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Emergy and co-emergy

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ABSTRACT

We introduce a method of calculating emergy that requires only ordinary algebra without any reliance on special rules to account for co-production. This is accomplished by using an intermediate computation "co-emergy", and treating co-production as a problem of scale. In addition, we compare emergy calculations using inputs to the system with emergy calculations using what was used up in the system. It is shown that this can lead to slightly different results. We show how these methods can be used to compute emergy in systems at steady state, with imports and exports and with changes in stocks. These techniques allow direct comparison of competitive species, industries, or technologies using standard methods of linear algebra. It also enables us to include the efficiencies of various processes explicitly, which can help in the formulation and testing of conjectures about the relationships between emergy and local and system-wide efficiencies.

1. Introduction

It is often observed that traditional methods of economic analysis are inadequate to deal with valuing the contribution of environmental resources to human welfare, let alone the well being of the planet. One of the major problems is that money is not used for transfers of materials, chemicals, or energy in nature. The only thing universally used in transfers of both nature and man, even including ideas and information, is energy itself. However there is no strict analogy between money and energy since money ostensibly maintains its potency while passing through a system whereas energy's capabilities degrade (Odum, 1973). The total energy inputs, of one type, as a measure of the work done by nature to generate resources, both natural and manmade, can be viewed as a rough analogy to the total requirements of input–output analysis. Rough because first, we are dealing with external inputs and flows through the system rather than cycling within it. And second, we need to put all those inputs on an equivalent basis of energy of one type (most economies run on only one currency).

This paper is about, from one point of view, an accounting procedure to assess the total energy inputs, of one type, to a system required to support the activities or production of some associated subsystem. The numbers obtained from these assessments can be used to compare system-wide efficiencies of competing processes, and can be used as proxies for the importance of those subsystems to the system as a whole. In order to equitably compare processes with vastly different inner workings, or differing in their position in the hierarchy of the system, energy inputs need to use a common metric. Typically energy inputs of multiple types are traced back to their origins as solar inputs to the earth. If that is neither possible nor practical then the inputs are put on some commensurate basis to solar inputs by comparisons to transformations to a common energy form acting under certain efficiency constraints (e.g. petroleum to electricity compared to solar to wood to electricity).[1] "In order to put the contributions of different kinds of energy on the same basis, we express all resources in terms of the equivalent energy of one type required to replace them. A new name is defined: EMERGY (spelled with an "M") is defined as the energy of one type required in transformations to generate a flow or storage" (Odum, 1988). Another definition of emergy is given as "...the available energy of one kind previously used up directly and indirectly to make a service or product. Its unit is the emjoule" (Odum, 1996). Although these two definitions appear on the surface to be of trifling difference, they are on closer reflection quite different. And although the definition is usually given in the latter form, it is the former one that is the basis of almost all calculations heretofore. In this paper we show how emergy using both definitions can be calculated using the methods described herein and how both definitions have their strengths and usefulness in analyzing some system properties.

[1] By our use of the terms "type" and "solar inputs" we mean at a macroscopic level, and averaged over various dimensions of availability and use respectively. These details are dealt with elsewhere, see for example, Tilley (2003), or Odum (1996)

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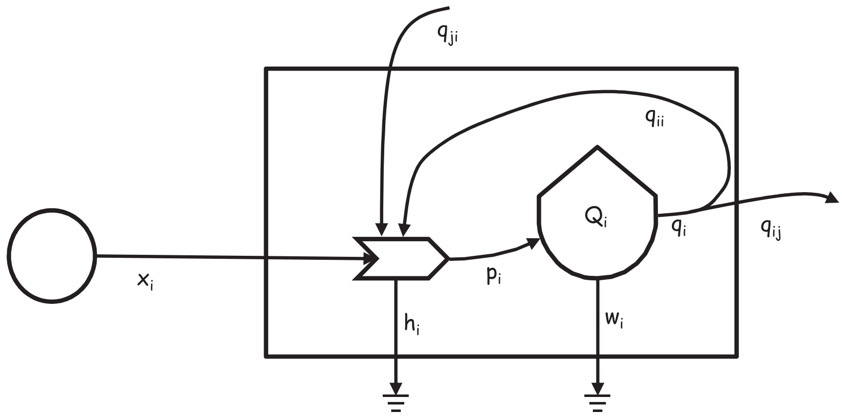

Fig. 1. The labeling scheme for a single sector of a system or economy with the main flows discussed in this analysis. We use Odum's energy systems language Odum and Environment (1971) Circles – "source" symbol, i.e. external resources (in terms of energy); box – an economic sector or other well defined unit consisting of production and storage; chevron – "interaction" symbol, i.e. sector production function; "tank" symbol – storage; lines – energy flows. Lines leading to ground symbol are heat and other second law losses from production (h) and depreciation and decay of stocks (μ). See text for further details.

The method outlined here is a review, elaboration and development of the "track summing method" (Odum, 1996) first developed using linear algebra techniques in Tennenbaum (1988). We will try to cover all the *major* conceptual issues involved in applying our method. In Section 2.1 we establish basic notation and labeling scheme. In Section 2.2 we discuss the calculation of *source* emergy and transformities. In Section 2.3 we discuss the calculation of *sink* emergy and transformities. Using standard matrix algebra, in Section 2.4 we show how the special case of computing the emergy of co-products might be dealt as an issue of scale and without any recourse to special computational rules. In Section 2.5 we generalize the situation to include trade and changes in stocks. And finally we include an appendix where we demonstrate one possibility for how these computations might be used to compare the system wide efficiencies of competitive subsystems.

2. Methods

2.1. Model

For our first example we assume a simple case of a system where each sector's output (product) is treated in the aggregate so that we avoid complications dealing with co-products. All sources are in solar units and there is a single external source, if any, per unit. For economic systems, our "sectors" will explicitly include all components of GDP (including personal and government expenditures, changes in inventories, imports and exports, etc.) and value added (wages, salaries and other forms, of income that represent human labor and effort). In addition environmental inputs and services to the economic system are included regardless of whether any human endeavor or effort was made in obtaining them. See Fig. 1

For a system of n compartments we have the following energy flows related to a particular sector i (flows to the $n+1$st "unit" are exports[2]). Energy (or energy content of raw materials as well as non-competitive imports) are denoted by x_i and diagramed coming from a circle outside the boundary of the system and flowing to the interaction (production symbol). Energy content of newly produced product (gross production) is denoted by p_i and is diagramed as coming from the interaction symbol to the tank symbol (storage). Energy flow out of storage i being used by any components of the system, including self use and exports, is q_i, and the portion of that flow to another particular sector j is denoted $q_{i,j}$.

Table 1
Labeling conventions and some definitions of symbols used in this paper.

Relationship	Explanation
$q_i = \sum_{j=1}^{n+1} q_{i,j}$	Total of useful outflow of product to all sectors and exports
$r_i = x_i + \sum_{j=1}^{n} q_{j,i}$	Total inflow of energy, material & product from all sectors
$\frac{dQ_i}{dt} = p_i - q_i - w_i$	Rate of change of stored product
$f_{i,j} = q_{i,j}/q_i$	Fraction of total useful output of unit i used by unit j $(\sum_{j=1}^{n+1} f_{i,j} = 1)$
$a_{i,j} = q_{i,j}/p_j$	Gross production coefficients[a]
$h_i = r_i - p_i = \mathcal{H}_i(r_i)$	Production losses (energy costs)
$\eta_i = p_i/r_i$	Energy conversion efficiency
$w_i = p_i - q_i = \mathcal{W}_i(Q_i)$	Storage losses (or deaths; a function of stock level Q_i)
$\omega_i = q_i/p_i$	Storage (or survival) efficiency
$u_i = h_i + w_i$	Total energy losses of unit i
$\eta_i\omega_i = q_i/r_i$	Overall efficiency of the unit i

[a] The gross production coefficients ($a_{i,j} = q_{i,j}/p_j$) are different from the IO technical coefficients ($\underline{a}_{i,j} = q_{i,j}/q_j$) available for many states and countries economies. The relationship between the two is, in the simplest case, $a_{i,j} = \omega_j \underline{a}_{i,j}$ where $a_{i,j}$ is the production coefficient, $\underline{a}_{i,j}$ is the published technical coefficient, and ω_j is the storage efficiency of compartment j. In addition we include explicit coefficients for environmental inputs and labor, and may include trade, capital expenditures, or other components of final demand, etc.

We will call this output *distributed production*, and it equals self-use production ($q_{i,i}$) plus net production.[3] Lines leading to ground symbol are losses from production h_i and depreciation and decay of stocks independent of the production process w_i. Storage of energy (or the energy content of capital stocks) is denoted Q_i. We also have the following relationships (Table 1)

At steady state we have $dQ_i/dt = 0 = p_i - q_i - w_i$, so that $p_i = q_i + w_i$. Also at steady state $p_i = r_i - h_i$ and $r_i = q_i + h_i + w_i$.

2.1.1. Energy balance for a simple system at steady state

For a system of three compartments or sectors (see Fig. 2 for example) the energy of gross production can be equated to the energy inputs less production losses,

$$p_1 = x_1 + q_{1,1} + q_{2,1} + q_{3,1} - h_1\,,$$

$$p_2 = x_2 + q_{1,2} + q_{2,2} + q_{3,2} - h_2\,,$$

$$p_3 = x_3 + q_{1,3} + q_{2,3} + q_{3,3} - h_3\,.$$

[2] Imports (goods and materials that are also produced within the system) and changes in storage will be dealt with in Section 2.5.

[3] We use net production in the economic sense of the word as opposed to the ecological sense. The ecological meaning takes into account any production exceeding respiration and includes production allocated for growth.