productivity in industrialized societies.

interdependent and constrained by: (i) FI/CI, that is the ratio Fixed Investment/Circulating Investment (related to the population structure and time allocation); and (ii) ET/DI_{AP}, that is the return of the circulating investment (depending on the type of interaction the system has with the environment). In fact, only when the return of the circulating investment (ε) is high will the system be able to allocate a large fraction of human time to fixed costs, such as maintaining a sensible fraction of non-working population (retired, students, unemployed) at an acceptable standard of living, or enlarging the service sector in the process of technological development of pre-industrial societies.

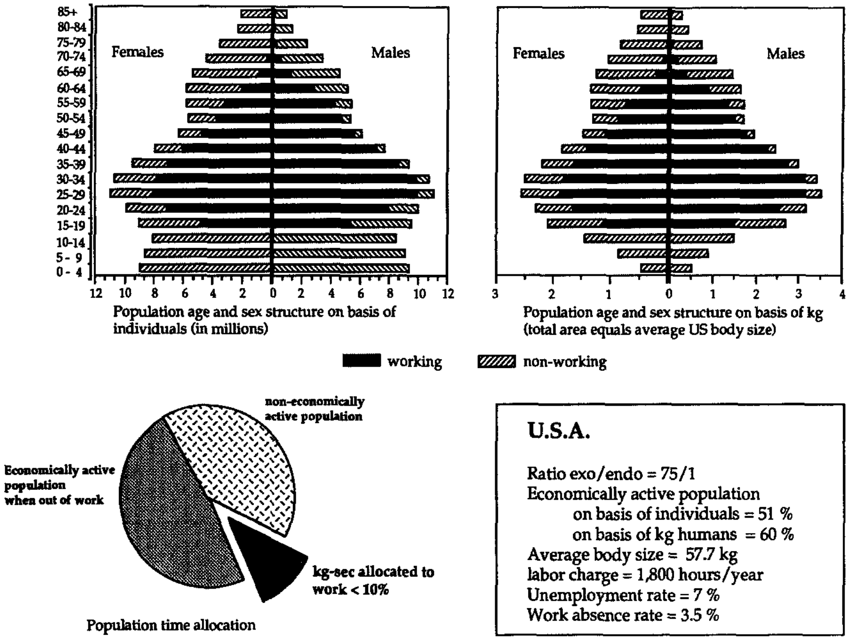
Another consequence of the interdependence of the parameters affecting the dynamic equilibrium is that the system can only reach a new equilibrium by adjusting all parameters together at the same time. This is because a change in any parameter, either FI/CI (referring to social structure), η and β (referring to technological performance of power supply sector), or ET/DI_{AP} (referring to the type of interaction with the environment), will affect all the others, generating a feedback effect. This explains "jumps" in the level of energy dissipation which occur as a social system evolves in complexity reaching new forms of equilibrium. For example, a well-developed service sector requires a high ratio FI/CI. This implies that big quantities of the energy input feeding society have to be generated with little direct investment (high ET/DI_{AP}). Therefore, such a society must exploit an energy source that enables a high return of ET per unit of DI_{AP} (e.g., exosomatic energy systems based on fossil fuels).

Moreover, a high value of ET (high exo/endo ratio, e.g., 75/1) coupled with little human time allocated to the power-supply sector means that, in biophysical terms (considering actual power flows), the density of the energy flow generated per hour of labor in this sector must be huge. In fact, a large flow of ET must be processed, distributed and directed by a small fraction of human activity [in the USA less than 5% of the total time allocated to work is spent in mining, transportation, and utilities providing energy (USBC, 1991)]. This implies that, at the lower hierarchical level, within particular chain links of the power supply system (in specific plants) technology must be able to match enormous power peak demands and conversions must reach very high density of energy flows. For example in a 1200 MWe Fossil Power Plant, where η is about 40%, the energy throughput of fossil energy is about 3000 MWatt. Assuming an operating force of 70 people divided in three shifts, the energy throughput per person per shift is 130 MWatt. Each worker in a shift regulates in 1 hour of labor a flow of exosomatic (commercial) energy of 110 million kcal. When the endosomatic flow of an adult worker is calculated (assuming 220 kcal/hr for this particular job) the resulting exo/endo energy ratio is in the order of 500,000/1.

The Productivity of Human Time

Knowing the share of human time allocated to work and the exo/endo energy ratio (both at the level of society), we can calculate the productivity of one hour of human work. Figures 8 and 9 provide numerical examples of the assessment of the productivity of human time for a highly industrialized (USA) and a pre-industrial society (rural Burundi). The same amount of energy that is produced (in the form of exosomatic energy throughput) on average by 1 hour of labor in a society can be assumed to be the "opportunity cost" of 1 hour of labor in that society. In fact, since the energy budget of society has to be balanced, hours of labor that produce less than the average have to be balanced by hours of labor that produce more.

To obtain the share of total human time allocated to work for developed countries, we first adjust the economically active population for the unemployment rate. This reduction varies according to specific situ-



U.S.A.

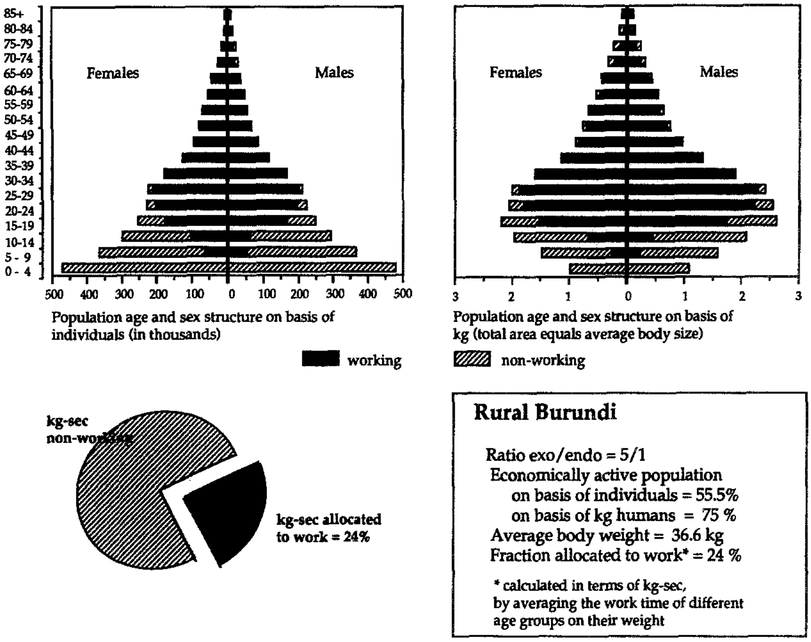
Ratio exo/endo = 75/1
Economically active population
on basis of individuals = 51 %
on basis of kg humans = 60 %
Average body size = 57.7 kg
labor charge = 1,800 hours/year
Unemployment rate = 7 %
Work absence rate = 3.5 %

Fig. 8. Population structure and time allocation for the U.S.

ations, but for most industrialized societies it is in the range of 5–10%. To obtain the fraction of time allocated to work of the population actually employed, we have to divide the labor charge per year (a value generally in the range of 1600–2500 hr/year) by the hours in 1 year (=8760). This fraction should be further reduced because of work days lost for various reasons, such as illness and strikes. This reduction is generally in the order of magnitude of 2–15% (Dawkins et al., 1985).

In the United States, the economically active population is 50.9% (ILO, 1990). Accounting for an unemployment rate of about 7%, we find that 47.3% of the U.S. citizens are actually working. Assuming a labor charge of 1800 hr/yr (36 hr/wk, 50 wk/yr), and correcting this for a work-time loss of 3.5% (Taylor, 1979), we find that the fraction of time of the working population actually spent in work is 20% (≈1750 hr per year). The resulting fraction of *total* human time in the U.S. allocated to work is 9.5% (0.20 × 0.473).

According to our assessment, 1 average hour of labor within the U.S. costs and must produce about 100,000 kcal of exosomatic energy, which is the quantity of energy needed to provide a return of 230,000 kcal/day per capita on average at societal level. This value is obtained by dividing the



Rural Burundi

Ratio exo/endo = 5/1
Economically active population
on basis of individuals = 55.5%
on basis of kg humans = 75 %
Average body weight = 36.6 kg
Fraction allocated to work* = 24 %

* calculated in terms of kg-sec, by averaging the work time of different age groups on their weight

Fig. 9. Population structure and time allocation for Burundi.

average per capita energy consumption per hr (230,000/24 = 9600 kcal) by the fraction of total human time allocated to work (9600/0.095 ≈ 100,000). Note that the biological (muscular) flow of energy spent by 1 hour of human labor is generally in the range of 150–950 kcal (Durnin and Passmore, 1967).

In rural Burundi (Fig. 9) the fraction of total time allocated to work, calculated per kg of population at societal level, is 24% [estimated from data published by McSweeney (1979), Bério (1984), and Mueller (1984)]. The ratio exosomatic/endosomatic energy is assumed to be 5/1, which is a little higher than the one reported in Table II for Burundi. In this way, we feel that the assessment can be better extended to other rural societies which also use little fossil energy but more animal power than Burundi. In this type of society, 1 hour of labor costs and must produce an amount of exosomatic energy that is "only" 21 times the metabolic energy consumed during work (5/0.24).

The average body weight in Burundi is 36.6 kg (James and Schofield, 1990) or much lower than in the USA (57.7 kg), whereas the metabolic energy spent per kg is higher, that is more than 3 W/kg. Both these values depend on the population structure and the pattern of time allocation. This means that these differences in body size and labor charge are closely related to the mechanism sustaining the energy budget (as shown in Figs. 4 and 9)—especially to the parameters characterizing the power-supply system—rather than to specific situations of malnutrition or low agricultural productivity.

In rural societies with a population structure and profile of time allocation similar to the one found in Burundi, the average return per hour of labor is in the order of 2000 kcal. Because of the assumptions implied by the model, this refers to the input of exosomatic energy used, that is biomass burned, used to obtain animal power, or converted for other uses. This means that in semidesertic areas the availability of exosomatic energy input can become a limiting factor to the carrying capacity before the food supply does. For example, the World Bank (1985) forecasts a rural population of 40 million for the Sahelian and Sudanian zones of West Africa for the year 2000. In this scenario the shortage of fuel wood supply (19.1 million people would be short of wood) will be more severe than food shortage (3.7 million people would be short of food).

As illustrated in Figs. 8 and 9, expressing the population age structure in kg of humans instead of individuals results in a sensible change in the description of the system. For example, in 1989, the economically active population of the USA was 50.9% in terms of individuals (ILO, 1990), but 60% when calculated on the basis of kilograms [average body weights for sex and age classes are from James and Schofield (1990)]. In Burundi, this difference is even more evident: the active population makes up 55% in terms of individuals (ILO, 1990), but 75% in terms of kg. This is due to the fact that a large part of the non-active population (children and elderly) has a smaller body size than the economically active population (adults).

This is a major distinction that must be observed when applying this model to pre-industrial societies operating at a low exo/endo energy ratio (<10/1). In these societies the assessment of the energy budget has to be performed referring to kg of population (kg of working population and kg of non-working population) rather than to individuals. Parameters such as demographic structure, life-span, labor charge, and time allocation have a direct effect on the endosomatic energy flow (the W/kg of metabolic energy spent in society) and these effects cannot be neglected when dealing with societies at low exo/endo levels. Actually, due to the limitation of technology (inability to increase further the ratio exo/endo) these parameters are the only ones on which society has influence to increase the flow of exosomatic energy (the energy throughput) that stabilizes social structures and functions. Since the hierarchical level of society implies a different optimization strategy than the one provided by adopting an individual perspective, this leads to a low standard of living of individual members of society (small body size, short life-span, high labor charge, child labor, no retirement, no services).

In industrial societies operating at a high ratio exo/endo (>30/1) changes in the "efficiency" of endosomatic flows of energy (body size, population structure) are irrelevant for the balance of the energy budget. The budget is balanced by the ratio between the productivity of commercial energy ($GNP/GJ; GJ = giga Joules = 10^9 Joules) and the cost of commercial energy (GJ/$). Thus, a counter-intuitive fact in a society such as the USA based on commercial energy (Fig. 6), a higher fraction of non-working kg of population, a large request for services, and more "individual spare time for consuming" actually boost the ability of society to expand its activity by dragging more oil into the economy. The more oil that is used the better, since 1 Joule produces enough added value to buy 12 more (at least as long as environmental concerns are ignored, but the stability of ecological systems will eventually limit such an expansion).

THE CHANGING ROLE OF HUMAN LABOR IN RELATION TO TECHNOLOGICAL DEVELOPMENT

The Importance of Human Power in the Energy Budget of Society

Pre-Industrial Societies (Low Exo/Endo Ratio)

Where the exo/endo energy ratio is low, the energy budget of society is heavily influenced by those parameters affecting the flow of endosomatic energy in the CI sector, especially the ones affecting the efficiency of power generation. In this case, it is the endosomatic flow that generates most of the useful energy used to collect the exosomatic energy input and that therefore defines the density of the energy throughput in society. Even small changes in parameters such as body size or life-span, can reduce the performance of the power-supply system and bring the system out of the range of sustainability. For example, an increase in the fraction of non-working kg of the population (a first effect induced when food and health care are provided by humanitarian organizations) can increase the fixed cost above the spare fraction of the energy returned by the circulating investment (Giampietro and Pimentel, 1992).

It is important to realize that the real constraint operating within this type of society is the low ratio of FI/CI. Since human labor provides the bulk of the "power supply" of these societies, the low power level per capita and the low efficiency of the power sector limit the ability to react to external perturbations, to accomplish dramatic changes (capitalization or massive changes in basic exploitation strategies), and to respond to challenges from the outside world. Due to these operating constraints, in the energy budget of pre-industrial societies there is no "spare" useful energy (disposable energy income) that can be allocated to tasks other than food procurement, reproduction and maintenance of the current social structures (CI). Scientific and technological development, major investments in infrastructure, or development of new economic sectors, education, and health care (all included in FI) can be afforded only in limited quantity, if they have to be paid with useful energy generated within the society.

Post-Industrial Societies (High Exo/Endo Ratio)

Where the exo/endo ratio is high, it is the balance of exosomatic flows that is important and this is basically regulated by the economic (market) mechanism. What is limiting this type of society is access to more capital and more energy, that in turn is limited by the ability of society to produce more economic value (goods and services to be traded in exchange). In industrialized societies the massive switch toward exosomatic power generates a tremendous multiplicative effect on the efficacy of 1 hour of human labor. Human labor no longer implies the delivery of muscle power to the environment, but rather the generation of a flow of information to regulate the power flows delivered by exosomatic, technical devices. Moreover, the multiplicative effect that technology has on human power makes an hour of labor of men and women, young and old, fat and thin, tall and short, evenly productive.

The Exo/Endo Ratio and the Role of Labor

Human labor provides a flow of applied power as well as a flow of information. Depending on the nature of society's power-supply system, the nature of the contribution provided by 1 hour of human labor can change dramatically. In societies where technology is poorly developed and the exo/endo energy ratio is low, humans perform activities in ecosystem exploitation based on traditional, common knowledge in which the flow of information provided by the individual is highly redundant and therefore generating a low value added. Because of this redundancy, the return for one particular activity can be assumed to be proportional to the quantity of human power delivered (with little variations among workers). Therefore, the value added is mainly generated by the flow of power delivered. This explains the "pre-industrial" idea that the value of a good should reflect in some way the quantity of human labor (the flow of useful energy) that went into its production.

In developed high-technology societies employees are mainly providing flexible flows of information for a much more specialized economy powered by machines. Workers, even in the industrial or agricultural sectors, are providing a flow of information to direct machines (exosomatic energy flows) that deliver power at levels thousand times higher than manpower. The economic output is proportional to: (i) the contribution of exosomatic energy conversions directly performed during the work, and indirectly required by the level of capital invested per worker; and (ii) the "quality" of the flow of information that is implied in the job (the position of the activity in the hierarchy). Generally speaking, the value added of 1 hour of labor—as well as the income provided by a job position—is proportional to the quality of the information provided by the worker during that hour. This means that, in general, the higher the wage, the lower the physical requirement of the job.

Again we want to stress that in our model, assessments of the energetic return or better of the amplification of endosomatic energy flows provided by an hour of human labor can be defined only at the level of society. When individual situations are considered (for example, when comparing the return per hour of labor of a worker of an industrial plant to that of the director of the plant) we can use only economic indicators, such as income.

Sex Differentiation of Work in Pre-Industrial Societies

Traditional farming systems based on human labor are characterized by low power levels, and avoidance of peaks of labor demand. Nevertheless, most farming systems are faced with seasonal concentrations of the production cycle and consequently with seasonal peaks of labor demand. The labor bottlenecks that exist in crop cultivation and livestock herding tend to occur in different seasons. Peak labor requirements can occur during the wet season for agriculturalists or during the dry season for pastoralists. Where the two agricultural systems exist together, they tend to function as supplementary, at least in terms of labor requirements. The cooperation between systems with complementary characteristics in their energy flows has been discussed by Isbell (1978; the concept of "energy averaging") and Tainter (1988). The use of multiple crops and livestock, typical of traditional farming, tends to spread the requirement of human power throughout the year, thereby reducing the indirect costs of the idleness of human power.

Table III. Endosomatic Energy Expenditures (EEE) of Men and Women Performing the Same Work at Different Power Levels (Theoretical Assessment)

Work = lifting 100 kg of sand for 5 m of height on stairs.
Three power levels are defined as follows:
Case 1—the work is done in 3 trips, carrying 33.3 kg each time.
Case 2—the work is done in 10 trips, carrying 10 kg each time.
Case 3—the work is done in 50 trips, carrying 2 kg each time.

	Capable?	E.E.E. (Joules)	Cheaper
Case 1			
Men	Yes	198,198	N.A.
Women	No	N.A.	N.A.
Case 2			
Men	Yes	188,769	By 2%[a]
Women	Yes	193,050	
Case 3			
Men	Yes	424,710	
Women	Yes	347,490	By 22%[a]

The assumptions are:	Energy expenditures	Time required (sec)
Case 1	7 × BMR both sexes (very heavy)	360
Case 2	5 × BMR women, 4 × BMR men	600
Case 3	3 × BMR women, 3 × BMR men	1,800

Man BMR = 1.21 W/kg
Coming from the equation[a] $BMR = BW \times 0.0485 + 3.67$ (BMR = MJ/day) where BW = kg of body weight has been assumed to be 65 kg.
Woman BMR = 1.17 W/kg
Coming from the equation[a] $BMR = BW \times 0.0364 + 3.47$ (BMR = MJ/day) where BW = kg of body weight has been assumed to be 55 kg.

[a] James and Schofield (1990).

We discussed earlier the limitations of an assessment of labor productivity based only on energy consumption, since the power level at which useful energy is delivered can affect the final value of a Joule of useful energy. Here we briefly discuss this point, illustrated with an example of the assessment of the performance of men and women in terms of both energy consumption and power level at which the work is performed.

The importance of the power level in assessing labor productivity is illustrated by a simplified example in Table III, in which the performances of men and women are estimated for the work of carrying 100 kg of sand up stairs 5 m in height (the physical definition of work includes no time requirement). As noted earlier, we could do this work in many different ways, for example: (i) 3 trips in each carrying 33.3 kg; (ii) 10 trips in each carrying 10 kg; or (iii) 50 trips in each carrying 2 kg. The high power level requirement of the first option would prevent many women (as well as some men) from performing the work in a short time. In this situation, the larger body size of men would provide a clear competitive advantage (threshold value). On the other hand, light repetitive work as in the third case gives the advantage to women, as their smaller body size and lower metabolism require less energy expenditure to complete the work.

This theoretical example illustrates the importance of considering power level requirements when dealing with the physiology of work performance. The measure of productivity in terms of energy expenditure per work done used in the field of work physiology cannot be used to study labor productivity in pre-industrial societies as it does not consider power levels. Although it provides data related to the energy input required by society, it cannot be used to assess the energy efficiency in converting food energy into useful energy, because it is like trying to compare the performances of different trucks by measuring the gasoline consumed, without specifying the performance (e.g., distance, speed, load).

From a "power supply" perspective, the traditional allocation of tasks by gender can be seen as an important factor in optimizing the allocation of human power during peak requirements. Men are generally employed in activities with high power requirements, whereas women are employed in light repetitive and time-demanding tasks. In activities requiring a low power level, it is cheaper—in terms of energy—for society if women perform the work rather than men, because of the lower metabolism related to their smaller body size. This "energy saving" is amplified by the traditional differentiation of roles: in many developing, rural societies women work many more hours per year than men (e.g., Edmundson and Edmundson, 1988). On the other hand, in societies powered by exosomatic conversions, as is the case in modern, Western societies, no discrimination is possible on the basis of power level between men and women.

CONCLUSION

Because economic processes are related to multilevel hierarchical structures, it is not possible to assess labor productivity on all levels involved by using only one scientific discipline (this applies to economics, human physiology, or energy analyses). Each discipline is a window that describes the system under a limited perspective. Energy analysis shares this limitation, but still can be usefully employed to deal with the concept of labor productivity and provide valuable insights. The model of energy analysis proposed in this article can be used to explore the complex relationships that exist between the productivity of human labor and the constraints and opportunities related to the level of technological development of society.

The model shows that population structure and human time allocation in the economy are affected by the energy budget and *vice versa.* In developing countries, the economic process is mainly affected by the constraints typical of endosomatic energy conversion and therefore faces critical power constraints. The low productivity of human labor in energetic terms (low energy output per hour) and the consequent low standard of living actually affect the social and population structure and depend on the type of interaction the society has with its environment and natural resources. The feasibility of proposed technologies and development policies to "improve" developing societies must always be assessed in terms of consistency among all the parameters involved in balancing a society's energy budget.

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