EMERGY SYNTHESIS 3:
Theory and Applications of the Emergy Methodology

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Current Technical Problems in Emergy Analysis

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ABSTRACT

Technical problems related to the determination of the emergy base for self-organization in environmental systems are considered in this paper. The comparability of emergy analysis results depends on emergy analysts making similar choices in determining the emergy base for a particular system and the reproducibility of results depends on clear communication of the assumptions and methods used. Four problem areas considered in this paper are (1) the choice of a planetary baseline, (2) avoiding double counting in determining the renewable emergy base for the system, (3) the emergy received by a system versus the emergy absorbed, and (4) the expanding emergy base for global self-organization. More than one planetary baseline can be justified (e.g., $9.26 \times 10^24$ sej y$^{-1}$ and $15.83 \times 10^24$ sej y$^{-1}$). The baseline value depends on the assumptions made about connectivity and causality within the global processes used to determine the equivalence of the earth’s primary energy sources. Transformities are convertible from one baseline to another by multiplying by a factor. The renewable emergy base for a system can be determined using the same rules to avoid double counting regardless of the baseline used. The baseline used should always be reported in any emergy study. The emergy actually used within a system (absorbed) is the basis for system organization and determines the transformities of system products. The emergy received by a system gives the potential for organization and use and may be related to the general attractiveness of an area for investment. A theoretical explanation of the expanding emergy base for global self-organization follows: ecological, economic, and social systems are organized hierarchically in different realms of increasing complexity as a function of increasing energy transformation. The self-organization of such systems is based on the interaction and distribution of the co-products of primary planetary processes and the addition of emergy sources from pulsed global storages, i.e., fossil fuel and shared information. A rationale for estimating human work contributions to system organization using learned knowledge and the technology used is put forward. Following the guidelines and suggestions given in this paper will increase the reproducibility and comparability of emergy analysis results and may increase the acceptance of Emergy Analysis in the broader scientific community.

INTRODUCTION

Energy Systems Theory (Odum 1971, 1994) and its offshoots such as energy/emergy analysis (Odum 1978) and environmental accounting (Odum 1996) have been rapidly evolving areas of inquiry for more than 30 years. H.T. Odum’s tremendous intellectual creativity and his zealous search to expand and improve scientific knowledge and use it for the betterment of the world have been the primary driving forces behind this progress. His death in 2002 has brought practitioners in this field to a time of transition. On one hand, we want to preserve and promote the excitement of intellectual creativity upon which so much progress in these fields has been based. On the other, for his work and
ours to become accepted, used, and respected in the broader scientific community, our analyses must be reproducible, our assumptions must be clearly stated and their consequences acknowledged, and there must be some agreement among practitioners on what constitutes good practice in the field. The latter will require some degree of standardization in reporting results to insure that energy studies are reproducible and comparable. For example, at the United States Environmental Protection Agency, we have been challenged to demonstrate the utility of emergy analysis in the evaluation of the economic and ecological effects of environmental policies. One criterion for success in this endeavor is that the scientific community understands the analysis method and accepts it as valid. The proof of success is that other scientists in the Agency and in the broader scientific community begin to use our methods and quote our results. For these events to occur, emergy practitioners must have a set of accepted methods and practices that allow our investigations to be reproduced and compared.

Emergy analyses have been performed at each stage in the development of the method over the past 30 years, and as our understanding of concepts and methods evolved the planetary baseline for determining transformities was expanded and refined. New baselines, under the constraint that double counting be minimized, led to different sets of rules for determining the emergy base of the systems analyzed. Because of this rapid evolution, the results of many analyses reported in the literature are not exactly comparable. Table 1 shows estimates of the renewable emergy base for 7 states, the emergy sources used to determine the base, and a reference giving the source of the information. Different rules were used to calculate the renewable emergy base in six of seven state studies performed from 1979 through 1999. In addition, practitioners of emergy analysis have not always been careful to use the most recent transformities and document the sources of values and assumptions used in their analyses.

In this paper, we examine several issues affecting emergy analysis that will require consistent treatment in the future, if results are to be comparable. (1) The same planetary baseline must be used for all transformities in an analysis. (2) The rules to avoid double counting should be independent of the baseline. (3) The emergy base for system organization is a function of the spatial resolution of the emergy inputs. (4) The emergy coming into a system may be measured at two points: (a) the point of entry where energy is received and (b) the point of use where energy is absorbed. (5) A consideration of the emergy base for world biomes (Brandt-Williams et al. manuscript) led to the realization that the emergy base for a given level of organization in a nested hierarchy depends on the properties of emergy as a second law quantity, i.e., emergy is the energy of one kind previously used up in a formation process, where many different kinds of energy input have been converted to a single kind by multiplying each by its appropriate transformity. Because each co-product of a formation process carries the entire emergy required as input (Odum 1996), the sum of the co-products of a system carries more emergy than the original input, but the emergy of individual co-products cannot exceed the emergy of the inputs. Emergy calculations are based on underlying energy flows that satisfy the conservation principle (1st law); however, as explained above the emergy calculus is not constrained strictly by this principle. Therefore, where organization at a given level in a nested hierarchy is formed using the co-products of the preceding level, the emergy base for each succeeding level will be somewhat greater than the preceding one. Specifically, this property may be identified with the “emerging forms” of higher ordinality that are determined by the generative component of transformity as explained by Giannantoni (this volume). Of course the emergy base will also expand increasing the generative component of transformity when a new source of emergy is utilized in the process of self-organization at any level. The implications of the expanding emergy base for environmental accounting are briefly considered.

**PLANETARY BASELINES**

The geobiosphere of the earth receives and processes energy from three primary sources: solar radiation, the deep heat of the earth including both residual heat and radioactive decay, and the gravitational attraction of the sun and moon on the earth. These energies interact in different
Table 1. Comparison of the determination of the renewable emergy base for 7 states in the United States. Sources counted in the base for renewable emergy absorbed (✓) and received (✗).

<table>
<thead>
<tr>
<th>Year</th>
<th>WV²</th>
<th>NC¹</th>
<th>AK¹</th>
<th>AR²</th>
<th>TX³</th>
<th>ME¹</th>
<th>FL¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable energy absorbed (X E20 sej y⁻¹)</td>
<td>6.8</td>
<td>19</td>
<td>404</td>
<td>20</td>
<td>39</td>
<td>15</td>
<td>66</td>
</tr>
<tr>
<td>Renewable energy received (X E20 sej y⁻¹)</td>
<td>152</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergy base (X E24 sej y⁻¹)</td>
<td>9.26</td>
<td>9.44</td>
<td>9.44</td>
<td>9.44</td>
<td>8.0</td>
<td>10.53</td>
<td>8/9.44</td>
</tr>
<tr>
<td>Chemical potential rain on land (l) and/or sea (s)</td>
<td>✓</td>
<td>✓</td>
<td>(s)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Runoff</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earth cycle (mountain area)</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tides</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Waves</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>River geopotential absorbed</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>River, chemical potential absorbed</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>River chemical potential received</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference⁴</td>
<td>a.</td>
<td>b.</td>
<td>c.</td>
<td>d.</td>
<td>e.</td>
<td>f.</td>
<td>g.</td>
</tr>
</tbody>
</table>

¹ If all rain runs off to the coastal ocean then all the chemical potential energy of rain is used in the system. Transformity is 18200 sej/J with no double counting.
² Because rain carries two different kinds of energy (chemical potential and geopotential) and is split to drive two different processes (evapotranspiration, ET and runoff, RO) that result in different products (vegetation and landform), both are counted in the emergy absorbed. In the past, different assumptions have been made which assigned these two flows as splits or co-products in a hierarchy leading to different rules to avoid double counting and different transformities. If ET is a split of rain (Tr= 18,200 sej/J) and if additional energy transformation is required for the physical energy in streams (Tr = 27,200 sej/J ). If evapotranspiration and runoff are global co-products, ET has a transformity of 28,100 sej/J and the geopotential energy of streams is the same as above (Campbell 2003).
³ Transformity for rain has tide removed (Tr=15300 sej/J), thus tide can be counted in the base (Odum 1996).

In order to drive many global processes producing co-products, e.g., wind, rain, ocean currents, tides, the earth cycle of uplift and subsidence, etc. Environmental accounting using emergy depends upon the ability to convert energies of all kinds to solar emjoules. To accomplish this, a solar emergy baseline for the earth must be established. To establish a planetary baseline from which all other transformities for the global system can be calculated, the joules of energy supplied in the earth’s deep heat and the gravitational attraction of the sun and moon must be expressed as solar emjoules. This can be accomplished by evaluating any global process to which the sun and one or more of the other inputs contribute. Figure 1 shows the interconnected system of atmosphere, oceans, and crust that forms the earth’s geobiosphere. The earth’s primary emergy inputs, gravitational attraction of the sun and moon (G) deep earth heat (E) and solar insolation (S) combine in driving two global processes: (1) the annual production of geopotential energy in the world oceans and (2) the earth cycle of uplift and subsidence. All three primary inputs are shown contributing to each of the global processes in Figure 1. In fact, differences in the planetary baseline are directly related to the degree of connectivity among the three primary sources in the global processes evaluated to determine the equivalence between them. Of course, the baseline will also change if a new energy source is added to the inputs.

Table 2 shows the differences in the planetary baseline as the energy sources considered and the degree of connectivity assumed to exist between them have changed over the time of development.
Three of the baselines (the 9.26, 10.58, and 15.83) listed may be reasonable choices based on current knowledge, but only the 9.26 and 15.83 baselines are in use by practitioners. The 9.26 baseline is an updated version of the 9.44 baseline of Odum (1996). The method used to calculate the transformity of tidal energy for the 9.26 baseline (Campbell 2000) parallels the method that Odum and Odum (1983) used to determine a transformity for the earth’s deep heat, and thus it is preferable to the 9.44 baseline, which did not calculate the transformity of the tide directly. The 15.83 baseline was determined using a matrix solution (Collins and Odum 2000) for a completely interconnected global network. Both of these baselines are reasonable based on our current state of knowledge (Figure 1, Table 2) and the advantages and disadvantages of each are considered below.

**AVOIDING DOUBLE COUNTING AND THE EMERGY BASE FOR A SYSTEM**

The different modes of interaction among the three primary energy sources (S, E, and G) determine the planetary baselines, but the degree of interaction does not affect the double counting question for 1st order methods of determining the renewable energy base for a system. This is true because in 1st order methods planetary processes are considered to be one interconnected system of mutually necessary subsystems (Odum 1996), thus the entire energy of the earth is assumed to be necessary for the formation of all planetary co-products, regardless of the baseline. As a result the rules to minimize double counting in determining the natural energy base for a given system (a
given area of the earth) will be the same for all baselines. The simple rule to avoid double counting when using the 15.83 or the 9.26 baseline to determine the renewable emergy base for a system is to only count the largest inflowing emergy of all the co-products of the planetary system (including tide) as the emergy base for any given area of the earth. Under this rule different areas in the same system may count different single emergies as the direct base, e.g., tide for a state’s area of coastal ocean and the chemical potential energy of rain for the land area of the coastal state can be added together to get the renewable emergy received by the entire area of the state. The same resolution for averaging the emergy inflows must be used to insure that bases are comparable. Where emergy inflows are concentrated in space, higher resolution of the inputs will result in a greater emergy base for the system. For example, at a resolution of 100 m, the zone of breaking waves would be resolved for a coastal system and the wave emergy absorbed might be added to the emergy base for the system after adjustment of the area of the other inputs, and if it is the largest input received over the area of the 100 m coastal strip. This dependence on spatial resolution requires that the emergy analyst consider differences in the emergy signature across the landscape, thus areas of different biogeographic characteristics are considered separately and the largest emergy inflows to each are combined to represent the total system. If the partial contributions of each primary energy source (S, G, and E) to a planetary production process can be determined the transformity of that global product would be determined on the basis of some fraction of the planetary baseline. In this case, the partial fractions of independent emergy input from all sources to a given area could be added without double counting.

To define the emergy base for a system the fraction of the largest emergy received that is absorbed by a given area of the system should be determined. Rain is often the largest emergy input to a given land area and its contributions (chemical and geopotential energy) have been counted in several ways (Table 1). Note that the emergy of rain absorbed is split into two different processes, the chemical potential used (primarily in evapotranspiration) and geopotential energy used (primarily as runoff); therefore, these two are added to determine the emergy of the rain absorbed (Odum et al. 1988a).

The emergy received by a system is augmented by cross boundary fluxes of energy and matter bringing additional emergy into the system from other areas. Only the largest of the co-products of a single process is counted as inflowing emergy received, e.g., the chemical potential energy in river water flowing into the system is counted when it is larger than the geopotential energy delivered at the border. The amount of these energies leaving the system must also be determined and the difference

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**Table 2.** Comparison of planetary baselines in chronological order. S, E, and G, refer to the primary planetary emergy inflows solar insolation(S), the earth’s deep heat (E), and gravitational attraction of the sun and moon (G) as shown in Figure 1.

<table>
<thead>
<tr>
<th>Planetary Process Evaluated</th>
<th>Baseline X 10²⁴ sej y⁻¹</th>
<th>Sources Considered</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geopotential Energy Production</td>
<td>Earth Cycle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Method was not used</td>
<td>Method was not used</td>
<td>4.0 (3.93)</td>
<td>S only</td>
</tr>
<tr>
<td>Method was not used</td>
<td>S and E</td>
<td>8.0</td>
<td>S and E</td>
</tr>
<tr>
<td>Method was not used</td>
<td>S and E</td>
<td>9.44</td>
<td>S, E, and G</td>
</tr>
</tbody>
</table>
between the emergy entering and the emergy leaving is the emergy absorbed by the system. The cross boundary emergy flows in both the received and absorbed categories are summed and added, respectively, to the largest emergy directly received and absorbed over the system area. The totals give the emergy received and the emergy absorbed by that system as the renewable base to support self-organization. The methods for determining the cross boundary flows of emergy are the same for all baselines.

Each baseline has logical advantages and disadvantages. The 15.83 baseline assumes that everything in the global system is connected and it assumes that all connections are necessary and substantive inputs to the two global processes evaluated (Table 2). This is logically consistent with the reasoning commonly used in holistic systems thinking. When using the 9.26 baseline (Table 2), tides do not contribute to the earth cycle and the earth’s deep heat does not contribute to the annual production of geopotential energy in the world oceans. This view is arguably more realistic based on the actual quantities of energy from the various sources used in these two processes. For example, tidal currents move sediment around but often this movement results in no net motion in the seaward direction, thus it would make little or no contribution to the earth cycle of uplift and subsidence. While the position of the continents (determined by the earth cycle) does affect the local tide height and therefore the amount of geopotential energy generated on earth by gravitational attraction at any given time, the rate at which the continents change position is negligible over the time scale of a year for which the production of geopotential energy is being evaluated (Campbell 2000). One can argue that the earth cycle does not affect the geopotential of the world oceans on time scales shorter than several million years and thus it should not be considered as a material contributor to this process when establishing equivalence between solar radiation and gravitational attraction for analyses that consider timescales of 10,000 years or less (Campbell 2000).

Emergy Analysis results usually depend on relative differences; therefore, the choice of a baseline is somewhat arbitrary. Both baselines use similar rules to avoid double counting since only one emergy input (the largest) from any set of co-products constitutes the renewable emergy base for any given area of the earth. Problems related to what to count to avoid double counting are removed by the rule of counting only the largest input for any given area. In the past, when more than one planetary input was counted in the base of a system (Odum et al. 1987, Brown et al. 1993) the transformity of the primary input (e.g. chemical potential energy of rain) was adjusted to remove the partial contribution of the additional emergy source included (e.g. tide). The development of a calculus to determine the partial contribution of all sources would give a complete and exact measure of the emergy base for any system. In the absence of such a method the rule to count only the largest source of the energies supplied by planetary co-products to any given area is a good first order approximation to the emergy base for that area. This rule completely avoids double counting but in doing so it gives a conservative estimate of the emergy base for the system. As long as transformities are set relative to the same planetary baseline and the emergy base for system organization is determined at the same spatial resolution, emergy analyses are comparable.

**EMERGY RECEIVED AND EMERGY ABSORBED**

An important factor to keep in mind when determining the emergy base for a system is the distinction between the emergy received and the emergy absorbed. The emergy received, \( R_r \), is the emergy that enters the system. It represents the potential that a system has for self-organization. The emergy absorbed, \( R_a \), is the emergy that is actually used by the system in its organizational processes. Almost all of the energy flows entering a system can be evaluated at the point of reception and at the point of absorption. For example, incident solar radiation is received by the system but the reflected radiation must be subtracted from the incident radiation to get the solar radiation absorbed. The energy of the rain at the elevation where it falls on the land is the geopotential energy received, but only the fraction that runs off is absorbed doing geological work in the system. In general, the emergy absorbed by the system is the value of interest in an emergy analysis. The energy actually used within a system...
is the basis for calculating the transformities of the system’s products. In general, emery analysts have consistently used the emery absorbed to determine the emery base for systems. In past studies often the entire chemical potential energy of the rain has been used as the emery base for certain states, e.g., Florida, Texas, Maine, North Carolina, rather than the chemical potential energy of evapotranspiration as was done for Arkansas and West Virginia. This apparent discrepancy can be explained by the fact that certain systems, e.g., coastal states and lakes and their watersheds (Brandt-Williams 1999) effectively absorb (use) almost 100% of the chemical potential energy of rainfall when both the land and contiguous area of continental shelf or lake basin are considered.

In general, the emery received by the system is often calculated as an intermediate step in determining the emery absorbed. It may be useful to report both these numbers in emery analyses. The emery received may be useful in certain indices, because it indicates the potential for system development and thus it may be related to the general attractiveness of an area for investment. The distinction between the emery received and the emery absorbed may be more complicated because one could argue that all the emery received is necessary for the observed use, and therefore, the emery base for the system should be that received. Again the accurate reporting of assumptions and calculation is imperative for comparability of analyses.

**COMPLEXITY AND THE EXPANDING EMERGY BASE FOR GLOBAL SELF-ORGANIZATION**

The emery base for a given system depends on the properties of emery itself as well as on the baseline chosen for expressing transformities and the rules used to determine the renewable emery absorbed. A property of the transformation of energy is a tendency to build increasingly more complex hierarchically ordered structures as long as sources of available energy continue to exist in the environment. According to the energy transformation hierarchy principle, proposed by Odum (1996) as a 5th law of thermodynamics, energy-based hierarchies develop using the inputs of available energy (exergy) at all scales of organization and pass these products to systems at other hierarchical levels to drive self-organization there. The position of any component or process within the hierarchies built by the transformation of energy is indicated by its transformity or the emery required to make a unit of energy of the product. Emery is a second law concept that tracks the energies of all kinds required for production; therefore, systems that produce co-products amplify the emery base for the next tier of complexity where other systems use the co-products in their own self-organization. The emery base for each succeeding level of complexity must expand, if all inputs are required for each co-product and co-products act to create nested levels of organization. Thus, the emery base for all the nested systems organized using the products of a larger scale system can exceed the emery base at the level of the larger system. This observation does not violate any rule of emery accounting (see Odum 1996 and Giannantoni this volume). Also, there is no double counting involved because only the largest co-product is counted as the emery base for any given area (see the example below). For example, the biomes are organized using the co-products of the primary planetary system organization (Figure 2), thus we might expect the emery base for all the biomes to be greater than that for the primary planetary organization. To see that this must be true, consider a world where only two ecosystems exist: (1) Rainforest, which covers ¼ of the area of the earth and desert, which covers the remaining ¾. Furthermore assume that only two planetary co-products exist, rain and wind and that 90% of the rain falls on the rainforest and that the wind blows equally over the earth’s surface. Using the 15.83 E24 sej y⁻¹ baseline and the rules for determining the emery base for an area of the earth given above, the emery base for the rainforest is 15.83 E24 sej y⁻¹ (emery base for global rain) times 0.90 (the fraction split to rainforest) or 14.25 E24 sej y⁻¹ and the emery base for the desert area is 15.83 E24 sej y⁻¹ (emery base for global wind) times 0.75 (the fraction split to desert) or 11.87 E24 sej y⁻¹, thus the total emery supporting organization of the two biomes, which cover the entire surface of the earth is 26.12 E24 sej y⁻¹.
Figure 2. Increasing complexity of system organization is shown as a function of increasing energy transformation. The interaction and distribution of co-products and the utilization of new emergy sources in nested hierarchical systems of increasing transformity cause the emergy base for self-organization to expand.
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The emergy base supporting system self-organization will also expand when a new source is added to the emergy signature (Brown and Ulgiati 1999). When a new emergy source such as fossil fuel becomes available it drives additional self-organizational processes that increase complexity. The emergy base for the products produced by systems using the new source will be greater than that of the former system. Products passed from one scale of organization to another carry the emergy of the originating scale and they can change the emergy base for the systems that they enter as feedbacks. Figure 2 illustrates the concept of an expanding emergy base generating systems of greater complexity as the number of energy transformations increases. Levels or realms of organization may be related to the introduction of new or formerly unexploited energy sources that drive self-organization and open up new possibilities for energy transformation. Four levels or realms of planetary self-organization are identified in Figure 2.

The geobiosphere (Level 1) receives the three primary energy sources entering the earth, and through the transformation of these sources in the interacting network of the atmosphere, oceans, and crust, many co-products are produced. The energy transformations at this primary level are required to produce the co-products, i.e., wind, rain, tidal flows, ocean currents, etc. that interact to create the nested scales of increasingly more complex realms of order that are the earth’s living systems. Hierarchies of structure and process are created at each level of self-organization., e.g., the continental landmass that results in different transformities for rain over the land and sea (Odum 1996, Campbell 2003) is created at the primary level of the geobiosphere. The nested levels (2-4) of ecological organization are based on the co-products of the global system using primary energy inflows. The primary energy inflows also enter into more complex systems as inputs, but their transformation processes on the global scale are unique, generating co-products that are different in kind and/or magnitude from similar products generated on smaller scales of organization. For example, sun drives the planetary heat engine, which generates wind, waves, currents, and rain at the global scale. At smaller scales the sun supplies the energy to drive photosynthesis of green plants. Both of these processes of energy transformation are critical for ecosystem organization but the processes are qualitatively very different. Even when the product of the transformation of solar energy is similar to its larger scale products, e.g., the generation of sea and land breezes due to differential heating, these breezes differ substantially in scale and magnitude from the winds generated at the global scale.

The biomes and ecosystems are the next level of complexity in planetary self-organization driven by energy transformation and made possible by the interaction and distribution of global co-products. The total emergy base supporting the biomes is larger than that of the planet (see example above). Around 1850, when our modern industrial civilization added fossil fuel energy as a major input driving self-organization, the emergy base for planetary organization was expanded. Note that from a top down perspective, economic organization on level three contains the biomes and ecosystems as a nested element, upon which they exert controlling actions, whereas from a bottom up perspective economic systems are nested within and depend on the biomes for support. The use of fossil fuel emergy to support global self-organization resulted in a qualitative change in the nature of the products and processes organized, as well as, an increase in the number of energy transformations and the complexity of the resulting organization. Even though fossil fuel energy was generated by the primary planetary energy inputs mediated through carbon fixation of the biomes over millions of years, the present rapid use of this storage makes it behave like an additional energy source driving global self-organization as a pulse on the limited time scale of its use and depletion. From this perspective, human use of fossil fuel resources to create industrial society has expanded the emergy base for the earth.

The biomes at organizational Level 2 and the economy at Level 3 are nested within society (Level 4), which is characterized by the use of shared information in the self-organization operating at this level. Shared information in the form of human learning and technology may also act like an additional emergy source expanding the emergy base for this level. These information storages are created over a long period of time compared to the time of their use. For example, to train a generation of people in the present U.S. education system takes from 18 to 30 years depending on the skill level.
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of the occupation. An additional 20 years or more of work experience may be needed to fully develop the emery delivered to the system by an individual. Technology has an even longer turnover time. For example, the personal computer developed from early experiments on transistors at the Bell Telephone Laboratories in 1947 (the development of transistors allowed the miniaturization of electronic circuits) to become the dominant technological tool in the modern home and office 50 years later (http://www.islandnet.com/~kpolsson/comphist/). Antecedent technologies go back to James Clerk Maxwell and early experiments with electromagnetism during the mid 19th century (http://www.northwinds.net/bchris/pre1900.htm). If we assume a turnover time of about 50 years for shared information, there may be enough separation between the use of this emery in determining the transformity of human work contributed to annual economic production and its creation, to justify considering it an additional emery source driving the self-organization of society.

IMPLICATIONS OF THE EXPANDING EMERGY BASE FOR ENVIRONMENTAL ACCOUNTING AND EMERGY ANALYSIS

The expanding emergy base for self-organization and the higher levels of complexity that result from adding “new” sources to the global emergy signature may express a fundamental property of transformity derived from the energy hierarchy law as discussed by Giannantoni (this volume) and further elucidated by Brown (this volume). One of the primary implications of this insight is that social processes will have an expanded emergy base compared to economic processes. Higgins (2003) performed an emergy analysis of the Oak Openings Region of Ohio, which included a detailed evaluation of some social processes. She showed that indices calculated in her study were not readily comparable to past emergy analyses that only considered the environmental-economic interface. The implication from her results and the theoretical arguments given above is that the emergy base and level of organization should be considered when comparing the results of emergy analyses. Emergy analyses using the same planetary baseline are directly comparable when they are performed for the same realm of organization (Figure 2). Thus, the emergy-economic indices calculated in a study that also evaluated social processes Level 4) including components of shared information as an additional emergy source cannot be compared directly with the same indices determined by only evaluating the environmental-economic interrelationships on Level 3. However, all level three analyses using the emergy base appropriate to that level, i.e., fossil fuel and the global co-products should be comparable, given the caveats discussed above. In a holistic view, the division into levels 2-4 is somewhat artificial. These three levels of global self-organization are all based on the interaction of planetary co-products and they are nested in both the power and control pathways so that levels of greater complexity control the lower levels and the less complex levels physically support and maintain higher levels of organization which are nested within them (Figure 2). The three doubly nested levels of organization together encompass self-organized structures and processes of the entire earth. Furthermore, there are many cross scale (level) links, e.g., anthropogenic enhancement of global nitrogen fixation, greenhouse gas emission, etc that imply that we should really be doing the nested hierarchies (Levels 2-4) as a single system.

An evaluation of the role of shared information in economic production (a cross-level link) offers a solution to a long-standing problem in emergy analysis. This problem is to determine the emergy of human work contributions to economic production independent of the monetary value of those contributions. Campbell (this volume) points out emergy analysts need to independently estimate the emergy of human work contributions to economic production, if emdollars are to be used to accurately represent the relative contributions of human and environmental work on an emergy balance sheet that includes monetary and environmental liabilities. Figure 3 shows a socioeconomic system illustrating the way that four emergy sources interact to determine system organization. In the figure, $R_n$ is the renewable emergy used, $N_0$ is the emergy of renewable resources being used in a
Figure 3. This energy systems model of global socioeconomic organization shows the nested hierarchy of ecosystems, economy, and society. Four emergy sources (renewable emergy, fuels and minerals, renewables used faster than they are replenished and shared information) used to support global societies are shown.

nonrenewable manner, F is emergy in fuels, and SI (PI when estimated from money flows) is the emergy of shared information in human work contributions, both pure service and the human service used in making and supplying products.

Money assigns all value to human work and none to the work of nature; therefore, money undervalues economic products in proportion to the fraction of the total emergy required that is derived from the unpaid work of nature. Current practice in emergy analysis allows the average value of human service, as represented by the emergy-to-money ratio for the economy, to be used to estimate the human work contributions to the total emergy used in the system (U). This logic is circular and a value for the emergy-to-money ratio cannot be found except through a recursive solution. The money flowing through the economy of a state in a year is the Gross State Product (GSP). If the emergy to dollar ratio (U/GSP) of the economy is assumed to represent the average emergy contributed by human service, equations (1-5) show the nature of the problem, where Z is the emergy-to-money ratio.

\[ U = R_a + N_0 + F + PI \quad \text{(1)} \]

\[ \text{Let, } X = R_a + N_0 + F \]

\[ \text{then, } U = X + f(\$ U) \quad \text{(3)} \]

\[ \text{and, } Z = U / \text{GSP} \quad \text{(4)} \]

\[ \text{substituting for } U, \ Z = \{X + f(\$ U)\} / \text{GSP} \quad \text{(5)} \]

While this approximation is useful in the absence of better information and can be justified because it introduces small errors in the average value when the emergy to dollar ratio is from a much larger system, it does not provide an independent estimate of the emergy in human work for which the dollars are paid. In addition, the same problem recurs for systems on all scales. Economists attribute all monetary value to human work contributions and none to the work of the environment and emergy analysts use the environmental emergy contributions to estimate human work by assuming that all value originates first from the emergy contributions of the environment. The latter is true, but as we pointed out earlier, pulsed feedback from storage can change the emergy base for self-organization for a limited time. Neither of these solutions will allow an accurate estimation of the relative contributions of humans and the environment to economic production. It would be better to obtain an independent
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estimate of human work contributions as the application of shared information (SI), which will allow the GSP$ to be redistributed as emdollars that total to EM$P, the emdollar product, as follows:

Let $Y = SI$ then, $U = X + Y$  \hspace{1cm} (6)

and $Z = (X + Y)/GSP$ \hspace{1cm} (7)

\[ EmSP = \sum_{i=1}^{n} x_i \cdot \frac{1}{Z} + \sum_{j=1}^{m} y_j \cdot \frac{1}{Z} \]  \hspace{1cm} (8)

\[ U = \sum_{i=1}^{n} x_i + \sum_{j=1}^{m} y_j \]  \hspace{1cm} (9)

where $x_i$ and $y_j$ are each one of the n emergy flows in the environment or the m emergy flows in the economy, respectively. GSP$ is equal to EM$P and the distribution of emdollars will accurately reflect the actual work contributions of both nature and humanity. The dollars paid for human service can still be converted to emergy flows at an average rate using the ratio of $Y$ to GSP$.

A key question to be answered is what, if anything, do humans contribute to the emergy base for a system above that required from the renewable environmental emergy and fossil fuel emergy required to support them? Two important emergy storages that determine the productivity of human labor and the productive effects of capital are, respectively, the learned knowledge of the people, $L$, and the technological status of the society, $T$. Figure 4 gives an energy systems diagram for determining the emergy base driving the monetary flows of a region, including inputs for the learned knowledge of the people and their use of technology. Both of these inputs are emergy storages of shared information (Figure 3), which have accumulated over a relatively long period of time (as described above) and both are required for the work contributions that humans make to economic production in any given year. In fact, the money paid to people for their labor is in large part a function of their knowledge and the importance of the technologies that their knowledge allows them to use. We propose that these two information sources are in effect additional emergy inputs that characterize the emergy base for socioeconomic systems. Together they establish a transformity for human labor used in the system and the emergy contributed in this manner represents the contributions of work done in the past to present work. In fact, the transformity, i.e., the kind and quality of the work done by humans in annual economic production processes is a function of this information and that is the test for including it as the unique emergy contribution of humans to the system for which they receive money. The contribution of these information storages is qualitatively different from the contribution of material infrastructure to production. For example, primary production in a forest depends on the stored biomass of the trees, but this storage does not change the quality of the work done, it simply allows more of it by increasing evapotranspiration. In contrast human labor using the learning and technology of the ancient Roman culture accomplished very different work compared to that done in the industrial age of 19th century England. The transformity of human labor in these two societies was different and the human emergy contributed to self-organization was also different beyond the difference in environmental contributions and fossil fuel use.

Odum (1996) points out that emergy accounting, which does not include an evaluation of information inputs is incomplete. If shared information is an additional emergy source as implied by our analysis, methods to estimate its contribution to the emergy base of systems must be developed.

These methods will also give an independent estimate of the transformity of human labor. Information is not diminished by its use, but it depreciates and requires a maintenance cycle of extracting, copying, operating, testing, and selection as described in Odum (1996). The emergy
required for the information cycle of creation and maintenance for learned knowledge and technology must be evaluated to make an independent estimate of the transformity of human work in the system. The energy required for the most recent information cycle might be considered as the minimum energy base for the information in use at any given time. In the simplest case, the joules of human labor used in the economy in a given year might be multiplied by an average transformity for the knowledge of the people and by the transformity for the level of technology in use. A combination of these two energies (corrected for double counting) is a first order estimate of the energy contributed to the system as a result of human labor using the shared information base.

In summary, the energy support for socioeconomic systems should include an independent estimate of the contributions of people. An evaluation of the energy required for material support, education, and technology use can provide an estimate independent of the monetary value of labor. Emergy-to-money ratios calculated on this basis and used to convert emergy flows in the environment and economy to emdollars will redistribute the annual money flow (GSP) so that the energy-money unit reflects the actual buying power, which is based on the direct work contribution of an item to economic production. This modification will change the value of the total energy used in the system probably resulting in higher emergy to money ratios, because the energy of human service is expected to increase in the expression. A human emergy to dollar ratio (Y/GSP$) could be calculated that would measure directly the human service purchased by each dollar. This change will result in an independent determination of the human service contribution in the expression for total energy use.
As a practical result, human work contributions may be given greater value in terms of emdollars and we will avoid, for the most part, the problem of crudely estimating human emergy contributions by using dollars and the emergy-to-money ratio in a circular manner.

CONCLUSIONS

Emergy researchers should report the planetary baseline used in each analysis, the spatial resolution of the renewable emergy base, and the values of and sources for the transformities used. The effects of spatial resolution on the emergy base for systems needs to be further evaluated. The renewable emergy absorbed by the system should be given and the renewable emergy received might also be reported. Emergy analysts need to be aware of the expanding emergy base for systems organized on different realms of complexity and the position of their system within this hierarchy of planetary self-organization. Comparison of systems within a given level of complexity will have qualitatively similar emergy bases. Further development of environmental accounting tools like the emergy balance sheet depends on the development of methods to make independent estimates of human work contributions to economic production. A rationale for estimating human work contributions to systems using learned knowledge and technology use was given. If emergy researchers follow the reporting guidelines given in this paper, the reproducibility and comparability of energy analysis results should improve and this improvement in communication may increase the acceptance of Emergy Analysis in the broader scientific community.

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