Handbook of Emergy Evaluation

A Compendium of Data for Emergy Computation
Issued in a Series of Folios

Folio #1
Introduction and Global Budget

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Preface, Handbook of Emergy Evaluation

Emergy, spelled with an "m," is a universal measure of real wealth of the work of nature and society made on a common basis. Calculations of emergy production and storage provide a basis for making choices about environment and economy following the general public policy to maximize real wealth, production and use (maximum empower). To aid evaluations, this handbook provides data on emergy contents and the computations on which they were based. A series of Folios are to be issued. Folio #1 introduces concepts and evaluates the empower of the geobiosphere.

There may be Folios by many authors, who take the initiative to make new calculations or assemble results from the extensive but dispersed literature. Data on emergy content are in published papers, books, reports, theses, dissertations, and unpublished manuscripts. Tabulating unit emergy values and their basis is the main purpose of this handbook. Presentations document the sources of data and calculations. As received, Folios will go to reviewers, back to authors for revision and back for publication. Each will have an index to indicate the page where emergy is evaluated. Each Folio should be usable without reference to other Folios.

Policy on Literature Review and Consistency

This handbook is based on emergy evaluations assembled from various reports and published literature plus new tables prepared by Folio authors. Our policy is to present previous calculations with due credit and without change except those requested by original authors. This means that unit emergy values in some tables may be different from those in other tables. Some tables may be more complete than others. No attempt is made to make all the tables consistent. Explanatory footnotes are retained. The diversity of efforts and authors enriches the information available to users, who can make changes and recalculate as they deem desirable to be more complete, update, or otherwise revise for their purposes.

The increase in global emergy base of reference to 15.83 E24 sej/yr (Folios #1 and #2) changes all the unit emergy values which directly and indirectly are derived from the value of global annual empower. Two alternatives are suggested when using the values from this handbook with previously published unit emergy value: Either increase the older values or decrease the new values by a factor for the change in the base used. For example, to use unit emergy values based on the 1996 solar empower base (9.44 E24 sej/yr), multiply those values by 1.68. Or, multiply the emergy values of this handbook by 0.60 to keep values on the older base. – Howard T. Odum and Mark T. Brown

Introduction to Folio #1

Folio #1 briefly reviews the concepts of energy hierarchy and definitions of emergy and related quantities. Emergy of something is found by summing the inputs from the network of connecting inputs. Thus, emergy requires a view of the surrounding system. Energy systems diagrams are drawn and evaluated to document the source of values presented. In this first Folio main emergy contributions to the geobiosphere of the earth are given, which are the basis for many other emergy evaluations. Three recurring inflows are the available energy of the sun, the tide, and high temperature heat deep in the earth's crust. From these, unit emergy values are estimated for global rain, rivers, waves, and currents. The non-renewable fuels and minerals now in rapid use by the human economy are contributing even larger emergy flows.

Definitions and the Energy Hierarchy

The following paragraphs contain definitions and a brief explanation of emergy concepts. A more complete introduction is given elsewhere (Odum 1996), but unit emergy values are updated in these Folios.

There is evidence that all energy transformations can be arranged in an ordered series to form an energy hierarchy (Odum, 1988, 1996). For examples, many joules of sunlight are required to make a joule of fuel, several joules of fuel to make a joule of electric power, many joules of electric power to support information processing in a university, and so forth. Because different kinds of energy are not equal in contribution, work is made comparable by expressing each in units of one form of energy previously required. This quantity is *Emergy* (spelled with an "m") (Odum, 1986, 1988) and is sometimes called "energy memory" (Scienceman, 1987).

Emergy is the availability of energy of one kind that is used up in transformations directly and indirectly to make a product or service. The unit of emergy is the *emjoule*, a unit referring to the available energy of one kind consumed in transformations. For example, sunlight, fuel, electricity, and human service can be put on a common basis by expressing them all in the emjoules of solar energy that is required for each. In this case the value is a unit of *solar emergy* expressed in *solar emjoules* (abbreviated sej). Although other units have been used, such as coal emjoules or electrical emjoules, this handbook expresses all its emergy data in solar emjoules.

On all scales, the energy hierarchy is a network of interconnecting energy transformations. In this handbook diagrams are used to show the inputs that are evaluated and summed to obtain the emergy of a resulting flow or storage. All the diagrams are arranged from left to right so that there is more available energy flow on the left, decreasing to the right with each successive energy transformation. For example, abundant solar energy is utilized in transformations to support a small amount of high quality energy of a person living on the land. The left to right organization also corresponds to increasing scale of territory and turnover time.

Transformity is one example of a unit emergy value and is defined as the *emergy per unit energy*. For example, if 4000 solar emjoules are required to generate a joule of wood, then the solar transformity of that wood is 4000 solar emjoules per joule (abbreviated sej/J). Transformities increase from left to right in the energy hierarchy diagrams. Solar energy is the largest but most dispersed energy input to the earth. *The solar transformity of the sunlight absorbed by the earth is 1.0 by definition*.

Emergy accompanying a flow of something (energy, matter, information, etc.) is easily calculated if the unit emergy is known. The flow expressed in its usual units is multiplied by the emergy per unit of that flow. For example, the flow of fuels in joules per time can be multiplied by the transformity of that fuel (emergy per unit energy in solar emjoules/joule). A flow of emergy is named empower. Emergy flows in this handbook are in units of solar empower (solar emjoules per time).

The emergy of a storage is readily calculated by multiplying the storage quantity in its usual units by the emergy per unit. For evaluating flows or storages, values of emergy/unit make emergy evaluations rapid and practical.

Left-right Energy Systems Diagram

As illustrated in Figure 1, every energy transformation box has more than one input, including larger energy flows from the left, lesser amounts from units in parallel, and small but important controlling energies feeding back from the right. The first step in any evaluation is to draw the energy systems diagram to identify the inputs to be evaluated. Items and flows are arranged from left to right in order of their unit emergy.

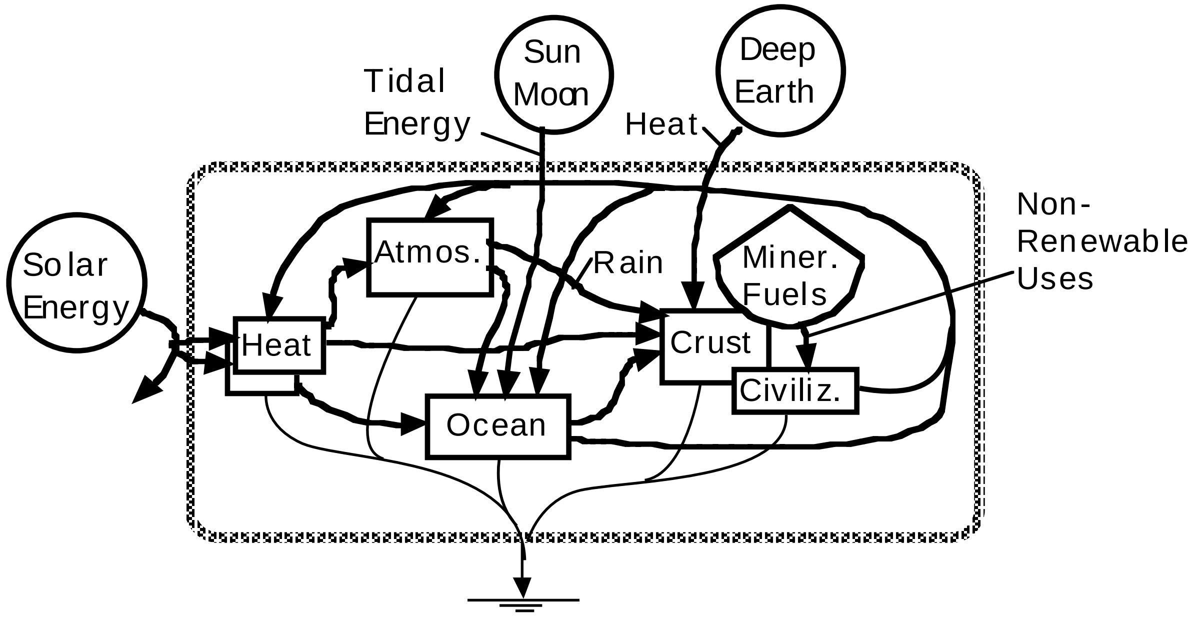

Figure 1. Energy transformation network arranged with decreasing energy from left to right. The system is aggregated to recognize that the inputs and all main components are necessary to all the other components and processes. Abbreviations: Atmos. = atmosphere; Civiliz. = civilization; Miner. = mineral reserves.

In Figure 1, where all the components interact and are required for the others, the emergy for all the internal pathways is the same. After millions of years of self organization, the heating transformations by the sun, the atmosphere, ocean, and land are organized simultaneously to interact and contribute mutual reinforcements. Therefore, the energy flow of each jointly necessary process is the sum of the emergy uses from the three sources.

<u>Splits and Co-products</u>

Depending on the way the evaluator aggregates the parts and processes, there may be more than one output from an energy transforming unit. In the simple case represented in Figure 2a an output flow "splits" into two flows of the same kind. The empower is divided but the transformity and emergy per mass are the same. For example, a water stream is divided into two, which are separated for different uses later. Notice the way the energy systems diagram represents an emergy split (Figure 2a).

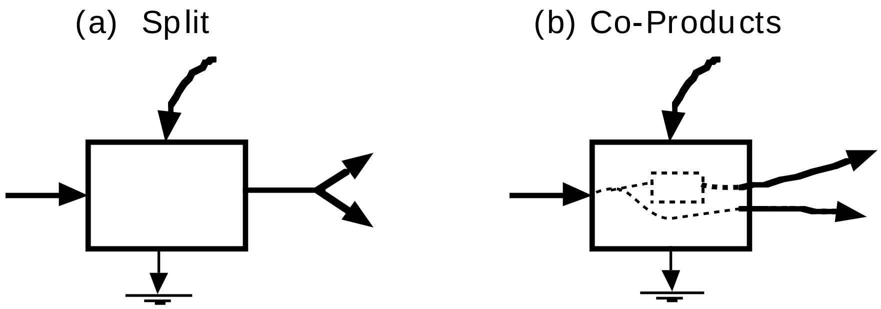

Figure 2. Comparison of product flows. (a) An output that splits; (b) two co-product flows.

Often there are outflows of a different kind which we call <u>co-products.</u> For example, flows of wool and mutton produced by the sheep agricultural system are co-products. As Figure 2b suggests, co-products have different transformities because they emerge from different stages in the series of transformations that may be aggregated within the system block that is evaluated. Co-products are drawn with separate outflow pathways. The emergy is the same for each, but the energy flows and transformities are different. Figure 1 is drawn with co-products only (no splits).

Emergy of Storages

To evaluate a stored quantity, it is necessary to sum the emergy of each of the inputs for the time of its contribution. Multiply input emergy inflows by the time it takes to accumulate the storage and exported yield, if any.

When something is growing, decreasing, or oscillating, its stored emergy contents and transformities are changing also. Where a system is adequately represented by a dynamic model, an algorithm can be added to plot the time sequence of emergy. Such simulations of emergy are a running calculation according to the emergy definition, summing the inputs to storages, multiplying these by their unit emergy, and subtracting emergy removals.

Evaluations Based on Averaged Inputs

Apparently all systems pulse with time intervals and pulse strength that increase with scale. To evaluate a process on one scale of time and space usually means using averages for each of the inputs from smaller scales where pulses are of high frequency. For example, for an evaluation of phenomena on the scale of human economy, yearly averages are often appropriate. On this scale we use average solar energy and average tidal energy. For calculations of global processes over a longer scale of time, we may use an average of inputs from the deep earth. Figure 1 can represent these evaluations, if we ignore the civilization's use of stored reserves.

Thus, for many purposes emergy evaluations are made with averaged inputs, a way to gain evaluation overviews. The result is emergy evaluation as if the system was in a steady state. For this procedure an emergy evaluation table is useful.

Preparation of an Emergy Evaluation Table

The calculations of emergy of something are made with an evaluation table. Table 1 is an emergy evaluation table of the main inputs to the geobiosphere of the earth (omitting until later the emergy use from non-renewable resources). The first column has a number for the footnote with details of sources of data and calculations. The second column has labels of the input items. The third column has the numerical value of the input in its usual units (joules, grams, dollars, individuals, bits, or whatever). Column 4 has the unit emergy values (emergy per energy, emergy per mass, emergy per money, emergy per individuals, emergy per bit, or whatever). Emergy of each line item is in Column 5, obtained by multiplying column 3 (input) and column 4 (emergy per unit input). At the bottom is the sum total of emergy inputs.

Table 1
Annual Emergy Contributions to Global Processes*
(Figure 1)

Note	Inputs & Units	Inflow units/yr	Emergy/Unit sej/unit	Empower E24 sej/yr
1	Solar insolation, J	3.93 E24	1.0	3.93
2	Deep earth heat, J	6.72 E20	1.20 E4	8.06
3	Tidal energy, J	0.52 E20	7.39 E4	3.84
4	Total	–	–	15.83

* Not including non-renewable resources (see Table 3)

Abbreviations: sej = solar emjoules; yr = year; E3 means multiplied by 10^3

Footnotes to Table 1

1 Sunlight: solar constant 2 gcal/cm^2/min = 2 Langley per minute; 70% absorbed; earth cross section facing sun 1.27 E14 m^2.

2 Heat release by crustal radioactivity 1.98 E20 J/yr plus 4.74 E20 J/yr heat flowing up from the mantle (Sclater et al., 1980). Solar transformity 1.2 E4 sej/J is from Folio #2 based on an emergy equation for crustal heat as the sum of emergy from earth heat, solar input to earth cycles, and tide.

3 Tidal contribution to oceanic geopotential flux is 0.52 E20 J/yr. Solar trans-formity 7.4 E4 sej/J from Folio #2 following Campbell (1998) is based on an emergy equation for oceanic geopotential as the sum of emergy from earth heat, solar input to the ocean, and tide.

An evaluation is easy if there are reference data on emergy per unit for column 4. If the table is an evaluation of a storage, the result is in solar emjoules. If the table is an evaluation of a product flow, the result is in solar emjoules per time.

Calculating Unit Emergy Values

After a table is prepared that evaluates all the inputs, unit emergy values of products can be calculated. This is often done in a second table. For example, in Table 2 the solar emergy input total (15.83 E24 sej/yr from Table 1) is divided by each product's ordinary measure (number of joules, grams, dollars, individuals, bits, etc.). The unit values that result are useful for other emergy evaluations. Thus, any emergy evaluation generates new emergy unit values. For example, Table 2 calculates unit emergy values for some main flows of the earth.

Table 2
Emergy of Products of the Global Energy System

Note	Product and Units	Emergy* E24 sej/yr	Production units/yr	Emergy/Unit sej/unit
1	Global latent heat, J	15.83	1.26 E24	12.6 sej/J
2	Global wind circulation, J	15.83	6.45 E21	2.45 E3 sej/J
3	Global precipitation on land, g	15.83	1.09 E20	1.45 E5 sej/g
4	Global precipitation on land, J	15.83	5.19 E20	3.1 E4 sej/J
5	Average river flow, g	15.83	3.96 E19	4.0 E5 sej/g
6	Average river geopotential, J	15.83	3.4 E20	4.7 E4 sej/J
7	Average river chem. energy, J	15.83	1.96 E20	8.1 E4 sej/J
8	Average waves at the shore, J	15.83	3.1 E20	5.1 E4 sej/J
9	Average ocean current, J	15.83	8.6 E17	1.84 E7 sej/J

* Main empower of inputs to the geobiospheric system from Table 1 not including non-renewable consumption (fossil fuel and mineral use).

Footnotes to Table 2

1 Global latent heat, evapotranspiration 1020 mm/yr,
(1020 mm/yr)(1000 g/m^2/mm)(0.58 kcal/g)(4186 J/kcal)(5.1 E14 m^2)

= 1.26 E24 J/yr.

2 Global wind circulation, 0.4 watts/m^2 (Wiin-Nielsen and Chen, 1993)
(0.4 J/m^2/sec)(3.15 E7 sec/yr)(5.12 E14 m^2/earth) = 6.45 E21 J/yr

3 1.09 E11 m^3/yr (Ryabchikov, 1975)
(1.09 E14 m^3)(1 E6 kg/m^3) = 1.09 E20 g/yr

4 Chemical potential energy of rain water relative to sea water salinity
(1.05 E20 g/yr)(4.94 J Gibbs free energy/g) = 5.19 E20 J/yr

5 Global runoff, 39.6 E3 km^3/yr (Todd, 1970)
(39.6 E12 m^3/yr)(1 E6 g/m^3) = 3.96 E19 g/yr

6 Average river geopotential work; average elevation 875 m.
(39.6 E12 m^3/yr)(1000 kg/m^3)(9.8 m/sec^2)(875 m) = 3.4 E20 J/yr

7 Chemical potential energy of river water relative to sea water salinity
(3.96 E19 g/yr)(4.94 J Gibbs free energy/g) = 1.96 E20 J/yr

8 Average wave energy reaching shores, (Kinsman, 1965)
(1.68 E8 kcal/m/yr)(4.39 E8 m shore front)(4186 J/kcal) = 3.1 E20 J/yr

9 Average current: 5 cm/sec (Oort et al., 1989); 2 year turnover time
(0.5)(1.37 E21 kg water)(0.050 m/sec)(0.050 m/sec)/(2 yr) = 8.56 E17 J/yr

2. Emergy Budget of the Geobiosphere

The example used to introduce the emergy evaluation table and the procedure for calculating unit emergy values was the annual budget of emergy flow (empower) supporting the geobiosphere (atmosphere, ocean, and earth crust). Table 1 includes emergy of the main inputs to the geobiosphere as they existed before the development of civilization. The main inputs include the solar energy, the tidal energy, and the heat energy from the deep earth. Not evaluated here are other inputs from space, the high energy radiation of solar flares, cosmic rays, meteorites and stellar dust. All of these vary with oscillations and pulses, and their emergy values vary with intensities of these inputs.

Temporary Emergy Inputs to the Geobiosphere

In the last two centuries, the production and consumption processes of the human civilization has reached a scale with global impact by using the large emergy in the geologic stores of fuels and minerals. Because these storages are being used much faster than they are being generated in geologic cycles, they are often called non-renewable resources. They are actually very slowly-renewed resources. Table 3 summarizes these additional components of the global emergy budget using estimates from Brown and Ulgiati (2000). The evaluations of these non-renewable emergy flows used transformities that were based on the global empower base of 9.44 E24 sej/yr. For use with the global empower base 15.83 E24 sej/yr, multiply by 1.68.

Table 3
Annual Emergy Contributions to Global Processes
Including Use of Resource Reserves*

Note	Inputs & Units	Inflow J/yr	Emergy/Unit# sej/unit	Empower E24 sej/yr
1	Renewable inputs	--	–	9.44
	Nonrenwable energies released by society:			
2	Oil, J	1.38 E20	5.4 E4	7.45
3	Natural gas (oil eq.), J	7.89 E19	4.8 E4	3.79
4	Coal (oil eq.), J	1.09 E20	4.0 E4	4.36
5	Nuclear power, J	8.60 E18	2.0 E5	1.72
6	Wood, J	5.86 E19	1.1 E4	0.64
7	Soils, J	1.38 E19	7.4 E4	1.02
8	Phosphate, J	4.77 E16	7.7 E6	0.37
9	Limestone, J	7.33 E16	1.62 E6	0.12
10	Metal ores, g	993 E12 g	1.0 E9 sej/g	0.99
Total non-renewable empower		–	--	20.46
Total global empower		--	--	29.90

Abbreviations: sej = solar emjoules; yr = year; E3 means multiplied by 10^3; t = metric ton; oil eq. = oil equivalents
* Modified from Brown and Ulgiati (2000) using global base 9.44 E24 sej/yr
# Values of solar emergy/unit from Odum (1996);

Footnotes for Table 3

1 Renewable Inputs: Total of solar, tidal, and deep heat empower inputs from Odum (1996).

2 Total oil production = 3.3 E9 Mt oil equivalent (British Petroleum, 1997)
Energy flux = (3.3 E9 t oil eq.)(4.186 E10 J/t oil eq.) = 1.38 E20 J/yr oil equivalent

3 Total natural gas production = 2.093 E9 m^3 (British Petroleum, 1997)
Energy flux = (2.093 E12 m^3)(3.77 E7 J m^3) = 7.89 E19 J/yr

4 Total soft coal production = 1.224 E9 t/yr (British Petroleum, 1997)
Total hard coal production = 3.297 E9 t/yr (British Petroleum, 1997)
Energy flux = (1.224 E9 t/yr)(13.9 E9 J/t) + (3.297 E9 t/yr)(27.9 E9 J/t)
= 1.09 E20 J/yr

5 Total nuclear power production = 2.39 E12 kwh/yr (British Petroleum, 1997).
Energy flux = (2.39 E12 kwh/yr)(3.6 E6 J/kwh)
= 8.6 E18 J/yr electrical equivalent

6 Annual net loss of forest area = 11.27 E6 ha/yr (Brown et al., 1997)
Biomass = 40 kg m^2; 30% moisture (Lieth and Whitaker, 1975)
Energy flux = (11.27 E6 ha/yr)(1 E4 m^2/ha)(40 kg m^2)(1.3 E7 J/kg)(0.7)
= 5.86 E19 J/yr

7 Total soil erosion = 6.1 E10 t/yr (Oldeman, 1994; Mannion, 1995)
Assume soil loss 10 t/ha/yr and 6.1 E9 ha agricultural land = 6.1 E16/g/yr
(assume 1.0% organic matter), 5.4 kcal/g
Energy flux = (6.1 E16 g)(.01)(5.4 kcal/g)(4186 J/kcal) = 1.38 E19 J/yr

8 Total global phosphate production = 137 E6 t/yr (USDI, 1996)
Gibbs free energy of phosphate rock = 3.48 E2 J/g
Energy flux = (137 E12 g)(3.48 E2 J/g) = 4.77 E16 J/yr

9 Total limestone production = 120 E6 t/yr (USDI, 1996)
Gibbs free energy phosphate rock = 611 J/g
Energy flux = (120 E12 g)(6.11 E2 J/g) = 7.33 E16 J/yr

10 Total global production of metals 1994: Al, Cu, Pb, Fe, Zn (World Resources Institute, 1996): 992.9 E6 t/yr = 992.9 E12 g/yr

In year 2000 the emergy contribution through the human civilization to the geobiosphere from the slowly renewed resources is greater than all the inputs before the industrial revolution. A symptom of the surge of temporary emergy inflow is the carbon-dioxide accumulation in the atmosphere that causes greenhouse effects that change the pattern and intensity of weather. Emergy of something measures what went into it from whatever source. Whether these temporary emergy inputs should be included in the tables for evaluation of the geobiosphere depends on the scale of consideration and whether the temporary inputs have become coupled to the process under study.

3. Discussion of Unit Emergy Measures

Folios of this handbook provide unit emergy values from previous evaluations. For these numbers the evaluation diagrams and tables are provided so that users can see the basis. Previous calculations can aid users making similar evaluations. Some, like those in this Folio, are based on large scale global systems, but others may determine values for the same products by evaluating a small scale example. In general, less emergy/unit is required to make a small product than to make a larger one of the same kind. Transformity is a measure of the scale of energy convergence.

This handbook mainly presents transformities and other unit emergy measures as observed in real systems. Emergy and transformity are measures of open thermodynamic systems. Energy transformation systems may operate at different speeds according to the output input loading. The greater loading and slower speed the higher the efficiency. However, power output is maximum for a moderate, intermediate efficiency, neither as fast as possible nor as loaded as possible (Odum and Pinkerton, 1955).

According to Lotka's maximum power principle (1922), self organizing systems develop designs that maximize power. Partridge (1975, 1978, 1981) and Obrien and Stephens (1995) find evidence that the atmosphere operates at maximum power. Engineers usually design mechanical and electrical systems for maximum power output. Emergy and transformities of systems that have been in successful operation for a long time are appropriate for evaluations intended to find the best possible contribution consistent with competitive operation. Transformities observed in such systems may approach the most efficient possible for maximum power conversions.

Transformity

Transformity is a kind of efficiency measure, since it relates all the inputs to an output. The lower the transformity the more efficient the conversion. It follows from the second law that there is some minimum transformity which is consistent with maximum power operations. We don't have a way to calculate this, but we can use the lowest transformity found in long-operating systems as an approximation. If a transformity is used to estimate the theoretical potential of some system, it is appropriate to use the best (lowest) transformity known.

On the other hand, to evaluate some real system, an observed transformity for a similar system can be used. Newly designed systems may not be as efficient as they will become with further trial and error selection. In either case, users may be comfortable in using values from processes similar to those which they study.

Sometimes values are calculated from proposed systems, an important way to appraise a system before it is actually constructed and operated. By leaving out necessary inputs or being inaccurate regarding what is required, such theoretical calculations of unit emergy values may be too high or too low. Yet the calculation may be valuable to others, especially where other evaluations are not available.

Emergy per Unit Money

Money is paid to people for their services; they use it to buy real wealth. The amount of wealth that money buys depends on the amount of emergy supporting the economy and the amount of money circulating. An average emergy/money ratio in solar emjoules/$ can be calculated by dividing the total emergy use of a state or nation by its gross economic product. It varies by country and generally decreases each year. This emergy/money ratio is useful for evaluating service inputs given in money units where an average wage rate is appropriate. Large and special service inputs such as information inputs to a university by people may need evaluation with transformities appropriate for each level of education.

Emergy per Mass

Solids may be evaluated best with data on emergy per unit mass for its concentration. Because energy is required to concentrate materials, the unit value of any substance increases with concentration. Elements and compounds not abundant in nature therefore have higher emergy/mass ratios when found in concentrated form since more work was required to concentrate them, both spatially and chemically. High grade ores or diamonds are an example of highly concentrated matter.

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