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Emergy assessment of global renewable sources

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

[a] Department of Environmental Engineering Sciences, University of Florida, United States
[b] Department of Sciences and Technologies, Parthenope University of Napoli, Italy
[c] School of Environments Beijing Normal University, Beijing, China

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ABSTRACT

The empower that is derived from solar, geothermal and tidal sources drives the productive processes of the geobiosphere and is responsible for developing exergy gradients (work potential) to be transformed into secondary exergy sources (wind, and chemical potential of rain water) and tertiary sources (chemical and geopotential energy of river discharges and the available energy of breaking waves). In this paper we use the geobiosphere emergy baseline (GEB) to compute transformities for secondary and tertiary renewable exergy sources. We also refine methods used to compute secondary and tertiary sources.

In particular, we develop an emergy accounting procedure for landscape systems that prevents double counting. We suggest that when evaluating landscape systems, the geobiosphere tripartite (solar, tide, geothermal) solar equivalent inflows be summed, and compared to the largest of the secondary and tertiary flows. The driving energy for the landscape system is then the larger of these two values.

Additionally, we suggest that defining spatial and temporal boundaries is critical to emergy evaluations. Spatial boundaries should be three dimensional and include a depth below the land surface, in order to compute geothermal exergy inflows, and a height above the land surface, to include adsorption of geostrophic winds and other atmospheric phenomena. Moreover, specifying the temporal boundaries of an analysis helps to allocate driving emergy sources properly, especially related to landscape scale analyses.

1. Introduction

1.1. Geobiosphere emergy baseline (GEB)

The three main driving forces of solar, geothermal and gravitational potential exergy provide a total emergy contribution to the geobiosphere of 12.0E+24 seJ y^{-1} (Brown et al., 2016). In the past 20 years, there have been numerous baselines, which have contributed to a certain amount of uncertainty, especially when comparing evaluations by different authors. In his book Environmental Accounting, Odum (1996) computed a total emergy support to the geobiosphere of about 9.44E+24 sej y^{-1}. Later, Odum et al. (2000) calculated the global empower as 15.83E+24 sej y^{-1}. Brown and Ulgiati (2010) computed a baseline of 15.2E+24 sej y^{-1}. Campbell in several publications (Campbell et al., 2005, 2010; Campbell, 2000) had computed a baseline of 9.26E+24 sej y^{-1}. Each time there is a change in the reference baseline the unit emergy values[1] (UEVs) which directly and indirectly were derived from it must also change. When using UEVs computed with a specific GEB, their conversion to the new 12.0E+24 seJ yr^{-1} baseline is computed by multiplying the UEV by the ratio of the new baseline to the previous one.

1.2. Solar equivalent exergy of the GEB

Table 1 is a synthesis of the GEB that resulted from three studies by Brown and Ulgiati (2016), Campbell (2016) and De Vilbiss et al. (2016) using most recent estimates of global data. In order to represent tidal exergy and geothermal exergy on the same basis with solar exergy, so that they may be added to form the GEB, these studies used three different methods of equivalence to express them as solar equivalent exergy (abbreviated seJ). The methods have in common the fact that they each computed solar equivalence ratios

* Corresponding author. Tel.: +1 352 3922424; fax: +1 352 3923624.
E-mail addresses: mtb@ufl.edu (M.T. Brown), sergio.ulgiati@uniparthenope.it (S. Ulgiati).

[1] Unit emergy value is the generic term for the ratio of emergy per unit that includes, transformity (seJ/J), specific emergy (seJ/g) and the ratio of emergy to money (seJ/$).

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Table 1
Summary of tripartite exergy flows, solar equivalence ratios and related solar equivalent exergy (Brown et al., 2016).

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

[a] Average of the exergy from Brown and Ulgiati and Campbell.
[b] Average of the SERs from Brown and Ulgiati and Campbell.
[c] GEB rounded to two significant figures.

Table 2
Solar transformities of secondary global available energy flows.

Item	Global solar equivalent exergy (seJ J^{-1})	Exergy flux (E+20 J y^{-1})	Transformity[a] (sej J^{-1})
Surface wind	1.20E+25	151.2	800
Land rain, chemical potential	3.74E+25	5.34	7000
Ocean rain, chemical potential	9.56E+25	19.51	4900

[a] Rounded.

(SERs: solar equivalent exergy per unit of exergy; seJ J^{-1}) that when multiplied by the exergy of the tripartite flows, yielded solar equivalent exergy (the last column in Table 1).

The inflowing exergy from the tripartite is available to drive geobiosphere processes and its availability is "destroyed" as it is used up and assigned to secondary and tertiary renewable flows as well as to all the downstream chain of products. By definition, one solar equivalent joule (1 seJ) of inflowing exergy that drives the secondary, tertiary, etc. processes of the geobiosphere, when destroyed, translates into one solar emjoule (1 sej). The conversion of units from seJ (equivalent exergy of inflows) to sej (availability used up, emergy) is as follows:

$$X\,\text{seJ} \times \frac{1\ \text{sej}}{1\ \text{seJ}} = X\,\text{sej} \tag{1}$$

while the quantitative amounts of flows (X) are derived from calculations.

2. Secondary and tertiary global renewable emergy

The global empower derived from the tripartite of solar, geothermal, and tidal exergy drives the productive processes of the geobiosphere and is responsible for developing the potential energy gradients that are transformed into secondary and tertiary renewable exergy sources. Based on the hierarchical organization of geobiosphere processes, we categorize the renewable flows of available energy into *secondary sources* (wind, and chemical potential of rain water) and *tertiary sources* (chemical and geopotential energy of river discharges and the available energy in breaking waves).

2.1. Transformities of secondary global available energy flows

The geobiosphere's tripartite of solar, tidal and geothermal exergy is linked in a hierarchical web which generates secondary global flows that include wind and rainfall. The hierarchical web of energy flows of the geobiosphere illustrated in Fig. 1 shows the main driving energies and the pathways of available energy flows linking the continents, oceans and atmosphere. The diagram makes visible the interconnected nature of the geobiosphere which results in the transformation of driving energies into secondary energy flows, with the products of all three driving energies acting collectively to build structure and increase power flows. Table 2 summarizes these secondary flows, their available energy, and their transformities. Transformities are computed by dividing the driving emergy by the flow of available energy for each secondary source.

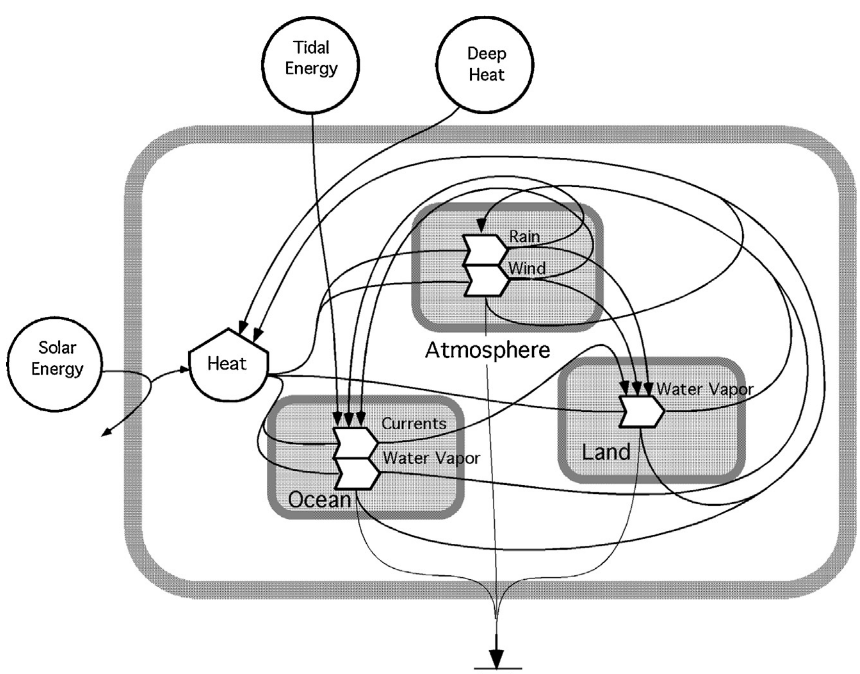

Fig. 1. Secondary emergy flows of the geobiosphere (rain, wind, and ocean currents driven by tripartite of solar, tidal and geothermal exergy. Cumulative stored heat in the geobiosphere is heat that has a gradient with the average environmental temperature and the heat sink represents energy that is dispersed and has no gradient with the environment and therefore is not capable of doing work.

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Note that we have rounded these transformities to two or three significant figures, depending on the magnitude of the number.

In the following we provide details of the calculations for each secondary energy source.

2.1.1. Wind energy

Several methods have been proposed for computing a transformity for surface wind. Odum (1996) used a GEB of 9.44E+24 seJ y^{-1} and 10% of total flux of wind energy (2.0E+12 J y^{-1}; [Monin, 1972]) to compute a surface wind transformity of 1496 sej J^{-1}. Later, Odum (2000) computed several wind transformities for various types of wind, including hurricanes, mesosystems (thunderstorms and squall lines), and temperate cyclones using a GEB of 15.83E+24 seJ y^{-1}. Transformities were as follows: hurricanes, 648 7sej J^{-1}; mesosystems, 912 sej J^{-1}; and temperate cyclones, 3230 sej J^{-1}. He used a general figure of 1 w m^{-2} as the kinetic energy dissipated by surface winds and computed a surface wind transformity of 983 sej J^{-1}.

Here we develop an approach to computing a wind transformity based on a method proposed by Odum (1999), where he referenced Reiter (1969) and suggested that the ratio of surface wind speed to geostrophic wind speed was 0.60, and thus the difference was potential energy adsorbed by surface processes. But instead of using the ratio of surface to geostrophic wind speed, we compute the wind energy absorbed using geostrophic drag coefficients and average 10 m wind speed over ocean and land.

We compute the wind energy that is absorbed by computing the geostrophic wind speed based on average global 10 m wind speed, then applying the following equation:

$$E_{wind} = \frac{1}{2}\rho * K_{GN} * V^3 * A * T \qquad (2)$$

where ρ = air density = 1.23 kg m^{-3}; K_{GN} = geostrophic drag coefficient 1.26E−3 (over sea) and 1.64E−3 (over land) taken from Garratt (1992); A = area = 3.62E+14 m^2 (ocean), 1.75E+14 m^2 (land); T = 3.15E+7 s y^{-1}; V = geostrophic wind velocity (V) computed as follows

$$V = V_{ref}\left(\frac{H}{H_{ref}}\right)^{\alpha} \qquad (3)$$

where V_{ref} = reference velocity = 6.64 m s^{-1} (ocean), 3.28 m s^{-1} (land); H_{ref} = reference height = 10 m; H = height for velocity (V) = 1000 m; α = surface roughness exponent = 0.1 (ocean), 0.25 (land) (Manwell et al., 2010).

The reference velocity was taken as the global average 10-m height wind speed over the ocean of 6.64 m s^{-1}; that over land of 3.28 m s^{-1} (Archer and Jacobson, 2005). The 10-m wind speed is the international standard height for placement of wind measuring instruments. Due to surface drag, even over seemingly smooth surfaces, laminar wind speed decreases to near zero at the surface of the earth. Thus the 10-m wind speed does not adequately represent the total dissipation. However, by applying Eq. (3) to the 10-m wind speed, the geostrophic wind speed at 1000 m can be computed (Fig. 2) and then wind energy dissipated between the geostrophic wind and ground surface can be computed using Eq. (2).

Wind transformity was computed using Eq. (2) and the average geostrophic drag coefficients for sea (N = 11) and land (N = 7) from a review by Garratt (1992):

$$E_{ocean} = \frac{1}{2}\rho * K_{GN} * V^3 * A * T = 9.87\text{E+}21\ \text{J y}^{-1}.$$

$$E_{land} = \frac{1}{2}\rho * K_{GN} * V^3 * A * T = 5.24\text{E+}21\ \text{J y}^{-1}.$$

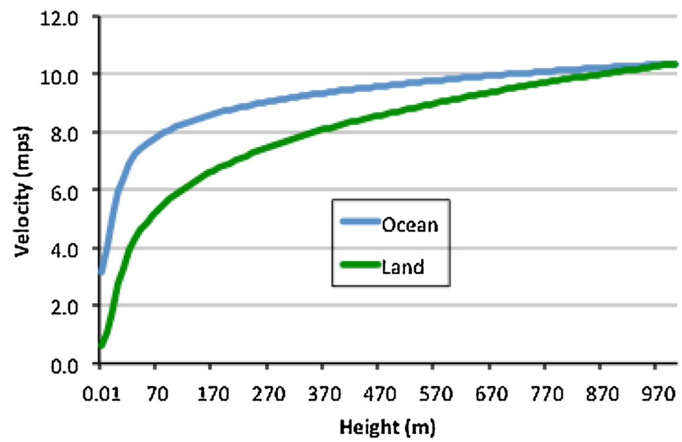

Fig. 2. Graph of wind speed with height based on relationship in Eq. (2) and 10-m wind speeds of 6.64 m s^{-1} over oceans and 3.28 m s^{-1} over land.

$$Tr_{wind} = \frac{12.0\text{E+}24\ \text{seJ y}^{-1}}{9.87\text{E+}21 + 5.25\text{E+}21}\left(\frac{1\ \text{sej}}{1\ \text{seJ}}\right) \approx 800\ \text{sej J}^{-1}$$

2.1.2. Rain (chemical potential)

Several methods have been proposed for computing global rainfall transformity. Odum (1996) used a GEB of 9.44E+24 seJ y^{-1} and chemical potential energy (4.94 J/g) of continental rainfall (105,000 km^3 y^{-1}) to compute a rain transformity of 18,200 sej J^{-1}. Later, Odum (2000) computed chemical potential transformities for continental rain at different elevations, including surface rainfall, using a revised GEB of 15.83E+24 seJ y^{-1} and rainfall of 1.09E+20 g y^{-1}, yielding a transformity of surface rainfall of 24,000 sej J^{-1}. Campbell (2003) computed several different transformities for rainfall (3 global, 5 terrestrial) using different estimates of precipitation and a GEB of 9.26E+24 seJ y^{-1}, yielding an average transformity of 18,100 sej J^{-1}.

The one thing that each of these rainfall calculations share in common is that the entire GEB is used to compute transformities. Setting aside the fact that different GEBs were used and that different estimates of rainfall were used, the calculations derive the transformity for rainfall by dividing GEB by the Gibbs energy of *terrestrial rainfall.* In other words, the assumption was made that the entire GEB is required to produce terrestrial rain.

Clearly a case can be made that assigning the entire GEB to only that portion of global precipitation that falls on land may not accurately track the emergy required. A better method may be achieved by representing the flows of available energy in water between compartments as a network or matrix of flows and invoking operations from linear algebra (i.e. Input–output analysis [I–O analysis]) to solve for transformities simultaneously.

Fig. 3 of the global water cycle shows the flows of water between three main storages, ocean, continents, and atmosphere driven by the GEB. In Fig. 3a, the quantity of water flowing between compartments is given based on data from (Bengtsson, 2010). Taken as a web of water flows, transformities can be computed using a method of I–O analysis that computes transformities as eigenvalues of the matrix of available energy flows between compartments. Fig. 3b shows the available energy of water flows between compartments, computed using the difference between chemical potentials (Gibbs free energy) of the flows from one compartment to the next. The Gibbs energy between atmosphere and ocean and continents is 4.72 J/g assuming 10 ppm total dissolved solids (TDS) in rainfall and 35,000 ppm in ocean and cellular interstitial fluids. The Gibbs energy of continental runoff, assuming 150 ppm TDS in runoff and 35,000 ppm in the ocean is 4.70 J/g. The Gibbs energy of water

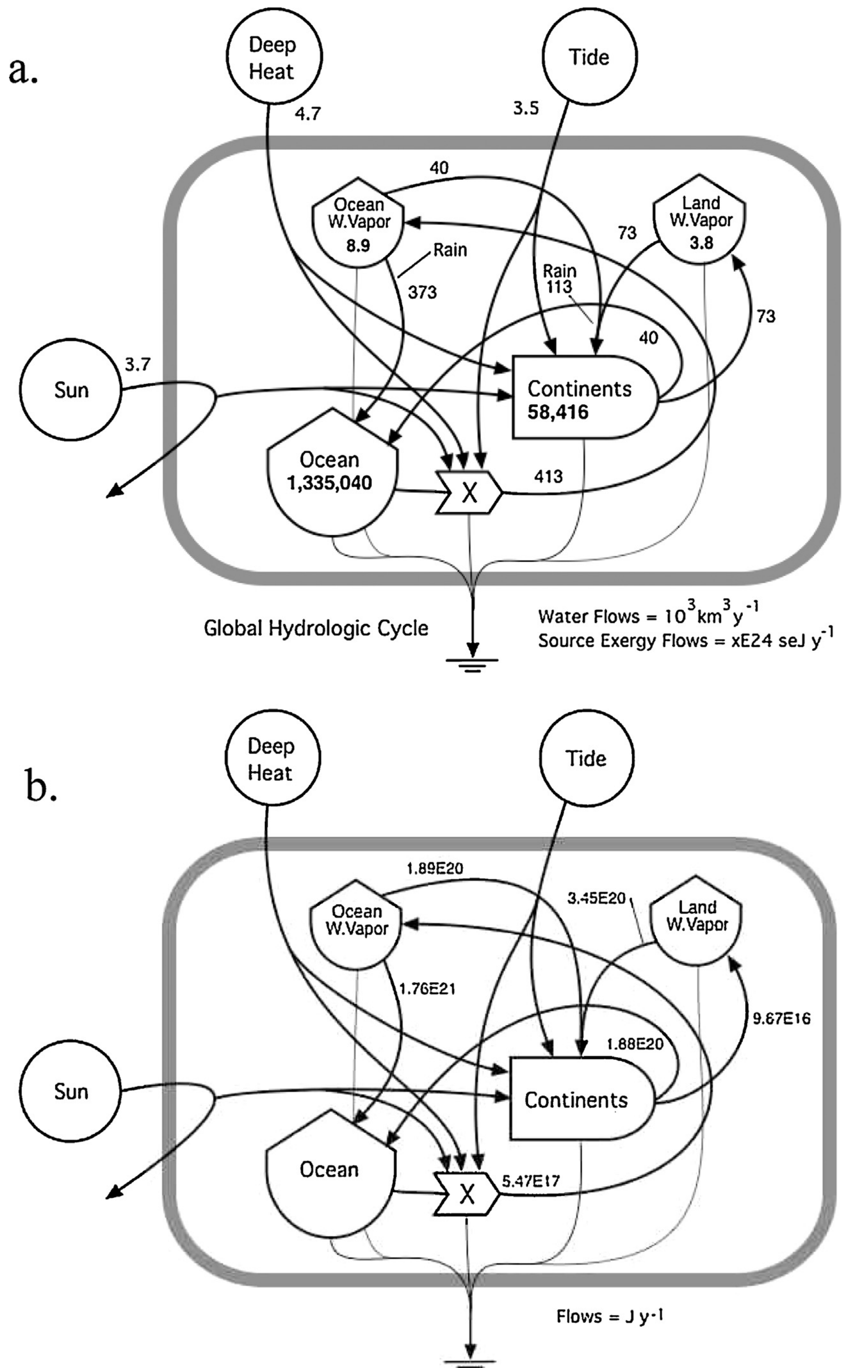

Fig. 3. Global water cycle. The top diagram, (a), shows major storages in ocean, and atmosphere and on land, and the flows of rain, runoff, and evaporation and transpiration (data are from Bengtsson, 2010). Storages in are 10^3 km^3 and flows are 10^3 km^3 yr^{-1}. Bottom diagram, (b), has pathways evaluated as available energy flows (J yr^{-1}).

evaporated and transpired from ocean and continents is 0.0012 J/g, assuming a TDS of 1 ppm and rain with assumed TDS of 10 ppm.

The flow data from the global water cycle diagram were organized into a from/to matrix format (Table 3). Flows of water between compartments from Fig. 3 were entered in appropriate cells in the matrix (Table 3a) and converted to available energy (Table 3b) using the Gibbs energy for individual flows. Column A is the emergy input to land, ocean, land atmosphere and ocean atmosphere divided assuming 30% land and 70% ocean (according to surface). Further the atmosphere absorbs 29.8% of solar energy (Trenberth et al., 2007) and 5.4% of tidal momentum is dissipated in the atmosphere (Munk and Wunsch, 1998).

Using the MMULT and INVERSE functions in EXCEL, the inverse matrix of available energy flows (matrix A1,E4) is multiplied by the emergy vector in column F (see Table 3b). The EXCELL formula for the computation is given in Column G of Table 3b.

Table 3c shows the resulting transformities from the matrix computation for rain on land (≈7000 sej J^{-1}) and ocean (≈4900 sej J^{-1}) in column G.

Table 3a
Solar equivalent exergy (seJ y^{-1}) in column A, and volume of water (10^3 km^3 y^{-1}) flows between compartments (columns B–E).

	To↓	A S, T, DH	B Land	C Ocean	D L. Atmos.	E O. Atmos.	F Vector (sej)
1	S, T, DH	1.00	0	0	0	0	1.0
2	Land	2.98E+24	−113	0	73	40	1.0
3	Ocean	6.96E+24	40	−413	0	373	1.0
4	L. Atmos.	6.16E+23	73	0	−73	0	1.0
5	O. Atmos.	1.44E+24	0	413	0	−413	1.0

Table 3b
Solar equivalent exergy (seJ y^{-1}) and available energy (J y^{-1}) of water flows between compartments. Column G is the EXCEL formula to multiply the matrix inverse by vector in column F.

	To↓	A S, T, DH	B Land	C Ocean	D L. Atmos.	E O. Atmos.	F Vector (sej)	G (sej J^{-1})
1	S, T, DH	1.00	0	0	0	0	1.0	MMULT(MINVERSE(A1:D4),E1:E4)
2	Land	2.98E+24	5.34E+20	0	3.45E+20	1.89E+20	1.0	MMULT(MINVERSE(A1:D4),E1:E4)
3	Ocean	6.96E+24	1.88E+20	1.95E+21	0	1.76E+21	1.0	MMULT(MINVERSE(A1:D4),E1:E4)
4	L. Atmos.	6.16E+23	9.67E+16	0	3.45E+20	0	1.0	MMULT(MINVERSE(A1:D4),E1:E4)
5	O. Atmos.	1.44E+24	0	5.47E+17	0	1.95E+21	1.0	MMULT(MINVERSE(A1:D4),E1:E4)

Table 3c
Solution of inverse multiplication of matrix A1,D4 with vector E1,E4.

	To↓	A S, T, DH	B Land	C Ocean	D Atmos.	E Vector (sej/J)	F sej/J	G Transformity (sej J^{-1})
1	S, T, DH	1.00	0	0	0	0	1.0	1
2	Land	2.98E+24	5.34E+20	0	3.45E+20	1.89E+20	1.0	**7008**[a]
3	Ocean	6.96E+24	1.88E+20	1.95E+21	0	1.76E+21	1.0	**4912**[b]
4	L. Atmos.	6.16E+23	9.67E+16	0	3.45E+20	0	1.0	1789
5	O. Atmos.	1.44E+24	0	5.47E+17	0	1.95E+21	1.0	738

[a] Rounded to 7000.
[b] Rounded to 4900.

Table 4
Solar transformities of tertiary global available energy flows.

Item	Solar equivalent exergy (seJ J^{-1})	Exergy flux (E+20 J y^{-1})	Transformity (sej J^{-1})
River flow, geopotential	3.74E+24	2.91	12,800
River flow, chemical potential	3.74E+24	1.76	21,300
Waves absorbed on shore	7.89E+24	18.90	4200

The driving emergy of terrestrial rainfall is computed as follows:

$$Emergy_{T.rain} = \text{Rainfall} * \text{Gibbs energy} * Tr_{rain}$$

where

Rainfall = 1.13E+5 km^3 y^{-1} (terrestrial) and 3.73E+5 km^3 y^{-1} (oceanic);
Gibbs energy = 4.723 J/g;
Tr_{rain} = 7000 sej J^{-1};

$$Emergy\ T.rain = 1.13\text{E+}20\ \text{g}\ y^{-1} * 4.723\ \text{J}\ \text{g}^{-1} * 7000\ \text{sej}\ \text{J}^{-1} = 3.74\text{E+}24\ \text{seJ}\ \text{y}^{-1}$$

2.2. Transformities of tertiary global available energy flows

The global available energy of tertiary flows is driven indirectly by the primary flows, but directly by splits of the biosphere's available energy. The tertiary flows include the chemical and geopotential energy of river discharges and the available energy in breaking waves on shorelines of continents. Table 4 summarizes the average annual available energy in river discharges and breaking waves, their driving emergy and computed global average transformities. Details of the computations of the tertiary transformities are as follows:

2.2.1. Geopotential energy in rivers

The continental runoff, also known as river geopotential and called rain geopotential by Odum et al. (2000) is computed from the average annual global river discharge (3.73E+4 km^3 y^{-1}) from Dai et al. (2009) and average continental elevation, 797 m (Eakins and Sharman, 2012). Both the river discharge and continental elevation used by Odum et al. (2000) were somewhat different than these values (3.96E+4 km^3 y^{-1} and 875 m, respectively). The geopotential energy is given by:

$$Energy_{river\ geopot.} = \text{mass} * \text{gravity} * \text{height}$$

$$Energy_{river\ geopot} = 3.73\text{E+}4\ \text{km}^3\ \text{y}^{-1} * 1.0\text{E+}12\ \text{kg}\ \text{km}^{-3} * 9.8\ \text{m}\ \text{s}^{-2} * 797\ \text{m} = 2.91\text{E+}20\ \text{J}\ \text{y}^{-1} \quad (4)$$

The emergy of continental rainfall (3.74E+24 seJ/yr.; see above) is the emergy driving river discharge, rather than the GEB, thus the average transformity of river geopotential is:

$$Tr_{river\ geopot.} = \frac{3.74\text{e+}24\ \text{seJ}\ \text{y}^{-1}}{2.91\text{E+}20\ \text{J}} \left(\frac{1\ \text{sej}}{1\ \text{seJ}}\right) \approx 12,800\ \text{sej}\ \text{J}^{-1}$$

2.2.2. Chemical potential energy of river discharge

River discharges are 3.73E+4 km^3 yr^{-1} (Dai et al., 2009). We depart from Odum et al. (2000) and assume an average dissolved solids concentration of 150 ppm, therefore a Gibbs free energy = 4.71 J/g; the total available energy in river discharges is as follows:

$$Energy_{river\ chem.pot.} = (\text{Mass})(\text{Gibbs energy})$$

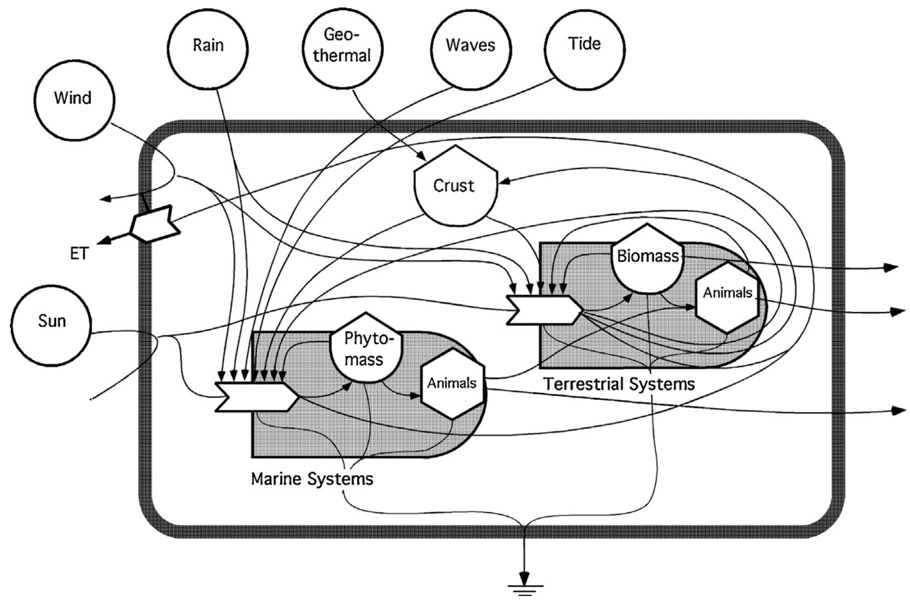

Fig. 4. Energy systems diagram of a landscape system used to evaluate the renewable emergy input in Table 5.

$$= 3.73\text{E+4 km}^3\ \text{y}^{-1} * 1\text{E+15 g km}^{-3} * 4.71\ \text{J g}^{-1}$$
$$= 1.76\text{E+20 J y}^{-1}. \quad (5)$$

Emergy of continental rainfall is 3.74E+24 sej y^{-1} (see above), thus the transformity of rivers chemical potential is:

$$Tr_{river\ chem.pot.} = \frac{3.74\text{e+24 seJ y}^{-1}}{1.76\text{E+20 J}} \left(\frac{1\text{ sej}}{1\text{ seJ}}\right) \approx 21,300\text{ sej J}^{-1}$$

2.2.3. Wave energy

The global transformity for breaking waves is reevaluated using different total wave energy from updated sources since the earlier evaluation by Odum et al. (2000) as follows:

Annual global gross theoretical wave power = 6.0E+13 W (Wang and Huang, 2004)

$$Energy_{waves} = 6.0\text{E+13 W} * 3.15\text{E+7 s y}^{-1} = 1.89\text{E+21 J y}^{-1} \quad (6)$$

Differing from the assumption of Odum et al. (2000), where the GEB was the driving emergy for waves, we assume only the wind energy over oceans (see above) driving ocean waves, equal to 9.87E+21 J y^{-1}, yielding

$$Emergy_{wind} = Energy_{wind} * Tr_{wind} = 9.87\text{E+21 J y}^{-1} * 800\text{ sej J}^{-1}$$
$$= 7.89\text{E+24}$$

and

$$Tr_{waves} = \frac{7.89\text{E+24 seJ y}^{-1}}{1.89\text{E+21 J}} \left(\frac{1\text{ sej}}{1\text{ seJ}}\right) \approx 4200\text{ sej J}^{-1}$$

2.3. Calculating renewable emergy inputs to local systems

The process of evaluating the driving emergy inputs to a local portion of the earth's surface, is summarized in systems diagram in Fig. 4. The diagram is of an average square kilometer of the Earths surface area that includes both land and the submerged portion of the continental shelf. We use an average of the global landscape to illustrate how to calculate input energies, thus we have taken the land area, coastal length and area of continental shelf of globe and scaled them so that the km^2 represents the distributions of these components on earth. The systems diagram shows the flows of driving energies interacting with the marine and terrestrial ecosystems driving the cycles of materials and energy. Some energy exits the system as degraded energy that no longer has the ability to do work and some is exported to the larger environment in which this subsystem is embedded.

Time domain of the analysis is one year. The upper and lower system boundaries for this system are 1500 m in elevation to 1000 m depth in the earth's crust. The upper system boundary of 1500 m was chosen to include the atmospheric boundary layer for the purposes of computing the wind exergy absorbed, since, on the average, the boundary layer is between 1 and 2 km in height (Thompson, 1998). With a different upper boundary than that used to compute the geobiosphere emergy baseline, we must re-compute the Carnot efficiency for solar radiation, based on the temperature difference of the upper boundary and that of the earth's surface, in order to compute the available energy of solar radiation used by the system. We assume a temperature at the top of the boundary (1500 m altitude) to be $T_C = 0\,^{\circ}$C or 273.15 K. The temperature of the sun (T_H) is 6000 K and therefore the Carnot efficiency, given by $1 - T_C/T_H$, is $1 - 273.15/6000 = 95.4\%$.

While the lower boundary could be the bottom of the crust, we have chosen 1 km below the surface to include geothermal inputs that match the time frame of this analysis (1 year)[2]. Calculation of geothermal exergy relies on computing a Carnot efficiency for the energy in the thermal gradient between the temperature of the heat source and the temperature of the reference environment. In this case the reference temperature (average temperature at earth's surface) is taken as 287 K (i.e. 273 K plus 14 °C average surface temperature of the Earth) and the temperature at 1000 m is 317 K

[2] We understand that this lower boundary is somewhat arbitrary, however, since the timeframe of the investigation is one year, we are excluding most geologic processes, which take place over longer time frames. The geothermal inputs to land areas that are a portion of earth surface should not necessarily be all of the deep heat, but instead, should reflect that input which actually drives geothermal processes of the studied system. In this case we have chosen 1 km instead of the entire depth of the crust. If we were evaluating one hectare of forest, we might use a lower boundary of between 10 and 100 m. The depth has a direct impact on the Carnot efficiency and thus the available geothermal energy.

Table 5
Emergy evaluation of annual renewable inputs to 1 km of the Earth's surface.

Note	Item	Data	Units	SER (sej J^{-1})	Transformity (sej J^{-1})	Solar Emergy (E+15 sej)
Global tripartite						
1	Sunlight	7.10E+15	J	1		7.1
2	Earth cycle, heat flow	1.90E+11	J	4900		0.9
3	Tide, kinetic energy	9.17E+10	J	30, 900		2.8
Sum of tripartite						10.9
Secondary and tertiary sources						
4	Wind, kinetic energy	2.09E+13	J		800	16.7
5	Waves, kinetic energy	2.68E+12	J		4200	11.3
6	Rain, chemical potential	2.58E+12	J		7000	18.1
7	Runoff, geopotential	7.17E+10	J		12,800	0.9
8	Runoff, chemical potential	6.87E+11	J		21,300	14.6
Largest of 2nd and 3rd sources						18.1

1. Solar energy:
   Area = 1.00E+06 m^2 (sum of land and shelf area)
   Insolation = 1.09E+06 J cm^{-2} y^{-1} (estimate)
   Albedo = 30.00 (% of insolation)
   Carnot efficiency = 0.93
   Energy (J) = (area)*(avg insolation)*(1-albedo)*(Carnot efficiency) = (1.0E+6 m^2)(1.09E+6 J cm^{-2} y^{-1})(E+04 cm^2 m^{-2})(0.70)(0.93) = 7.10E+15 J y^{-1}
   SER = 1.0 sej J^{-1}
2. Earth cycle:
   Area = 1.00E+06 m^2
   Heat flow = 2.00E+06 J m^{-2} y^{-1} (International Heat Flow Database, 2010)
   Carnot efficiency = 9.50% = 1 − (287 K/317 K)
   Energy (J) = (area)(heat flow)(Carnot efficiency) = (1.0E+6 m^2)(2.0E+6 J m^{-2} y^{-1})(9.5E−2) = 1.90E+11 J y^{-1}
   SER = 4900 sej J^{-1}
3. Tidal energy:
   Area = 1.00E+05 m^2
   Avg tide range = 0.50 m (estimate)
   Percent absorbed = 50%
   Density = 1.03E+03 kg m^{-3}
   Tides/year = 7.30E+02 (estimate – 2 tides/day in 365 days)
   Energy (J) = (shelf)(0.5)(tides/y)(mean tidal range)^2(density of seawater)(gravity) = (1.0E+5 m^2)(0.5)(730 y^{-1})(1.0 m)^2(1.03 kg m^{-3})(9.8 m s^{-2}) = 9.17E+10 J y^{-1}
   SER = 30,900 sej J^{-1}
4. Wind energy:
   Land area = 9.00E+05 m^2
   Shelf area = 1.00E+05 m^2
   Density of air = 1.23E+00 kg m^{-3}
   Land wind velocity = 3.28E+00 m s^{-1} (Archer and Jacobson, 2005)
   Geostrophic wind = 1.04E+01 m s^{-1} (see wind calculation above – Fig. 2)
   Land wind absorbed = 7.12E+00
   Ocean wind velocity = 6.64E+00 m s^{-1} (Archer and Jacobson, 2005)
   Geostrophic wind = 1.04E+01 m s^{-1} (see wind calculation above – Fig. 2)
   Ocean wind absorbed = 3.76E+00
   Land drag coeff. = 1.64E−03 (Garratt, 1992)
   Ocean drag coeff. = 1.26E−03 (Garratt, 1992)
   $$\text{Energy (J)} = (\text{land area})(\text{air density})(\text{drag coefficient})(\text{wind velocity absorbed})^3 + (\text{ocean area})(\text{air density})(\text{drag coefficient})(\text{wind velocity absorbed})^3$$
   $$= (8.5\text{E}+5\ \text{m}^2)(1.23\ \text{kg m}^{-3})(0.03)(7.12\ \text{m s}^{-1})^3(3.15\text{E}+7\ \text{s y}^{-1}) + (1.5\text{E}+5\ \text{m}^2)(1.23\ \text{kg m}^{-3})(0.0001)(3.76\ \text{m s}^{-1})^3(3.15\text{E}+7\ \text{s y}^{-1})$$
   Energy (J) = 2.09E+13 J y^{-1}
   Transformity = 800 sej J^{-1}
5. Wave energy:
   Shore length = 5.00E+01 m
   Wave height = 5.00E−01 m (estimate)
   Depth = 3.00E+00 m (estimate)
   Wave velocity = 5.42E+00 m s^{-1} (velocity = sq. root of gravity*shoaling depth)
   Energy (J) = (shore length)(1/8)(density)(gravity)(wave height^2)(velocity)(3.14E+7 s y^{-1}) = (5.0 m)(1/8)(1.025E+3 kg m^{-3})(9.8 m s^{-2})(0.5 m)^2(5.42 m s^{-1})(3.15E+7 s y^{-1}) = 2.68E+12 J y^{-1}
   Transformity = 4200 sej J^{-1}
6. Rain, chemical potential energy:
   Land area = 9.00E+05 m^2
   Shelf area = 1.00E+05 m^2
   Rain (land) = 0.65 m y^{-1} (Bengtsson, 2010)
   Transpiration rate = 75%
   Rain (shelf) = 1.08 m/yr (Bengtsson, 2010)
   Energy (J) = (land area)(rainfall)(% transpired)(Gibbs energy of rain) + (Shelf area)(rainfall)(Gibbs energy of rain)
   = (9.0E+5 m^2)(1.12 m)(75%)(1000 kg m^{-3})(4.72E+03 J kg^{-1}) + (1.0E+5 m^2)(0.8 m)(1000 kg m^{-3})(4.72E+03 J kg^{-1}) = 2.58E+12 J y^{-1}
   Transformity = 7000 sej J^{-1}
7. Runoff, geopotential energy:
   Land area = 9.00E+05 m^2
   Rainfall = 0.65 m
   Avg. elev. = 50.00 m (estimate)
   Runoff rate = 25%
   Energy (J) = (land area)(% runoff)(rainfall)(avg elevation)(gravity) = (9.0E+5 m^2)(1.12 m)(1000 kg m^{-3})(50 m)(9.8 m s^{-2}) = 7.17E+10 J y^{-1}
   Transformity = 12,800 sej J^{-1}
8. Runoff, chemical potential:
   Land area = 9.00E+05 m^2
   Rainfall = 0.65 m
   Runoff rate = 25%
   Energy (J) = (land area)(rainfall)(% runoff)(Gibbs energy of runoff) = (9.0E+5 m^2)(1.12 m)(25%)(1000 kg m^{-3})(4.70E+03 J kg^{-1}) = 6.87E+11 J y^{-1}
   Transformity = 21,300 sej J^{-1}

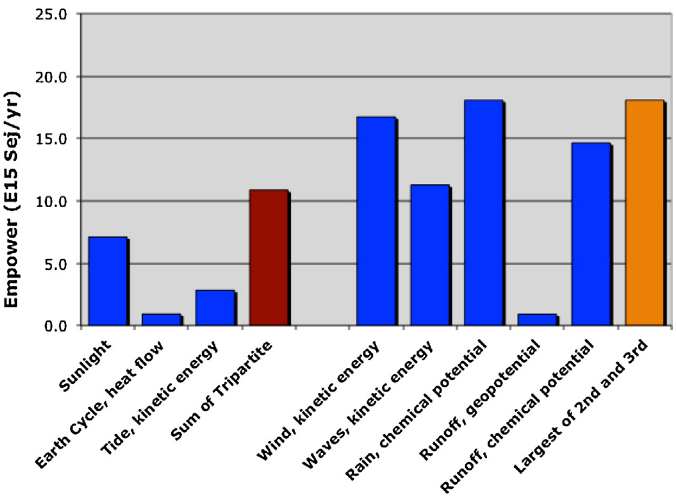

Fig. 5. Annual emergy signature of 1 km square of Earth surface, showing the sum of the tripartite baseline compared to the largest of the secondary and tertiary emergy inputs (in this case the largest is rain, chemical potential). Land area = 9.0E+5 m^2, ocean shelf area = 1.0E+5 m^2.

(temperature increases by 3 °C per 100 m) and the Carnot efficiency is 1 − (287/317) = 9.5%

As an example, Table 5 is an emergy table for an "average" square kilometer of the earth's surface. Of the total area we have assigned, somewhat arbitrarily, 90% to land and 10% to coastal shelf (that portion of the continental shelf that is part of land system). As is usual, the source flows are expressed as available energy and then multiplied by their transformities to yield emergy in the last column. Footnotes to the table explain the assumptions and computations for each flow. An emergy signature graph of the average kilometer of Earth's surface is given in Fig. 5.

2.4. Driving emergy of local systems: a proposed calculation method

In past evaluations, it was customary to take the largest of the renewable input emergy as the emergy driving the system. Evaluations were done in this way to avoid double counting input emergy since it was reasoned that all renewable inputs were co-products of the geobiosphere tripartite. To some extent this is true, but only for the secondary and tertiary renewable sources. The global tripartite are separate sources and can be added, since we have calculated the transformities and the emergy of these flows from a system of equations that assumes they are independent while acting together. As a consequence, their emergies can be added, but the emergies of their "products" cannot, because each of them "embodies" a fraction of the tripartite baseline. For this reason, we suggest a new computational procedure to assign emergy sources to landscape systems. This new method sums the tripartite sources and compares this quantity with the largest of the secondary and tertiary sources. Which ever is the larger of these two quantities is taken as the driving emergy of the landscape system. In Table 5, the sum of the tripartite baseline is 10.9E+15 sej y^{-1}, while the largest of the secondary and tertiary sources is 18.1E+15 sej y^{-1}. Using this new computational procedure, the emergy driving the landscape system is the largest between these two quantities, namely 18.1E+15 sej y^{-1}.

3. Summary and concluding remarks

Establishing both spatial and temporal boundaries for emergy evaluations is necessary in order to compute the emergy driving a system. Boundaries need be 3 dimensional so that not only is land area considered, but height above and depth below the Earth's surface are also specified since driving energies are defined by system boundaries. Without a sufficient vertical boundary, wind energy that is absorbed at the earth's surface cannot be computed, and without a specified depth below the earth's surface, the geothermal contributions cannot be computed as well.

Transformities that are given in this paper use global average available energy. As such they are average transformities. It should be understood that there is no single tranformity for any given product, since no two processes are alike. This also holds for the processes of the geobiosphere. For instance, there are many transformities for rain since precipitation varies with altitude, is affected by mountains, and depends on the weather systems in complex ways, etc. Rainfall in any particular location may have a higher or lower transformity depending on the source area and intensity of the solar energy driving the cycles that produce it. However, calculation of transformities on a site specific basis for each of the driving energies is not an easy undertaking, because of the uncertainties inherent in estimating the input variables. Therefore, to simplify evaluations, average global transformities are used.

In this paper we apply the new geobiosphere emergy baseline, which is 12.0E+24 seJ y^{-1}, provide significant refinements of the treatment of secondary and tertiary emergy sources, and suggest a different accounting procedure for landscape systems. Finally, we suggest that a better method of computing global transformities for secondary and tertiary sources is to develop a network of energy flows that includes cycling and to use the modified Odum and Collins (2003) "Eigen value" technique (Zarba and Brown, 2015). Transformities computed using this network technique would represent independent transformities and when multiplied by exergy input flows to a landscape system, the resulting emergies could be added.

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