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Computing the geobiosphere emergy baseline: A novel approach

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ABSTRACT

We demonstrate a new and novel approach to calculate Earth's geobiosphere emergy baseline (GEB). In this method we use gravitational potential energy dissipated in the generation of Earth's main renewable energy sources. From this gravitational perspective, we recognize three refinements to our understanding of Earths driving energies. First we acknowledge the recent literature suggests that Earth's geothermal energy is from two separate sources, decay of radioisotopes and primordial heat, thus warranting separate solar equivalence ratios (SERs). Second, tidal energy dissipation can be viewed as the loss of Earth's rotational kinetic energy (KE), due to gravitational interaction between Earth/Moon/Sun and frictional forces in Earth's oceans. Seen in this way we draw an equivalence between loss of Earth rotational KE and tidal energy dissipated. Third, Earth's rotational KE and primordial heat are coupled processes of the gravitationally induced accretion of Earth.

The four sources of available energy to the geobiosphere, solar radiation, tidal energy dissipation, primordial heat, and radiogenic heat, are expressed as a ratio of gravitational emergy needed to produce them. After all four sources are expressed by their gravitational transformities, solar equivalences are computed by dividing their gravitational transformity by the gravitational transformity of solar radiation, resulting in solar equivalent ratios. Using solar equivalences, we combine the four sources to express the emergy driving all planetary phenomena. The method yields four different baselines depending on the allocation procedure used to assign gravitational exergy of Earth's accretion to it is rotational KE and primordial heat. The GEBs ranged between 11.1E+24 seJ J^{-1} and 13.8E+24 seJ J^{-1}.

1. Introduction

In this paper we develop a new approach to computing solar equivalents for the driving energies of the geobiosphere (sunlight, tidal momentum and deep heat). The motivation for this new approach came from a sequence of realizations and questions regarding the present accounting for the GEB:

- First, it is inappropriate to label the ratio of solar exergy to tidal exergy, or solar exergy to geothermal exergy, as a *transformity*. This ratio of seJ J^{-1} tidal or geothermal exergy is a 'solar equivalence ratio', rather than 'solar transformation ratio' (Raugei, 2013).
- There are, in the present GEB accounting, no nuclear UEVs (e.g. sej J^{-1} ^{238}U). While most elements and minerals are used for their chemical properties, some elements are used for their nuclear energies. Nuclear fuels are inappropriately characterized by chemical properties (e.g. concentration) if used as a nuclear fuel and therefore when used in this way, their UEVs should be based on their nuclear properties.
- Recognition that the Earth's primordial heat and radiogenic heat are derived from two different sources and have different transformities, calculated on the basis of their transformation of gravitational exergy into heat, as clarified below.
- Recognition that the interaction of gravitational potential of the Earth–Moon–Sun system with Earth's rotational kinetic energy is responsible for the tides. Specifically, Earth's rotation kinetic energy is directly dissipated via tidal friction.
- Finally, we postulated that it might be possible to express solar radiation, Earth's rotational kinetic energy, radiogenic heat and Earth's relic heat in a single quantity, the gravitational potential energy dissipated to produce them.

The new approach in this paper evaluates the gravitational potential energy dissipated in the production of each of the geobiosphere energy sources (sunlight, geothermal and tidal exergy) and then draws an equivalence to solar energy resulting in solar equivalent ratios (SERs) and solar equivalent exergy for each of the driving energies. A basic paradigm being challenged with this approach is that of backwards calculated equivalences

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(Raugei, 2013). Since solar energy in no way actually contributes to radiogenic heat, Earth's relic heat, or its rotational kinetic energy, it is apparent that these do not embody solar exergy and are inappropriately characterized as solar emergy. As is well understood, in the past, computations of Earth's deep heat and tidal energy input involved backwards calculation of equivalents to express each of these sources as solar *equivalent* energy. In this new approach we utilize forward calculation of the gravitational potential energy (GPE) that was dissipated in their production.

Forward computation of the geobiosphere emergy baseline (GEB) requires characterizing a common source of potential energy that generates each of the exergy sources to the geobiosphere. Gravitational potential energy can be shown to be the ultimate source of energy that generates sunlight (the intense pressure generated by the sun's gravity), radioisotopes (extreme temperatures and pressure resulting from gravity collapse of stars), Earth's primordial heat (heat left from the gravity induced Earth formation), and tidal energy (interaction of Earth–Moon–Sun gravitation with Earth's rotational energy). The objective of this approach is to calculate *gravitational transformities* (gej/J) for the geobiosphere sources. From the gravitational transformities (gej/J), solar equivalent energy ratios (seJ/J)[1] can be computed using the ratio of gej/J of sunlight to express each source in common solar energy based units. Once in a common unit (seJ) the sources may be added to express Earth's driving exergy sources as the GEB.

2. Methods

Conceptually the idea is that gravitational potential energy (GPE) is the source for generation of higher quality energy like concentrated heat, sunlight, concentrations of matter, or rotational energy. For our purposes GPE is the lowest quality from which the others can be computed. In a paper on cosmology and emergy, Odum (in Brown et al., 2004) wrote:

> In the vast realm of space, stars and other units that self organize are *gravity produced*. . .. Under the pull of *gravity*, units of matter condense, storing energy and developing structure. The resulting increased *gravity* captures more material. The potential energy of mass falling inward together is concentrated and transformed into heat and energy of rotation. When the *gravity* and temperature are high enough, fusion reactions convert the mass of hydrogen into energy, turning such units into light emitting stars.[emphasis added]

Simply put, we compute gravitational transformities (gej/J) for each of the driving energies of Earth and then using the gravitational transformity of solar radiation, compute solar equivalent exergy (seJ) for the others. Table 1 shows the relationship between the gravitational transformity of sunlight to the gravitational transformity of the other sources τ_R/τ_S yielding solar equivalence ratios[2] (SER) for each source. The following paragraphs outline the methods and assumptions necessary for these equivalence calculations.

Table 1
Summary of proposed relationship between the gravitational transformity of and the SERs of the remaining exergy sources to the geobiosphere.

Geobiosphere energy source	Transformity symbol[a]	Units	SER (seJ J^{-1})
Sunlight	${}_g\tau_S$	gej/J	1
Radiogenic heat	${}_g\tau_R$	gej/J	${}_g\tau_R/{}_g\tau_S$
Primordial heat	${}_g\tau_Q$	gej/J	${}_g\tau_Q/{}_g\tau_S$
Tidal energy	${}_g\tau_K$	gej/J	${}_g\tau_K/{}_g\tau_S$

[a] We define a new gravitational transformity as the gravitational emergy per joule of exergy and use the symbol ${}_g\tau$ to differentiate it from solar transformity.

2.1. Redefinition of geothermal and tidal inputs

2.1.1. Deep heat

To accurately account for Earth's deep heat, primordial heat and heat generated by radionuclides should be accounted for separately. *Deep heat* was the term used in the past for the combined geothermal inputs to the geobiosphere that came from heat stored in the core of the Earth and heat from radiogenic sources. These are independent sources of heat exergy, which are generated from different processes and therefore should have different SERs. As a result, we have separated geothermal inputs to the geobiosphere into primordial heat and radiogenic heat, computing separate SERs for each.

2.1.2. Tidal energy

Gravitational attraction of the Earth–Moon–Sun system interacts with Earth's rotational kinetic energy to produce tides on Earth. Over the years the input of energy to the geobiosphere from this phenomena has been referred to as tidal input, tidal potential, tidal momentum, or tidal energy. The exergy input is relatively well known, about 1.17E+20 J yr^{-1} (Munk and Wunsch, 1998). Most of this exergy is dissipated in the oceans (about 96%) while a small fraction is dissipated in the land masses (4%).

The result of the gravitational "pull" by the Moon (and to a much lesser extent, the Sun), is that kinetic energy of the Earth's rotation is being dissipated, partly transformed into thermal energy and partly contributing to the orbital potential energy of the Moon. Earth's rotation is slowing down and the moon is moving farther away. The relationship between Earth's decreasing rotational KE and tidal exergy is direct. Thus if we compute a SER for Earth rotational kinetic energy, we can then apply this to the tides.

2.2. Gravity produces solar radiation

Siegel et al. (in this issue) developed a method to calculate a gravitational transformity of solar radiation based on the quantity of gravitational potential energy (GPE) that is dissipated in the generation of light. Essentially, the exergy content of solar heat was used to calculate translational kinetic energy of particles that fuse in the sun. Assuming kinetic energy is equal to GPE, only the reference frame changes (according to Einstein), this translational kinetic energy became the numerator in the ratio of gravitational transformity for sunlight. The denominator is the quantity of solar radiation output from the hydrogen fusion reactions responsible for our sun's light.

In large part, the sun's light is produced from what are known as the PPI and PPII fusion cycles (Table 2). The weighted average of the

[1] A note on units. We use different nomenclature for solar equivalent joule (seJ) and solar emjoule (sej). The units of solar equivalent exergy are solar equivalent Joules, abbreviated seJ (note the capital J). The abbreviation of the energy unit, Joule is always capitalized, thus solar equivalent joules are abbreviated using a capital J. A lower case 'j' in sej represents solar emjoules. An emjoule is not available energy, it is a record of available energy previously destroyed, thus we use the lower case "j". The GEB is expressed in seJs (solar equivalent joules) whereas subsequent geobiospheric resources (e.g. wind, rain, fossil fuels, etc.) are expressed in sej (solar emjoules). The distinction is not arbitrary as it clearly integrates the concepts put forth by Raugei (2013) that the independent energies driving the geo-biosphere (i.e. geothermal energy, Earth's tidal energy, or radionuclides) are in no way directly or indirectly a transformation of sunlight. Therefore they do not embody solar energy and are thus more appropriately characterized by equivalences.

[2] When describing the ratio of solar equivalent exergy to exergy the use of the term transformity is incorrect, since transformity is defined as the ratio of solar emergy to available energy (sej/J). Since the solar equivalents of tidal dissipation and geothermal heat are not emergy, it is more correct to refer to the ratio seJ/J as a solar equivalence ratio (SER).

Table 2
Summary of gravitational transformities for sunlight (from Siegel et al., in this issue).

	PPI cycle	PPII cycle	Weighted average
Gravitational transformity (gej/J)	7.74E−4	7.10E−4	7.65E−4
Contribution to total solar output	86%	14%	

Table 3
Summary of transformities for Earth's major heat contributing radionuclides.[a]

Isotope	$_g\tau_G$ (gej J^{-1})	$_g\tau_G$ sunlight (geJ j^{-1})	SER (seJ J^{-1})
^{40}K	6.19	7.57E−04	8.20E+03
^{232}Th	3.18	7.57E−04	4.20E+03
^{235}U[b]	2.93	7.57E−04	3.90E+03
^{238}U	2.8	7.57E−04	3.70E+03

[a] From Siegel et al. (in this issue).
[b] Contribution to the GEB from ^{235}U is very small.

gravitational transformities of these two cycles compose the gravitational transformity of sunlight (7.57E−04 gej J^{-1}). That is, 1321 J of solar radiation are yielded for every joule of gravitational energy supplied (Siegel et al., 2016).[3]

2.3. Gravity produced the heavy elements

The production of heavy isotopes is fundamentally similar to the production of sunlight. However, it requires much hotter temperatures and pressures. The synthesis of heavier elements requires more gravitational potential energy than for lighter ones. Elements heavier than iron are only produced in stars far more massive than our sun. In fact, the extreme temperatures, in combination with the necessary chemical constituents, for synthesis of elements heavier than iron may only occur in the end of life type II supernova of a massive star.

A summary of the gravitational transformities of Earth's major radioisotopes is given in Table 3 (from Siegel et al., in this issue). The gravitational transformities (column 2) for the elements decreases with weight, in what seems to be a contradiction to the statement above about heavier elements requiring more energy to synthesize. However, the decreasing gravitational transformities are the result of the heavier elements having higher decay energies (the denominator in the ratio of gej J^{-1}). SERs for each of the elements, given in the last column of Table 3 were computed using the relationships given in Table 1.

2.4. Gravity produced Earth's rotational energy and primordial heat

Production of the Earth's rotational KE and primordial heat are coupled. Gravitational potential energy dissipated during the formation of the Earth produced both the primordial heat and the Earth's rotational KE, as shown in Fig. 1.

[3] There are two important factors that cause this UEV to be the reverse of solar derived UEVs. The first is that nuclear fusion is a quantum mechanical process that involves a phenomenon called quantum tunneling, whereby protons can sometimes tunnel over the coulomb barrier in another atom even if it does not have sufficient energy to overcome the coulomb repulsion force. To overcome this barrier, nuclei have to collide at high velocities, so their kinetic energies drive them close enough for the strong interaction to take place and bind them together. Thus while gravitational energy is required to bring them close together, tunneling enables fusion to occur that would otherwise not occur and for the released energy to be larger than expected if it was only due to gravitational energy dissipation.
The second reason for the low UEV is that, internal energy is supplied by the transmutation of mass. Although very little mass is lost in these fusion reactions, and the total number of protons is conserved, there is a small amount of mass that is transmuted during each reaction which has relatively large energies according to the energy-mass equivalence $E = mc^2$.

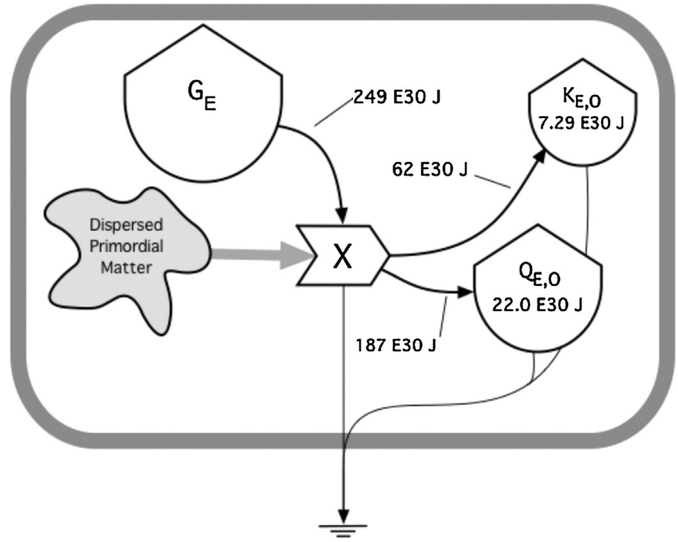

Fig. 1. Aggregated diagram of the accretion process generating Earth's primordial heat ($Q_{E,O}$) and rotational kinetic energy ($K_{E,O}$) (data are from Table 4). The time frame for this analysis begins after the materials in the Earth's solar system have begun to form protoplanetary disks; therefore the dispersed matter is shown as a cloudlike storage, rather than a source.

2.4.1. Earth's rotational energy

To compute the gravitational exergy required to generate the rotational KE of Earth, we first estimate the Earth's gravitational binding energy. Gravitational binding energy of a system is the energy required to "unbind" the system by overcoming gravity and separating the system into a diffuse mass infinitely far away from its center of mass. Back-calculating, it is equal to the work done by gravity to bring the matter together from infinitely far away. In other words, gravitational binding energy is the energy required to produce a "solid Earth" out of the protoplanetary disk of gas and dust.

Considering Earth a spherical mass of uniform density, the gravitational binding energy G_E is a function of the gravitational constant $G = 6.674\text{E} - 11\ \text{Nm}^2\ \text{kg}^{-2}$, and Earth's mass $M = 5.97\text{E} + 24$ kg and radius $R = 6.37\text{E} + 6$ m.

$$G_E = \frac{3GM^2}{5R} = 2.24\text{E} + 32 \quad \text{J} \tag{1}$$

However, given that Earth has a non-uniform density profile, the actual binding energy computed by Stacey and Davis (2008) is $G_E = 2.49\text{E} + 32$ J. From this, Earths original rotational kinetic energy $K_{E,0}$ and thermal energy $Q_{E,0}$ were formed.

Earth's rotational energy is a storage of kinetic energy, which gradually transforms into heat and lunar geopotential energy. We assume that Earth's rotational energy is not replenished on any time scale, it only dissipates. The rotational kinetic energy storage is the resultant transformation of primordial gravitational potential energy dissipated as the gas and dust cloud collapsed to create Earth (de Pater and Lissauer, 2010). Some rotational energy may have come from frictional drag with the protoplanetary disk, however most was accumulated from the relative motions of accreted material. Earth's rotation kinetic energy is expressed by the following:

$$K_E = \frac{I\omega^2}{2} = 2.24\text{E+32}\,\text{J} \tag{2}$$

where I and ω are respectively Earth's moment of inertia (~8.0E+37 kg m^2; Wolfram Alpha, 2015) and angular velocity (~7.29E−5 rad/s; Wolfram Alpha, 2015). The angular momentum of the Earth–Moon system is conserved. As the rotation of Earth slows its rotational kinetic energy is translated to heat and lunar

Table 4
Summary of energies associated with Earth's accretion.

Item	Symbol	Energy (E+30 J)
Gravitational potential[a]	G_E	249
Earth rotational KE[b]	$K_{E,O}$	7.29
Earth primordial heat[c]	$Q_{E,O}$	22

[a] Stacey and Davis (2008).
[b] Eq. (2).
[c] Eq. (4).

orbital potential energy. The Earth–Moon angular momentum L (Morishima and Watanabe, 2004) is the product of its moment of inertia and angular velocity (3).

$$L = I\omega = 3.46\text{E} + 34 \quad \text{J s} \tag{3}$$

This momentum was once contained solely in the Earth, assuming the moon was formed via a giant impact with a Mars sized object (Canup, 2014). Holding L constant (conservation of angular momentum) we can find ω_0 of the Earth by substituting Earth's original moment of inertia, $I_{E,0}$. Moment of inertia is linearly related to mass of the object, assuming uniform density. For an estimate we can approximate $I_{E,0} = I_E((m_E + m_m)/m_E) = 8.10\text{E}+37$ kg m^2; where $((m_E + m_m)/m_E)$ is the percent increase of the Earth's mass with the Moon's mass (7.35 E + 22 kg) added. The original angular velocity of the Earth was approximately $\omega_0 = L/I_{E,0} = 4.27\text{E} - 4$ rad/s (or 4.09 h/day). At this speed, using Eq. (2), $K_{E,0} = 7.29\text{E}+30$.

Note that using the expression $GPE_O = G((m_E + m_m)/2r)$ where G, m_E, and m_m are as defined above, and $r = 3.85\text{E}8$ m is the semi-major axis between Earth and Moon, and the rate of orbital recession is $dr/dt = 3.82$ cm yr^{-1} (Williams, 2000), the rate of change of orbital gravitational potential energy is $dGPE_O/dt = 0.24$ TW. This value is approximately 6.4% of the total tidal braking of the Earth, which is 3.7 TW (Munk and Wunsch, 1998). Hence 93.6% of the dissipation of Earth's rotational kinetic energy dissipates as heat, facilitated by tidal friction. 96% of tidal braking occurs in the ocean, hence about 90% of Earth's decceleration occurs in the oceans.

What we here compute is a gravitational transformity, and solar equivalence, of Earth's despin of which 9/10ths becomes ocean tides and eventually heat. For this reason it is acceptable that we use our solar equivalence for Earth's despin to approximate the solar equivalence of ocean tides.

2.4.2. Earth's primordial heat

The original thermal energy Q_0 of the Earth is the current thermal energy Q plus the heat flux since the origin of Earth dQ/dt (4). Labrosse and Jaupart (2007) show that the annual $dQ/dt \cong 35$ TW. Since circa 4.5 Ga for a total of about 5.0E+30 J. The current internal thermal energy is $Q = 1.7\text{E}3 + 1$ J (Juapart et al., 2007). Therefore, $Q_{E,O}$ is as follows:

$$Q_{E,0} = \frac{dQ}{dt}t + Q = 2.20\text{E} + 31 \quad \text{J.} \tag{4}$$

The flow of gravitational exergy and the resulting Earth rotational KE and primordial heat that result from the formation of Earth are given in Table 4 and summarized in Fig. 1.

2.4.3. Assigning GPE to Earth rotational KE and primordial heat

The Earth's rotational KE and primordial heat are coupled products within this analysis framework (Fig. 1). The coupling complicates the computation of the GEB because of questions regarding allocation of the GPE to each of these products of accretion. We identified five alternative ways of assigning the GPE to Earth's rotational KE and primordial heat, shown in Fig. 2. The first is to assign the GPE to each of the products based on an efficiency of production on each pathway, however these efficiencies are unknown. Two other alternative algebras are to assign GPE to either one of the two products equal to their energy, and assign the remainder to the other. These two alternatives represent the two extremes in the range of possibilities made available by the by-product allocation procedure. A fourth alternative is to treat the accretion process as a split of the GPE assigning the GPE to each pathway weighted by the energy on each pathway. The final alternative is to treat the two flows as co-products. However, the result of this algebra would be that when computing the GEB, the smaller of the two could not be added, since to add both would double count the GPE (Brown and Herendeen, 1996).

3. Results

3.1. Radiogenic heat contributions

The exergy inputs to the geobiosphere from radiogenic sources are given in the third column of Table 5. We estimate that the percent of total radiogenic heat flux from ^{238}U, ^{232}Th and ^{40}K is 40%, 40% and 20% respectively. These are rounded estimates from recent KamLAND neutrino detection experiments for ^{238}U and ^{232}Th energy contributions (Gando et al., 2011), and the bulk silicate Earth (BSE) predicted value for ^{40}K (McDonough and Sun, 1995). We use an overall average geothermal contribution from radiogenic sources of 15.7 TW, which is 46% of total geothermal input of 34.6 TW (Brown and Ulgiati, in this issue). The forth column reproduces the radionuclide SERs from Table 3. The solar equivalent exergy contribution of radiogenic heat to the geobiosphere given in the last column of Table 5 and is the product of the exergy (column 3) and the SER (column 4). We compute an average SER for the three main radioisotopes (^{238}U, ^{232}Th, and ^{40}K) of 4.6E+3 seJ J^{-1}.

3.2. Earth rotational KE and primordial heat UEVs

We considered the transformation of primordial GPE into Earth's rotational kinetic energy and internal thermal energy to be spontaneous. Further, we assumed that the generation of rotational KE and internal thermal energy were coupled and considered five alternative ways of allocating GPE to the two products. The results of these allocation procedures are given in Table 6. Solar equivalence ratios for rotational KE and primordial thermal exergy were computed by first allocating the GPE between the two pathways based on the allocation procedure and a gravitational transformity (geJ J^{-1}) was computed for each exergy source. Then the gravitational transformity was divided by the gravitational transformity of sunlight (geJ J$_{solar}$$^{-1}$). The resulting SERs are listed in Table 6.

Table 5
Exergy, solar equivalent ratios and solar equivalent exergy contribution of the radioisotopes.

Isotope	(TW)	Exergy contribution (E+20 J yr^{-1})	SER[a] (seJ J^{-1})	Solar equivalent exergy contribution (seJ yr^{-1})
^{238}U	6.3	2.0E+20	3.70E+03	7.3E+23
^{232}Th	6.3	2.0E+20	4.20E+03	8.3E+23
^{40}K	3.1	9.9E+19	8.20E+03	8.1E+23
Total	15.7	4.9E+20	4.60E+03	2.27E+24

[a] SERs are from Siegel et al. (in this issue).

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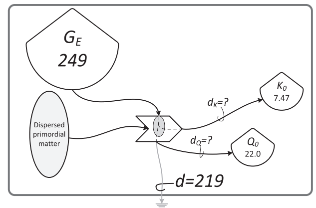
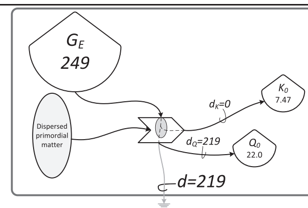
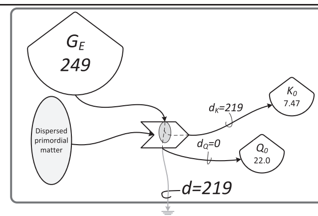
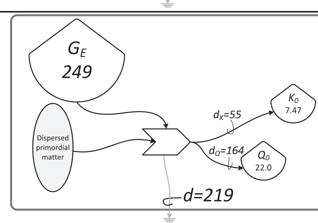
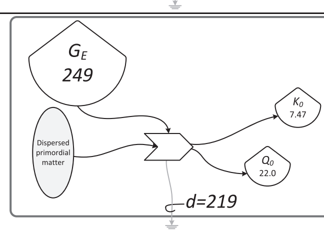
Method	Allocation of dissipation	Diagram	Mathematical effect	Pros	Cons
By-product (1)	Separately to rotational energy and primordial heat according to literature values for the efficiency of their production processes		$\tau_K \neq \tau_Q$ $\tau_K, \tau_Q > 1\ gej/J$	Additive. Most accurate representation of reality.	Values unknown.
By-product (2)	Total GPE assigned to primordial heat		$\tau_Q > \tau_K$; $= 1\ gej/J$	Additive.	Unfalsifiable analyst decision.
By-product (3)	Total GPE assigned to rotational energy		$\tau_Q = 1\frac{gej}{J}$; $< \tau_K$	Additive.	Unfalsifiable analyst decision.
Split	GPE of each flow is proportional to the exergy of each final storage.		$\tau_K = \tau_Q$ $\tau_K, \tau_Q > 1\ gej/J$	Additive.	No quality distinction between heat and rotational energy.
Co-product	Total GPE allocated to both outputs,		$\tau_K \neq \tau_Q$ $\tau_K, \tau_Q > 1\ gej/J$	Most simplistic.	Co-products cannot be added.

Fig. 2. Five alternative configurations to assign gravitational potential energy to Earth rotational KE and primordial heat.

Table 6
Solar equivalence ratios that result from the different allocation procedures of the gravitational potential energy of Earth's accretion.

Source		Exergy (J)	By-product #1		By-product #2		By-product #3		Split		Co-product	
			${}_g\tau_G$ (gej/J)	SER (seJ/J)	${}_g\tau_G$ (gej/J)	SER (seJ/J)	${}_g\tau_G$ (gej/J)	SER (seJ/J)	${}_g\tau_G$ (gej/J)	SER (seJ/J)	${}_g\tau_G$ (gej/J)	SER (seJ/J)
Gravitational input	G_E	2.49E+32										
Rotational KE	K_O	7.29E+30	?	?	1.00	1300	31.1	40,700	8.5	11,100	34.2	44,600
Primordial Heat	Q_O	2.20E+31	?	?	11.0	14,400	1.00	1300	8.5	11,100	11.3	14,800

${}_g\tau_G$, gravitational transformity.
SER, solar equivalence ratio.

Depending on allocation, the SERs for rotational KE and primordial heat differ. There was no clear way to determine the allocation algebra without a much better understanding of the Earth's accretion process. Certainly, in the process of coalescing, some of the rotational KE was also turned into heat, adding further to the complexity of allocation decisions. So our decision was to present all allocation alternatives for which we had data. Notice in Table 6, that we did not have the appropriate data to determine allocation of GPE in the first alternative (co-product #1) thus we have eliminated this alternative from further discussion. By-product #2 allocation, which makes primordial heat the main product and rotational KE the by-product, results in rotational KE having a SER of

Table 7
Summary of the solar equivalence ratios and solar equivalent exergy that results for the different allocation of GPE to Earth rotational KE and primordial heat.

Source	Exergy[a] ($J y^{-1}$)	By-product #1		By-product #2		By-product #3		Split		Co-product	
		SER ($seJ J^{-1}$)	Solar equivalent exergy ($seJ y^{-1}$)	SER ($seJ J^{-1}$)	Solar equivalent exergy ($seJ y^{-1}$)	SER ($seJ J^{-1}$)	Solar equivalent exergy ($seJ y^{-1}$)	SER ($seJ J^{-1}$)	Solar equivalent exergy ($seJ y^{-1}$)	SER ($seJ J^{-1}$)	Solar equivalent exergy ($seJ y^{-1}$)
Sunlight	3.60E+24	?	?	1	3.60E+24	1	3.60E+24	1	3.60E+24	1	3.60E+24
Tide dissipation	1.17E+20	?	?	1300	1.52E+23	40,700	4.76E+24	11,100	1.30E+24	44,600	5.22E+24
Primordial heat	5.32E+20	?	?	14,400	7.66E+24	1300	6.92E+23	11,100	6.60E+24	14,800	7.87E+24
Radiogenic heat	4.95E+20	?	?	4600	2.28E+24	4600	2.28E+24	4600	2.28E+24	4600	2.28E+24
GEB			?		1.37E+25		1.13E+25		1.38E+25		1.11E+25[b]

SER, solar equivalence ratio: solar equivalent joules per joule of exergy.
[a] Exergy of solar insolation is equal to 3.6E+24 J yr^{-1} (Brown and Ulgiati, in this issue).
Primordial heat equal to 54% of total heat (34.6 TW). Assumes average of ranges given in Table 5, Brown and Ulgiati (in this issue). SER is from Table 6.
Radiogenic heat equal to 46% of total heat (34.6 TW). Assumes average of ranges given in Table 5, Brown and Ulgiati (in this issue). SER is from Table 5.
Tidal dissipation is computed using Earth rotational KE dissipated and assuming conservation of energy. Exergy of tidal input from Munk and Wunsch (1998). UEV is from Table 6.
[b] To avoid double counting, GEB is equal to sum of sunlight, tidal dissipation, and radiogenic heat and does not include primordial heat.

1300 seJ J^{-1} and primordial heat a SER of 14,400 seJ J^{-1}. By-product #3, makes rotational KE the main product and the primordial heat the by-product and results in SERs of 40,700 seJ J^{-1} and 1300 seJ J^{-1} respectively. A split of the gravitational exergy between rotational KE and primordial heat results in equal SERs (11,100 seJ J^{-1}) for both products. Realistically, rotational KE and primordial heat accomplish very different kinds of work, and likely posses different SERs. Finally, since it is conceivable, based on our understanding of the accretion process that the generation of rotational KE and primordial heat are co-products, this is a somewhat attractive alternative, however, co-products result in the fact that they cannot be added if re-united (Brown and Herendeen, 1996). Thus, co-product allocation, only adds further complexity to a final GEB and its subsequent use in evaluations of geobiosphere processes.

3.3. The geobiosphere emergy baseline

Table 7 lists the main sources of exergy to the geobiosphere of Earth, the SERs resulting from each of the allocation procedures, the final solar equivalent exergy from each source, and when summed the GEB. The GEB varies between 11.1E+24 seJ yr^{-1} to 13.8E+24 seJ yr^{-1}, depending on the allocation procedure.

3.3.1. Earth tidal input

Tidal input energy from the combined Earth–Moon–Sun system is relatively well known, about 1.17E+20 J yr^{-1} (Munk and Wunsch, 1998). Assuming that the loss of Earth rotational KE is equal to the tidal drag that results from the combined Earth, Moon, Sun system Table 7 lists the solar equivalent exergy inputs to the geobiosphere from the dissipation of Earth rotational KE. The exergy ranges from 1.5E+23 seJ yr^{-1} to 5.2E + 24 seJ yr^{-1}).

3.3.2. Primordial heat contribution

We estimated a primordial heat contribution of 18.7 TW, which is 54% of total geothermal energy input of 34.6 TW (Brown and Ulgiati, in this issue) yielding a total primordial thermal exergy of 5.32E+20 J yr^{-1}. Applying the SERs for primordial heat from Table 6, the result is solar equivalent exergy contribution listed in Table 7, which ranges from 6.9E+23 seJ yr^{-1} to 7.87E+24 seJ yr^{-1}.

3.3.3. Radiogenic heat contribution

We estimated the heat input to the geobiosphere from radionuclides as 46% of total geothermal exergy equal to 4.95E+20 seJ yr^{-1}. Since the SERs do not differ for each, the geobiosphere input is the same for each alternative (2.28E+24 seJ yr^{-1}).

4. Summary and conclusions

This method of computing solar equivalents for Earth's driving inputs yielded a geobiosphere emergy baseline between 11.1 E+24 seJ yr^{-1} and 13.8 E+24 seJ yr^{-1}. The method is a "forward computation" of solar equivalences using the gravitational energy required to produce the main sources driving Earth's geobiosphere. We recognized that there are two different sources of geothermal exergy to the geobiosphere, radiogenic and primordial, and that these sources have different SERs reflecting their differences in origin. We used the SERs for radioisotopes from Siegel et al. (in this issue) to compute solar equivalences of the contribution of radiogenic heat to the geobiosphere. We used the Earth rotational KE as a way of estimating the emergy input to the geobiosphere from the tidal influence of the Earth–Moon–Sun system. Most of the gravitational interaction between the Earth–Moon–Sun system, which is expressed as a decrease in rotational KE of the Earth, is converted to heat by frictional losses in the oceans. Thus a SER for Earth's rotational KE closely represents the UEV of tidal dissipation. We also computed solar equivalences for primordial heat and Earth's rotational KE, based on several allocation procedures.

4.1. Split of the GPE to generate Earth rotational KE and primordial heat

The fact that the generation of Earth's rotational KE and primordial heat are coupled within this analysis framework complicated the computation of the GEB because of questions regarding allocation of the GPE to each of these products of accretion. There were five options for assigning GPE to Earth rotational KE and primordial heat (Fig. 2). The first was to assign the GPE to each of the products based on an efficiency of production on each pathway, however these efficiencies are unknown. Two other potential algebras were to assign GPE to either one of the two products equal to their energy, and assign the remainder to the other. These two options represent the two extremes in the range of possibilities made available by the by-product allocation procedure. A fourth option was to treat the accretion process as a split of the GPE. Finally, if they were treated as co-products, when computing the GEB, the smaller of the two would not be added to the GEB that resulted. Since we had no definite method for allocation, our result is a range for the GEB (11.1 E+24 seJ yr^{-1} to 13.8 E+24 seJ y^{-1}). While we feel that this is not perfect, the GEB range that results from this allocation procedure is a strong support for a GEB within this range.

4.2. Final thoughts

It should be understood that this method of computing the UEVs of geobiosphere energy sources uses a very different method of analysis and frame (boundaries) of reference from all other previous and current methods. The assumptions made regarding Earth accretion and the forward computation method are particularly vexing and obviously include large uncertainties. That said, since this exercise in computing the geobiosphere driving emergy was initiated as one of several approaches, it will not drive the ultimate decision on a unified GEB, but will provide important reinforcement. Combined with the results of other methods it will strengthen the final unified GEB by virtue of the fact that it approaches the computation from a forward computational method; a method in striking contrast to the others, and yet yields a very comparable result.

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