OSU~EmEa – 5

Geobiosphere Emergy Baseline

The history of the Geobiosphere Emergy Baseline

Solar equivalents, Solar emergy

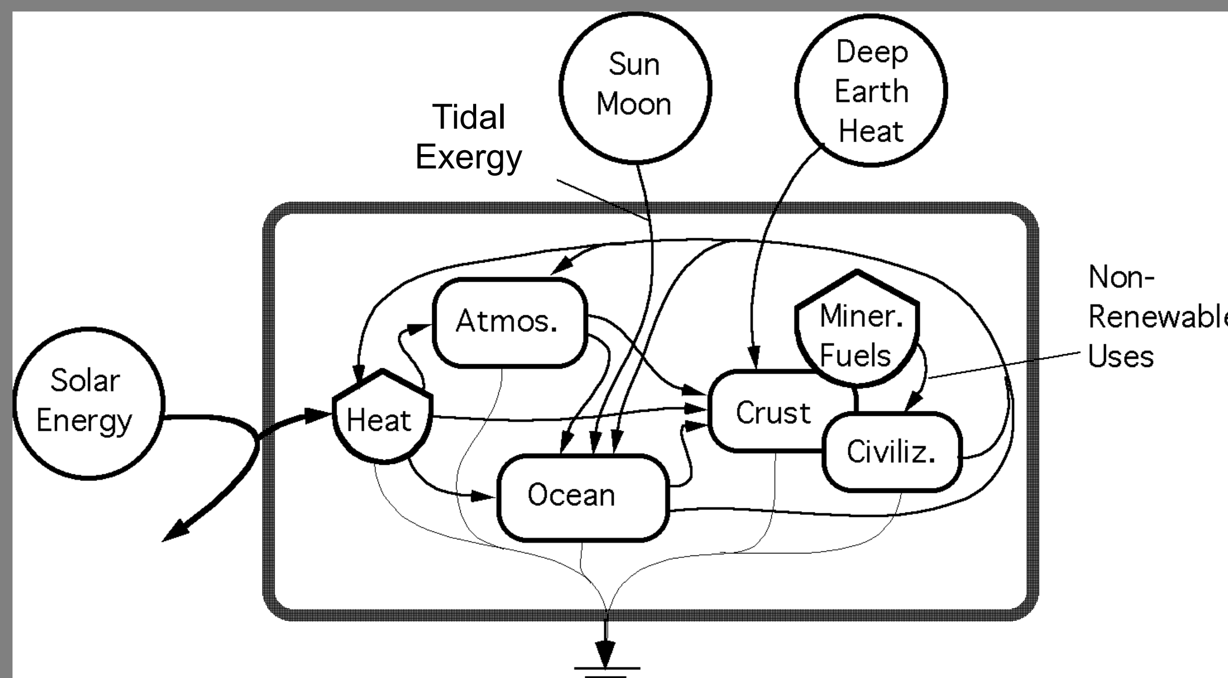
The Geobiosphere Emergy Baseline….

Over the past 30 years, the
Geobiosphere Emergy Baseline
(GEB)
has evolved

Emergy Flow (Empower) Supporting The Geobiosphere….

Three main exergy fluxes driving the geobiosphere:

Sunlight, Tidal Exergy, and Deep Heat



Emergy Flow (Empower) Supporting The Geobiosphere….

Total Emergy = Solar Emergy +Tidal Emergy+ Deep Earth Heat Emergy

Recall: Solar emergy = exergy flow * transformity

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By definition the Emergy from Solar input has transformity =1.0

Transformities for the other two exergy sources must be calculated

~

Empower Supporting the Geobiosphere….

Solar Emergy…

Solar energy flow: 3.93 E24 J/yr based on solar constant 2 gcal/cm^2/min, 70 % absorption, and 1.27 E14 m^2 cross section facing the sun.

Solar Energy = 2cal/cm^2/min* 5.26 E5 min/yr*0.70*1.27E14m^2*1E4 cm^2/m^2

= 3.93 E24 J/yr

Solar Transformity = 1.0 sej/J by definition

Empower Supporting the Geobiosphere….

Prior to 2000…

Total emergy driving the geobiosphere = 9.44 E24 sej/yr

Table 1. Annual Emergy Contributions to Global Processes* (after Odum et al. 1996)

Note	Input	Units	Inflow units/yr	Emergy/Unit sej/unit	Empower (E24 sej/yr)
1	Solar insolation	J	3.93 E24	1.0	3.93
2	Deep earth heat	J	6.72 E20	6,055	4.07
3	Tidal energy	J	8.52 E19	16,842	1.44
4	Total	--	--		9.44

(Odum H.T.,1996. Environmental Accounting: Emergy and Environmental Decision Making. John Wiley & Sons, New York

Empower Supporting the Geobiosphere….

After 2000…

Total emergy driving the geobiosphere = 15.83 E24 sej/yr

Table 1. Annual Emergy Contributions to Global Processes* (after Odum et al. 2000)

Note	Input	Units	Inflow units/yr	Emergy/Unit sej/unit	Empower (E24 sej/yr)
1	Solar insolation,	J	3.93 E24	1.0	3.93
2	Deep earth heat,	J	6.72 E20	1.20 E4	8.06
3	Tidal energy,	J	0.52 E20	7.39 E4	3.84
4	Total	--	--		15.83

(Odum, H.T. 2000. Emergy of Global Processes. Folio #2: Handbook of Emergy Evaluation. Center for Environmental Policy, University of Florida, Gainesville, FL.)

The GEB Re-examined….

Following the Eighth Biennial Emergy Conference (January, 2014), the need for revisiting the procedures and assumptions used to compute the Geobiosphere Emergy Baseline emerged as a necessity to strengthen the method of Emergy Accounting and remove some sources of ambiguity and potential misunderstanding.

The GEB Re-examined….

The result was three approaches to evaluating the GEB:

Brown, M.T. and S. Ulgiati. 2016. Assessing the Global Environmental Sources Driving the Geobiosphere: A Revised Emergy Baseline. *Ecological Modelling,*

Campbell, D.E. 2016. Emergy Baseline for the Earth: Review of the Science and a New Calculation. *Ecological Modelling,*

De Vilbiss, C., M.T. Brown, E. Seigel, and S. Arden. 2016. A New Approach to the Planetary Emergy Baseline. *Ecological Modelling,*

The GEB Re-examined….

In addition, two other papers address important related issues:

Brown, M.T. and S. Ulgiati. 2016. Emergy Accounting of Global Renewable Sources . *Ecological Modelling*

Siegel, E., M.T. Brown, C. De Vilbiss, S. Arden. 2016. Calculating solar transformities of the four major heat-producing radiogenic isotopes in the Earth's crust and mantle. *Ecological Modeling*

But first....

A note about units and nomenclature

A Note About Units….

Since solar energy in no way actually contributes to radiogenic heat, Earth's relic heat, or its tidal energy, it is apparent that these do not embody solar exergy and are inappropriately characterized as solar emergy.

(after Raugei, 2013)

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 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).

A Note About Units….

Solar equivalent joules are abbreviated using a capital “J”. A lower case 'j' in sej represents solar emjoule.

An emjoule is not available energy, it is the memory of available energy destroyed in the past, thus we use the lower case “j”.

When describing the ratio of solar equivalent exergy to exergy of tides and geothermal sources 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) .

A Note About Units….

seJ = solar equivalent Joule

sej = solar emjoule

SER = solar equivalence ratio (seJ/J)

T_R = Transformity (sej/J)

The Solar Equivalent Baseline

Solar Equivalent Baseline….

Inflow	Brown and Ulgiati			Campbell			De Vilbiss et al.		
	Exergy	SER (seJ J^{-1})	Solar Equivalent Exergy (E+24 seJ yr^{-1})	Exergy	SER (seJ J^{-1})	Solar Equivalent Exergy (E24 seJ yr^{-1})	Exergy	SER[b] (seJ J^{-1})	Solar Equivalent Exergy (E24 seJ yr^{-1})
Solar energy absorbed	3.60E+24	1	3.6	3.85E+24	1	3.85	3.60E+24	1	3.6
Geothermal Flows[a.]	9.78E+20	5,500 (985)	5.4 (0.95)	9.20E+20	4,200	3.86		7,500[c]	
Primordial Heat							5.95E+20	10,400	5.5
Radiogenic							4.95E+20	4600	2.3
Tidal energy absorbed	1.17E+20	26,300 (3800)	3.1 (0.44)	1.11E+20	35,400	3.92	1.17E+20	17,700	2.1
Total global empower			12.1 (1.51)			11.6			13.5

Solar Equivalent Baseline….

Summary of GEB and Solar Equivalence Ratios and Solar Equivalent Exergy derived from Brown & Ulgiati, Campbell & DeVilbiss et al.

Inflow	Exergy[a.]	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	4,900	4.7
Tidal energy absorbed	1.14E+20	30,900	3.5
Total Global Empower			12.0

a. Average of the exergy from Brown & Ulgiati (2016), Campbell (2016)

b. Average of the SERs from Brown & Ulgiati (2016), Campbell (2016)

c. rounded to two significant figures

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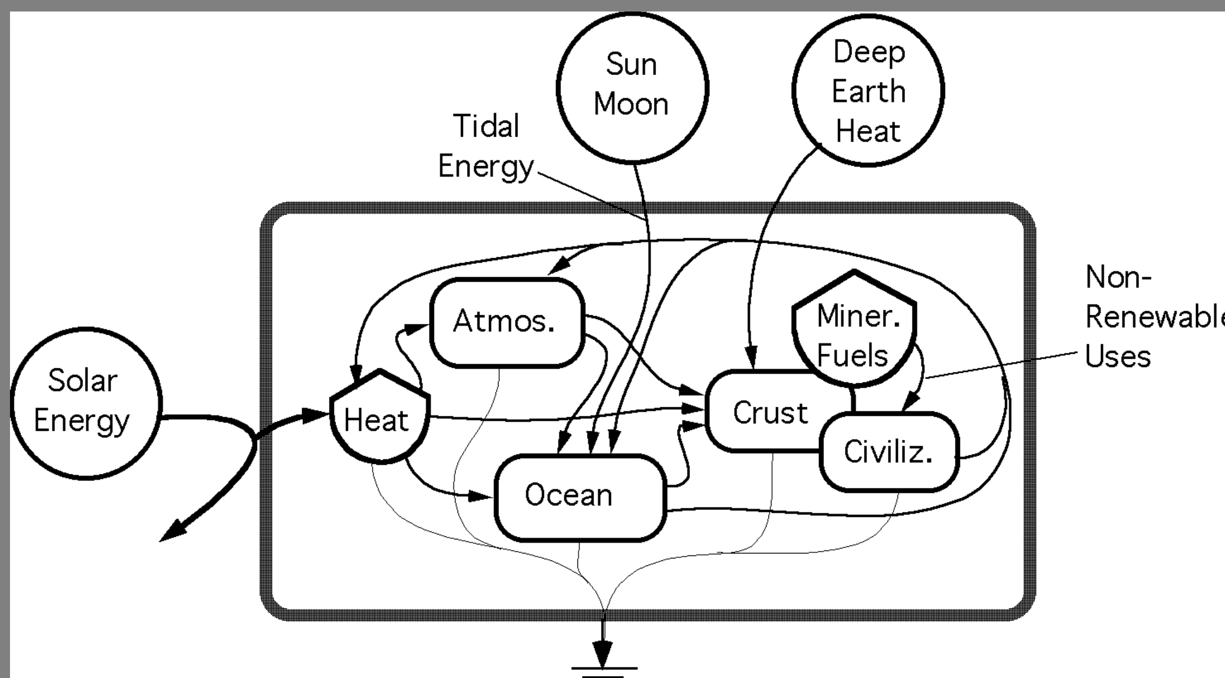
Emergy of Renewable Secondary and Tertiary Global Sources

Computation of primary, secondary and tertiary global renewable sources, Accounting principles to avoid double counting

Emergy Flow (Empower) Supporting The Geobiosphere….

Three main flows driving global processes, Sunlight, Tidal Energy, and Deep Heat



Empower Supporting the Geobiosphere….

Geobiosphere emergy = Sum of inputs

= Solar Emergy +Tidal Emergy+ Deep Earth Heat Emergy

Recall:
Solar equivalent emergy = exergy flow * SER

By definition the Emergy from Solar input has SER =1.0

SERs for the other two energy sources were computed and equal :

Tide = 30,900 seJ/J

Deep Heat = 4,900 seJ/J

Empower Supporting the Geobiosphere….

Total Emergy driving the geobiosphere = 12.0 E24 sej/yr

Summary of GEB and Solar Equivalence Ratios and Solar Equivalent Exergy derived from Brown & Ulgiati, Campbell & DeVilbiss et al.

Inflow	Exergy[a.]	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	4,900	4.7
Tidal energy absorbed	1.14E+20	30,900	3.5
Total Global Empower			12.0

a. Average of the exergy from Brown & Ulgiati (2016), Campbell (2016)

b. Average of the SERs from Brown & Ulgiati (2016), Campbell (2016)

c. rounded to two significant figures

Empower Supporting the Geobiosphere….

The emergy sources to most systems also include secondary and tertairy renewable sources that are produced by the Geobiosphere Emergy Baseline (GEB)

The secondary renewable sources are:

Wind
Rain

The tertiary renewable sources are:

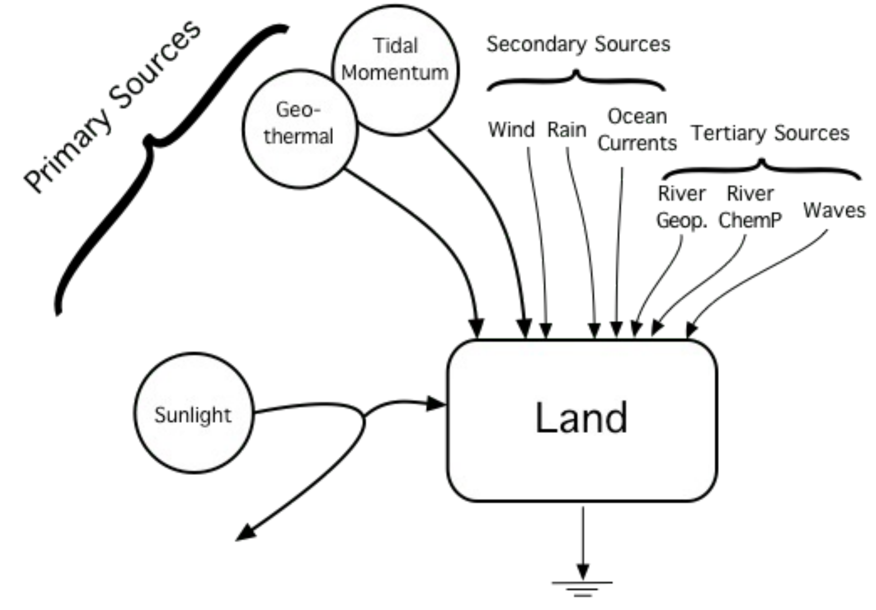
River flow , geopotential
River flow, chemical potential
Waves

Empower Supporting the Land & Water Ecosystems….

IMPORTANT Consideration…

Input Emergy =

Maximum of Sum of the Primary vs. largest of the secondary & tertiary sources

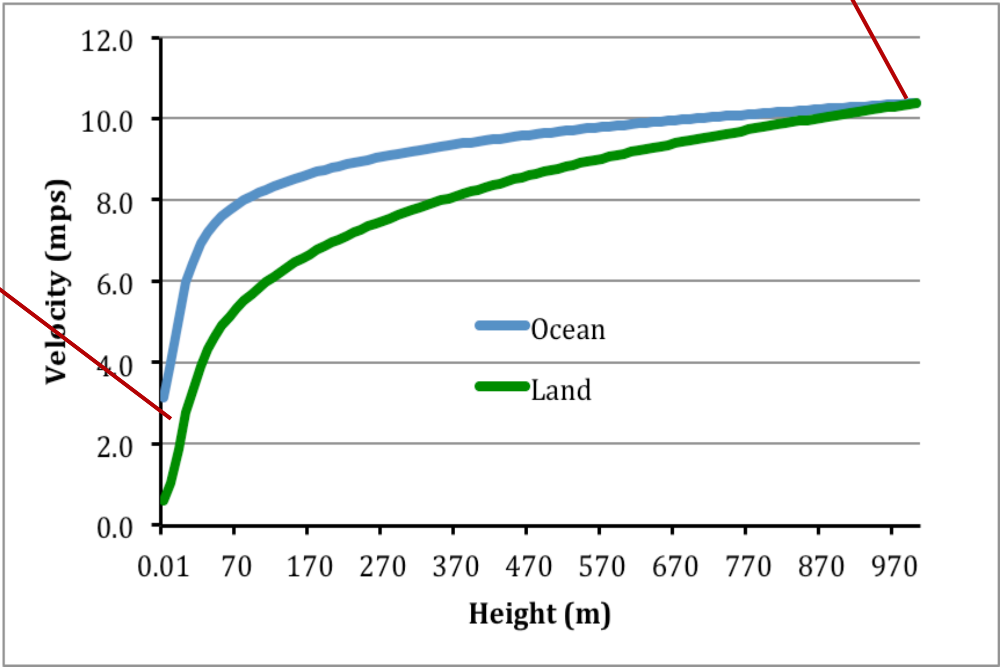


Emergy of Secondary “Renewable” Sources….

Wind...

Geostrophic Wind Speed

Land surface wind speed



The measured wind speed is used to compute the geostrophic windspeed. The assumption is that the entire wind is absorbed.

Emergy of Secondary "Renewable" Sources…. WIND

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

Where,

ρ = Air density = 1.23 kg m^{-3}

K_{GN} = geostrophic drag coefficient 1.26E-3 (over sea) and 1.64 E-3 (over land) taken from Garratt, (1992)

A= *area = 3.62 E14* m^2 *(ocean), 1.75 E14* m^2 *(land)*

T = *3.15 E7 s* y^{-1}.

V = geostrophic wind velocity (V) computed as follows

$$V = V_{ref} * (Z/Z_{ref})^a \qquad (2)$$

Where,

V_{ref} = Reference velocity = 6.64 m s^{-1} (ocean), 3.28 m s^{-1} (land)

Z_{ref} = Reference height = 10 m

Z = height for velocity V = 1000 m

α = surface roughness exponent = 0.01 (ocean), 0.25 (land) (Manwell et al., 2010)

Emergy of Secondary "Renewable" Sources…. WIND

Exergy of wind is computed using Eq.1

$E_{ocean} = ½\ \rho * K_{GN} * V^3 * A * T\ = 9.87E21\ J\ y^{-1}$.

$E_{land} = ½\ \rho * K_{GN} * V^3 * A * T\ = 5.25E21\ J\ y^{-1}$.

Tr_{wind} = 12.0 E24 seJ y^{-1}/ (9.87E21 J y^{-1} + 5.25E21 J y^{-1})
≈ 790 sej J^{-1}

Emergy of Secondary "Renewable" Sources…. RAIN

Gibbs free energy (exergy) in rain is computed by the following formula:

$$\Delta G_i = -\frac{RT}{w} ln\left({}^{c_i}/_{c_{ii}}\right)$$

Where:

R = universal gas constant; 8.3145 J mol $^{-1}$
T = temperature surface; 288.25 k
w = molecular weight of water; 18.015 g mol $^{-1}$
c_l = concentration of water in rain; 999,990 ppm
c_{ii} = concentration of water in seawater; 965,000 ppm

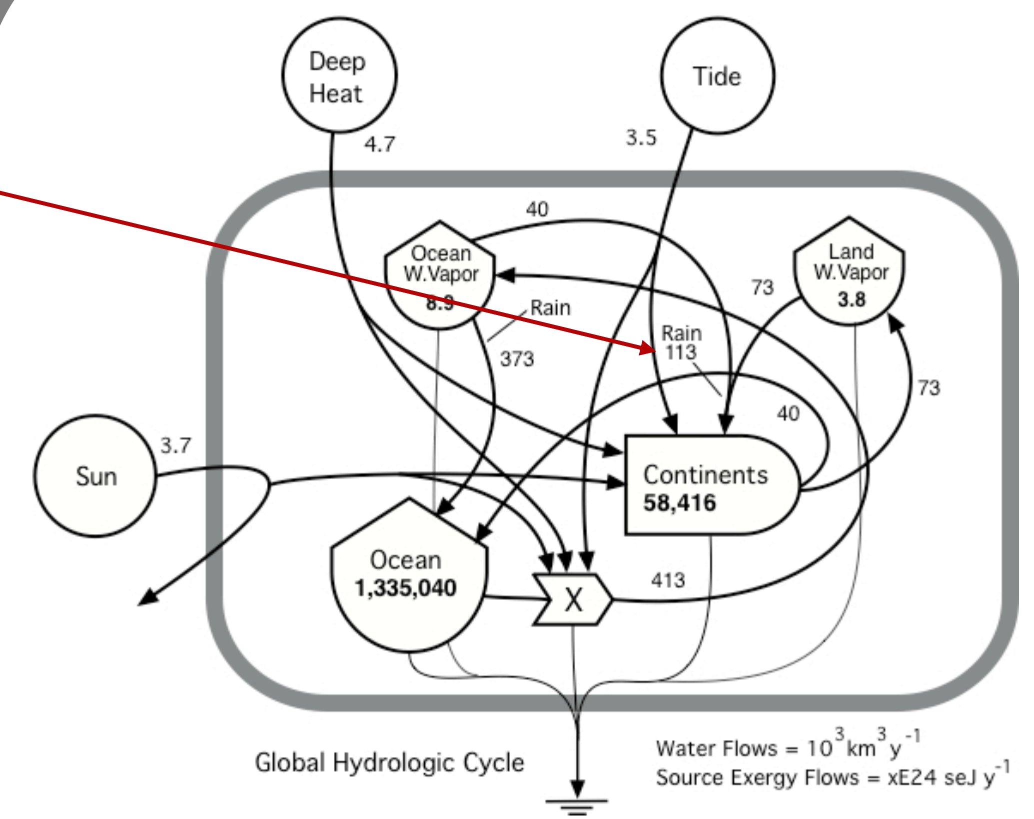
ΔG_i = 4.72 J g $^{-1}$

Emergy of Secondary "Renewable" Sources…. RAIN

Rain on Land

= 113, 000 $km^3\ yr^{-1}$

= 1.13 E20 $g\ yr^{-1}$

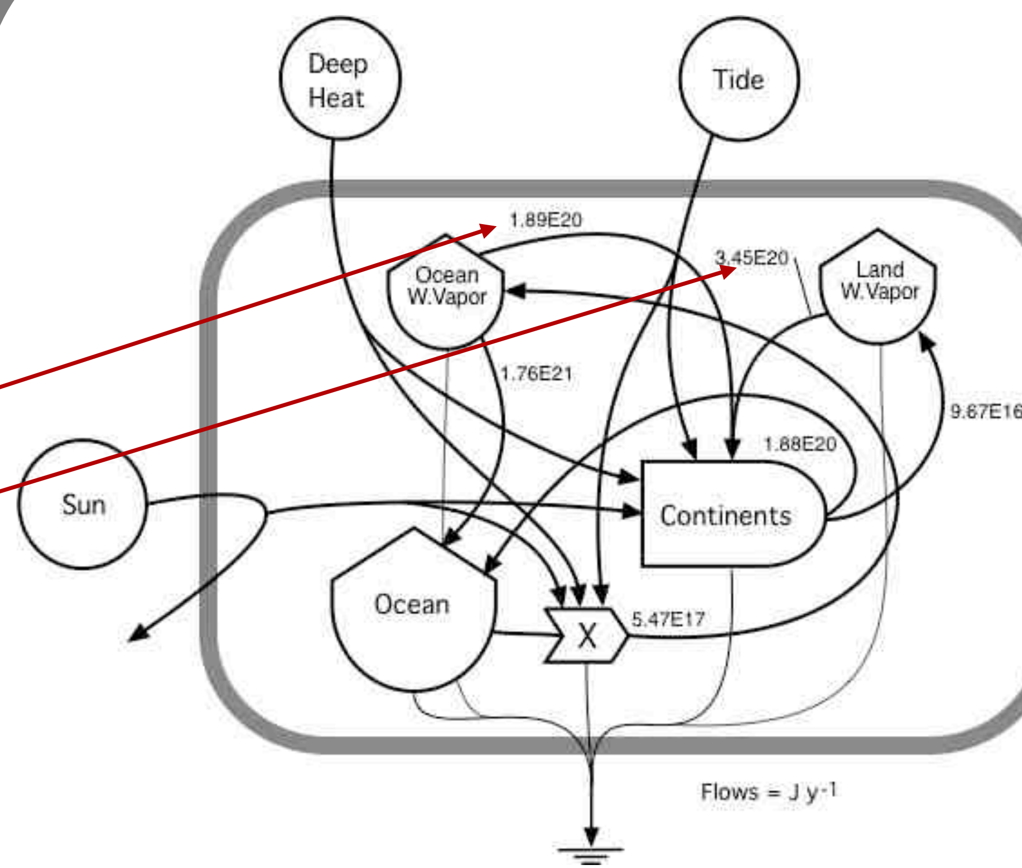


Emergy of Secondary "Renewable" Sources…. RAIN

Rainfall exergy

= 1.89 E20 + 3.45 E20

= 5.34 E20 J yr $^{-1}$



Emergy of Secondary "Renewable" Sources…. RAIN

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

Volume (km3) water

To↓	S,T,DH	Land	Ocean	L. Atmos	O. Atmos	Vector
S,T, DH	1.00	0	0	0	0	1.00
Land	5.79E+24	-113	0	73	40	0.00
Ocean	6.06E+24	40	-413	0	373	0.00
L. Atmos	4.93E+23	73	0	-73	0	0.00
O. Atmos	1.15E+24	0	413	0	-413	0.00

Available Energy

To↓	S,T,DH	Land	Ocean	L. Atmos	O. Atmos	Vector	Transformity (sej/J)
S,T, DH	1.00	0	0	0	0	1.00	1
Land	5.79E+24	-5.34E+20	0	3.45E+20	1.89E+20	1.00	**11982**
Ocean	6.06E+24	1.88E+20	-1.95E+21	0	1.76E+21	1.00	**4796**
L. Atmos	4.93E+23	9.67E+16	0	-3.45E+20	0	1.00	1433
O. Atmos	1.15E+24	0	5.47E+17	0	-1.95E+21	1.00	591

Emergy of Secondary “Renewable” Sources…. RAIN

Emergy Driving Terrestrial Rainfall

5.71 E21
2.10 E23
1.41 E22
4.47 E24
4.73 E23
4.73 E23
1.11 E24
6.28 E24 seJ yr^{-1}

Tidal emergy absorption		
Unit	% Absorbed	Emergy (seJ/y)
L. Atmos.	0.2%	5.71E+21
O. Atmos	0.4%	1.33E+22
Land	6.0%	2.10E+23
Ocean	93.5%	3.27E+24
	100.0%	3.50E+24

Geothermal emergy absorption		
Unit	% Absorbed	Emergy (seJ/y)
L. Atmos.	0.3%	1.41E+22
O. Atmos	0.7%	3.29E+22
Land	95.0%	4.47E+24
Ocean	4.0%	1.88E+23
	100.0%	4.70E+24

Solar Emergy absorption		
Unit	% Absorbed	Emergy (seJ/y)
L. Atmos.	8.9%	4.73E+23
O. Atmos	20.9%	1.10E+24
Land	21.1%	1.11E+24
Ocean	49.1%	2.60E+24
	100.0%	5.29E+24

Emergy of Secondary “Renewable” Sources…. RAIN

$Exergy_{Rain}$ = (Mass)(Gibbs energy)
= 1.13E15 g yr^{-1}*4.72 J g^{-1}
= 5.34 E20 J y^{-1}.

$Tr_{Terr\ Rain}$ = 6.3 E24 seJ y^{-1}/ 5.34 E20 J y^{-1}
≈ 12,000 sej J^{-1}

Emergy of Secondary “Renewable” Sources….

Solar transformities of SECONDARY global available energy flows			
Item	Global Solar Emergy (seJ y^{-1})	Exergy Flux (E20 J y^{-1})	UEV (sej J^{-1})
Surface wind	1.20E+25	151.20	800
Rain, Chemical potential	6.30E+24	5.33	12,000
Ocean currents	1.20E+25	1.58	75,900

Emergy of Tertiary “Renewable” Sources…RIVER goepotential.

Geopotential Energy in Rivers - The continental runoff, also known as river geopotential is computed from the average annual global river discharge (3.73 E4 $km^3\ y^{-1}$) from Dai et al. (2009) and average continental elevation, 797 m (Eakins and Sharman, 2013).

And the energy is given by:

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

Emergy of Tertiary "Renewable" Sources…RIVER goepotential.

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

$Energy_{river\ geopot} = 3.73\ E4\ km^3\ y^{-1} * 1.0E12\ kg\ km^{-3} * 9.8\ m\ s^{-2} * 797\ m$
$= 2.91\ E20\ J\ y^{-1}$

The emergy of continental rainfall (6.28 E24 seJ/yr.) is the emergy driving river discharge, rather than the GEB, thus the average transformity of river geopotential is:

$Tr_{river\ geopot} = 6.3\ E24\ seJ\ y^{-1} / 2.91\ E20\ J \approx 22{,}000\ sej\ J^{-1}$

Emergy of Tertiary “Renewable” Sources…RIVER chem. potential.

Chemical Potential Energy of River Discharge – Global River discharge is 3.73 E4 km^3 yr^{-1} (Dai et al., 2009). We assume an average dissolved solids concentration of 150 ppm, therefore a Gibbs free energy = 4.71 J g^{-1}; the total available energy in river discharges is as follows:

$$Exergy_{river\ chem.pot.} = (Mass)(Gibbs\ energy)$$
$$= 3.73\ E4\ km^3\ y^{-1} * 1E15\ g\ km^{-3} * 4.71\ J\ g^{-1}$$
$$= 1.76\ E20\ J\ y^{-1}.$$

Emergy of continental rainfall is 12.0 E24 sej y^{-1}, thus the transformity of rivers chemical potential is:

$$Tr_{river\ chem\ pot} = 6.3\ E24\ seJ\ y^{-1} / 1.76\ E20\ J \approx 35{,}800\ sej\ J^{-1}$$

Emergy of Tertiary "Renewable" Sources…WAVES.

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 wave power = 6.0 E13 W (Wang and Huang, 2004)

$$Exergy_{waves} = 6.0\ E13\ W * 3.15\ E7\ s\ y^{-1} = 1.89\ E21\ J\ y^{-1}$$

we assume only the wind energy over oceans driving ocean waves, equal to 8.13E21 J y^{-1}, yielding:

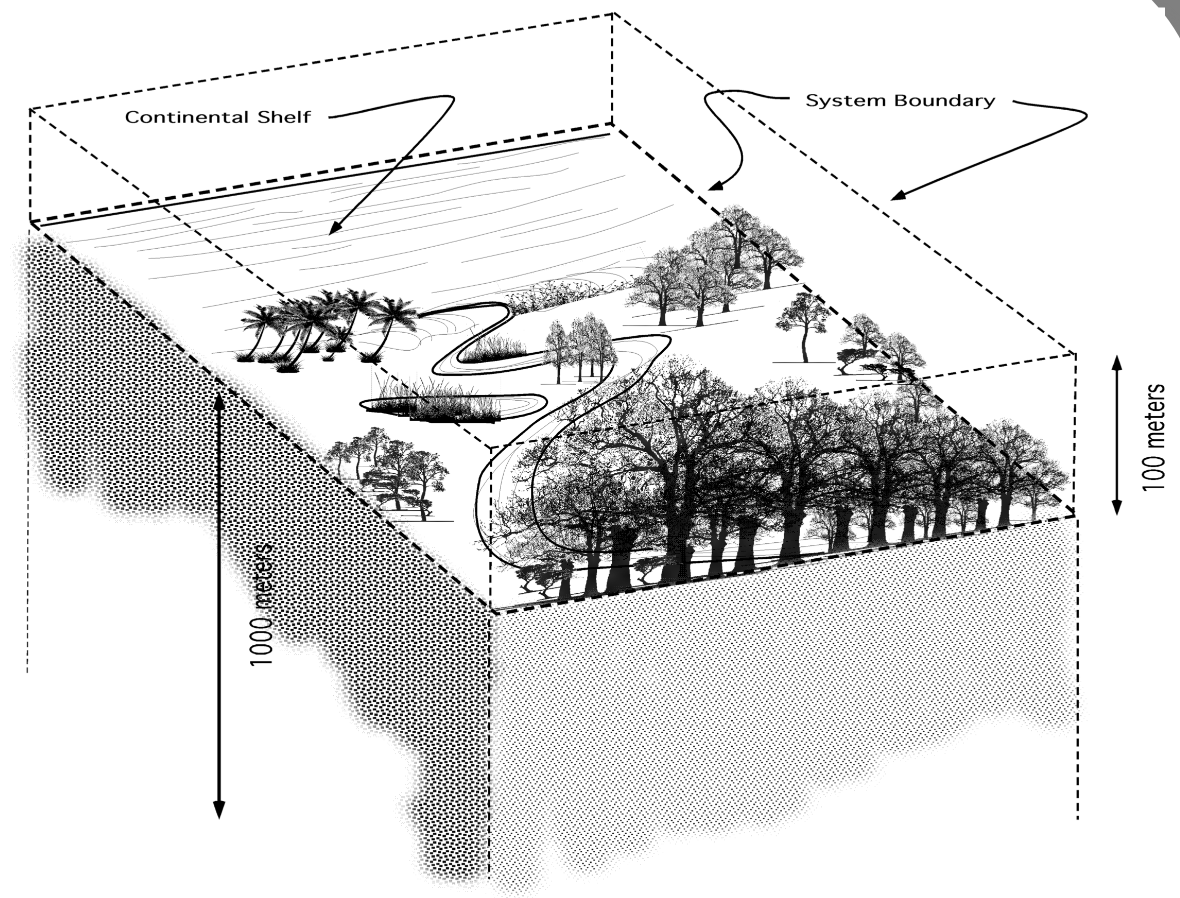
$$Emergy_{wind} = Energy_{wind} * Tr_{wind}$$
$$= 9.87\ E21\ J\ y^{-1} * 790\ sej\ J^{-1}$$
$$= 7.8\ E24\ seJ\ y^{-1}$$

$$Tr_{waves} = 7.8\ E24\ seJ\ y^{-1}/1.89\ E21\ J\ y^{--1} \approx 4{,}100\ sej\ J^{-1}$$

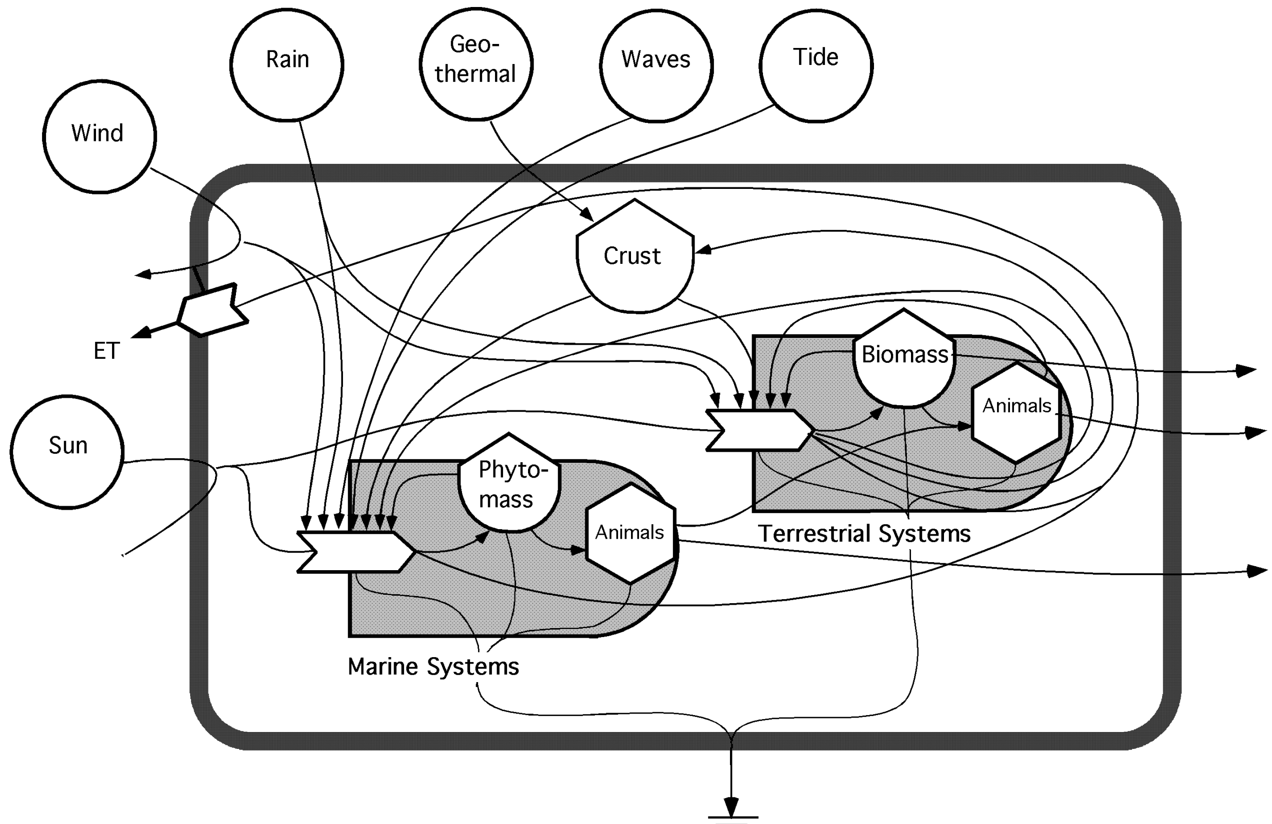
Emergy of Tertiary “Renewable” Sources….

Solar transformities of TERTIARY global available energy flows			
Item	Solar Emergy ($sej\ y^{-1}$)	Exergy Flux ($E20\ J\ y^{-1}$)	UEV ($sej\ J^{-1}$)
River flow, geopotential	6.28E+24	2.91	22,000
River flow, chemical potential	6.28E+24	1.75	35,800
Waves absorbed on shore	7.80E+24	18.90	4,100

Annual Renewable Inputs to 1km of the Earth Surface….

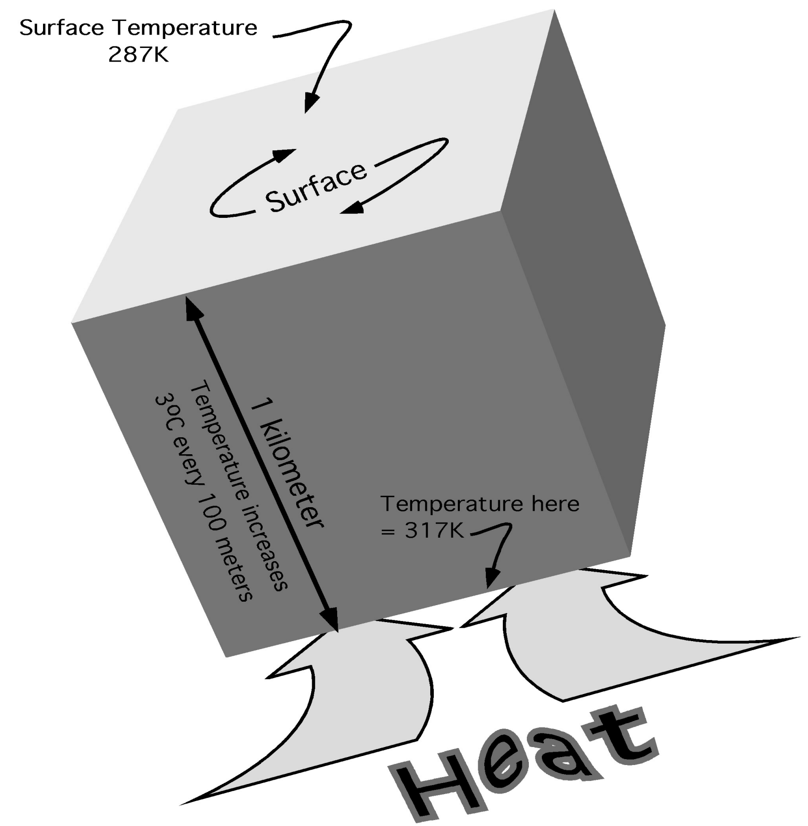


Annual Renewable Inputs to 1km of the Earth Surface….



Annual Renewable Inputs to 1km of the Earth Surface….

To compute the contribution of geothermal exergy to surface system...only 9.5% of heat is usable.



Carnot Efficiency $\eta = 1 - T_C/T_H = 9.5\%$

Where:

T_C is the COLD Temperature (287k)

T_H is the HOT Temperature (317K)

Annual Renewable Inputs to 1km of the Earth Surface….

Accounting method to avoid double accounting…

1. Sum the GEB
2. Compare to the largest of the secondary and tertiary inputs
3. The largest of these two values is the renewable emergy driving the system.

Table 4. Emergy evaluation of renewable inputs to 1 kilometer of the Earth's surface

Note	Item	Raw Units		Transformity (seJ/unit)	Solar Emergy (E15 seJ)
Global Tripartite:					
1	Sunlight	7.10E+15	J	1	7.1
2	Earth Cycle, heat flow	2.00E+11	J	4900	1.0
3	Tide, kinetic energy	1.63E+11	J	30900	5.0
	Sum of Tripartite				**13.1**
Secondary and Tertiary Sources					
4	Wind, kinetic energy	2.41E+13	J	790	19.0
5	Waves, kinetic energy	1.15E+12	J	4100	4.7
6	Rain, chemical potential	3.43E+12	J	12000	41.2
7	Runoff, geopotential	1.04E+12	J	22000	23.0
8	Runoff, chemical potential	6.28E+11	J	35800	22.5
	Largest of 2nd and 3rd sources				**41.2**

Annual Renewable Inputs to 1km of the Earth Surface….

Accounting method to avoid double accounting…

1. Sum the GEB
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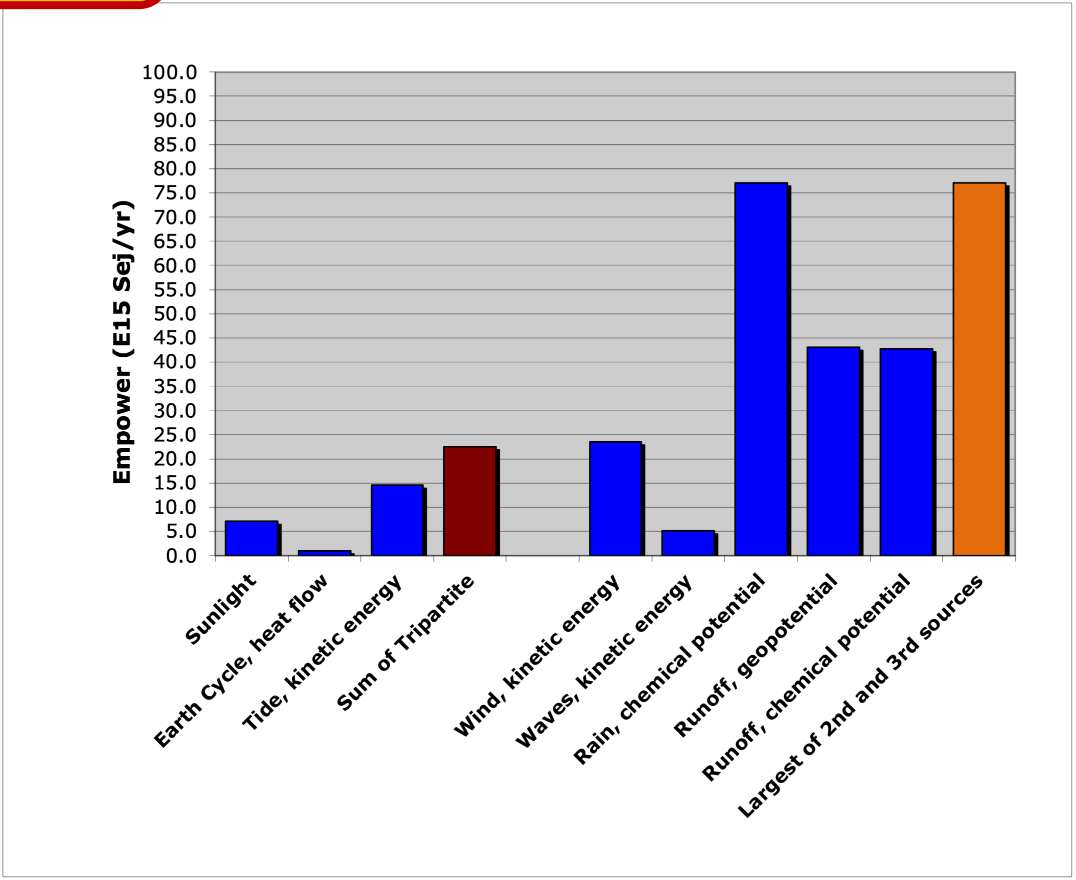
2	Earth Cycle, heat flow	2.00E+11	J	4900	1.0
3	Tide, kinetic energy	1.63E+11	J	88800	14.5
	Sum of Tripartite				**22.6**
Secondary and Tertiary Sources					
4	Wind, kinetic energy	4.53E+13	J	520	23.6
5	Waves, kinetic energy	1.15E+12	J	4400	5.0
6	Rain, chemical potential	3.43E+12	J	22470	77.1
7	Runoff, geopotential	1.04E+12	J	41240	43.0
8	Runoff, chemical potential	6.28E+11	J	68180	42.8
	Largest of 2nd and 3rd sources				**77.1**

Annual Renewable Inputs to 1km of the Earth Surface….

Emergy Signature



Questions?

Comments?

Concerns?