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Transformity dynamics related to maximum power for improved emergy yield estimations

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ABSTRACT

H.T. Odum originally defined transformity as the amount of energy of one type required to generate a unit of energy of another type with the caveat that the energy production system was operating under competition at optimum loading for maximum power. The caveat has been mostly ignored in emergy evaluations, often because it is difficult to identify when or whether a transformity was produced at maximum empower. We developed the model TechnoPulse to explore the temporally dynamic relationship between transformity and empower. As TechnoPulse cycled through four distinct phases of birth, growth, decline and recovery, maximum empower was accompanied by minimum transformity for the production flow. Conversely, the period of minimum empower corresponded to maximum transformity. After the "birth" of the new energy form, the period of growth saw empower increase as tranformity declined. Since transformity is the reciprocal of efficiency, maximizing empower also increased efficiency. We found that the non-pulsing situation had higher empower than pulsing, but that pulsing maximized power and minimized tranformity (maximized efficiency). We found that the national production of electricity in the US followed the pattern observed from the growth portion of the TechnPulse simulation by maximizing empower and minimizing transformity over the period 1995–2006. A contrast of two methods for estimating the emergy yield of systems (emergy summation based on common practices and transformity multiplication based on using minimum transformity at maximum empower) applied to PV electricity production revealed starkly different interpretations for PV's role and viability as a primary source of electricity, but more importantly suggested that there is a easy rationale for employing each method. Finally, emergy evaluations can be improved by heeding Odum's original definition of tranformity and using the minimum tranformity corresponding to maximum empower.

1. Introduction

The energy-based environmental accounting methodology known as emergy accounting relies heavily upon transformities, originally defined by Odum (1988):

> " . . . we defined a new quantity, the transformity, which is the amount of energy of one type required to generate a unit of energy of another type (in real competitive conditions of optimum loading for maximum power). "

When the all of the input energies are traced back to solar energy, the transformity is called the solar transformity and is defined as the total solar emergy required per unit of available energy generated. It has units of solar energy joules per J (sej/J).

One of the basic concepts behind transformity is that energy transformation systems require a multitude of energy forms as "reactants" (e.g., photosynthetically active radiation, electricity, high temperature heat, chemical free energy of freshwater) to generate an energy product that has characteristics different from each reactant, often in multiple dimensions (e.g., chemical phase, energy density, mass density, color, information content). Typically, chains or networks of energy transformation systems are linked so that output from one is an input for others. Since the second law of thermodynamics dictates that the useful energy generated as output must be less than the total input energy, the solar transformity of the energies generated increases across the linked energy transformation systems.

Odum (1996) suggested 10 methods for estimating solar transformities (Table 1). A database of published solar

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Table 1
Methods suggested by Odum (1996, p. 277) for estimating solar transformities.

1. Evaluate main energy flows of geobioshpere aggregated as necessary coproducts
2. Evaluate energy flows of geobioshpere that are splits of the main flows
3. Evaluate environmental economic production examples
4. Evaluating accumulations in a stored reserve
5. Evaluating transformities by combinging other transformities
6. Evaluating transformations in published energy network diagrams
7. Tracking emergy of each source through network and combining
8. Evaluating network energy flow data with microcomputer program
9. Evaluating energy distribution graphs
10. Inferring transformity from hierarchical positions indicated by turnover time

transformities is now available on-line for a vast range of energy forms (Tilley et al., 2012).

Some of the most common uses of solar transformities include:

1) as a multiplier of energy inputs to estimate the solar emergy contributed by each individual source,
2) as a quantitative measure of hierarchical position in an energy network,
3) as a measure of the ability of two or more energies to interact productively,
4) as a multiplier of energy output to estimate solar emergy yield.

Today, in emergy accounting, arguably the most widely used property of the solar transformity is as a multiplier of individual energy inputs to estimate their solar emergy contribution (#1 listed above), while the other properties are utilized less often. Presciently, Odum (1996 p. 276) noted, “Not everyone realizes that a transformity of a product has several uses.” Rarely, do you find a published emergy study that utilizes a solar transformity as a multiplier of energy output to estimate solar emergy yield. Rather, today most emergy scientists invoke the guidance offered by Ulgiati and Brown (1998) who focused on only one of Odum’s methods for estimating solar transformities, and by default one method for estimating the solar emergy of the system’s yield. Namely, they promoted the use of:

$$Y = \Sigma M_i = R + N + F \tag{1}$$

where all terms are in sej and defined as: the system yield (Y), the ith input of emergy (M_i); all renewable inputs (R), all locally non-renewable inputs (N) and all purchased inputs (F) (see Fig. 1 for diagrammatic definition). The solar transformity (τ) estimator then becomes:

$$\tau = \frac{Y}{\varepsilon} \tag{2}$$

where ε is the available energy in J, giving τ units of sej/J.

Due to the multitude of processes available for transforming a feedstock energy from one form to another (e.g., chemical to mechanical), it is reasonable to expect that solar transformities for the same form of energy can have different solar transformities. For example, a perusal of the emergy database (Tilley et al., 2012) provided 47 estimates of the solar transformity of electricity, which included various feedstock sources such as coal, biomass, biosolids, hydrodams, natural gas, atomic energy, peat and wind, and several operational configurations, such as anaerobic digestion, steam turbines, combined heat and power, fuel cells, gas turbines, and internal combustion engines. The estimates ranged from a low of 18 kilo-sej/J-electric (ksej/J$_e$) for a wind turbine to a high of 7459 ksej/J$_e$ for an ethanol by-production plant with a mean of 572 ksej/J$_e$ and a median of 286 ksej/J$_e$. Thus, there is large variability in the solar transformity of electricity useful for industrial, commercial and residential consumption (i.e., 50 Hz, 120 V-AC). The range is 7441 ksej/J$_e$, which is 26 times the median. Recent work has identified the magnitude and sources of variability of solar transformity estimates and how the uncertainty can propagate through a series of emergy evaluations (Cohen 2003; Ingwersen 2010; Li et al., 2011; Hudson and Tilley, 2014).

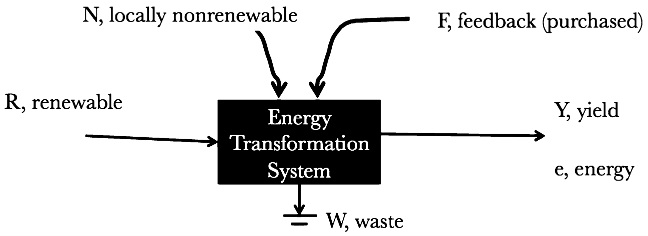

Fig. 1. Often it is blindly assumed that $Y = R + N + F$ holds for all systems, regardless of power maximization. Each term is in units of solar emergy (sej) and the solar transformity of output energy is Y/e. However, according to Odum (1988) this is only true if the energy transformation process is operating at optimum load for maximum power.

Some obvious questions that arise about variability in transformities include: (1) Why is the variability of the solar transformity of electricity so large? (2) What is the source of variability? Is it fuel feedstock, technical/mechanical conversion efficiencies, labor intensity, natural energies, financial capital intensity or something else? (3) What is the best value to use in other studies? (4) Does the quality of the electricity vary as much as the solar transformity? (5) Do these estimates meet Odum’s original definition of “real competitive conditions of optimum loading for maximum power”, making them true solar transformities? Or are they based on non-optimized systems, possibly evaluated early in their developmental phase?

If the systems were not optimized for maximum power, then Eq. (1) is invalid; simply summing the inputs to estimate the yield, while appearing to hold true to the definition of emergy, is misleading because it does not consider whether the system is performing at its best. Blindly applying Eq. (1) to a horribly inefficient system would estimate a high yield (and high solar transformity), whereas as a finely optimized system would generate a low yield (and low solar transformity).

Thus, what is often overlooked by emergy scientists when universally applying Eq. (1) is the latter part of Odum’s (1988) definition of transformity (i.e., “in real competitive conditions of optimum loading for maximum power”). Certainly, one can calculate the solar emergy required to make a form of energy for a system that is not at maximum power to obtain a ratio with units similar to solar transformity, but according to Odum’s maximum power caveat, that ratio is not a proper solar transformity. This would then call into question the results of studies that, for example, strive to understand the sustainability or emergy yield ratio of fuels and electricity generation for new or inefficient processes.

When an inefficient electricity production system generates a large solar transformity for electricity, this leads the investigator to assume that the electric yield has more solar emergy than if the