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Updated evaluation of exergy and emergy driving the geobiosphere: A review and refinement of the emergy baseline

Mark T. Brown[a,*], Sergio Ulgiati[b]

[a] Department of Environmental Engineering Science, Center for Environmental Policy, Phelps Lab., University of Florida, Gainesville, FL 32611, USA
[b] Department of Sciences for the Environment, Parthenope University of Naples, Italy

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ABSTRACT

Crucial to the method of emergy synthesis are the main driving emergy flows of the geobiosphere to which all other flows are referenced. They form the baseline for the construction of tables of Unit Emergy Values (UEVs) to be used in emergy evaluations. We provide here an updated calculation of the geobiosphere emergy baseline and UEVs for tidal and geothermal flows. First, we recalculate the flows using more recent values that have resulted from satellite measurements and generally better measurement techniques. Second, we have recalculated these global flows according to their available energy content (exergy) in order to be consistent with Odum's (1996) definition of emergy. Finally, we have reinterpreted the interaction of geothermal energy with biosphere processes thus changing the relationship between geothermal energy and the emergy baseline. In this analysis we also acknowledge the significant uncertainties related to most estimates of global data. In all, these modifications to the methodology have resulted in changes in the transformities for tidal momentum and geothermal energy and a minor change in the emergy baseline from 15.8E24 seJ/J to 15.2E24 seJ/J. As in all fields of science basic constants and standards are not really constant but change according to new knowledge. This is especially true of earth and ecological sciences where a large uncertainty is also to be found. As a consequence, while these are the most updated values today, they may change as better understanding is gained and uncertainties are reduced.

1. Introduction

Odum (1996, 2000) calculated the total environmental support to the geobiosphere in terms of the emergy concept,[1] a measure of the total available energy directly and indirectly involved in the geobiosphere processes. That work required the calculation of transformity factors[2] for the main driving sources of geobiosphere processes. The three main sources of available energy (Odum, 1996) are solar radiation received by Earth, tidal momentum created by the earth-sun-moon system, and geothermal energy from deep within the Earth. The Earth geobiosphere,[3] as shown in Fig. 1, is composed of a hierarchical web of components connected by flows of available energy, materials, and information that build potential energy and circulate materials. The web of processes and components that results from the interaction of this tripartite of energy sources sustains life on earth and benefits human economies in an almost infinite number of ways.

1.1. Concerns about reference baselines

Emergy analysts presently use a baseline that is derived from the work of H.T. Odum in a published Emergy Folio (Odum, 2000), the final result of a series of conceptual developments and recalculations. Early in the 1970s Odum and Odum (1976) used a baseline that only included the solar energy driving planetary ecosystems, later in the mid 1990s, Odum (1996) included tidal momentum and geothermal energy and converted them into equivalent solar emergy deriving a geobiosphere baseline of 9.44E24 seJ/yr. According to this conceptual framework, the three main flows (solar, tide, and deep heat) were characterized as having different energy quality expressed by higher transformities of tidal and deep heat relative to solar. In 2000 Odum refined the calculations of transformities of tide and deep heat based on better data and acknowledgement that the three forms of energy were

* Corresponding author. Tel.: +1 352 3922424; fax: +1 352 3923624.
E-mail address: mtb@ufl.edu (M.T. Brown).

[1] Emergy is the available energy of one type (usually solar exergy) that is required to produce something (Odum, 1996).

[2] Transformity is the unit emergy investment, i.e. the emergy required to generate a unit of available energy flow in a process (seJ/J). Sometimes flows are expressed in units of mass and the conversion ratio is called specific emergy (seJ/g). The generic term for both is Unit Emergy Value (UEV).

[3] We define the system boundaries of the geobiosphere as a spherical crown whose boundaries include the lithosphere (approx. 100 km below the surface) and extend to 100 km above the surface which contains 98% of the atmosphere mass.

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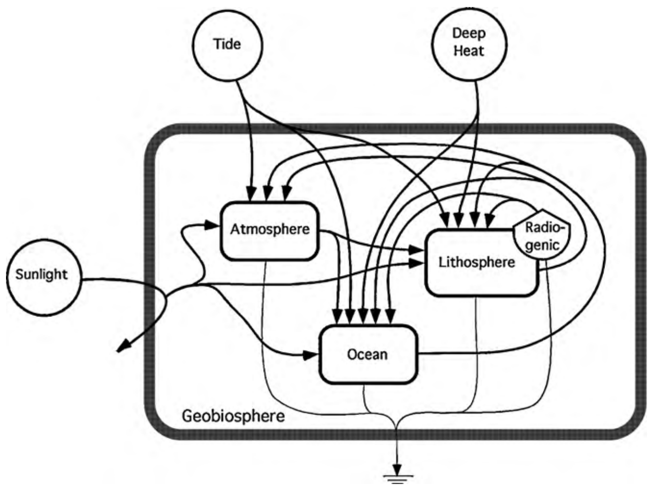

Fig. 1. Earth geobiosphere, a hierarchical web of components connected by flows of available energy, materials, and information that build potential energy and circulate materials.

linked and required a series of simultaneous equations in order to compute their transformities. The result was a new baseline of 15.83E24 seJ/yr and an increase in the transformities of tide and geothermal energy.

Some data on which those earlier calculations were based have been improved (earth deep heat and gravitational potential of tides) and there have been some comments and criticism (Ulgiati, 2000; Bastianoni et al., 2007; Sciubba, 2009; Chen et al., 2010) leveled at the emergy methodology based on the fact that energy was used in these earlier calculations instead of available energy, as Odum (1996) defined emergy. Ulgiati (2000) expressed the importance of using available energy (exergy) in calculations instead of just energy to maintain consistency with Odum's definition of emergy. Bastianoni et al. (2007) investigated linking transformities based on available energy with those based on energy. Sciubba (2009) noted the inconsistency in calculating baseline transformities using energy instead of exergy and claimed that this weakened the thermodynamic basis of the method.

All of these criticisms point out inconsistencies between the stated definitions of emergy and the current practice of some scientists using the method. In parallel to these criticisms, Chen (2006) suggested a different procedure to include available energy within the emergy framework, which lead to redefining Odum's concepts of emergy based on what the author calls embodied cosmic exergy. Then later, Chen et al. (2010) renamed their concept cosmic emergy, and calculated a baseline that translated into transformities equal to unity for the three exergy flows driving the geobiosphere. In so doing, they dismissed the concept of energy quality in the very moment they seemed to accept the emergy method. The main issue here is that the three main flows supporting the geobiosphere were considered equivalent in quality while it is apparent that they are generated through very different pathways and support the geobiosphere in very different ways. As a consequence of using the same transformity for all three flows, their total exergy consumed (45 TW) disregards the coupling of the solar, tidal and deep heat flows that drive all downstream processes and generate the renewable flows (wind, precipitation, oceanic currents etc) as well as the nonrenewable storages (top soil, minerals, fossil fuels) supporting environmental and economic systems. Their recalculation of Odum's (1996) Unit Emergy Values, in spite of using his original evaluative framework, results in values four to five orders of magnitude smaller and in some cases negative.

The concept that all driving forces on the planet originate from a larger time space scale (a cosmic scale) was pointed out by Brown (2004) in a paper originally drafted by Odum (2003) just prior to his death. These papers acknowledged that transformities could be based on a Universe baseline and suggested, in principle at least, that all solar transformities calculated for earth environment and economy could be put on a universal basis. However, it is important to note that even with a Universe baseline, solar, tidal and geothermal energy would be constrained to have different transformities because of their very different origin and quality. While this approach is theoretically interesting, there was little follow up since practical application is limited. Multiplying all flows on Earth by a cosmological correction factor does not change their relative importance to each other, adds a needless reference to an even more uncertain benchmark, and is unlikely to make resource management and environmental policy any easier.

As a result of all the above circumstances we have conducted a very careful review of the literature to update the data on available energy of the geobiosphere, have recalculated driving energies as exergy, and have further refined the methodology of calculating transformities of the available energies driving the geobiosphere. The results of which, presented in this paper reconfirm and further refine Odum's most recent work and emergy baseline.

We would like to underline that there is a very lively debate in progress about the relation between exergy and emergy and also about the biosphere benchmark baseline for emergy values. The baseline is extremely important as all UEVs are calculated from it. We believe that this paper has the potential to clarify at least some of the issues.

2. Global data sets: a review

The available energy of solar radiation received by earth is easily calculated as being approximately 93% of incoming energy flux, based on Szargut (2003) and following Petela (1964). The exergy and energy in tidal momentum received by earth are equivalent since the tidal energy results in oceanic geopotential energy ("*potential exergy is equal to potential energy when it is evaluated with respect to the average level of the surface of the earth*", Szargut et al., 1988). Geothermal energy must be converted to exergy and depends on the Carnot efficiency as defined by the temperature of the source and environmental temperature. Recently measurements of global heat flows have increased in number (now over 27,000 measurements worldwide) and accuracy, yet determinations of total heat flow from geothermal processes have large uncertainties both in sources and in quantities. Thus in our determinations of total global exergy and emergy fluxes, the geothermal sources are characterized by the largest uncertainty.

In this paper we give exergy power in terawatts (TW) and total annual exergy in Joules (J) in parentheses. We also use the notation "E12" to represent exponents (10^{12}).

2.1. Exergy of solar radiation

Of the exergy in solar radiation that is received by earth some is reflected by the earth's atmosphere and ground (albedo). That which is not reflected drives terrestrial, oceanic and atmospheric processes that in turn drive many others. Szargut (2003) calculates the mean annual exergy flow of solar radiation reaching the external layers of the atmosphere as 162,400 TW (5.12E24 J/yr) with atmospheric and terrestrial reflection given as 48,700 TW (1.54E24 J/yr) and 8200 TW (0.26E24) respectively. Thus the calculated albedo according to Szargut is 35%. In addition to direct solar radiation, Szargut computes that "relict radiation" (remaining after the big bang) equals 78,500 TW (2.48E24 J/yr) which is "1.02 times larger than the exergy flow of solar radiation adsorbed by the Earth's surface" (Szargut, 2003). However Szargut dismisses the relict radiation as not producing "...any lasting energy effect on the earth's surface."

Hermann (2006) puts the exergy of solar radiation reaching the Earth as 162,000 TW (5.11E24 J/yr) with a combined albedo of the atmosphere (34,000 TW [1.07E24 J/yr]) and earth surface (5000 TW [0.16E24 J/yr]) of 24%. Hermann also included an extraterrestrial source, calling it "extra solar radiation exchange" and stating that "The low temperature radiation permeating space in the vicinity of our solar system serves as a cold sink for our relatively warm planet, driving the transfer of 122,000 TW long-wave radiation energy from the terrestrial environment into space with an accompanying net input of 63,000 TW exergy" (Hermann, 2006).

Providing no further details of computations, Wall and Gong (2001) indicate the exergy of solar radiation received by the Earth as 160,000 TW (5.04E24 J/yr) and an albedo of 33% yielding a net exergy of solar radiation of 107,200 TW (3.38E24 J/yr).

Chen (2006) uses the term "cosmic exergy" associated with short wave solar radiation intercepted by the earth and computes solar radiation as 173,300 TW (5.47E24 J/yr) with 52,000 TW (1.64E24 J/yr) or 30% as "backscattered and reflected solar radiation".

Odum (1996) computed 178,000 TW (5.61E24 J/yr) as the energy of solar radiation received at the upper atmosphere and assumed 30% albedo yielding a net energy received by the Earth system of 124,600 TW (3.93E24 J/yr). If converted to exergy following Petela (1964) the equivalent exergy received at the upper atmosphere was 166,000 TW (5.23E24 J/yr) and net radiation received by Earth was 116,200 TW (3.66E24 J/yr), a value that is 7% lower than the energy valued used by Odum (1996) in calculations of the global energy/emergy budget.

In a recent paper Valero et al. (2010) evaluated the exergy resources of Earth and quoting Szargut (2003) restricts the focus for solar exergy flow to that which heats the land and water (43,200 TW [1.36E24 J/yr]), disregarding as not relevant the exergy flows supporting atmospheric and oceanic processes.

Table 1 summarizes the solar exergy used by researchers in their determinations of global exergy resources. The values vary from 160,000 TW to 173,300 TW.

2.2. Gravitational energy and tides on Earth

Tidal energy is contributed to the geobiosphere by the gravitational forces of moon and sun that pull air, earth, and especially the ocean, relative to the rotating planet, causing friction and heat dissipation. Tidal energy interacts with the ocean to generate gravitational potential energy (elevated waters), which drives currents, and its exergy is mainly dissipated in the shallows of the coastal zone. Specific tidal exergy is equivalent to the gravitational potential energy due to the height difference between tidal maxima and minima over the tidal record (Hermann, 2006). The earth contributes landform to the dynamics of the atmosphere-ocean.

The exergy of tides is a very small fraction of the total exergy contributed to the Earth system by all sources (including deep heat and solar radiation), yet its contribution to the Earth dynamics is huge, because it is strongly coupled to all the other global circulation phenomena (sea water circulation and mixing, as well as globe temperature regulation among others).

Table 2
Summary of tidal exergy used by researchers in their determinations of global exergy resources.

Global exergy power (TW)	Global exergy (J/yr)	Reference
2.7	8.50E+18	Munk and Macdonald (1960) and Odum (1996)
2.7	8.50E+18	Skinner (1986) and Valero et al. (2010)
3.7	1.17E+20	Munk and Wunsch (1998)
3.7	1.17E+20	Egbert and Ray (1999) and Hermann (2006)
2.4	7.57E+19	Wall and Gong (2001)
3	9.46E+19	Chen (2006)

Movement of vast masses of water requires a great deal of exergy, which Odum (1996) estimated to be 2.7 TW (0.85E19 J/yr), based on Munk and Macdonald (1960). Valero et al. (2010) use the same figure based on Skinner (1986). Munk and Wunsch (1998) updated the tidal exergy power value to 3.7 TW (1.17E20 J/yr) based on astronomical data, pointing out that 2.5 TW must be attributed to the moon/earth interaction and that small fractions of such a power (0.2 TW and 0.02 TW) respectively drive the Earth and atmospheric tides. Egbert and Ray (1999) confirm the 3.7 TW exergy power based on satellite altimeter data. Their value is used by Hermann (2006) in his quantification of global exergy resources of Earth. Wall and Gong (2001) estimate a tidal exergy value of 2.4 TW, while Chen (2006) provides an estimate of 3 TW. These two latter authors do not refer to any experimental study published in the literature, but seem to rely on average estimates of global Earth exergy resources.

Table 2 summarizes the tidal exergy used by researchers in their determinations of global exergy resources. The values vary from 2.4 TW to 3.7 TW.

2.3. Geothermal exergy

Geothermal energy drives geologic processes including sea floor spreading, reshaping and redistributing continents and mountain building. As one of the main driving energies of the geobiosphere and an important component of global heat flows, determining the global heat budget has recently garnered much interest in the scientific community.

Computations of geothermal exergy are relatively scarce in the literature. Wall and Gong (2001) show a source of geothermal exergy in their Fig. 8. The exergy flows on the earth but they do not evaluate the magnitude of the flow. Hermann (2006) estimated the geothermal heat flow as 45 TW (14.19 E20 J/yr) referencing Pollack et al. (1993). Hermann computes the exergy apparently using a Carnot efficiency of 0.71 based on a temperature of 1050 K at the crust/mantle interface yielding a total global geothermal exergy of 32 TW (10.09 E20 J/yr). Valero et al. (2010) referencing Jaupart and Mareschal (2004) extrapolate that the total geothermal exergy contribution to the Earth is 17.9 TW (5.64 E20 J/yr) using a

Table 1
Summary of solar exergy used by researchers in their determinations of global exergy resources.

Gross radiation received by upper atmosphere TW (E24 J/yr)	Net radiation received by Earth TW (E24 J/yr)	Albedo (%)	Reference
162,000 (5.11E24)	123,000 (3.88E24)	24%	Hermann (2006)
173,300 (5.47E24)	121,300 (3.83E24)	30%	Chen (2006)
162,400 (5.12E24)	105,500 (3.33E24)	35%	Szargut (2003)
160,000 (5.05E12)	107,200 (3.38E24)	33%	Wall and Gong (2001)
166,000 (5.23E24)	116,200 (3.66E24)	30%	Odum (1996)

crust thickness of 44 km, an average of heat production between 0.79 mW m^{-3} and 0.95 mW m^{-3} and the crustal heat flow component from 32 mW m^{-2} to 38 mW m^{-2}.

Since there is little existing data (and that which exists seems to vary significantly) it was necessary to review the literature on global heat flow and derive geothermal exergy from the heat flow literature by applying appropriate Carnot efficiencies.

2.4. Geothermal energy

There is much divergence in the recent literature regarding the geothermal heat flux of Earth and there is even less agreement on the sources of this heat (core cooling, radioactive decay, crustal contributions, etc.) The uncertainty surrounding estimates of the global heat balance stem from several sources: from a lack of understanding of the fundamental physical aspects of convection in the mantle, from securing new and more precise observations, and from a lack of adequate data on the constitute elements in the mantle and core. In addition, large uncertainty is also introduced because there is a lack of understanding of plate tectonic convection and the impacts of mantle dynamics on the atmosphere, the oceans, the continental crust, and the core (Korenaga, 2008). Thus, overall estimates for global geothermal energy vary greatly and have relatively large uncertainty.

Beginning in 1974, Williams and Von Herzen (1974) estimated total global heat loss at 42.7 TW (13.5 E20 J/yr). Davies (1980) estimated global heat loss at 41 TW (12.9 E20 J/yr) followed by Sclater et al. (1980) who put heat loss at 42 TW (13.2 E20 J/yr).

Pollack et al. (1993), using a "half space cooling" (HSC) model and the data set of the International Heat Flow Commission of the International Association of Seismology estimated total heat loss of 44.2 TW (13.9 E20 J/yr). Since their model did not agree with the measured ocean data they introduced a 1D ocean circulation that is warmed to explain why heat flux measurements did not agree with their modeled heat flows.

Kellogg et al. (1999) referencing Stein (1995) suggested that of the 44 TW (13.88 E20 J/yr) of the present-day heat flux out of Earth, 6 TW (1.89 E20) is generated within the crust by radioactive decay of U, Th, and K, and 38 TW (11.98 E20 J/yr) must be provided either by generation of heat within the mantle and core or by cooling of the planet.

Summarizing data and estimates of heat flow calculations from the past 5 decades, Jaupart et al. (2007) provide the following breakdown of global heat flows (numbers in parentheses are "preferred values"):

Total surface heat flows:	43–49 TW (46 TW)
Continental heat production:	6–8 TW (7 TW)
Heat flow from convection mantle:	35–43 TW (39 TW)
Out of which:	
Radioactive heat sources:	9–17 TW (13 TW)
Heat from core:	5–10 TW (8 TW)
Mantel cooling:	8–29 TW (18 TW)

Recently there has been disagreement over estimates of global heat loss. Generally there is little disagreement over the heat loss from continents, with most of the disagreement centering on the divergence of modeled heat loss in the oceans (i.e. Pollack et al., 1993) and measured data. In a break with earlier estimates of Earth heat loss, Hofmeister and Criss (2005) on the basis of geochemical arguments, develop three independent methods to ascertain Earth's mean oceanic heat flux suggesting that it is the same average flux as from the continents, and thus they propose that their methods constrain the global power to 31 ± 1 TW. Further they point out that these independent lines of evidence suggest that neither delayed secular cooling nor primordial heat are significant sources, which leads to the conclusion that current heat production must predominately originate in radioactive decay and is quasi-steady-state. The divergence of their heat loss (31 TW or 9.78 E20 J/yr) from that of earlier modeled estimates of Pollack et al. (1993) (44.2 TW or 13.9 E20 J/yr)) totalled 13.2 TW (4/16 E20 J/yr), a heat flux they suggest cannot be explained by a one dimensional circulation model of the oceans.

To further add to the complexity of interpreting heat flow data, Wei and Sandwell (2006) utilize a model independent numerical method to calculate oceanic heat output which lead them to estimate global output of 42–44 TW in agreement with the earlier studies.

Hamza et al. (2007) use a spherical harmonic analysis of the international heat flow database in calculations of global conductive heat loss. Their results were compatible with the observational data (heat flow data) and resulted in total global heat loss falling in the range of 29–34 TW, supporting the assertions of Hofmeister and Criss (2005).

Finally, Korenaga (2008) used geochemical and geophysical arguments and whole mantle conduction to delineate the most likely thermal budget of Earth and suggested a total heat loss of 36.5 TW with core heat loss of about 4.5 TW.

In summary, model-based estimates of oceanic heat flux provide an upper bound of 42–44 TW (Sclater et al., 1980; Pollack et al., 1993) while measurement-based estimates provide a lower bound of 31–35 TW (Hofmeister and Criss, 2005; Hamza et al., 2007; Korenaga, 2008). Core heat loss estimates vary from 1% to 20% of total heat loss (Sclater et al., 1980; Pollack et al., 1993), while heat production from radiogenic sources in the lithosphere is between 1% and 15% of total (Sclater et al., 1980; Jaupart et al., 2007).

3. Global exergy flows supporting the geobiosphere

The geobiosphere is a complex interconnected web of processes and components. The entire system is driven by the tripartite sources, sunlight, tidal momentum, and geothermal heat (Fig. 1). The geothermal sources include both deep heat from the Earth's core and radiogenic source heat from the decay of U, Th, and K in the earth's crust.

Review of the literature related to solar exergy yielded a range of values for net radiation driving the geobiosphere from 105,500 TW (3.33E24 J/yr) to 123,000 TW (3.88E24 J/yr) or about 15% variability. The value used for gross radiation in this analysis was 162,400 TW (5.12E24 J/yr) and net radiation of 113,700 TW (3.59E24 J/yr), which results from an albedo of 30%.

Recent measurements from satellite observations have refined tidal energy estimates. The current values exceed earlier estimates by as much as 27%. Based on our review, the value used in this analysis was 3.7 TW (1.17 E20 J/yr) as total tidal exergy of which 0.2 TW is dissipated in continental landmasses.

Geothermal exergy is computed from global heat flow. Of the three driving sources of exergy, geothermal has the most uncertainty. The uncertainty stems primarily from difficulties in estimating heat flow from the ocean crusts. In our review of the literature we found that generally there are two interrelated facets to this uncertainty. The first is the total amount of heat loss and the second is the sources of heat within the Earth. There are two schools of thought related to total heat loss. One school suggests that total heat loss amounts to between 43 TW and 49 TW (46 TW, preferred value) per year, while the other school estimates heat loss of between 29 TW and 34 TW (31 TW preferred value). Adding to the complexity are estimates of the amount of heat that originates in the core of the earth and the amount of heat generated by radiogenic sources. Some researchers estimate that there is little or no core contribution while others suggest that the core provides as much as 20% of the total heat loss. Estimates for radiogenic sources range from 15% to 1%.

3.1. Calculating exergy of geothermal energy

To compute the exergy of geothermal contributions to geobiosphere processes it is necessary to explicitly provide system boundaries and temperature of the heat sources in order to calculate incoming flows and Carnot efficiencies. Our assumed upper system boundary for the geobiosphere includes the atmosphere to an elevation of 80 km, that is the zone of air turbulence and atmospheric water cycle (0–10 km), protective ozone layer (10–50 km) and ozone generation (50–80 km) although in such an assumption other important protective layers (e.g. thermosphere and magnetosphere, up to 60,000 km) are disregarded in spite of their multiple important roles. Our lower boundary includes the lithosphere to a depth of 100 km. The lithosphere includes the crust and the upper most portion of the mantle and is the zone of earthquakes, mountain building, volcanoes, and continental drift. The highest core temperature is given by the melting point of pure iron (7600 K at a pressure of 329 GPa) and an average temperature at the Core mantle boundary is estimated as 4500 K (Stixrude et al., 1997). Calculating the average Carnot efficiency of core heat yields (4500 – 300)/4500 = 0.93. In the lithosphere, we have used an average temperature of 750 K based on a temperature at the lower limit of the lithosphere of 1200 K (Rudnick et al., 1998; Jaupart and Mareschal, 1999; Poudjom Djomani et al., 2001). Thus the average Carnot efficiency for lithosphere heat is (750 – 300)/750 = 0.6.

Applying a Carnot efficiency of 0.6 to the “preferred” high and low heat flow values from above, we obtain the following exergy of geothermal inputs to the geobiosphere from lithosphere heat sources:

27.6 TW (8.7E20 J/yr) – 18.6 (5.87E20 J/yr)

Radiogenic sources are estimated to be as high as 15% and as low as 1% of total geothermal heat. Since radiogenic sources of heat are within the lithosphere, we applying the same Carnot efficiency (0.6) to them yielding the following exergy:

4.1 TW (1.3E20 J/yr) – 0.3 TW (0.1E20 J/yr)

A final source of uncertainty related to geothermal exergy is the portion of total heating that comes from the core (∼0–16%). Applying these possible percentages and a Carnot efficiency of 0.93 to the preferred values, above, we obtain the following exergy contribution from the core:

∼0 TW – 4.4 TW (1.4E20 J/yr)

3.2. Combining exergy sources

Sources of exergy to the geobiosphere are summarized in Table 3. When expressed as exergy solar exergy absorbed by Earth dominates being over 4000 times as large as the next largest contributor, geothermal exergy. Tidal exergy absorbed amounts to only 0.003% of the total exergy driving the geobiosphere. Total geothermal exergy is divided between heat from the core, radioactive decay and crustal sources. Since the calculated Carnot efficiencies of the three sources of geothermal energy are different (0.6 for crustal heat and radioactivity in the lithosphere, and 0.93 for heat from the core) the proportion of total heat assigned to each source has significant impact on the total geothermal exergy. In addition, since crustal heat is generated as a product of tidal energy absorbed and sunlight absorbed, it should not be counted as a source lest we double count the exergy from tide and sun.

Table 3
Exergy inputs to geobiosphere processes.

Note	Source	Exergy power and annual flow	
		TW	E20 J/yr
1	Solar	113,700	35,856.40
2	Tidal	3.7	1.17
3	Geothermal (total)	27.6–18.6	8.7–5.9
	- Crustal sources	27.0–8.1	8.5–2.6
	- Radioactive decay	4.1–0.3	1.3–0.1
	- Heat from core	4.4–∼0	1.4–∼0

Notes. (1) Estimates of net solar exergy (subtracting an albedo of 30%) vary between 105,500 TW and 123,000 TW. (2) While the estimates of tidal exergy absorbed by Earth vary between 2.4 TW and 3.7 TW, the most recent estimates (3.7 TW) based on detailed satellite measurements were felt to be refined enough to minimize variability. (3) Based on literature review, the largest variability in exergy sources is geothermal exergy with total variability equaling nearly 30%, the portion from radioactive decay varying between 1% and 15%, and from core heat 16% to less than 1%.

Table 4
Energy inputs to geobiosphere processes (from Odum, 2000).

Note	Source	Energy	
		TW	E20 J/yr
1	Solar	124,600	39,300.00
2	Tidal	1.65	0.52
3	Geothermal (total)	41.9	13.21
	- Crustal sources	20.6	6.49
	- Radioactive decay	6.3	1.98
	- Heat from core	15	4.74

Notes. (1) 3.93E24 J/yr based on solar constant 2 gcal/cm^2/min, 70% absorption, and 1.27E14 m^2 cross-section facing the sun. (2) Miller (1966). (3) Sclater et al. (1980).

4. Global emergy supporting the geobiosphere

Odum (2000) computed the emergy driving the geobiosphere using two simultaneous equations for crustal heat and oceanic geopotential generation, and two unknowns (the transformities of tide and deep heat) and using available estimates of solar, tidal, and geothermal energy as in Table 4. Here we use the same procedure[4] but apply the exergy from Table 3 to compute ranges of global emergy.

Comparison of the data in Table 4 with that in Table 3 reveals the differences in input data sets between Odum's analysis using energy and this evaluation. In this evaluation the exergy of sunlight is smaller by 8.8% as a result of applying the Carnot efficiency (0.93) to solar energy received. Tidal exergy is 125% higher as a result of newer more accurate measurements of tidal energy flux. Finally, geothermal exergy is between 34% and 56% smaller than the energy value used by Odum resulting from the application of Carnot efficiencies.

4.1. Calculating transformities of tide and geothermal sources

The general procedure is to first calculate transformities for tidal and geothermal exergy and then to apply these transformities to the flows of exergy. The transformity of sun is one, by definition, and the emergy of any exergy flow is the product of the exergy and its transformity. To calculate transformities for tidal and

[4] Odum (2000) used a slightly different system boundary than that used in this study, which resulted in radiogenic sources being summed with deep heat sources. Since he did not apply Carnot efficiencies to heat sources this was of little consequence, however with the realization that radiogenic sources are all within the lithosphere (with different Carnot efficiency than core heat) it was necessary to include the radiogenic sources together with the crustal sources of heat as separate from core heat.

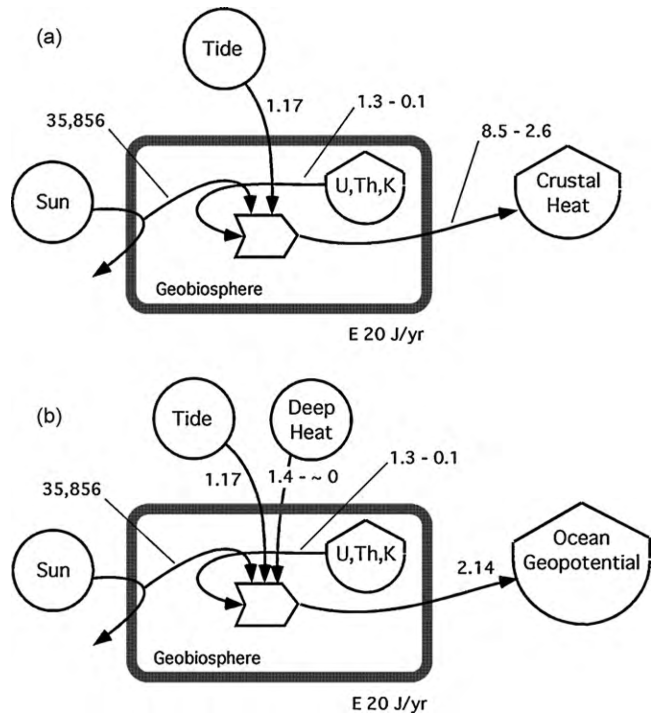

Fig. 2. Systems diagrams describing the relationships between global exergy sources generating (a) the exergy of crustal heat and (b) the exergy of ocean geopotential. Data in the figure refer to Tables 1–3.

geothermal exergy, two equations are written; one describing the emergy contributions to crustal heat and one describing the exergy contributions to ocean geopotential. Since they are two equations with two unknowns we can solve to determine each transformity. Given in Fig. 2 are systems diagrams that describe the relationships between global exergy sources and the exergy of crustal heat (a) and exergy of ocean geopotential (b) that are used in Eqs. (1)–(4) to calculate transformities of tide and geothermal exergy flows. Referring to Fig. 2a the total crustal heat used in calculating the transformity of tidal momentum is between 2.6 and 8.5 E20 J/yr and the ocean geopotential energy in Fig. 2b is estimated as 2.14 E20 J/yr (Table 5 of Oort et al., 1989 – estimates of the annual mean available gravitational potential and kinetic energy components in the world oceans). The remaining values used in Eqs. (1)–(4) are found in Tables 1–3.

Eq. (1) describes the relationship between exergy of the sun and tide interacting with radiogenic exergy and the generation of crustal heat. Referring to Fig. 2a it can be seen that total geothermal heat is generated by processes in the lithosphere (a function of sun, tide interacting with radiogenic sources in the crust) and deep heat from the core. Thus the equation describing the joint contributions of these inputs to crustal heat is as follows:

$$Sun\,(T_{rS}) + Tide\,(T_{rT}) + RadHeat\,(T_{rH}) = CrustHeat\,(T_{rH}) \quad (1)$$

where *Sun* is the exergy of net solar radiation; T_{rS} the transformity of solar exergy, 1.0 by definition; *Tide* the exergy of tidal momentum; T_{rT} the transformity of tidal exergy; *RadHeat* the exergy of radiogenic sources (Carnot ratio ≈ 0.6); *CrustHeat* the geothermal exergy flow that is generated from the crust (Carnot ratio ≈ 0.6), equal to total geothermal heat flow minus the exergy of the heat from the core (DeepHeat); and T_{rH} is the transformity of geothermal exergy.

In this equation, crustal heat is defined as the difference between total geothermal heat and the deep core heat source. It is important to note that exergy from radioactive decay is included as a driving energy in this equation because it's contribution is in addition to the sun and tide. The sun and tide are responsible for surface processes that include buried oxidized and reduced substances, friction of plates, and compression of sedimentary deposits.

Referring to Fig. 2b it can be seen that the production of oceanic geopotential exergy is a function of all three sources of exergy (solar, tidal, and deep heat) as well as radiogenic sources and thus the second equation is as follows:

$$Sun\,(T_{rS}) + Tide\,(T_{rT}) + RadHeat\,(T_{rH}) + DeepHeat\,(T_{rH}) = OcnGeoPot\,(T_{rT}) \quad (2)$$

where *DeepHeat* is the exergy of heat produced in the Earth's core (Carnot ratio ≈ 0.93); T_{rH} the transformity of geothermal exergy; *OcnGeoPot* the oceanic geopotential exergy (2.14 E20 J/yr, Oort et al., 1989); and T_{rT} is the transformity of tidal exergy.

Eq. (1) is subtracted from Eq. (2) and solved for T_{rT} as follows:

$$T_{rT} = \frac{(DeepHeat + CrustHeat)(T_{rH})}{OcnGeoPot} \quad (3)$$

The result of Eq. (3) is substituted into Eq. (1) and solved for T_{rH} as follows:

$$T_{rH} = \frac{Sun}{CrustHeat - RadHeat - (Tide * T_{rT})} \quad (4)$$

In all cases, the emergy equation for an exergy transformation process sets the empower of inputs equal to the empower of the output, where each term contains an exergy flow multiplied by its transformity. So, in Eq. (1), the empower of sunlight received by earth, plus the empower of tidal momentum plus the empower of radioactive decay of U, Th, and K in the Earth's crust result in the generation of crustal heat, the empower of which is equal to the sum of the inputs. In Eq. (2) the empower of ocean geopotential results from the sum of the input empowers of sunlight, tidal momentum, radioactive decay, and deep heat from the core.

4.2. Including the uncertainty of geothermal exergy

To evaluate the contributions of each of the three sources of exergy to the geobiosphere (sunlight, tide, and geothermal) given the ranges of values for geothermal sources, we used a Monte Carlo algorithm. We assumed an equal probability distribution between minimum and maximum values for total geothermal exergy and the proportions from deep heat and radiogenic sources and conducted 1000 iterations of the model using the above equations. Input data for the simulation are given in Table 3.

Fig. 3 shows the results of the Monte Carlo simulation of Eqs. (1) and (2). The *X*-axis on the graph is the percent of total geothermal exergy from the Earth's core, and the *Y*-axis is the total global emergy. Each data point represents a different combination of the three geothermal heat inputs (total geothermal heat, heat from radiogenic sources, and heat from the earth's core). The maximum and minimum values for each of these parameters were given in Table 3. The blue horizontal line represents the total global empower (15.83E24 seJ/yr) as computed by Odum (2000). The variation in results is caused by the uncertainty in knowledge about geothermal processes, the quantities of heat released by Earth, and the proportions of total heat that come from crustal processes, radioactive decay, and the cooling of the Earth's core. Variation of the results increases as larger proportions of total heat budget come from the Earth's core. We have constrained the model to agree with the main consensus regarding deep heat and radiogenic sources assuming that they contribute a maximum of 20% and 15% respectively.

Using the median values from the Monte Carlo simulation the data in Table 5 and Fig. 3 were generated. The median total global empower resulting from the simulation was 15.2E24 seJ/yr (±0.3). The median contributions to total global emergy budget from tidal and geothermal exergy were 8.3E24 seJ/yr (±0.15) and

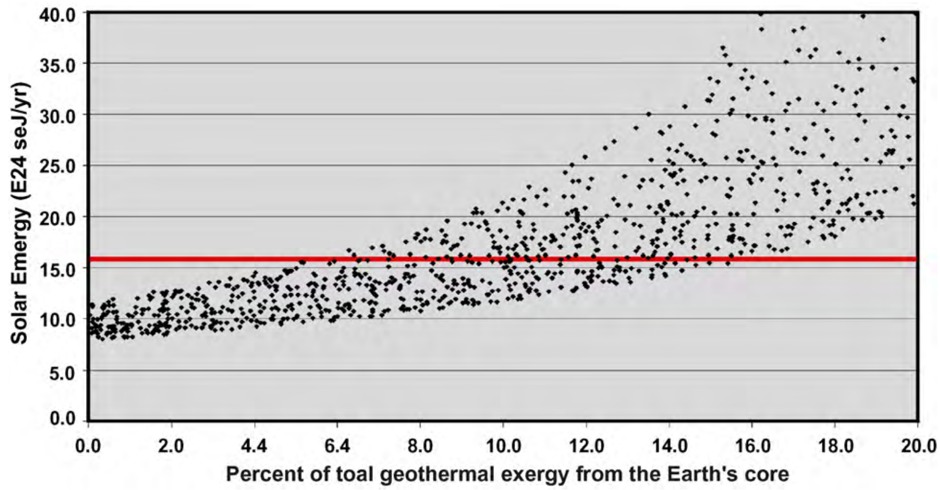

Fig. 3. Results of Monte Carlo simulation of Eqs. (1) and (2) showing the variation in total emergy driving the geobiosphere that results from the uncertainty in geothermal heat both in terms of total quantity and distribution between mantle and crust. The horizontal red line represents the median value of 15.2E24 seJ/yr. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 5
Emergy inputs to the geobiosphere calculated using exergy of main sources.

Note	Inflow	Solar transformity (seJ/J)	Empower[a] (E24 seJ/yr)
1	Solar energy absorbed	1	3.6
2	Crustal heat sources	20,300	3.3 ± 0.15
3	Tidal energy absorbed	72,400	8.3 ± 0.15
	Total global empower	–	**15.2 ± 0.3**

seJ/J = solar emjoules per joule.
Notes. (1) Transformity is 1.0 by definition; exergy flow: 3.59E24 J/yr. (2) Transformity is median value from emergy equation for crustal heat solved using Eqs. (1) and (2); median value for exergy release by radioactivity and deep heat from the Monte Carlo simulation was 5.1 TW (1.63E20 J/yr). The heat generated by crustal sources is not added here to avoid double counting. (3) Transformity is median value from Monte Carlo simulation of the emergy equation for geopotential of oceans. Energy flow 1.17E20 J/yr (Munk and Wunsch, 1998).
[a] Median values from Monte Carlo simulation of the emergy equations.

3.3E24 seJ/yr (±0.15) respectively. The calculated median transformities for tide and geothermal exergy are 72,400 seJ/J and 20,300 seJ/J respectively. The empower contribution to total geobiosphere emergy from sunlight was 3.6E24 seJ/yr.

Table 6 summarizes Odum's results from the 2000 study. Applying the energy sources listed in Table 4 to the above equations Odum obtained a total emergy driving the geobiosphere 15.83 E20 seJ/yr and computed transformities for tidal energy and geothermal energy were 73,923 seJ/J and 11,981 seJ/J respectively. Comparison of Odum's results (Table 6) and results from this analysis (Table 5) show that the new empower of solar inflow is about 8% lower than that previously computed by Odum and that the new empower of crustal heat sources is nearly 60% lower while the new value for tidal empower is 117% higher. Overall, the total global empower computed by Odum is about 4% higher than that computed in the present re-evaluation.

Table 6
Emergy inputs to the geobiosphere (Odum, 2000).

Note	Inflow	Solar transformity (seJ/J)	Empower[a] (E24 seJ/yr)
1	Solar energy absorbed	1	3.93
2	Crustal heat sources	1.2E4	8.06
3	Tidal energy absorbed	7.39E4	3.83
	Total global empower	–	**15.83**

seJ/J = solar emjoules per joule.
Notes. (1) Transformity is 1.0 by definition; energy flow: 3.93E24 J/yr based on solar constant 2 gcal/cm^2/min, 70% absorption, and 1.27E14 m^2 cross-section facing the sun. (2) Transformity from emergy equation for crustal heat solved in previous section; heat release by crustal radioactivity 1.98E20 J/yr plus 4.74E20 J/yr heat flow from the mantle (Sclater et al., 1980). (3) Transformity from emergy equation for geopotential of oceans in previous section. Energy flow 0.52E20 J/yr (Miller, 1966).
[a] Global annual energy flow times solar transformity.

Transformities for crustal heat sources and tidal energy absorbed computed in this re-evaluation are similar to those computed by Odum. The new transformity for crustal heat sources is 20,300 seJ/J compared to 12,000 seJ/J (69% higher) and that of tidal energy absorbed is 72,400 seJ/J as compared to 73,900 seJ/J, a value about 2% lower. Crustal heat sources are particularly sensitive to evaluation using exergy rather than energy, thus the transformities that result from the two evaluations are significantly different. When applying the exergy-based crustal heat transformity to surface heat flow measurements in the future, it is critical that researchers first compute the exergy of the flow.[5]

5. Summary and conclusions

Re-evaluation of the global empower that is the baseline for all transformities was undertaken because new measurements have resulted in more refined estimates of tidal energy absorbed by Earth, estimates of geothermal energy and sources have wide uncertainty, and the inclusion of exergy instead of energy promises to provide more meaningful comparisons with other researchers who are conducting research on large scale systems. While Odum (1996, 2000) defined emergy as "... the available energy of one type (usually solar exergy) that is required to produce something", in practice, often energy, not exergy, was used to compute emergy. Such is the case for Odum's (1996, 2000) original computations leading to the global emergy baseline driving geobiosphere pro-

[5] This requires that first a realistic lower boundary of the system be identified for the crustal layer in the area of interest. The amount of heat flowing through the layer is capable of doing work (e.g. water evaporation and air convection) depending on the gradient in temperature between the lower and upper boundary. Considering that the average temperature of the land surface is approximately 293 °C and that the temperature of Earth increases by 30 °C/km depth, the ΔT and Carnot efficiency can easily be estimated. For example, assuming a depth of 1 km for the lower boundary, the ΔT would be equal to 30 °C and the Carnot efficiency would be approximately 0.1 (i.e. 10%). As a consequence, a heat flow of 65 mW m^{-2} would translate into an exergy flow of 6.5 mW m^{-2}. This effectively lowers the impact of the new relatively high transformity of crustal heat on future calculations of empower from crustal heat sources.

cesses. At the time that was done, the main focus of emergy researchers was the development of a consistent set of concepts, indicators and calculation procedures and it seemed that the existing uncertainties about global flows was such that using energy instead of exergy as a numeraire could not introduce any significant consequences. Later on, the increasing demand for consistency of procedures with basic emergy definitions and concepts called for a re-evaluation of global flows in terms of available energy. As a consequence, this allows the same numeraire to be used for computing transformities of all material and energy flows.

In our re-evaluation, we have updated estimates of the three main driving sources, explored the uncertainties in estimates of geothermal sources and heat flows, and recalculated all source energy as available energy (exergy). The net result of these modifications to the global baseline has been minor (if we assume median values from our Monte Carlo simulation results). As a result of such a timely and much needed re-evaluation and consistency check, the emergy baseline (Odum, 2000) was reinforced and so were the values of transformities of global flows. The importance of tidal emergy (gravitational potential) increased thanks to both an update of its exergy value and a lowering of importance of geothermal heat. An inherent uncertainty in the evaluation of global flows is still present and was not removed, since it originates in the lack of sufficient knowledge and understanding of several aspects of the Earth's dynamics.

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