Howard Odum’s “Self-organization, transformity and information”: Three decades of empirical evidence

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\textbf{ABSTRACT}

The Biosphere is self-organized into a hierarchy of energy transformations. More dilute forms of energy (e.g. solar energy) are concentrated in biological structures and through socioeconomic transformation processes forming energy outputs that are able to perform higher quality work. To assess the hierarchy level of different forms of energy in the Biosphere, over 30 years Howard T. Odum introduced the concept of “transformity”, i.e., the amount of available energy of the same kind (usually solar energy) needed to obtain a specific output of available energy of another kind. Transformities represent energy quality and have been calculated for a broad set of energy forms and products, both natural and anthropic. In this paper, we report on this broad literature illustrating how the energy quality hierarchy of the biosphere works. This study leads to the definition of lower and higher energy quality thresholds supporting H.T. Odum’s initial hypothesis of an inverse linear logarithmic relationship between energy quality and quantity. A model is proposed to obtain transformities from data on energy flows.

\textbf{Keywords:}
Self-organization
Complex systems
Transformation process
Energy hierarchy law

1. Overview

Forty years after Howard T. Odum's definition of the concept of energy quality (Odum, 1976), a critical mass of empirical evidence has been reached allowing us to provide a first picture of the energy quality hierarchy of the biosphere.

The idea of “self-organization”, i.e. the spontaneous emergence of ordered structures from interactions among initially disordered parts, permeates chemical and physical theories (Surrey et al., 2001; Lehn, 2002). Self-organization mechanisms are observed and studied in different systems, including biological, ecological, geological, social systems, and neural networks (Young and Crawford, 2004; Rietkerk et al., 2004; Ostrom, 2009; Bassett et al., 2006; Pfeifer et al., 2007). This volume of research helps explain the general functioning of the Earth, the common recurrence of similar designs in Nature (e.g. fractals), and evolution (Sneppen et al., 1995).

Explanations of self-organization have been provided during the past two centuries by scientists and theorists (Lotka, 1922). Focusing on energy flows, self-organization works through an ordered series of energy transformations. More dilute/disordered forms of energy (e.g. solar energy) are converted into more concentrated/ordered ones (e.g. chemical energy embodied in biological structures). Major insights on how self-organization works have been put forward by ecologists studying ecological food webs. Howard T. Odum (1924–2002) extended the idea of an ordered series of energy transformations in natural systems, or the universal energy hierarchy, to the whole biosphere including humans and information. One of the main contributions of H.T. Odum, his students and colleagues was the development of the “energy quality” concept as the descriptor of the hierarchical level of each form of energy throughout the biosphere (Odum, 1983).

Thirty years after the publication of H.T. Odum’s seminal paper on “Self-organization, transformity and information” in Science (Odum, 1988) and the award of the Crawford Prize of the Royal Swedish Academy of Science for his research on Nature’s dynamics, empirical evidence bearing on H.T. Odum’s ideas has been mounting, making it possible to test his assumptions on how energy flows are structured according to a hierarchy of energy quality.

In order to describe energy quality, H.T. Odum proposed a measure, “transformity”, which determines the level or position of each form of matter, energy, or information in the universal hierarchy of energy.

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quality. The transformity is defined as the available energy of one type (usually solar energy) that is necessary to obtain one unit of energy of another type. Precisely, transformities represent the amount of solar energy directly and indirectly used (expressed as solar emjoules, or sej) through the energy transformation chain to obtain a unit of a product of higher available energy and hierarchical level. According to the Principles of Thermodynamics, at each step along the energy transformation chain in the biosphere, a significant amount of available energy is lost (or degraded), i.e. energy availability decreases over subsequent transformations. At the same time, the energy quality of the remaining available energy increases. If the percent use of the available energy transferred at each step in the energy transformation chain remains constant then the chain of processes should form a line of the same slope when the whole data set is considered. Of course, each specific transformation chain may have a different "average efficiency".

H.T. Odum's ideas to understand self-organization were presented in his book "Environmental Accounting – Energy and Environmental Decision Making" (Odum, 1996) and since then used in thousands of scientific papers; including the calculation of hundreds of transformities referring to a broad set of energy types from natural and anthropic production systems. Transformities have been calculated to represent energy transformations at many scales of the biosphere from DNA (Abel, 2013), to products of industrial processes (Almeida et al., 2018), to global information flows within the internet (Di Salvo et al., 2017).

2. Examining three decades of empirical evidence

We reviewed this broad variety of empirical exercises (Table S1) in order to model a hierarchy of energy types based on the amount of direct and indirect solar energy required to obtain them. According to H.T. Odum, this relationship should be logarithmically linear relating decreasing energy quantities and increasing energy qualities (Odum, 1996).

The energy values considered in this work are representative of the energy flow available in the Biosphere for each transformation process in a year. The overall flow throughout the biosphere of each energy type has been retrieved by, and elaborated from, a list of different sources as described in detail in the supplementary material. Due to data availability, transformities have been grouped as follows: global renewable resources (such as earth cycle heat flow or evaporation from the oceans; see Table S2 in the Supplementary Materials), natural resource flows (see Table S2), fossil fuels, surface and ground-water, agriculture, biofuels, electricity, drinking water, chemical and materials industry, livestock and fish, agricultural and livestock industry, people (subsistence), people (education), information (geological), information (cultural), and information (genetic). Following (Odum, 1983, 1996, 2007; Odum and Odum, 2001) these groups have been related to each other (Fig. 1), depicting how different transformation processes might be linked together through energy flows. Fig. 1 is one representation of the Biosphere organized into hierarchical levels, with the environmental sources at the base. Going from the left to the right end of Fig. 1, each previous transformation process makes available a certain amount of energy for the subsequent transformation step. At the same time, reinforcing feedbacks amplify the energy available in previous transformations.

3. Procedure to group the transformities

- All transformities were updated to the 12.0 fE + 24 sej/yr baseline
- Employing the Harmonic average, one value was determined for each product/element. The harmonic mean was used to represent the values of items that have been calculated more than once (e.g., ethanol), which, to a certain extent, intensified the presence of outliers. Thus, due to the fact that the harmonic mean is not influenced as much by discrepant values and tends to minimize values, it was more adequate to represent the repeated items.
- The median value of the previous transformities was adopted to represent the group. The median represents the value in the middle of the data set when n is odd or the arithmetic mean of the values in the (n/2) and (n/2) + 1 positions when the data set is even. The median divides the data set into two halves of identical areas, and, in general, extreme values (both upper and lower) do not affect the median value. It is considered the most robust measure, since the insertion of new values will hardly cause changes in results.

The distribution of the transformities calculated during the last 30 years (Table S1) has been investigated and outliers have been identified within each group with the use of boxplots. The boxplot is a box diagram constructed using the references of minimum and maximum values, first and third quartile, median and outliers of the database. It is used to study the statistical measures of the data set. The center part of the chart contains the values that are between the first quartile and the third quartile. The lower and upper stems extend respectively from the first quartile to the lower limit and from the third quartile to the upper limit. All values lower than the first quartile value - 1.5 * interquartile range value and greater than the third quartile value + 1.5 * interquartile range value are considered outliers. The outliers were not considered abnormal, since transformities were calculated by several authors at different times, and there was no criterion to single them out. In Fig. 2, transformities are ordered from lower to higher values for each group according to their median values. This analysis shows how different groups of natural and anthropic transformation processes are ordered in an energy quality hierarchy.

As successive transformations take place throughout the energy quality hierarchy, the amount of available energy decreases, and the quality (transformity) of the remaining available energy increases. All the economic transformation processes identified in Fig. 1 ultimately depend on natural resources (including water and fossil fuels). Human

![Fig. 1. The hierarchical organization of the energy quality of the Geobiosphere, with global renewable resources and natural resources in the first compartment. Previous transformation processes produce available energy to support the subsequent transformations. Reinforcing feedbacks amplify the energy available in previous transformations. Economic processes include "Agriculture", "Biofuels", "Electricity", "Drinking water", "Chemicals and materials industry", "Livestock and fish", "Agricultural and livestock industry".](image-url)
society also depends on economic processes that generate the most concentrated/ordered forms of available energy, such as information (i.e. both cultural and genetic), which is able to perform the highest quality work. By considering the median values of the different groups of transformation processes (Fig. 2), the inversely proportional values of available energies and transformities can be presented in a simple linear regression graph (p < 0.001; R² = 65%; r = −0.81) at the Geobiosphere scale (Fig. 3), corroborating H.T. Odum’s intuition when the whole data set is considered. Each specific transformation chain may have different “average efficiencies” as shown by the two lines in Fig. 3, one for ecosystem-type systems (solid line) and one for technological systems (dashed line), which practically coincides with the line that covers the whole dataset.

Results shown in Fig. 3 could have several implications for the understanding of Earth dynamics. The linear logarithmic relationship hypothesized by Odum and corroborated in this present work allows discussing, at least, two extreme cases. On one hand, when the logarithm of transformity tends towards zero, the logarithm of energy tends to 23.8 (s.e.m ± 0.81; p < 0.05, where s.e.m: standard error of the mean and gives an idea of its accuracy). This represents the sum of the overall independent energy inputs to the Biosphere and confirms what has been already calculated in scientific literature (Brown et al., 2016). On the other hand, when the logarithm of energy tends to zero, the logarithm of transformity tends to its maximum ideal value of 39.5 (interception of x axis). This ideal value sets the boundary for the highest achievable process of energy concentration, or ordering, for the biosphere (including human-driven transformation processes). It also represents the maximum possible amount of solar energy embodied in 1 J of information.

The second relevant information provided by Fig. 3 is the definition of a constant mean value of the marginal relation between energy quality and energy quantity for the Geobiosphere (including human-driven transformation processes). Operationally, in order to increase
one order of magnitude of energy quality, around 75% of the energy quantity (energy flow) becomes unavailable to do work in the process (Eq. (1)).

\[ \frac{E_i}{E_r} = \left( \frac{T_i}{T_r} \right)^n \]  

(1)

Where \( E_i \) and \( E_r \) represent the energy quantity of the systems \( i \) and \( j \), \( T_i \) and \( T_r \) the corresponding transformities, and \( n \) the exponent (0.6036 for the universal diagram, Fig. 3).

The fraction of the available energy lost is lower than what is generally observed through subsequent steps over an ecosystem's trophic levels, which is around 90%; by Lindeman's 10% law (Lindeman, 1942). In fact, the Lindeman's law is only observed when the systems near the interface with nature are considered, the exponent \( n = 0.9914 \) from Eq. (1) for the series 1: Solar energy, 2: Global renewable sources, 3: Natural resources, 4: Fossil fuels, 5: Surface and ground-water, 6: Biofuels; 7: Agriculture. This implies that highly efficient human processes are overrepresented in the overall relation investigated here, which is influenced to some extent by the current technological levels of different production processes. Human processes are designed to reduce costs (such as in lean production) and are highly specialized. This specialization might lead to a higher efficiency of energy transfer. Society is always searching for more efficient outcomes, and this, reduces diversity and redundancy (which are sought in natural systems as a means for maximizing power under variable energy signatures) and increases efficiency through orienting and simplifying systems (Biggs et al., 2012). However, the exact reason is still unknown and requires further investigation.

Starting from the relationship represented in Fig. 3, it is possible to obtain the amount of solar energy needed to produce one unit of a product, a measure of its hierarchical energy quality level or, alternatively, the amount of energy flowing through the biosphere in a particular process can be determined. In order to do so, after adjusting for residuals and assessing the predictive power of the linear relationship found (see supplementary material), we propose two prediction graphs and “working-tables” (Fig. 4, S3) with reference values for energy flows and relative transformities (and vice versa) with 95% confidence intervals. There are large error bars on most of these numbers, and predictions are not possible just using this figure. Different physical processes trace out different lines of energy hierarchy, and the universal diagram may represent a useful advance, but it still requires more specific information.

Fig. 3 also provides an overall picture of transformities so far calculated in the literature and it identifies the gaps to be covered by future research. A relatively small amount of data is available for specific natural resources and ecological processes as well as regarding the energy required to produce different kinds of information (Table S1). This study allowed a first graphical representation of the hierarchical organization of the biosphere in terms of energy quality that could be further refined by focusing research where data is lacking.

4. Potential implications

The results of this study confirm the log-log linear relationship between energy quantity (annual energy flow) and energy quality, as described by H. T. Odum in 1988. Log–log relationships are frequently known as the signature for the operation of a power law (Andriani and Mckelvey, 2009), which has been used to represent complex aspects of how individuals, organizations, economies, and societies operate. In nature, trees, rivers, mountains, clouds, coastlines, and earthquakes show the operation of power laws (Jiang, 2015) formulated as a fundamental law in various disciplines – from physics to linguistics.

Complex systems evolved in non-linear manners, and many of them tend to be self-similar across levels (i.e. they display fractal behavior), and similar dynamics drive order-creation behavior at multiple levels - similarly scaling laws representing system dynamics appear at many orders of magnitude (Andriani and Mckelvey, 2009; West et al., 1997; Casti, 1994). Power laws can also describe fractals, suggesting a proportional relationship between two correlated measures. Odum’s hierarchical scaling, based on the structure of energy cascades, is a clear analogy with fractal structure. Both regular fractals and the Geobiosphere hierarchy have the same scaling process and self-similar patterns (Chen, 2017; Giannetti et al., 2012).

The main implications of this study are: (1) theoretically achievable and existing lower and higher boundaries of energy quality levels in the Geobiosphere can be defined; (2) a first order estimate of the amount of energy lost in each subsequent transformation step in the Geobiosphere was made; (3) two “working-tables” that can be used by researchers interested in self-organization to test the relationship between energy quality and quantity were constructed, allowing prediction of one as a function of the other (Fig. 4, S3); (4) and finally, gaps in the transformity values found in the scientific literature were identified, which require further research efforts to be fulfilled.
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Appendix A. Supplementary data

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References