EMERGY SYNTHESIS: Theory and Applications of the Emergy Methodology


Edited by
Mark T. Brown
University of Florida
Gainesville, Florida

Associate Editors
Sherry Brandt-Williams
Rookery Bay National Estuarine Research Reserve
Naples, Florida

David Tilley
Texas A&M University
Kingsville, Texas

Sergio U1giati
University of Siena
Siena, Italy

December, 2000

The Center for Environmental Policy
Department of Environmental Engineering Sciences
University of Florida
Gainesville, FL
A Revised Solar Transformity for Tidal Energy Received by the Earth and Dissipated Globally: Implications for Emergy Analysis.

Daniel E. Campbell

ABSTRACT

Solar transformities for the tidal energy received by the earth and the tidal energy dissipated globally can be calculated because both solar energy and the gravitational attraction of the sun and moon drive independent processes that produce an annual flux of geopotential energy in elevated ocean water. I assume that the available geopotential energy of the world oceans is the same regardless of how it is made; therefore, the transformity of the annual geopotential energy flux generated by solar energy should be approximately equal to that generated by the gravitational attraction of the sun and moon. This approximate equality is plausible, because the maximum power principle implies that in the long run the transformity of a product created by any process will approach the lowest thermodynamically possible value. The annual emergy contributed by solar radiation (3.93 E24 sej y⁻¹) and the earth's deep heat (4.07 E24 sej y⁻¹) was divided by the difference between the geopotential energy generated annually in the world oceans and the tidal energy dissipated annually in shallow water (21.4 E19 J y⁻¹ - 5.2 E19 J y⁻¹) to obtain a transformity of 24259 sej J⁻¹ for the part of the ocean's total potential energy generated by the solar heat engine, if solar emergy is the only important emergy source and 49383 sej J⁻¹ if both the solar heat engine and the earth's deep heat contribute. Using the assumptions given above, the transformity of the tidal energy dissipated globally is also approximately 24259 sej J⁻¹ or 49383 sej J⁻¹. The solar emergy used up globally by the dissipation of tidal energy is then 5.2 E19 J y⁻¹ multiplied by 24259 sej J⁻¹ or 49383 sej J⁻¹, equaling 1.26 E24 sej y⁻¹ or 2.58 E24 sej y⁻¹, respectively. The transformity of the gravitational energy of the sun and moon received by the earth is then 1.26 E24 sej y⁻¹ or 2.58 E24 sej y⁻¹ divided by 8.515 E19 J y⁻¹ which equals 14797 sej J⁻¹ or 30159 sej J⁻¹, respectively. Because the earth's deep heat makes a negligible contribution to determining variations in the geopotential of the world oceans except on long time scales, e.g., more than 1.0 E4 years, the solar transformity for the tides based on solar emergy alone is preferable for emergy analyses on short time frames, e.g., less than 10,000 years. These revised solar transformities for tidal energy establish new planetary baselines for emergy analysis, 9.26 E24 sej y⁻¹ for short (< 1.0 E4 y) and 10.58 E24 sej y⁻¹ for long period processes (> 1.0 E4 y). Spatial and temporal guidelines to avoid double counting in determining the emergy basis for local phenomena were suggested based on implications of this analysis.

INTRODUCTION

Emergy Analysis (Odum 1996) is an assessment method that can evaluate the contributions of humanity and nature to the overall well-being of an environmental system. This is accomplished by expressing all the products and services produced and consumed by a network of economic and ecological components and processes in terms of a single quantity, the energy of one kind, e.g., the solar joules, that were required to produce them. This quantity, called emergy, is defined as all the available energy of one
Chapter 21. A Revised Solar Transformity for Tidal Energy...

kind previously used up directly and indirectly to make a particular product or service (Odum 1996). The emjoule or embodied joule (Odum 1986) denotes the use of a particular kind of energy in the past and, therefore, it is the appropriate unit for emergy. Solar emjoules are commonly used as the emergy unit for evaluating environmental systems.

The transformity of a product or service is the emergy required to make a unit of that product or service, e.g., 18,199 solar emjoules (sej) are required to make one joule (J) of chemical potential energy in rain (Odum 1996). By convention the transformity of solar energy is 1. The available energy or exergy contents of many products have been tabulated and are widely available, e.g., the Gibb's free energies of reaction products are tabulated in the Hand Book of Physics and Chemistry. These quantities can be easily converted to emergy by multiplying the exergy in joules by the appropriate transformity (sej J⁻¹). Therefore, transformities are the key pieces of new information needed to evaluate the emergy of environmental products and services. Note that by convention transformities smaller than 1.0 x 10⁻⁵ sej J⁻¹ are reported to the nearest whole number because these values are often used as intermediaries in spreadsheet calculations to determine other values. This convention is not intended to imply that a transformity is known to 4 or 5 significant figures when the numbers input to the calculation are only reported to two or three significant figures. The future success of Emergy Analysis as a method for assessing environmental systems will depend on developing accurate and consistent methods for calculating transformities, documenting the uncertainty associated with these calculations, and developing a clear understanding of how to use these factors in determining the emergy basis for economic and ecological products, services, and systems.

The process of determining a new transformity begins by identifying all the energy transformations that contribute to the formation of the product or service being evaluated. By definition the solar transformity is the solar emergy required to make a joule of available energy in a product or service, so the next step is to determine the minimum set of required inputs that represents the maximum emergy contributed by independent emergy sources to produce a product, i.e., the emergy required without double counting. For example, many natural products are produced by the transformation of energy in a network (Figure 1). All products that are generated by the transformation of the external energy sources in the network are co-products of the same system and the emergy from all sources is required to make any product in the network. If more than one of these co-products contributes emergy to the formation of a product or service under evaluation only the co-product contributing the highest emergy is counted. If the emergy of other co-products is added to the emergy required to make the product or service being evaluated, the emergy that the co-products contribute to the process will be counted more than once. The method of calculation used here leads to a consideration of practical methods for minimizing the problem of double counting in determining the emergy basis for natural products and services.

The largest system of interest to us in calculating transformities for environmental products and services is the planetary web of processes that generates natural products such as the wind, rain, waves, tides, etc. (Figure 1). These global products often supply much of the energy transformed to make other ecological and economic products and services. All products in the planetary web are created by the transformation of the earth’s three primary independent sources of energy which are (1) solar radiation, (2) the earth’s deep heat, and (3) the gravitational attraction of the sun and the moon. Furthermore, all natural products and processes on Earth are created by the transformation of the energies in the products of the planetary web. When these three primary energy sources to our earth are expressed in terms of a single kind of energy, a planetary baseline is established for determining the transformities of products and services provided on a global basis. The planetary baseline itself is primarily of academic interest because, as long as all transformities are determined relative to the same baseline, the results of an analysis will change little if the baseline is moved. The more interesting question is how should the products of the planetary web be combined to determine the emergy basis for products and services without double counting. In an appendix to Campbell (1998) Campbell and Odum applied the method used by Odum and Odum (1983) to estimate the solar transformity of the earth’s deep heat to calculate a revised transformity for the tidal energy received by the earth and the tidal energy dissipated, globally. In this paper I present the assumptions and calculations in more detail and consider the implications of this
approach for Emergy Analysis. In addition, I suggest a rationale for combining the three independent energy sources to the planet to avoid double counting in the determination of the emergy basis for economic and ecological products and services.

METHODS

Odum and Odum (1983) used an elegant method to determine the solar transformity of the earth's deep heat. The key to making an equivalence between these two independent emergy sources was to recognize that they both contribute to creating the same product, i.e., the earth's cycle of uplift and subsidence. Over the long run the Maximum Power Principle will guide both of these processes toward the lowest thermodynamically possible transformity in making the product. Therefore, the transformity of the portion of the earth cycle driven by solar emergy will be approximately equal to the transformity of the portion driven by the emergy from the earth's deep heat. The heat flux from the earth's crust is commonly measured by geologists (Lachenbruch and Sass 1977, Decker 1987). This heat flow is the result of the underlying geologic activity and the erosive action of wind and rain on the land surface. In addition, solar emergy contributes to this heat flux through the burial of organic matter in sediments. Odum and Odum (1983) found that the flux of residual heat from the earth's mantle and the heat generated in the crust by radioactive decay had been estimated by Sclater et al. (1980). They estimated the solar transformity of the earth's heat driving the cycle of uplift and subsidence by subtracting the geologic heat fluxes (radioactive decay and residual heat flux) from the total heat flux out of the earth's surface. The remaining heat flux from the crustal surface can be attributed to the part of the earth cycle driven by solar emergy which passes energy downward into the crust as compression and chemical potentials (Odum 1996). The ratio of the annual solar energy input to the planet divided by this energy flux is then the solar transformity of the portion of the earth cycle driven by solar emergy. Since both the solar heat engine and the earth's radioactive and residual heat contribute emergy to drive the same geologic process, i.e., the earth cycle of crustal movements, by the logic given above we can assume that the solar transformity of the earth's radioactive and deep heat contributing to the earth cycle will be approximately the same as that estimated for the solar heat engine's contribution to the total crustal heat flux.

If the following four assumptions hold, the method of Odum and Odum (1983) can be applied to determine the solar transformity of the tidal energy received and dissipated globally. (1) The annual flux of available geopotential energy due to elevated water in worlds oceans is the same regardless of source. Thus, the total available geopotential energy of elevated water in the world oceans will have the same transformity as the available geopotential energy created by the gravitational attraction of the sun and moon and the solar heat engine. (2) On the time scale of one year, the available geopotential energy of the world's oceans is in steady state, thus all the available geopotential energy that is created in a given year is dissipated in that year. If this assumption was on average false, there would be an accumulation or decline of the total potential energy in the global ocean over a series of years and this is not observed. (3) The elevation of the ocean surface relative to a reference level at a depth of 1000m is caused by the solar heat engine including its effect in delivering fresh water to the oceans, the gravitational pull of the sun and moon, and the spatial distribution of continental land masses. (4) The dissipation of tidal energy in the deep oceans is less than 0.001 of that in shallow water (Miller 1966). Given these assumptions, the solar transformity of the portion of the geopotential energy in the world oceans that is generated annually by the solar heat engine can be estimated if the total and the fraction of the total generated annually by the tides is known.

The following algebra may be used to determine the solar emergy contributed to the planetary baseline by the gravitational attraction of the sun and moon from which the transformities for the tidal energy received, \( J_{R} \), and tidal energy dissipated globally, \( J_{DP} \), can be calculated. The annual flux of geopotential energy, \( J_{G} \), in the world oceans is made up of a portion generated by the solar heat engine, \( J_{S} \), and a portion generated by the gravitational attraction of the sun and moon, \( J_{T} \). The first step in calculating a transformity is to determine the emergy sources used in producing the product in this case the annual flux of available geopotential energy in the world oceans. There are only three possible emergy sources to
consider, solar emergy, $EM_s$, the energy in the earth’s deep heat, $EM_e$, and the emergy supplied by the gravitational attraction of the sun and moon, $EM_m$. According to our assumptions the emergy basis for creating the annual flux of geopotential energy in the world oceans must be either:

$$EM_E + EM_T + EM_S \quad \text{or} \quad EM_T + EM_S \quad \text{or} \quad (1)$$

$$EM_T + EM_S \quad \text{or} \quad (2)$$

Using the fundamental relationship, $Energy = Energy \times Transformity$ or $Em_i = J_i t_i$, and the transformity of the total annual flux of geopotential energy in the world oceans, $t_G$, we can write the following relations:

$$t_{G1} = EM_E + EM_T + EM_S + J_G \quad \text{and} \quad (3)$$

$$t_{G2} = EM_T + EM_S + J_G \quad \text{or} \quad (4)$$

Figure 1. A partially evaluated diagram of the three independent energy sources supporting global energy flows and generating available geopotential energy in the world oceans.
where the subscripts 1 and 2 refer to the two different emergy bases given in (1) and (2). By our assumptions the available geopotential energy in the world oceans is the same product regardless of source, and therefore, its emergy can be split according to the energy contributed in the various products. The transformity (emergy/energy) of all the products must be equal, i.e., the transformities of the available geopotential energy created by the tide, $\tau_{GT}$, solar energy, $\tau_{GS}$, as well as the total, $\tau_{G}$, are equal. In addition, the tidal energy dissipated annually in shallow water, $J_{TD}$, is approximately equal to the geopotential energy created by the tide, $J_{GT}$. Now $\tau_{TD} = EM_{T} / J_{TD}$ may be substituted into equations (3) and (4) to give,

$$\tau_{G1} = EM_{T1} / J_{TD} = (EM_e + EM_{T1} + EM_s) / J_G$$ and

$$\tau_{G2} = EM_{T2} / J_{TD} = (EM_{T2} + EM_s) / J_G$$

Solving for $EM_{T1}$ and $EM_{T2}$,

$$EM_{T1} = J_{TD} (EM_e + EM_s) + (J_G - J_{TD})$$ and

$$EM_{T2} = J_{TD} EM_s + (J_G - J_{TD})$$

All values in these two equations are known except, $EM_{T1}$ and $EM_{T2}$, the emergy contributed to the planetary baseline by the gravitational attraction of the sun and moon for each of the two possible energy bases. After determining the $EM_{T1}$ and $EM_{T2}$, the transformities for the tidal energy received, $\tau_{R1}$, and dissipated, $\tau_{TD1}$, and $\tau_{TD2}$, can be calculated using the gravitational energy received annually by the earth, $J_R$, and the tidal energy dissipated in shallow water, $J_{TD}$,

$$\tau_{R1} = EM_{T1} / J_R$$ and $$\tau_{R2} = EM_{T2} / J_R$$

$$\tau_{TD1} = EM_{T1} / J_{TD}$$ and $$\tau_{TD2} = EM_{T2} / J_{TD}$$

RESULTS

If the solar emergy flux to the earth, $EM_s$, is 3.93 $10^24$ solar emergy units y$^{-1}$ (Odum 1996), the gravitational energy transmitted to the earth, $J_g$, is 8.515 $10^19$ joules y$^{-1}$ (Munk and MacDonald 1960), the tidal energy transmitted to shallow water, $J_T$, is 5.2 $10^9$ joules y$^{-1}$ (Miller 1966), and the annual production of available gravitational potential energy in the top 1000 m of the global ocean, $J_o$, is 21.4 $10^9$ joules y$^{-1}$ (Oort et al. 1989), the following calculations and assumptions can be used to determine solar transformities for the tidal energy dissipated and the tidal energy received by the earth. Alternatively, these numbers can be substituted into the equations in the methods section to yield similar results.

The fraction of the available geopotential energy of the oceans created annually by solar emergy is equal to the total available geopotential energy created annually minus the geopotential energy created by the tide. If almost all of the available geopotential energy produced annually by gravitational attraction is transmitted to shallow water and dissipated there, the available geopotential energy produced annually by solar emergy, $EM_s$, is 16.2 $10^19$ joules y$^{-1}$.

$$21.4 E19 \text{ joules } y^{-1} - 5.2 E19 \text{ joules } y^{-1} = 16.2 E19 \text{ joules } y^{-1}$$

The solar transformity of the portion of the available geopotential energy created annually by the solar heat engine, $\tau_{S2}$, is then:
Chapter 21. A Revised Solar Transformity for Tidal Energy...

3.93 E24 joules y\(^{-1}\) + 16.2 E 19 joules y\(^{-1}\) = 24259 sej J\(^{-1}\) (12)

This is also the transformity for the portion of the available geopotential energy in the world oceans generated by the gravitational attraction of the sun and moon, \(\tau_{T2}\). Transformity does not change when a system shifts energy from potential to kinetic form with conservation. Since almost all the tidal geopotential energy is transmitted to shallow water and dissipated there the solar transformity of the tidal energy dissipated in shallow water is approximately the same as that of the tidal geopotential energy generated. The emergy contributed to the planetary baseline by the tides, \(E_{M_{T2}}\), is then:

\[ 5.2 \text{ E19 joules y}^{-1} \times 24259 \text{ sej J}^{-1} = 1.26 \text{ E24 sej y}^{-1} \] (13)

The solar transformity of the gravitational energy of the sun and moon received by the earth, \(\tau_{R2}\), is then:

\[ 1.26 \text{ E24 sej y}^{-1} + 8.515 \text{ E19 joules y}^{-1} = 14797 \text{ sej J}^{-1} \] (14)

The new planetary baseline using this revised transformity for tidal energy is:

\[ 3.93 \text{ E24 sej y}^{-1} + 4.07 \text{ E24 sej y}^{-1} + 1.26 \text{ E24 sej y}^{-1} = 9.26 \text{ E24 sej y}^{-1} \] (15)

These transformities are correct if the only important emergy sources required to produce the available geopotential energy of elevated water in the oceans are the gravitational attraction of the sun and moon and the solar heat engine. However, it is well known that the elevation of the water surface in the ocean also depends on the geometry and the distribution of land forms both locally and globally (Macmillan 1966). The distribution of landforms is a consequence of the earth cycle as discussed above, which requires a major input of emergy from radioactive decay and residual heat for its operation. This emergy contributed by the earth’s heat is also required to produce a given quantity of geopotential energy in the world oceans. To see that there must be a geologic input to creating the potential energy of the oceans imagine an earth without continents and thus no geologic input to the upper zone. Would the oceanic geopotential energy created annually by the attraction of the sun and moon be different?

If the deep heat emergy from the earth contributes to the formation of the available geopotential energy in the ocean by creating the distribution and geometry of the continental land masses and coastal shelves, the non-tidal emergy input should be 8.0 E24 sej y\(^{-1}\) (3.93 E24 sej y\(^{-1}\) from solar and 4.07 E24 sej y\(^{-1}\) from deep heat of the earth, \(E_{M_{E}}\) (Odum 1996). The solar transformity of the geopotential energy in the oceans created annually by the solar heat engine, \(\tau_{S1}\), is now:

\[ 8.0 \text{ E24 sej y}^{-1} + 16.2 \text{ E19 joules y}^{-1} = 49383 \text{ sej J}^{-1} \] (16)

By reasoning similar to that applied above this transformity can also be applied to the available geopotential energy of the world oceans generated by the gravitational attraction of the sun and moon, \(\tau_{T2}\), and to the tidal energy dissipated in shallow water, \(\tau_{TD2}\). The solar emergy used up globally in the dissipation of the available geopotential energy produced annually by the tides, \(E_{M_{T1}}\), is then:

\[ 5.2 \text{ E19 joules y}^{-1} \times 49383 \text{ sej J}^{-1} = 2.568 \text{ E24 sej y}^{-1} \] (17)

and the solar transformity of the gravitational energy received by the earth, \(\tau_{R2}\), is:

\[ 2.568 \text{ E24 sej y}^{-1} + 8.515 \text{ E19 joules y}^{-1} = 30159 \text{ sej J}^{-1} \] (18)
The new planetary baseline using the transformaty for tidal energy received that includes the contribution of earth processes is:

\[ 3.93 \times 10^{24} \text{ sej y}^{-1} + 4.07 \times 10^{24} \text{ sej y}^{-1} + 2.57 \times 10^{24} \text{ sej y}^{-1} = 10.57 \times 10^{24} \text{ sej y}^{-1} \]  

\[ (19) \]

**DISCUSSION**

Figure 1 illustrates the planetary web of interactions between the earth’s three independent energy sources and the production systems of the land, oceans, and atmosphere. The three planetary system components, oceans, atmosphere and land are completely interconnected by important feedbacks. For example, the land surface elevation and roughness affect wind movement in the atmosphere and the atmospheric winds erode the land and redistribute particles over the earth’s surface. Many other examples of the connections between these planetary subsystems could be given but the important point is that all the global energy flows are the products of this interconnected web. Solar energy interacts directly with all three planetary subsystems, whereas the earth’s deep heat contributes energy primarily to the oceanic and terrestrial subsystems. The gravitational attraction of the sun and moon interacts most strongly with the oceans, but it also results in lesser tidal effects in the atmosphere and land mass (Cartwright 1999).

The relative magnitude of the contribution that each of these three independent energy sources makes to the production of eight global energy flows is shown in Table I. The contributions are classified as (1) immediate, meaning that changes in the annual emergy supplied by a forcing function are reflected in the global energy flux in that year; (2) long term, meaning that there is a substantial contribution of the present state of an environmental variable to producing a global energy flow, but the emergy inputs driving the variable must act for a long time, e.g., millions of years, to result in a substantial change in that global energy flow; and (3) negligible, meaning that the emergy supplied by a source is so small relative to other sources that it can be ignored for practical purposes. This table can be used to help avoid double counting in determining the emergy basis for local ecological and economic organization on our planet. For example, if one emergy input is negligible for global energy flow, A, but makes an immediate contribution to energy flow, B, and another independent emergy source makes an immediate contribution to A but has a negligible influence on B, the two may be counted together in determining the emergy basis of a phenomenon without double counting. Therefore, the emergies of the tidal energy absorbed and the chemical potential energy in rainfall can both be added to determine the emergy basis for organization in a coastal region without double counting (see Table 1). Emergy sources that make a long-term contribution to a global energy flow do not need to be added to the emergy basis for organization in a region on time scales very much shorter than their period of effective action. The period of effective action might be defined as the time needed to produce a 1% change in the global energy flow.

Questions about double counting can also be clarified by considering the separation of input emergies in space and time. Spatial separation of inputs avoids double counting. For example, the major emergy inflows are often different over the land and water portions of a system composed of a coastal body of water and its watershed. The primary emergy source for coastal waters is often the tidal energy absorbed, whereas, over land it is often the chemical potential energy in rainfall. When these emergy inputs are determined based on the respective water and land areas where each dominates there can be no double counting. According to the information in Table 1 the chemical potential energy of rainfall might be added over the water area as well as the land with little risk of double counting. However, the emergy in chemical potential energy of rainfall and in the physical energy of the wind could not be added over the same area without double counting, since they are both immediate co-products of the solar heat engine.

Separation in time is a second test to determine what emergy inputs should be counted as part of the emergy basis of a product, service, or system. Transformities are calculated based on the time needed to produce a product or service quickly and efficiently. In some cases the amount of a product that is created depends on the energy previously used up over a very long period of time in a process that is a part of a much larger system, e.g., the contributions of emergy from the earth’s deep heat to creating the
Table 1. An estimate of the nature of the contributions made by earth’s three independent energy sources to producing global energy flows within the planetary web.

<table>
<thead>
<tr>
<th>Global Energy Flow</th>
<th>Independent Energy Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solar Radiation</td>
</tr>
<tr>
<td>Wind</td>
<td>Immediate</td>
</tr>
<tr>
<td>Rain, geopotential</td>
<td>Immediate</td>
</tr>
<tr>
<td>Rain, chemical potential</td>
<td>Immediate</td>
</tr>
<tr>
<td>Waves</td>
<td>Immediate</td>
</tr>
<tr>
<td>Tides</td>
<td>Negligible</td>
</tr>
<tr>
<td>Streams, geopotential</td>
<td>Immediate</td>
</tr>
<tr>
<td>Streams, chemical potential</td>
<td>Immediate</td>
</tr>
<tr>
<td>Earth cycle</td>
<td>Immediate</td>
</tr>
</tbody>
</table>

tidal geopotential energy of the world oceans as discussed above. In such cases there is a legitimate question of how these long term inputs should be handled.

A simple test for the separation of processes in time is to compare the change in production that occurs as a consequence of the observed variations in the long period emergy input over a quick and efficient production time to the change in production caused by variations in the immediate inputs during the same time. If the change in production caused by variations in the long-term input are negligible compared with the expected changes caused by the immediate inputs, the long-term input may be considered as a constant. In this case, a negligible quantity of emergy is being supplied from the long term process during the time period of an efficient production cycle. Emergy from the long-term process is causing changes in the production cycle at an infinitesimally small rate, and therefore, it can be omitted as an emergy input to the production process on short time scales. However, if the stored emergy in a product from a larger system is being used up in a production process at a rate faster than it is being replenished, the contributions of the long-term storage must be counted in the emergy basis for the short term product, e.g., soil loss in agricultural production (Odum 1996).

Odum (1996) originally determined the transformity of the tidal energy dissipated by assuming that tidal currents had the same transformity as the current in a large river, i.e., the Mississippi. He obtained a value of 27764 sej J\(^{-1}\) for tidal energy dissipated and 16,842 sej J\(^{-1}\) for tidal energy received. These numbers are 13.8% greater than the values calculated in this paper using solar emergy alone. For comparison the two best estimates for the tidal energy dissipated globally given in Miller (1966) differ by 11.2%. The transformity of river current proves to be a good approximation for tidal current transformity, when compared to the value calculated by this method. The present method follows that used by Odum and Odum (1983) to estimate the transformity of the earth’s deep heat, therefore, the solar emergy contributed to the planetary baseline by the earth’s deep heat and the emergy contributed by the gravitational attraction of the sun and moon have now been determined in a consistent manner. The revised transformities presented in this paper should be more accurate than those currently in use. However, two different transformities for both the tidal energy received and tidal energy dissipated globally were calculated in the results section. A question remains as to when each of these two alternatives should be used.

The argument on the temporal separation of the significant action by emergy sources in a production process presented above leads to the conclusion that the transformities for the tidal energy dissipated and received globally based on solar emergy alone are the best ones to use in determining the
transformation of systems, products, and processes on short time scales, e.g., 10,000 years or less. This assumes that the present configuration of the continents and oceans is essentially a constant over time periods shorter than 10,000 years, therefore, the emergy contribution of the earth cycle to year to year variations in the available geopotential of the world oceans is negligible. Effectively, no energy from the earth cycle is used up in producing the tides on such short time scales. The larger global transformation for tidal energy that includes the contribution of the earth’s deep heat is appropriate for processes operating on long time scales (>10,000 years) over which the annual geopotential energy generated by the gravitational attraction of the sun and moon could change as a result of continental drift sea level rise or fall etc. The conclusion from this discussion is that the emergy baseline for planetary products and services is relative and may differ if the significant inputs to the production process change as a consequence of shifting time scales or other relevant factors, e.g., the development of our fossil fuel based industrial society.

ACKNOWLEDGMENTS

I thank H.T. Odum for his suggestions and counsel in developing these new transformations for tidal energy. I thank G. Pesch, J. Kiddon, E. Dettmann, and Jonathan Garber for helpful internal reviews of the manuscript. The opinions expressed in this paper are my own and do not necessarily reflect those of the USEPA or anyone else. This paper is contribution number NHEERL-NAR-2170 of the Atlantic Ecology Division, National Health and Environmental Effects Research Laboratory, United States Environmental Protection Agency.

REFERENCES


-263-