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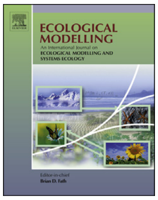

The geobiosphere emergy baseline: A synthesis

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ABSTRACT

The concept of emergy defined as the available energy (or exergy) of one form used up directly and indirectly to produce an item or action (Odum, Environmental Accounting Emergy and Environmental Decision Making, John Wiley & Sons, Inc., 1996) requires the specification of a uniform solar equivalent exergy reference, or geobiosphere emergy baseline (GEB). Three primary exergy sources of different origins interact to drive processes within the geobiosphere. Each of these sources are expressed in solar equivalent exergy from which, all other forms of energy can be computed, so that they may be expressed as emergy in units of solar emjoules. If emergy practitioners reference their work to a single agreed-upon baseline, then all research products resulting from the application of the emergy approach will be inherently consistent and valid comparisons can then be made easily. In this paper, we synthesize information from three new calculation procedures of the emergy baseline for the geobiosphere and propose a unified solution.

1. An emergy baseline

The geobiosphere is driven by three sources, the available energy from solar radiation, geothermal sources and dissipation of tidal momentum. Together they make up the geobiosphere emergy baseline (GEB). The geobiosphere, defined by the spatial scale of 100 km above to 100 km below the Earth's surface and a temporal domain of one year, forms the basis for determining the fluxes of available energy. The use of different temporal domains in determining the GEB may be possible depending on the availability of the necessary data (see Campbell, 2016). For example, the GEB over decadal climate cycles or even Milankovitch cycles of about 100,000 years might be calculated; however, such time domains are not well matched to the human time frame where most data are collected on an annual basis. Changes in state variables of the combined system of humanity and environment are easily measured on an annual basis and represent the integration of the many smaller cycles (daily, weekly, semi-annual, etc.). We believe that an annual cycle is the appropriate time domain for calculating the GEB. Generally we have found that most researchers dealing with global energy balances have adopted an annual cycle for their evaluations (Chen, 2005; Hermann, 2006; Szargut, 2003; Valero et al., 2010). For processes occurring over longer time scales, the amount of available energy can be extended proportionally.

2. Solar equivalency vs. solar emergy

A significant contribution of the emergy concept is the recognition that there are different forms of available energy crossing the biosphere boundary, each originating from a different source. Because of this fact, we are forced to express two of them (deep heat and gravitational energy) in terms of one of the others (e.g., the direct solar insolation) by means of *equivalency factors*. The result is the annual amount of direct available energy supporting the biosphere, expressed in terms of *solar equivalent exergy*, named the "geobiosphere emergy baseline" (GEB). Equivalent in this context means equal in quality or value, or corresponds in value to another. Thus while tidal and geothermal inputs are different forms of available energy, to obtain a GEB of common units we express them in equivalent units of solar exergy. There are numerous ways of establishing equivalency; three of which are explored in this issue (Brown and Ulgiati, 2016; Campbell, 2016; De Vilbiss et al., 2016). In these papers the authors have adopted the convention that the GEB is expressed in *solar equivalent exergy*, or *solar equivalent joules* (abbreviated seJ, note the capital J) to differentiate the units computed as solar equivalent exergy from *solar emergy* (units are solar emjoules, and abbreviated sej, note the small j).

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3. A brief history

There have been numerous geobiosphere emergy baselines as the science of emergy analysis has matured (Brown and Ulgiati, 2004). In the very early conceptualizations of the theory, Odum (1971) considered solar energy as the basis for all other forms of energy, estimating 1000 joules of sunlight to produce 1 joule of organic matter and about 42 E + 6 joules of solar energy to produce $1 of human service. Later on, Odum (1976) differentiated between plants, wood, and fossil fuels expressing them in fossil fuel equivalents, but still using only solar input to the geobiosphere as the primary source. In 1983 (Odum and Odum, 1983), a solar equivalent of geologic heat sources (termed “deep heat” or “deep Earth heat”) was estimated and then included, along with sunlight, in the “solar emergy basis of the global processes”. With the publication of Environmental Accounting, Odum (1996) added a solar equivalent of tide to the global solar emergy base, resulting in a baseline of 9.44 E + 24 seJ y^{-1}. The first emergy folio, Odum (2000), used a method of simultaneous equations to compute the solar equivalence of tide and deep heat that yielded a “global empower base” of 15.83 E + 24 seJ y^{-1}. Campbell (2016) provides an in-depth historical review of the science related to the calculation of emergy baselines.

Since 2000, researchers have proposed several baselines as alternatives to the 9.44 E + 24 seJ y^{-1} baseline put forward in Odum (1996). Some of these baselines have used completely different models than that originally proposed by Odum (1996). For example, Chen (2005) introduced the concept of “cosmic emergy” which used as its baseline cosmic exergy due to the radiative difference between the sun and the cosmic background. Unfortunately, the method assumed all exergy sources generated by the geobiosphere to have equal quality. Raugei (2013) proposed a scalar baseline where the three fundamental inputs of exergy to the geobiosphere (sunlight, tidal momentum, and geothermal heat) were kept separate at all times, not unlike the three independent axes of Cartesian space. Several baselines have been proposed by Campbell (2000); Campbell et al. (2005, 2010), and Brown and Ulgiati (2010) computed a baseline using the methods of Odum (2000), but with newer data. These various baselines, ranging from 9.26 E + 24 to 15.83 E + 24 seJ y^{-1} were based on different methods of computation, different assumptions regarding system organization, and/or inclusion/exclusion of emergy sources driving biosphere processes. Over the years, the different GEBs have generated some confusion and concern within the scientific community, because different baselines yield different numerical values when analyzing products and processes, and comparison between evaluations using different baselines has proved to be challenging.

4. The baseline reexamined

Following the Eighth Biennial Emergy Conference (January, 2014), the need for revisiting the procedures and assumptions used to compute the geobiosphere emergy baseline emerged as a necessity to strengthen the method of Emergy Accounting and remove sources of ambiguity and potential misunderstanding. The papers presented in this issue of Ecological Modelling are the result of that awareness, and represent an effort to move towards a solution to such an important and urgent issue. Our goal was to approach the computation of the GEB from very different perspectives, using three different methods of analysis and different estimates regarding the quantities of driving exergy as well as varying modes of interaction between the exergy inflows and systems of the geobiosphere. In the end, if the three methods yielded similar results, the ultimate goal was to develop a synthesis document to clarify the baseline issue and perhaps, result in the adoption of a single baseline. Our reasoning was that several different approaches to the GEB computation, carried out by different emergy practitioners, would allow for accommodation of different perspectives and postulations related to integration of the driving energies into a single emergy baseline. Of course, given the significant uncertainty that exists in our understanding of the geobiosphere system, as well as in the available data about global processes, we did not expect that each approach would yield the same baseline, but rather that results achieved through different procedures and assumptions might fall within an acceptable range of values. In so doing, a single agreed upon baseline might be selected to reflect a reconciliation of diverse perspectives within a scientifically sound estimate of uncertainty.

Three papers published in this issue of Ecological Modeling result from that discussion:

Brown and Ulgiati’s (2016a) paper “Assessing the Global Environmental Sources Driving the Geobiosphere: A Revised Emergy Baseline.

Campbell’s (2016) paper, “Emergy Baseline for the Earth: A Historical Review of the Science and a New Calculation”.

De Vilbiss et al.’s (2016) paper “A New Approach to the Planetary Emergy Baseline”.

In addition, two other papers address important related issues:

Brown and Ulgiati’s (2016b) paper “Emergy Accounting of Global Renewable Sources”.

Seigel et al.’s (2016) paper “Calculating Solar Transformities of the Four Major Heat-producing Radiogenic Isotopes in the Earth’s Crust and Mantle”.

The first three papers, Brown and Ulgiati (2016a,b), Campbell (2016), and De Vilbiss et al. (2016), represent three different methods of computing the GEB. Brown and Ulgiati (2010) revisited their earlier analysis; reevaluating the exergy of geothermal sources by means of more recent data and re-simulating their model to compute new solar equivalence values for tidal momentum adsorbed by Earth and geothermal exergy. Campbell used the transitive property of equalities to estimate equivalences between the exergy of solar radiation and Earth’s deep heat exergy flow, and between solar exergy and the tidal exergy dissipated in the oceans. De Vilbiss et al. used a forward computation method of the dissipation of gravitational potential energy (GPE) in generating sunlight, radioisotopes, Earth’s relict heat, and Earth’s rotational energy to compute an equivalence between solar energy and the other driving energy flows.

The fourth and fifth papers, are related, but do not compute a GEB. Brown and Ulgiati (2016b) computed UEVs for secondary and tertiary renewable energy sources, while Siegel et al. (2016) provided a novel computation and derivation of UEVs for the radionuclides.

5. Solar equivalents

In all three cases, the resulting GEB is expressed as solar equivalent exergy, whose abbreviation is seJ. Solar equivalent exergy is computed as an equivalence between sunlight and the other sources comprising the GEB, recognizing the suggestion put forth by Raugei (2013) that the independent energies driving the geobiosphere (i.e., geothermal heat, and the gravitational energy absorbed) are not directly or indirectly a transformation of sunlight. We have adopted the convention that solar equivalent exergy uses the abbreviation seJ, since the units of solar equivalency are solar equivalent joules and the abbreviation of joule is always capitalized. Computations for subsequent products of the Earth’s geobiosphere

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(e.g., rain, wind, waves, etc) result in units of solar emergy, whose units are solar emjoules and whose abbreviation is sej. The use of the lower case "j" results from the fact that the units of emergy are emjoules. Emjoules are not available energy, but instead a measure of the exergy used in the past to create a storage or flow of exergy in the present. We therefore stress that emjoules are not joules in the thermodynamic sense of the unit and the "j" should not be capitalized.

The three studies that form the basis for this synthesis used different methods of equivalence to express tidal dissipation and geothermal exergy as solar equivalent exergy. The methods have in common the fact that each of them computed solar equivalence ratios (SERs: solar equivalent exergy per unit of exergy; seJ J^{-1}). When SERs are multiplied by the exergy of the primary sources to the geobiosphere, flows of solar equivalent exergy are obtained. It is important to point out that SERs are not transformities, as transformity is defined as the solar emergy required directly and indirectly to produce one joule of output from a process, and its units are sej J^{-1}. Nor are they unit emergy values (UEVs) as they are not the emergy per unit of mass, energy or money, but instead they are solar exergy equivalence ratios.

6. A unified geobiosphere emergy baseline

Table 1 lists the exergy inflows, SERs, and total solar equivalent exergy of the three studies (Brown and Ulgiati, 2016a,b; Campbell, 2016; De Vilbiss et al., 2016). The three methods yielded GEBs of 12.1E + 24 seJ y^{-1}, 11.6E + 24 seJ y^{-1} and 13.5E + 24 seJ y^{-1} respectively. Since Brown and Ulgiati used a Monte Carlo technique to estimate solar equivalent joules per joule, their procedure yielded not only mean values but estimates of standard deviation (in parentheses). The De Vilbiss et al. approach yielded four different baselines depending on the allocation procedure used to assign gravitational exergy of the Earth's accretion to its rotational kinetic energy and to its primordial heat. The values ranged between 11.3E + 24 seJ J^{-1} and 13.8E + 24 seJ J^{-1}. Because of the procedural uncertainty associated with allocation of the accretion exergy, as clearly pointed out by De Vilbiss et al. (2016), it was difficult to include these values in the synthesis, without biasing the final result. The range of values from the De Vilbiss et al. analysis, however, provides strong verification that a computed GEB within that range is appropriate.

We have therefore computed a final synthesis GEB based on the two approaches by Brown and Ulgiati (2016a,b) and Campbell (2016), and the resulting value falls within the range computed by De Vilbiss et al. (2016). The mean of the two approaches (12.1 seJ y^{-1} and 11.6 seJ y^{-1}) was 11.9 E + 24 seJ y^{-1}, which considering the fundamental uncertainty in our estimates (std. dev. ± 12% of the mean), can be rounded to 12.0 E + 24 seJ y^{-1}. Table 2 summarizes the means for exergy flows and SERs for the three geobiosphere sources. The average produced from the two methods is a working estimate of the baseline that should be used in all subsequent emergy evaluations. As has been the custom in the past, in most cases to convert data obtained with analyses performed under an earlier baseline to this new baseline, the data should be multiplied by the ratio of the new baseline to the older one.

In moving forward, we suggest that all GEBs from this point forward be identified with the subscript of the year of their development. Thus this GEB would be identified as GEB_{2016} with the understanding that as we learn more about Earth planetary science and even cosmology there is still room for future refinement and new GEBs. However, from this time forward the use of all older GEBs is strongly discouraged based on the inaccuracies and problems elucidated in Campbell (2016).

Table 1
Summary of geobiosphere emergy baselines from Brown and Ulgiati (2016a,b), Campbell (2016), and De Vilbiss et al. (2016).

Inflow	Brown and Ulgiati			Campbell			De Vilbiss et al.		
	Exergy	Solar equivalence ratio (seJ J^{-1})	Solar equivalent exergy (E + 24 seJ y^{-1})	Exergy	Solar equivalence ratio (seJ J^{-1})	Solar equivalent exergy (E + 24 seJ y^{-1})	Exergy	Solar equivalence ratio[a] (seJ J^{-1})	Solar equivalent exergy (E + 24 seJ y^{-1})
Solar energy absorbed	3.60E + 24	1	3.6	3.85E + 24	1	3.85	3.60E + 24	1	3.6
Geothermal flows[b]	9.78E + 20	5500 (985)	5.4 (0.95)	9.20E + 20	4200	3.86		7500[c]	
Primordial heat							5.95E + 20	1300–14,800	0.7–7.9
Radiogenic							4.95E + 20	4600	2.3
Tidal energy absorbed	1.17E + 20	26,300 (3800)	3.1 (0.44)	1.11E + 20	35,400	3.92	1.17E + 20	1300–44,600	0.15–5.2
Total global empower			12.1 (1.51)			11.6			12.5

[a] The SERs presented here represent an average from the De Vilbiss et al. (2016) paper.
[b] De Vilbiss et al. (2016) computed separate SERs for radiogenic and primordial heat, while Campbell (2016) and Brown and Ulgiati (2016a,b) computed only one SER for geothermal flows.
[c] Weighted average of primordial and radiogenic transformities.

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Table 2
Summary of GEB and solar equivalence ratios and solar equivalent exergy derived from Brown and Ulgiati and Campbell.

Inflow	Exergy[a]	Solar equivalence ratio[b] (seJ J^{-1})	Solar equivalent exergy[c] (E + 24 seJ y^{1})
Solar energy absorbed	3.73E + 24	1	3.7
Geothermal flows	9.52E + 20	4900	4.7
Tidal energy absorbed	1.14E + 20	30,900	3.5
Total global empower			12.0

[a] Average of the exergy from Brown and Ulgiati (2016a,b) and Campbell (2016).
[b] Average of the SERs from Brown and Ulgiati (2016a,b) and Campbell (2016).
[c] Rounded to two significant figures.

7. Conclusions

In this series of papers, we overcome a major hurdle to the further development and consistency of emergy evaluation by developing a synthesis of several approaches that results in a single, well-researched, geobiosphere emergy baseline. The use of a consistent and accepted baseline is an important step toward a reproducible and reliable methodology. While we have elucidated three very different interpretations of Earth geophysics and extraterrestrial processes, the differences in the three approaches can be seen as a strength, when the results reinforce one another as we found for the value of the average baseline from these studies. We believe that the methodological differences are outweighed by the great advantage of having a consistent GEB for future evaluations. Therefore, we present this synthesis of current and past research on the GEB to the community of emergy scientists as a reflection of past work and as a basis for comparable emergy studies in the future.

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