
ON THE ENERGETIC COST OF HUMAN SOCIETIES: ENERGY CONSUMPTION AS AN ECONOMETRIC INDEX

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This study attempts to focus on the energetics of human societies, by studying the relationship between social development and energy consumption. Some attempts to link economics to thermodynamics have been made (Georgescu-Roegen, 1996 for example), but for most researchers, its practicality is still not demonstrated. Thermodynamic theory, specially irreversible thermodynamics may be applied to the study of human sociality, thanks to recent advances in theoretical aspects of the dynamics of complex systems (Zotin and Lamprecht, 1996). Thermodynamic approaches allow to study external expressions of a system, hinting to possible underlying dynamic mechanisms but without tackling them directly. From this perspective, the following question seems relevant to the understanding of the temporal evolution of human societies: (i) Is the increase in social complexity, measured as the number of individuals living in a given society, correlated to an increase in efficiency of energy use by the society (optimization principle), or (ii) is it rather related to an increase in energy consumption per unit of biomass (thermodynamic prediction)? The answer to this question is relevant to the choice of variables which may reflect important dynamic features of societies, allowing for more objective econometrics or sociometrics.

Some optimization theories derived from biological theory supposes that evolution tends to create ever better adapted organisms (or societies). In this context, if sociality is considered to be a higher form of expression of life and thus a sophisticated product of evolution, societies should optimize the use of energy, as can be extrapolated from various optimization principles proposed for biological systems, such as optimization of average fitness (Dobzhansky, 1951), maximal efficiency in resource utilization (MacArthur, 1962), minimal metabolized energy per unit biomass (Hannon, 1979), maximum energetic power (Torres, 1991), minimal rate of entropy dissipation (Nicolis and Prigogine, 1977). On the other hand, irreversible thermodynamics predicts that as social systems represent higher levels of complexity compared to non-social systems, they are further away from a stationary state, and consequently require more energy for their maintenance (Jaffe, 1984, Jaffe and Hebling-Beraldo, 1993; Lamprecht and Zotin, 1978).

Thus, two diverging theoretical hypothesis predict different outcomes in the relationship between energy consumption per capita and increased social development. These hypotheses have been tested experimentally in ant societies (Jaffe and Fonck, 1994; Fonck and Jaffe, 1996) and termite colo-

nies (Muradian, *et al.* 1997). The conclusion reached was that there is a complex non-linear relationship between colony size and energy consumption per unit mass in these social insects. Results showed that at certain critical colony sizes, the colonies energy consumption is larger than the sum of the average energy requirement of the individual workers, and near maximal colony sizes, the energy consumption of the colony per unit mass tends exponentially to that of the average individual worker. It seems therefore that social complexity is related to energy consumption in a discontinuous manner and is bound by both, the negentropy content of a society (the thermodynamic hypothesis) and social optimization mechanisms (the biological hypothesis). The thermodynamic hypothesis seems to apply for the formation of societies or when comparing social systems with non-social ones, whereas the biological hypothesis applies to comparisons of societies of different degrees of development or size. Here we want to explore the generality of this phenomenon and its eventual relevance to human societies.

FORMULATION OF THE PROBLEM

Essentially, three hypotheses should be considered when in-

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vestigating the possible relationship between the degree of social organization of a society and its energy consumption:

a) Optimization hypothesis: Social life is energetically more efficient, resulting in a reduction of energy expenditure per biomass unit. Given that solitary life precedes social life, social organization should result in optimization of energy use, as societies adapt to environmental constraints. More evolved or adapted societies should thus consume less energy per capita than more primitive ones.

b) Thermodynamic hypothesis: Social life implies an increment in energy costs per individual. In this sense, the social unit would be more than the sum of its parts. Such an outcome would be a prediction of irreversible thermodynamics theory applied to dissipative structures, i. e. living systems. The society with its members and their interactions forms a complex system that maintains a certain organization, thus requiring external energy proportional to the degree of "orderliness" or negentropy of the society. Thus, more evolved societies should require more energy per individual.

c) Neutral hypothesis: Social life has no effect on the energy consumed by members of the society; the energy intake of the whole society equals the sum of the consumption of each individual, which is similar to that of an isolated individual. This is normally assumed among biologists for estimates of the energy expenditure (Brian, 1978; Godwin, 1982; for example)

In human societies, the energy consumption of the social expenditure, i.e. fuels, electricity, carbon, etc. are orders of magnitude higher than the energy consumed by all individuals as food, i.e. the caloric or biological energy consumption of the society (Odum and Odum, 1981). Thus, it seems safe to simplify the energy consumption measurements of human societies by taking into account only the energies accounted for in the national government statistics.

METHODS

The data used were obtained from the following sources:

- Report on World Development, World Bank, Washington, D.C. (1980-83, 1987, 1988, 1990-94).

TABLE I
LINEAR CORRELATION COEFFICIENTS FROM COMPARISONS BETWEEN BIOLOGICAL INDICATORS OF COUNTRIES AND GROSS NATIONAL PRODUCTS PER CAPITA (GNPC) OR TOTAL ENERGY CONSUMPTION PER CAPITA (TECC). DATA FOR 1992.

Biological indicator	log(GNPC)	log(TECC)	difference
Infant mortality	0.67	0.78	+ 0.11
Life expectancy	0.72	0.78	+ 0.06
% of low weight newborns	0.47	0.46	- 0.01
Female life expectancy:	0.72	0.79	+ 0.07
Male life expectancy:	0.70	0.76	+ 0.06
Female - Male life expectancy	0.35	0.46	+ 0.11

All coefficients are significant at $p < 0.0001$

TABLE II
ROBUSTNESS OF VARIOUS INDICES, ESTIMATED BY THE VARIANCE GIVEN AS STANDARD DEVIATION (SD) IN THEIR CORRELATION WITH LOG(TECC) FOR DIFFERENT YEARS.

Index	1979	1986	1989	1990	1991	1992	SD
GNPC	0.68	0.83	0.70	0.60	0.63	0.78	0.088
Infant mortality	0.70	0.68	0.69	0.72	0.72	0.78	0.036
Life expectancy	0.78	0.73	0.76	0.75	0.80	0.78	0.025
% of low weight newborns	-	0.42*	-	0.46	-	0.46	0.022

* data for 1985

All coefficients are significant at $p < 0.0001$

Table III
COMPARISONS OF CORRELATION COEFFICIENTS BETWEEN SELECTED INDICES AND THE LOGARITHM OF TOTAL ENERGY CONSUMPTION PER CAPITA (TECC) OR THE LOGARITHM OF ELECTRIC ENERGY CONSUMPTION PER CAPITA (EECC). DATA FROM 1990.

Index	EECC	TECC
Nr. of countries	12	12
Infant mortality	0.63	0.66
Life expectancy	0.68	0.72
% of low weight newborns	0.49	0.37

All coefficients are significant at $p < 0.02$

TABLE IV
LINEAR CORRELATION COEFFICIENTS (R) BETWEEN THE LOGARITHM OF ELECTRICITY CONSUMPTION PER CAPITA (LOG(EECC)) AND THAT OF POPULATION SIZE (LOG(POP)) OF TOWNS AND CITIES IN THREE COUNTRIES. THE SIGNIFICANCE OF THE CORRELATION IS GIVEN AS THE PROBABILITY OF THE DATA BEING NOT CORRELATED (P) AS GIVEN BY AN ANOVA WITH SAMPLE SIZE N.

Country	r	p	n
Brazil	-0.52	<0.0001	64
USA (Georgia and Tennessee)	-0.35	0.002	72
Denmark	-0.35	0.02	43

- Electric Data Systems Branch of the Energy Information Administration 1990-1994, USA.
- Centrais Elétricas Brasileiras S.A. (ELETROBRAS), (1991).
- Brazilian Institute Statistics and Geography (IBGE), (1991).
- Cámara Venezolana de la Industria de la Energía Eléctrica (CAVEINEL), 1991.
- Oficina Central de Estadística e Informática (OCEI), Venezuela, 1991.
- Danske Elvaerkeres Forening, Denmark, 1992.

The variables used were:

- Percent of low weight newborns: The percentage of newborns with less than 2.5 kg.
- Life expectancy: Average life span of individuals.
- Infant mortality: Number of children which died before reaching one year of age per 1000 births.
- Population: Pop, number of individuals.
- Total energy consumption: TEC, consumption of all types of energy (oils, gas, coal, hydroelectric, nuclear, geothermal, others), expressed in kg of oil equivalent.
- Total electric energy consumption: EEC, expressed in megawatt, including residential, industrial and other electricity consumption.
- Gross National Product: GNP in US \$.

Data were analyzed using the statistical package Statistica.

RESULTS

The relation between the biological parameters commonly used to assess the degree of social development of countries, i.e. infant mortality, life expectancy and the percentage of low weight newborns, should be indicative of the cohesiveness of societies regarding their institutions and programs for providing basic services for the biological well-being of their inhabitants. These parameters were correlated with the total energy consumption per capita (TECC) of

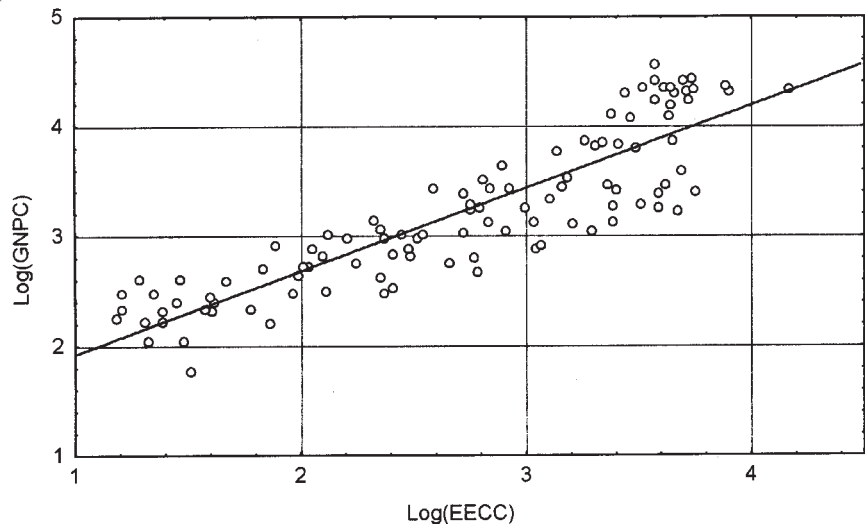


Fig. 1: Relation between GNPC and EECC for 120 countries in 1992.

TABLE V
LINEAR CORRELATION (R) BETWEEN THE LOGARITHM OF EECC (LOG(EECC)) AND THAT OF POPULATION SIZE (LOG(POP)) FOR STATES IN DIFFERENT COUNTRIES. SD INDICATES THE STANDARD DEVIATION OF THE DATA FOR EACH COUNTRY. ELSE AS IN FIGURE IV.

Country	SD	r	p	n
Japan	0.124	0.165	0.3	47
USA	0.127	-0.113	0.4	50
Brazil	0.248	0.572	0.0018	27
Venezuela	0.240	0.665	0.0007	22

the country and with its gross national product per capita (GNPC). The results (Table I) show that TECC has consistently higher correlation coefficients with these parameters than GNPC, except for the correlation with percentage of low weight newborns which showed similar correlation coefficients with both TECC and GNPC. These correlations were robust in the sense that different data sets taken at different years, consistently showed similar correlation coefficients with TECC (Table II). The highest variance of the correlations with TECC between different years was that with GNPC, suggesting that variations in GNPC are less correlated to vital statistics than those of TECC

The information for calculating TECC is normally not known for smaller social units, such as regions, cities and towns; whereas information on electricity consumption is more readily available for these human groupings. Thus, we tested the correlation between TECC and electric energy consumption per capita (EECC) for countries where

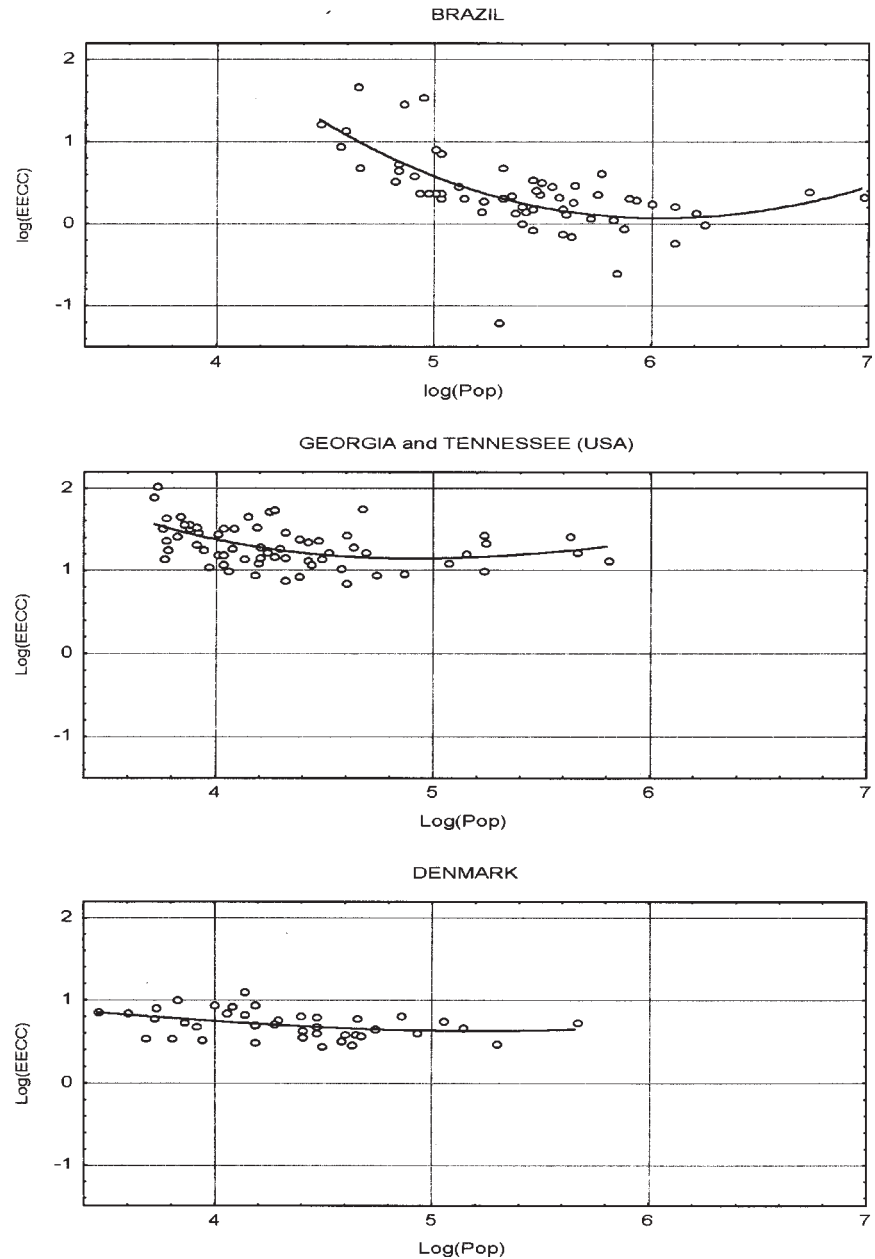
the data were available, which is given in Table III. As can be observed, the correlation between three biologically relevant indices and TECC is similar to that with EECC. The table gives the correlations for 12 countries for which data for both TECC and EECC were available, and the correlations between TECC and biological parameters for all 120 countries studied. These data suggest that both energy consumption indices were positively correlated. The indices GNPC, TECC and EECC correlate among each other. For 1992 the correlations between the available data was GNPC / TECC = 0.67, GNPC / EECC = 0.88 (see also Fig. 1), and EECC / TECC = 0.82.

When analyzing smaller human groupings, we could obtain data only for EEC. We found data for EEC of whole towns and cities for only three areas. The relationship between EECC and the number of inhabitants of the urban conglomerates, i.e. towns and cities (Figures 2- 4) showed that EECC diminished with increasing population of the conglomerate. This tendency was statistically

significant in all three cases examined (Table IV), although the sites differed in several aspects. Towns in Denmark may be considered to be stable old small urban conglomerates, those in USA are of more recent development but have a high energy consumption (nearly one order of magnitude higher than in Denmark), whereas Brazil, a much less developed country, shows a wider range of sizes in its cities. Two cities in Brazil (the megametropolis of Sao Paulo and Rio de Janeiro), however, showed larger EECC than what can be expected from a negative exponential function (as shown in Fig 2-4). Cities with extremely low EECC, such as Rio Branco (AC) and Sao Luis (MR) in Brazil, are cities with poor infrastructure and low socio-economic development. Thus, this way of analyzing towns and cities may help in identifying towns or cities which lag behind in infrastructure and economic development (Rio Branco and Sao Luis for example), or which are inefficient due to their extremely large size (Rio and Sao Paulo).

In all cases, EECC and its variance increased as the populations of the towns decreased (Fig. 2-4). Extrapolation of this tendency to very small human aggregates gives unrealistic high EECC, which are highest for data from Brazil and relatively lowest for Denmark. We were unable to obtain EECC data for very small towns or villages, but it may reasonably be assumed that a town with no inhabitants will consume no electricity or that isolated housing in rural Brazil have no electricity. Thus, a singularity must exist in the relationship between EECC and the size of villages in the region of very small towns. This discontinuity could be measured in insect societies (Jaffe and Fonck, 1994, Fonck and Jaffe 1996, Muradian, *et al* 1999) and is analogous to a physical-chemical system of phase transitions, compatible with thermodynamic predictions on the energy required for the organization of complex open systems (Lamprecht and Zotin, 1978). Thus, the results can be interpreted as a discontinuous increment in the average energy consumption of individuals in a society when a minimum of social structure is established, marking a singularity which defines a bifurcation, characteristic of a dissipative system. Once the society has been established, human aggregates seem to optimize the energy consumption of the society, where larger cities consume less electricity per inhabitant than relatively smaller ones.

Analysis of EECC in regions (i.e states) with varying population size is shown in Table IV. The data show that industrialized countries such as



Figs. 2-4: Total electric energy consumption of towns and cities with different population sizes.

Japan and USA have a more homogeneous EECC in the various states whereas in developing countries such as Venezuela and Brazil, the variance in EECC between the states is larger and a positive significant correlation between EECC and population is apparent, suggesting that industrialization and urban development is higher in more populated areas.

CONCLUSIONS

Considering the whole of the results, we propose a new hypothesis, resulting from a combination of the ther-

modynamic and the optimization principles, which could explain the energetics of human and possibly most animal societies. The hypothesis assumes the following:

- 1- The generally assumed neutral hypothesis is not valid.
- 2- The energetic cost of assemblages of organisms per unit of biomass is a function which is unknown below a minimum threshold size of villages, above which it decreases exponentially with increasing size of the system.

3- Established urban societies optimize the average energy consumption per individual as the society increases in size, where larger urban societies are more efficient in optimizing energy use.

Although alternative interpretations of the data and different statistical analyses could produce different conclusions, this work suggests that a general phenomenon, applicable to human and insect societies, may exist, which affects the energy consumption of the system, as energy balances allow to estimate the energetic cost of sociality in a given system. This work demonstrates the heuristic value of applications of irreversible thermodynamics to biological and social systems for the detection of new bio-social phenomena. The approach though does not allow to pinpoint the casual relationships explaining the variance in energy consumption. They only serve to pinpoint general constraints of complex systems and should be complemented with detailed sociological and economic analyses in order to get a better understanding of complex societies. We propose that energy consumption as an econometric index may

reflect socio-economic development better than alternative indices.

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